Multi-wavelength and Polarisation Studies
of Pulsars: the Crab, Vela, and PSR J0205+6449

A DISSERTATION SUBMITTED IN ACCORDANCE WITH THE
REQUIREMENTS FOR THE DEGREE OF DOCTOR OF
PHILOSOPHY IN THE COLLEGE OF SCIENCE

by

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December 6, 2014.
To my family
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Abstract

This thesis outlines the findings of a multi-wavelength and polarimetric study of a number of rotation-powered pulsars. Polarisation studies of pulsars are just one example of obtaining insight into the geometry of their emission regions. Such measurements provide observational constraints on the various theoretical models of the pulsar emission mechanism. Hence, it is possible to limit these competing models and find the model that best matches observations. A comparison of the optical light curves to the radio, X-ray, and $\gamma$-ray ones is also important to locate different emission regions in the neutron star magnetosphere.

The phase-averaged optical linear polarisation of the Crab nebula and pulsar was measured using observations from the HST/ACS. These findings were then compared to the results of hard-X-ray/soft-$\gamma$-ray polarisation observations of the system using INTEGRAL/IBIS. In both cases it was found that the polarisation position angle (PA) of the pulsar is aligned with its proper-motion and spin-axis. The optical polarisation of the entire inner nebula was mapped out and the polarisation of the inner synchrotron knot and wisps were determined.

From this analysis, the knot has been confirmed as the source of the highly polarised off-pulse emission seen in phase-resolved studies in the optical and $\gamma$-ray bands. No variation, at the 95% significance level, was found in the polarisation of the sources over the period of the HST/ACS observations.

The optical linear polarisation of the Vela pulsar was also studied using the HST/ACS. As in the case of the Crab, it was found that the PA of the pulsar is aligned with its proper-motion and spin-axis.

Another aim was to search for the optical counterparts to pulsars detected at other
wavelengths. To this extent, we used ground-based observations using facilities such as WHT, GTC, INT, and TNG. We used VLT data to search for the optical counterparts to two pulsars, PSR J1357−6429 and PSR J1048−5832, both of which are radio pulsars that have been detected by Fermi. Unfortunately, the optical counterparts of these pulsars were not detected.

However, a plausible optical counterpart to one particular pulsar, PSR J0205+6449, was detected using archival observations from Gemini-North. It is located at the centre of the 3C58 pulsar wind nebula (PWN). It has an optical spectral energy distribution (SED) that is pulsar like, with a power law index and $\Gamma_O = 1.9 \pm 0.5$, and a visual magnitude, $i' = 25.5$, this is consistent with that estimated via its $\gamma$-ray luminosity ($2.63 \times 10^{34}$ erg s$^{-1}$, $F_\gamma = 1.75 \pm 0.68 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$) and distance ($\sim 3$ kpc) (Abdo et al. 2012).
Declaration

The work in this thesis is based on research carried out at the Centre for Astronomy, School of Physics, National University of Ireland, Galway. No part of this thesis has been submitted elsewhere for any other degree or qualification and it is all my own work unless otherwise referenced in the text.

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“The copyright of this thesis rests with the author. No quotations from it should be published without the author’s prior written consent and information derived from it should be acknowledged.”
## Abbreviations and Acronyms

<table>
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<tr>
<td>ACS</td>
<td>Advanced Camera for Surveys</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>FOV</td>
<td>Field-of-view</td>
</tr>
<tr>
<td>GTC</td>
<td>Gran Telescopio Canarias</td>
</tr>
<tr>
<td>HST</td>
<td>Hubble Space Telescope</td>
</tr>
<tr>
<td>IBIS</td>
<td>Imager onboard the INTEGRAL Satellite</td>
</tr>
<tr>
<td>INT</td>
<td>Isaac Newton Telescope</td>
</tr>
<tr>
<td>INTEGRAL</td>
<td>International Gamma-ray Astrophysics Laboratory</td>
</tr>
<tr>
<td>IRAF</td>
<td>Image Reduction and Analysis Facility</td>
</tr>
<tr>
<td>ly</td>
<td>Light year</td>
</tr>
<tr>
<td>$M_{\odot}$</td>
<td>Solar mass</td>
</tr>
<tr>
<td>pc</td>
<td>Parsec</td>
</tr>
<tr>
<td>PSF</td>
<td>Point spread function</td>
</tr>
<tr>
<td>TNG</td>
<td>Telescopio Nazionale Galileo</td>
</tr>
<tr>
<td>VLT</td>
<td>Very Large Telescope</td>
</tr>
<tr>
<td>WFC</td>
<td>Wide Field Channel</td>
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<td>WHT</td>
<td>William Herschel Telescope</td>
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Publications


Philosophy

“The most beautiful and deepest experience a man can have is the sense of the mysterious. It is the underlying principle of religion as well as of all serious endeavour in art and science. He who never had this experience seems to me, if not dead, then at least blind. To sense that behind anything that can be experienced there is a something that our minds cannot grasp, whose beauty and sublimity reaches us only indirectly: this is religiousness. In this sense I am religious. To me it suffices to wonder at these secrets and to attempt humbly to grasp with my mind a mere image of the lofty structure of all there is”.


“What is the stars?” – Sean O’Casey, Juno & the Paycock.

“We are all in the gutter, but some of us are looking at the stars”. – Oscar Wilde.

“When you have eliminated the impossible, whatever remains, however improbable, must be the truth”.


“Not only is the universe stranger than we imagine, it is stranger than we can imagine”– Sir Arthur Stanley Eddington.
Chapter 1

Introduction

1.1 Pulsars

Pulsars are rapidly rotating magnetised neutron stars that emit beams of electromagnetic radiation from their poles, and are thought to be created in Type II supernova explosions. The outer layers of the star are blown off by the explosion. The central region collapses under gravity and the protons and electrons within the core combine to form neutrons. The neutron star retains most of the progenitor star’s angular momentum, and since it has only a small fraction of its progenitor’s radius, it is therefore formed with a very large rotation speed. The emitted radiation can only be observed when the beam of emission is pointing towards the Earth. This is what is known as the lighthouse effect, and most notably, gives rise to the pulsed nature that gives pulsars their name. The beam results from the rotational energy of the neutron star, which generates an electrical field from the movement of the very strong magnetic field, resulting in the acceleration of charged particles on the star’s surface, and the creation of an electromagnetic beam coming from the poles of the magnetic field. It appears as a pulse due to the misalignment of the rotation axis and the axis of the magnetic field of the star (Figure 1-1). This rotation slows down over time as the electromagnetic radiation is emitted.
Figure 1-1: The Pulsar geometry: The magnetic axis $\mu$ is inclined to the rotational axis $\Omega$ at an angle $\alpha$ and an observer views the phenomenon at an angle $\chi$ to $\Omega$. Image credit: Fig. 3.1 of Lorimer & Kramer (2004).
1.1.1 Discovery & Theory

The first pulsar was discovered by complete chance, as a radio pulsar, by Dame Jocelyn Bell-Burnell, then a graduate student, and her supervisor Anthony Hewish in Cambridge in 1967 (Hewish et al., 1968). Bell was using a radio telescope, tuned to a frequency of 81.5 MHz, to examine the scintillation that is observed when radio waves from distant sources, known as quasars, pass through the solar wind. She observed a radio signal (Figure 1-2) whose source passed over the fixed array of antennae every sidereal day and concluded it to be of cosmic origin (Bell-Burnell, 1983). To better resolve the signal, Bell used a faster recorder and discovered that the signal consisted of a series of regularly spaced radio pulses each 1.337 s apart. This particular pulsar was later dubbed CP 1919, the Cambridge pulsar, and is now known by a number of designators including PSR 1919+21, PSR B1919+21 and PSR J1921+2153. After finding a second similar object at another location Bell realised these must be real astronomical bodies. Bell also discovered the third and fourth radio pulsars.

![Figure 1-2: The discovery of the first pulsar, PSR B1919+21 ("CP" stands for the "Cambridge" pulsar). Image credit: Lyne & Graham-Smith (1990).](image-url)
Astronomers have now discovered over 2300\(^1\) radio pulsars and expect to discover thousands more in the coming years. The suggestion that pulsars were rotating neutron stars was put forth independently by Pacini (1968) and Gold (1969). Their work was proven beyond reasonable doubt by the discovery of the Crab pulsar, itself having a pulse period of 33 milliseconds (Lovelace et al., 1968). Most pulsars have periods between 0.25 s and 2 s. PSR J1841–0456 has the longest known period (P = 11.8 s) (Vasisht & Gotthelf, 1997) whereas PSR J1748–2446ad in the Globular cluster Terzan 5 is the fastest known pulsar (P = 0.00139 s) (Hessels et al., 2006). Timing measurements of pulsar periods challenge the accuracy of the best atomic clocks. Such precise measurements are possible due to the vast number of rotations that can be detected and measured, given their very short periods. Some young pulsars, like Crab and Vela, display glitches whereby their periods abruptly decrease by a very small amount ($\Delta P/P \approx 10^{-6}$ to $10^{-8}$). These spontaneous spin-ups are separated by uneven intervals of several years.

### 1.1.2 The Neutron star

Two years after the discovery of the neutron by James Chadwick in 1932, Baade & Zwicky (1934) published two new ideas in the history of astronomy. The first was the concept of supernova. The other was the possible existence of an object known as a “neutron star”. They stated the connection between these two proposals thus: “With all reserve we advance the view that a supernova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons”. These ideas were not taken seriously by the astronomical community until Landau (1938) aroused the interest of Oppenheimer in it as being a possibility. By the late 1960s, with the discovery of the Crab pulsar, the concept of neutron stars existing in space as the subsequent by-product of supernovae became accepted by astrophysicists.

\(^{1}\text{See catalogue and data available at www.atnf.csiro.au/research/pulsar/psrcat.}\)
1.1.2.1 Formation

Stars with masses in excess of $\sim 8 \, M_\odot$ evolve in a complex manner. In the stellar core, hydrogen is converted into helium through thermonuclear fusion. The thermal energy released from this process creates an outward pressure, which maintains the core in hydrostatic equilibrium and prevents collapse.

Once the core’s supply of hydrogen is exhausted, this outward pressure is no longer created. The core begins to collapse, causing a rise in both temperature and pressure, which becomes great enough to ignite helium and start the helium-carbon fusion cycle. This produces sufficient outward pressure to halt the collapse. The core expands and cools slightly, with a hydrogen-fusion outer layer and a hotter higher pressure helium-fusion center.

This process repeats itself several times: each time the core collapses, it is halted by the ignition of a further process involving larger nuclei and higher temperatures and pressures. Each layer is prevented from collapse by the heat and outward pressure of the fusion process in the adjacent inward layer. Also, each layer burns hotter and quicker than the previous one. The star eventually becomes layered like an onion, with the burning of more easily fused elements occurring in larger shells.

In the final stages, increasingly heavier elements with higher binding energy undergo fusion. The fusion of these heavier elements produces progressively less energy, and also at higher core energies photo-disintegration and electron capture occur, which cause further energy loss in the core, requiring a general acceleration of the fusion process to maintain hydrostatic equilibrium.

This culminates with the production of an iron core. Iron is the most stable of the elements and cannot undergo fusion, since this process is extremely endothermic. The outward pressure halting the star from collapse now ceases. It can only support the star through the degeneracy pressure of electrons in the core. If the star is large enough, then the iron core will exceed the Chandrasekhar limit ($1.4 \, M_\odot$). The forces holding atomic nuclei apart in the innermost layer of the core give way, and the core implodes due to its own mass.
The core collapses in on itself with velocities reaching up to 70,000 km s$^{-1}$, which results in a rapid increase in temperature and density. Through photo-disintegration, gamma-rays decompose iron into helium nuclei and free electrons, absorbing energy. Electrons and protons merge via electron capture, producing neutrons and electron neutrinos, which escape into space with a total energy of the order of the binding energy of the neutron star, approximately $3 \times 10^{46}$ J. This release of energy is $\sim 100$ times the amount of energy that the sun will produce over the course of its main-sequence lifetime.

The newly formed neutron core has an initial temperature of $10^{11}$ K. A further release of neutrinos cools down the neutron star, allowing a stable neutron star to form. The inner core eventually reaches a radius of about 10 km, and a density comparable to that of an atomic nucleus. Further collapse is immediately stopped by both the strong force and the degeneracy pressure of neutrons. The infalling matter, suddenly halted, rebounds, generating a shockwave that propagates outward. This is physics behind the phenomenon known as Type II supernovae.

Angular momentum is conserved during the collapse of the star, so the spin rate of the core increases significantly. Similarly, magnetic flux is conserved during a collapse since the magnetic field strength is proportional to $r^{-2}$. For example, if the Sun were to collapse down to the size of a neutron star, its magnetic field will be 10 billion times stronger.

### 1.1.2.2 Equation of state

The composition of the neutron star depends on the relationship between the internal density and pressure – the equation of state. Exact knowledge of the equation of state would allow one to determine most of the neutron star’s physical properties – for instance its radius for a given mass. The exotic nature of the highly compressed material that makes up neutron stars is different from that which can be studied in laboratories on Earth. Hence, theoretical calculations of the equation of state are uncertain. The models predict a maximum neutron star mass of about $2 \, M_{\odot}$ (Lat-
Accurate measurements of neutron star masses are obtained through timing observations of binary pulsars (Figure 1-3). However, reliable measurements of neutron star radii are difficult to obtain. For example, one can measure the thermal emission from the neutron star surface at optical and X-ray wavelengths. The observed luminosity can then be used to deduce the size of the emitting region. Even though this method provides the best estimates, the calculations are complicated by the strong gravitational fields and atmospheres of neutron stars. The neutron star’s gravity redshifts the observed thermal flux. As a consequence, one measures a temperature that is smaller than the real temperature at the surface. Hence, the inferred radius, $R_{\text{obs}}$, is larger than the intrinsic value $R$:

$$R_{\text{obs}} = \frac{R}{\sqrt{1 - \frac{2GM}{Rc^2}}} = \frac{R}{\sqrt{1 - \frac{R_S}{R}}}$$  \hspace{1cm} (1.1)$$

where $M$ and $R$ are the gravitational mass and radius of the star, $c$ is the speed of light, $G$ is Newton’s gravitational constant ($6.67 \times 10^{-11}$ N Kg$^{-2}$ m$^2$) and

$$R_S = \frac{2GM}{c^2} \approx 4.2 \text{ km} \left( \frac{M}{1.4 \text{ M}_\odot} \right).$$ \hspace{1cm} (1.2)$$

is the Schwarzschild radius.

Neutron stars are thought to have atmospheres at their surface made up of thin plasma layers (Pavlov & Shibanov, 1978; Romani, 1987; Shibanov et al., 1992). Such atmospheres significantly modify the emitted luminosity from the neutron star, resulting in a spectrum that differs from that of a simple blackbody. Likewise, a strong magnetic field can modify the surface brightness profile, leading to hotter and cooler spots that may be misinterpreted. If these effects are not taken into account properly then one will infer incorrect values for the neutron star radii.

On the grounds that the speed of sound should be smaller than the speed of light in a neutron star, Lattimer et al. (1990) and Glendenning (1992) derive a lower limit for the neutron star radius:
\[ R_{\text{min}} \approx 1.5 R_S = \frac{3GM}{c^2} = 6.2 \text{ km} \left( \frac{M}{1.4 \ M_\odot} \right). \quad (1.3) \]

Assuming that the neutron star is stable against collapse due to centrifugal forces, an upper limit can be derived:

\[ R_{\text{max}} \approx \left( \frac{GMP^2}{4\pi^2} \right)^{1/3} = 16.8 \text{ km} \left( \frac{M}{1.4 \ M_\odot} \right)^{1/3} \left( \frac{P}{\text{ms}} \right)^{2/3}. \quad (1.4) \]

Most models predict a radius in the range of 10–12 km (Lattimer & Prakash, 2001), which are well in agreement with the theoretical lower and upper limits.
Figure 1-3: The distribution of neutron star masses. These are inferred from timing observations of binary pulsars. Image credit: www.stellarcollapse.org/nsmasses and Lattimer (2012).
1.1.2.3 Structure & composition

After an equation of state, that relates the density and pressure, has been obtained, a model of the neutron star can be calculated by integrating the general-relativistic versions of the equations of stellar structure. This allows the identification of the composition of the neutron star material at different densities (Figure 1-4). Oppenheimer & Volkoff (1939) were the first to calculate a quantitative model of the neutron star. The model is as follows. The outer crust consists of heavy nuclei, in the form of either a fluid “ocean” or a solid lattice, and relativistic degenerate electrons. Near the surface, the nuclei are most likely iron. At greater depths and densities, increasingly neutron rich nuclei are found until neutron drip begins at the bottom of the outer crust \( (\rho \approx 4 \times 10^{14} \text{ Kg m}^{-3}) \). The inner crust consists of a three-part mixture of a lattice of nuclei such as krypton, a superfluid of free neutrons, and relativistic degenerate electrons. At the bottom of the crust \( \rho \approx \rho_{\text{nuc}} \), and the nuclei dissolve. The interior of the neutron star consists mainly of superfluid neutrons, with a smaller number of superfluid, superconducting protons and relativistic degenerate electrons. There may or may not be a solid core consisting of pions or other elementary particles. The density at the center of a 1.4 M\(_{\odot}\) neutron star is about \( 10^{18} \text{ Kg m}^{-3} \).

1.1.2.4 Evidence for Core-Collapse Origin

Well over half of all stars are members of multiple star systems. However, only a small fraction of pulsars are known to belong to binary systems. Furthermore, pulsars move through space much faster than 1,000 km s\(^{-1}\). Both of these details are consistent with a supernova origin for pulsars. This is explained by the fact that a core-collapse supernova explosion is likely to be spherically asymmetric (Lyne & Lorimer, 1994), so the forming pulsar could receive a kick that may eject it from the binary system that it may have been initially part of. Moreover, such a kick could propel the pulsar at high speed away from its formation point. In addition to this, just like O and B stars, pulsars are concentrated along the Galactic plane, and this also points in favour of a core-collapse supernova origin for neutron stars.
1.1.2.5 Types of Neutron star

Pulsars are not the only kind of neutron star that exist. A variety of different species have now been identified. One group is known as magnetars. These neutron stars have enormous magnetic field strengths, inferred from spin-down to be in the range of $10^{14} - 10^{16}$ G. There are two sub-groups of magnetars, Anomalous X-ray pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs), which were originally thought to be separate and unrelated sources. The energy source of these stars is not from the spin-down alone but by the release of energy from their unprecedented magnetic fields. For a detailed review of magnetars, see Woods & Thompson (2006). There is also a group of intermittent radio pulsars characterised by their brief radio bursts with durations between 2 and 30 ms. They are called Rotating Radio Transients (RRATs). The average time between bursts ranges from about 4 minutes to 3 hours. The first discoveries were made by McLaughlin et al. (2006) and there are about 12 known objects. Several hundred glitches have been observed in radio pulsars and magnetars whereby the star undergoes a sudden spin-up (increase in an angular velocity). This is due possibly to the interior superfluid rotating faster than the crust. Archibald
et al. (2013) report the detection of an “anti-glitch ”from a magnetar – a sudden spin-down.

1.2 Population Distribution

The best way of describing the general population distribution of pulsars is through a $P-\dot{P}$ diagram (Figure 1-5). This is a logarithmic plot of pulse period derivative, $\dot{P}$, as a function of pulse period, $P$. Both $P$ and $\dot{P}$ can be obtained through high levels of precision timing measurements and provide insight into the spin evolution of neutron stars. For this reason the $P-\dot{P}$ diagram is often referred to as the pulsar equivalent of the Hertzsprung-Russell diagram. Using the canonical pulsar model, one is able to represent lines of constant age and magnetic fields. The diagram clearly shows the distinction between “normal” pulsars and millisecond pulsars. The differences are due to the different ages and magnetic field strengths of these two populations. The plot shows that “normal” pulsars reside at the top right of the plot. These are young ($\sim 10^3$ yrs) with strong magnetic fields ($B \approx 10^{12}$ G), large pulse period ($P > 0.1$ s), and large period derivative. Whereas, located at the bottom left are millisecond pulsars. These are much older ($\geq 10^4$ yrs) with weaker magnetic fields ($B \approx 10^8$ G), smaller pulse period ($\sim$ ms), and period derivative. Indeed, a plot of the distribution of pulse periods for all detected pulsars is bimodal, again revealing the two groups (Figure 1-6). The vast majority of pulsars are located in or near to the galactic plane, with approximately 85% of pulsars lying within $\pm 20^\circ$ latitude of the galactic plane (Figure 1-7).
Figure 1-5: The P- $\dot{P}$ diagram shows the nature and evolution of detected pulsars. It is a plot of the absolute value of the time derivative of pulse period, $\dot{P}$, versus pulse period, P. Special classes of pulsars are depicted separately: Normal pulsars, Anomalous X-ray pulsars (AXP) or Soft Gamma-ray Repeaters with pulsations, high-energy pulsars with emitted frequencies between radio and infrared or higher, and binary pulsars. Figure generated using data available from http://www.atnf.csiro.au/research/pulsar/psrcat/ – see Manchester et al. (2005).
Figure 1-6: The distribution of periods for 1968 pulsars. Figure generated using data available from http://www.atnf.csiro.au/research/pulsar/psrcat/ – see Manchester et al. (2005).

Figure 1-7: The galactic distribution of the detected pulsars. The vast majority of pulsars are located in or near to the galactic plane, with approximately 85% of pulsars lying within $\pm 20^\circ$ latitude of the galactic plane. Image credit: Fig. 1 of Taylor et al. (1993).
1.3 Binary Systems

An important additional difference between normal pulsars and millisecond pulsars is binarity. Orbiting binary systems are observed for about 80% of all millisecond pulsars but less than 1% of all normal pulsars. The orbiting companion star is either a white dwarf, main-sequence star, or another neutron star. The existence of binary pulsars originates from an evolutionary scenario, which begins with two main-sequence stars (Figure 1-8). The more massive primary star evolves first and eventually detonates as a supernova to form a neutron star. The high velocity imparted to the neutron star due to the conservation of angular momentum, and the significant mass loss during the supernova are enough to disrupt most (in excess of 90%) binary systems (Radhakrishnan & Shukre, 1985). The neutron stars that do remain bound to their companions spin down as normal pulsars for $10^6$–$10^7$ yrs. Later, the smaller secondary star comes to the end of its main-sequence life and turns into a red giant star. The gravitational field of the neutron star attracts matter from the red giant star, thus forming an accretion disk. The system is then visible as an X-ray binary. The accretion of matter transfers orbital angular momentum to the neutron star, thereby spinning it up to much shorter periods. The mass of the secondary star determines the ultimate fate of the binary system. Hulse & Taylor (1975) discovered the first binary pulsar system. Lyne et al. (1987) discovered the first millisecond pulsar, PSR B1821–24, in a globular cluster (M28). To date a total of 144 pulsars have been detected in 28 globular clusters.
1.4 Pulsar Models

The two main pulsar models, the canonical model and the standard model, are now presented and discussed. The canonical model describes the energetics of the pulsar, whereas the standard model describes the nature of the environment surrounding it.

1.4.1 Canonical Model

This model is used to describe pulsar energetics. It relates the pulse period and pulse period derivative to the magnetic field. It was developed by the following authors: Pacini (1968), Gold (1969), and Ostriker & Gunn (1969). Pacini (1967) discussed the energetics of the neutron star by assuming the conservation of magnetic flux in the formation of the neutron star from a supernova, which results in a misaligned rapidly rotating dipolar magnetic field. The rotation of the neutron star results in the radiation of a monochromatic low frequency electromagnetic wave, whose intensity is given by the dipole approximation:

\[
I = \frac{2 m^2 \sin^2 \Theta \Omega^4}{c^3}
\]  

(1.5)

where \( m \) is the magnetic dipole moment and \( \Omega \) is the rotation frequency of the pulsar (\( \Omega = \frac{2\pi}{P} \), where \( P \) is the pulsar’s period of rotation).

\[
|m| = \frac{B_p R^3}{2}
\]  

(1.6)

Through studies of the Crab pulsar it was found that the total amount of energy stored rotationally and magnetically could power the Crab nebula. In 1968 Pacini wrote a paper containing a more detailed analysis, showing a release of rotational energy from the star. It also placed an upper limit of \( \sim 10^{12} \) G on the surface magnetic field of the pulsar, in agreement with flux conservation. Gunn & Ostriker (1969) built upon this model so as to relate the angular momentum carried by the dipole radiation to
the radiation loss. The dipole radiation carries angular momentum, \(L\), such that:

\[
\frac{dL}{dt} = \frac{1}{\Omega} \frac{dE}{dt}
\]  

(1.7)

1.4.1.1 Spin evolution

As mentioned, pulse periods increase with time. This is because the emission is powered by the rotational kinetic energy of the neutron star. The rate of loss of rotational kinetic energy:

\[
\dot{E} \equiv -\frac{dE}{dt} = -\frac{d(I\Omega^2/2)}{dt} = -I\Omega\dot{\Omega} = 4I\dot{P}P^{-3}
\]

(1.8)

where \(I\) is the moment of inertia and \(\dot{E}\) is called the spin down luminosity and it represents the total power output of the neutron star. For the canonical moment of inertia \(I = 10^{45} \text{ g cm}^{-2}\):

\[
\dot{E} \approx 3.95 \times 10^{31} \text{ erg s}^{-1} \left( \frac{\dot{P}}{10^{-15}} \right) \left( \frac{P}{s} \right)^{-3}
\]

(1.9)

1.4.1.2 Age estimate

The spin-down model, expressed in terms of pulse period, becomes \(\dot{P} = K P^{2-n}\), a first-order differential equation, which when integrated and assuming \(K\) is a constant, and a braking index \(n \neq 1\):

\[
T = \frac{P}{(n - 1) \dot{P}} \left( 1 - \left( \frac{P_0}{P} \right)^{n-1} \right)
\]

(1.10)

where \(P_0\) is the spin period at birth. Using the assumption that the period at birth is much shorter than the present value and that the spin-down is due to magnetic dipole radiation \((n = 3)\), the characteristic age of the pulsar is given by:
\[ \tau_c \equiv \frac{P}{2\dot{P}} \approx 15.8 \text{ Myr} \left( \frac{P}{s} \right) \left( \frac{\dot{P}}{10^{-15}} \right)^{-1}. \]  

(1.11)

One must note that this does not provide an exact age estimate because, for many pulsars, the assumption of a breaking index of \( n = 3 \) is not true. Measured values of breaking index range from \( n = 1.4 \) to \( n = 2.9 \) (Kaspi & Helfand, 2002). For example, the Crab pulsar has a characteristic age of 1,240 yrs, whereas the actual age of the pulsar is about 950 yrs from its connection to SN 1054. The youngest radio pulsar, PSR J0205+6449, associated with SN 1181 has a value of \( \tau_c = 5,370 \text{ yr} \).

1.4.1.3 Birth period

One can get an estimate of the period of the pulsar by rearranging equation (1.10):

\[ P_0 = P \left( 1 - \frac{(n - 1)}{2} \frac{T}{\tau_c} \right)^{\frac{1}{n-1}}. \]  

(1.12)

If the braking index of the pulsar has been measured, and if the true age of the pulsar is known independently (either through association with a historical supernova or through the expansion of the supernova remnant), then the birth period can be determined with reasonable accuracy. For example, the estimated birth period of the Crab pulsar is \( P_0 = 19 \text{ ms} \) (Lyne et al., 1993).

1.4.2 Standard Model

This model describes the environment around the neutron star itself – the magnetosphere. It assumes that pulsars are rapidly rotating, strongly magnetised neutron stars which themselves have a high conductivity. According to classical electrodynamics, the angular rotation of the neutron star \( \Omega \) will induce an electric field, \( E \), satisfying Ohm’s law:
E + \frac{1}{c} (\Omega \times v) \times B = 0 \quad (1.13)

Goldreich & Julian (1969) proposed that the resultant electrostatic forces are large enough to overcome the gravitational and electrostatic binding forces at the stellar surface. Hence, they are able to tear particles from the neutron star surface and release them into the field structure surrounding the stellar environment (Figure 1-9). This model assumes an aligned rotation and magnetic axes, and neglects the central charge of the neutron star and return current. Ignoring particle inertia and using the assumption that enough plasma is generated to satisfy Ohm’s law in the magnetosphere, the charge density in the magnetosphere, known as the Goldreich-Julian density, is given as:

\[ \rho_{GJ} = \frac{1}{4\pi} \nabla E = -\frac{\Omega \cdot B}{2\pi c}. \quad (1.14) \]

The pulsar magnetosphere is taken to co-rotate with the pulsar out to the light cylinder \( R_{LC} = cP/2\pi \) – the radial distance at which the co-rotational velocity tends to the speed of light. The plasma that fills the magnetosphere co-rotates with the magnetosphere and flows along the open field lines (those that extend beyond the light cylinder), where it can leave the magnetosphere and possibly contribute towards a magnetised pulsar wind. It is believed that the magnetic field surrounding the neutron star is of a dipole nature. Dipolar field lines obey the following relationship in spherical coordinates:

\[ \frac{\sin^2 \Theta}{r} = L. \quad (1.15) \]

In the case of an aligned rotator, an estimation of the polar cap opening angle as a function of the rotation frequency, \( \Omega \), as follows:
\[ \Theta_{pc} = \sin^{-1} \left( \frac{R_{ns}}{R_{LC}} \right)^{\frac{1}{2}} = \sin^{-1} \left( \frac{\Omega R_{ns}}{c} \right)^{\frac{1}{2}} \]  

(1.16)

where \( R_{ns} \) is the radius of the neutron star and \( R_{LC} \) is the radius of the light cylinder. The radius of the polar cap is estimated as:

\[ r_{pc} \approx R_{ns} \Theta_{pc} \approx \left( \frac{\Omega^2 R_{ns}^3}{c} \right)^{\frac{1}{2}}. \]  

(1.17)

The particle energy loss rate is calculated thus,

\[ \dot{N}_{pc} = \frac{\pi r_{pc}^2 \rho GJ}{e} \approx \frac{\Omega^2 R_{ns}^3 B_{ns}}{2ec} \]  

(1.18)

where \( B_{ns} \) is the surface magnetic field of the neutron star. The potential difference between the centre and the edge of the polar cap is given below:

\[ \Delta \Phi = \int E \cdot ds \approx \frac{1}{2} \left( \frac{\Omega R_{ns}}{c} \right)^2 R_{ns} B_{ns}. \]  

(1.19)

The pulsar ‘action’ is thought to occur within the open volume of the magnetosphere. Most emission theories and models conform to this viewpoint. To summarise, the standard model of pulsars is that of a rapidly rotating neutron star residing in a plasma filled magnetosphere with a magnetic dipole field inclined at an angle \( \alpha \) to the axis of rotation \( \Omega \). The whole action is viewed by an observer located at an angle \( \chi \) to \( \Omega \).
1.5 Energy Emission Models

These models describe where in the pulsar magnetosphere the charged particle acceleration that leads to the emission of radiation emanates from. The high-energy emission models include the polar-cap, outer-gap, two-pole caustic and slot-gap models. All pulsar emission models involve creation of electron-positron pairs above the magnetic poles of isolated, rotating magnetised neutron stars.

1.5.1 Polar-cap model

The origins of this particular model lie in the works of Sturrock (1971) and Ruderman & Sutherland (1975). Charged particles are accelerated due to a large residual electric field, reaching relativistic energies. Polar-cap models divide according to whether the particles originate in the space charged limited flow or from within a vacuum gap (see Figure 1-10). Sturrock (1971) proposed the free emission of particles of either sign from the neutron star surface with the assumption that the neutron star surface temperature ($10^4$–$10^6$ K) is greater than the ion or electron thermal emission.
temperature supplying the co-rotation charge. This is a space charge limited flow model. It assumes that the electric field is substantially radial for distances, $x$, than the radius of the polar cap above the location of the polar cap, $x < r_{pc}$, and is transverse to the magnetic field for $x > r_{pc}$. Moving along the curved magnetic field lines these particles produce gamma-ray photons either by emission on curved field lines (Ruderman & Sutherland, 1975; Arons, 1983) or by inverse Compton scattering on lower energy photons (Daugherty & Harding, 1986). As a result of the presence of the strong magnetic field, the gamma-ray photons can pair produce, forming magnetic one-photon electron-positron pair creation if the photon energy exceeds twice the rest mass of an electron ($E_\gamma \geq 2m_ec^2$) (Erber, 1966).

Ruderman & Sutherland (1975) devised an alternative approach with the assumption that the neutron star surface temperature does not exceed the ion binding temperature. The result is trapped ions. The co-rotation surface charge cannot now be supplied. A vacuum gap and an $E_\parallel$ at the surface are both formed. The vacuum grows and it is proposed that at some altitude electron-positron pair formation occurs in the strong magnetic field with these $e^-/e^+$ being accelerated and emitting gamma rays which in turn pair-produce thus emitting a pair creation cascade which shorts out the $E_\parallel$ at a specific height. It also supplies the magnetosphere with its co-rotation charge. Both of these models assume an accelerating potential which terminates at a height, $h$, above the polar cap surface where $h \sim r_{pc}$. The acceleration mechanism is strictly bound by the height of the vacuum gap which localises the rotational energy to the immediate vicinity of the polar cap with any emission a result of radiation processes for particles moving within and beyond the acceleration zone. Therefore, it is this region that is the primary location for subsequent polar-cap high-energy emission models.

The pair cascade model is essential to the plasma production and the high-energy radiation emission. The following are the various polar-cap pair cascade mechanisms proposed: for particles accelerated to Lorentz $\gamma$ factors of $10^2$–$10^6$, inverse Compton scattering from thermal X-rays from the neutron star surface is the main source of the $\gamma$-ray emission, whereas curvature radiation is the dominant radiative mechanism.
for Lorentz $\gamma$ factors $\geq 10^6$. It is found that for all but pulsars with very high magnetic fields (Harding et al., 2003) that inverse Compton pair formation fronts will not produce enough pairs to completely screen the $E_\parallel$. The result of which is Lorentz factors of $\gamma \sim 10^7$ which is now sufficient to produce a curvature radiation pair formation front which generates enough pairs to completely screen $E_\parallel$. Curvature radiation limits the particle acceleration and determines the high energy emission luminosity.

The polar-cap models of high-energy pulsar emission have had some relative successes. Sturrock (1971) was able to explain the luminosity spectrum of CP1919 and the radio luminosity spectrum of the Crab pulsar. However, inherent problems still remain. The models have difficulty in explaining any offset between the different emission bands peak arrival phases of PSR B1706−44, PSR B1951+32, and Vela. Moreover, the emission profiles produced by this model are inherently symmetric due to the observer’s line-of-sight traversing the cone of emission. This symmetry is not seen observationally. Another point worth noting is that the different emission bands within the Crab pulsar emission profile resemble each other closely throughout the pulsar’s emission spectrum. In contrast to this, in the case of the Vela pulsar, this resemblance is not shared across the bands of the emission spectrum. An understanding of the reasons behind these observed trends will be invaluable in developing an overall, self-consistent model of pulsar emission.

Through Fermi-LAT observations of gamma-ray pulsars, the polar-cap model has been effectively ruled out for high-energy emission. Fermi-LAT observations of the phase-averaged spectrum of the Vela pulsar have ruled out a super-exponential cutoff in the spectrum (Abdo et al., 2009), a prediction of the polar-cap models due to magnetic pair production attenuation (Daugherty & Harding, 1996). It is now believed that the gamma rays are formed high above the neutron star. Current models place the gamma-ray emission along the boundary between open and closed field lines. This leaves the outer-gap (Holloway, 1975), slot-gap (Arons, 1983) and variations of the striped pulsar wind, as the prime candidates for a theory of high-energy pulsar emission.
Figure 1-10: The polar-cap model. The figure shows space-charge limited flow (Sturrock, 1971) and vacuum gap accelerators (Ruderman & Sutherland, 1975) above a pulsar polar cap. $T_s$ is the neutron star surface temperature and $T_i,e$ are the ion or electron thermionic temperatures. Image credit: Fig. 1 of Harding (2007).

1.5.2 Outer-gap model

The outer gap scenario originates from Holloway (1975). The existence of gaps is also proposed for the outer magnetosphere, near the location of the null line $\Omega \cdot B = 0$, which separates the space charges of different sign. These vacuum gaps are devoid of any charge, possess $E_\parallel$ (due to the lack of charged particles to screen the electric field), and act as regions of potential particle acceleration. The vacuum gaps stretch outwards from the null charge surface to as far as the light cylinder radius (Figure 1-11). In order to generate the necessary accelerating potential, the charge density within these gaps must equal zero. If this were not the case, and there was charge available for re-distribution, then the charge would re-distribute itself and regions of large $E \cdot B \neq 0$ would not be sustainable.

Through assuming the standard pulsar model, Holloway (1975) point out that a vacuum gap is formed because charges escaping along the open field lines cannot be replenished from below and if left unchecked all the plasma beyond the null charge surface would flow out through the light cylinder giving a potential drop along $B$ resulting in an open circuit with no flow of current. Any emission produced is beamed
tangential to the local field lines thus forming four potential fan beams. These have emission directed both towards and away from the pulsar as charged particles of differing sign are accelerated in opposite directions and the two longer gaps are expected to emit more radiation than the two shorter gaps. The modern form of the outer gap model lies in the work of Cheng et al. (1986). The model involves particle acceleration, high-energy emission, and pair production. They proposed a mechanism which limits gap growth and introduces particles to the gap which would result in both self-sustaining in current flow and the emission of energy. In this scenario the only stable gaps that form within the magnetosphere are along the boundary with the closed volume and extend from the null charge surface out as far as the light cylinder radius.
Figure 1-11: The outer-gap model. The neutron star obliquely rotates around the vertical axis with magnetic inclination angle $\alpha$. The thin solid curves denote the magnetic field lines, while the dashed straight line denotes the null-charge surface, on which the magnetic field lines become perpendicular to the rotation axis. Outside the light cylinder, plasmas that are frozen to the magnetic field lines can only migrate outward (as a pulsar wind) because of the causality requirement in special relativity. The light-cylinder radius, becomes typically a few or several hundred neutron-star radii for young pulsars. In modern outer-gap models, it is proved that the outer gap extends between the stellar surface (because of a negative charge density in the lower altitudes) and the vicinity of the light cylinder (because of a positive charge density in the higher altitudes). Image credit: Fig. 1 of Hirotani (2013).
1.5.3 Two-pole caustic model

This is a geometrical emission model, developed by Dyks & Rudak (2003), to explain the high-energy light curves of rotation powered pulsars. They considered high-energy radiation from within the pulsar magnetosphere in regions confined to the surface of the last open magnetic field lines but extending from the neutron star surface out to the light cylinder (Figure 1-12). The gap is thin and is confined to the surface of the last open magnetic field lines, and the photon emissivity is uniform everywhere within the gap region. Included in the model are the special relativistic effects of the aberration of photon emission directions and the light time travel delays. This causes cancellation of phase shifts of photons emitted at different altitudes within some regions of the magnetosphere, which compresses the emission in the observers frame to a small range of phase. Therefore the light curves that result from this model are dominated by strong peaks that are of caustic origin. The caustic peaks of this model have the same origin as those that are formed as a result of outward emission above the null charge surface in the outer-gap models.

It is assumed that the inner boundary of the gap extends to the polar cap for all azimuthal angles. This means that the observer detects radiation emanating from both magnetic poles, in contrast to the outer-gap model in which the observer can only view high-energy emission from one pole. Hence, the two prominent peaks in the resulting light curve are associated with different magnetic poles. For each magnetic pole, two caustic peaks are formed in the plane. These are the dominant caustic and the subdominant caustic. The dominant caustic, the stronger of the two, is associated with the trailing part of the emission region. Whereas, the subdominant caustic is associated with the leading part of the emission region. Single peak gamma-ray light curves, such as that observed for B1509–58 (Kuiper et al., 1999), can be produced by this model using small viewing angles. This model is better at reproducing the observed geometrical features of high-energy light curves of pulsars than both the polar-cap model and the outer-gap model. The main features of the model are as follows: the light curve consists of two peaks, the peaks possess well developed wings,
there is a bridge emission component (inter pulse), there is a non-vanishing off pulse emission level and the radio pulse (precursor) arrives ahead of the leading peak.

1.5.4 Slot-gap model

This model is a modification of the polar-cap model. It was developed by Arons (1983), after noting the possibility of a high-altitude acceleration region, based on the findings of previous work by Arons & Scharlemann (1979), that the pair formation front (PFF) occurs at higher altitudes as the magnetic co-latitude approaches the last open field lines where the electric field vanishes (Figure 1-13). The PFF curves upward, approaching infinity and becomes asymptotically tangent to the last open field lines. If the electric field is screened above the PFF, a slot is formed between the pair plasma and the closed regions of the magnetosphere. The model differs from the polar-cap model in that the particles accelerated in the “slot-gap” reach altitudes of several stellar radii before initiating pair cascades. The slot-gap dominates the particle luminosity in short-period, dipolar objects while the surface gap is the better energy source for longer period objects with distorted surface fields. Another advantage that
this model has over the polar-cap model is the prediction of the emitted beam size from the neutron star surface. Those predicted by the polar-cap are too small to match the wide pulse profiles that are observed. While in the slot-gap model the emission beam is wide enough.

Modern versions of this model are also formulated (Harding & Muslimov, 2003). These incorporate general relativistic frame dragging (Muslimov & Tsygan, 1992) that allows particle acceleration in ‘favourable’ and ‘unfavourable’ curved field lines and also at all inclination angles. The radiation from pair cascades occurring along the interior edge of the slot gap is considered. The cascade radiation emission beam from the slot gap is a hollow cone centred on the magnetic axis. Muslimov & Harding (2004) extended this lower-altitude model (within a few stellar radii) to much higher altitudes (approaching the light cylinder) and found that the curvature radiation of the primary particles forms patterns as indicated in the two-pole caustic model (Dyks & Rudak, 2003).

The predicted fluxes are in agreement with observations, though the total luminosity is lower than that from the polar cap. This is because the slot gap has a small solid angle. Slot gaps are capable of putting sufficient energy into hard gamma-ray emission to explain the photon energetics of the Crab and Vela pulsars. A problem inherent with the model lies in the size of the inclination angles. The model requires small magnetic inclination angles that are comparable to the emission beam opening angle (100–200°). Considering the Chandra X-ray image of the Crab nebula; if the torus is orthogonal to the spin-axis, then the viewing angle is approximately 60°. Moreover, observations of other, more recently discovered pulsars, show small inclination angles (Harding et al., 2003).
Figure 1-13: The slot-gap model. The figure shows the outer boundary of the open field line region (where $E_{\parallel} = 0$) and the curved shape of the pair formation front (PFF) which asymptotically approaches the boundary at high altitude. The slot-gap exists between the pair plasma which results from the pair cascades above the PFF and the outer boundary. A narrow beam of high-energy emission originates from the low-altitude cascade on field lines interior to the slot-gap. A broader, hollow-cone beam originates from the high-altitude cascade above the interior edge of the slot gap. $\Delta \xi_{SG}$ is the slot gap thickness and $\theta_{0,SG}$ is the colatitude at the center of the slot-gap. Image credit: Fig. 1 of Harding & Muslimov (2003).
1.5.5 Striped-wind model

This model was introduced by Coroniti (1990) and Michel (1994). The emission comes from outside the light cylinder and relativistic beaming effects are responsible for the phase coherence of this radiation (Figure 1-14). The model from Pétri & Kirk (2005) agrees well with recent phase-resolved optical polarisation observations from the Crab pulsar (Slowikowska et al., 2009). Recently, Pétri (2011) developed a model that describes both the radio and high-energy emission. In this approach, a time-dependent emissivity in the striped-wind model is combined with a simple version of the polar cap emission model. The corresponding radio and gamma-ray light curves are then computed and compared to observations. They found that the phase lag and gamma-ray peak separation predicted by the model compares favourably with pulsars in the Fermi catalogue. An overestimate of the time lag by roughly 0.1 in phase for many pulsars suggests that the model requires more boundary conditions. This might be explained by magnetic field line bending and/or plasma flow within the magnetosphere.
Figure 1-14: The Striped-wind model. The magnetic topology of a relativistic MHD wind from an oblique rotator. Near the rotational equator, the toroidal magnetic field has an alternating polarity. The magnetic stripes are separated by thin current sheets. Away from the equator, the magnetic flux in the toward and away stripes is unequal if the dipole obliquity is not equal to $\pi/2$. Opposite flux regions of an initially high $\sigma$ wind slowly annihilate, this results in a low $\sigma$, thermally hot wind at large distances. Near the rotational poles, the toroidal magnetic field is helically wound, since the flux originates in a single polar cap. Image credit: Fig. 1 of Coroniti (1990).
1.6 Conclusions on pulsars

Though the field of pulsar astronomy is still in its infancy even with almost 50 years of research, it is at present enjoying a productive stage. To date astronomers have catalogued over 2,300 pulsars, and new technologies are continually emerging to study these objects in greater depth. Pulsars are detected and studied across the entire electromagnetic spectrum, from radio waves to gamma rays, and these multi-wavelength studies are crucial.

However, much uncertainty remains about the exact nature of pulsars. Few astronomical objects offer such a vast amount of observational data and still are lacking a concrete theoretical description. There has been no convincing model to explain their behaviour, the processes which create them, and the exact source of their emission. Some questions to be answered include the following. What is the structure and composition of the interior of the neutron star? To this end, an exact neutron star equation of state is required. Moreover, what is the nature of the neutron star magnetosphere; magnetic and electric fields? What are plasma densities involved and are there regions of additional pair creation? What radiation processes are involved? Where are the radio and high-energy emissions generated? Pulsars can also be used to test the theory of General Relativity and search for evidence of violation of Lorentz invariance. Solving these problems would not only further our knowledge and understanding of neutron stars but also fundamental physics at its most extreme.
A summary of the key findings of observations of pulsars across the spectrum, from the radio to gamma rays, is given in Chapter 2. This chapter also includes a brief overview of the Crab nebula and pulsar system.

Astronomical polarimetry as a science, and the instruments used for polarimetry are described in Chapter 3. These are the Hubble Space Telescope/Advance Camera for Surveys (HST/ACS), and the International Gamma-Ray Astrophysics Laboratory/Imager on Board the INTEGRAL Satellite (INTEGRAL/IBIS). This chapter outlines the characteristics of each instrument, their detectors, how the polarisation of sources are measured, and how instrumental polarisation is accounted for.

As this is a journal based thesis, the results section, Chapter 4, contains the peer-reviewed scientific publications. Strong polarisation is expected when the pulsar emission is generated by synchrotron radiation. Incoherent synchrotron emission follows a simple relationship between its polarisation profile and underlying geometry. Polarisation studies at other wavelengths, for instance in the gamma-ray band, can distinguish between emission processes such as curvature radiation in the pulsar magnetosphere, and synchrotron radiation generated outside the magnetosphere in the pulsar wind nebula (PWN). Hence, polarisation measurements of pulsars provide an unique insight into the geometry of their emission regions and therefore observational constraints on the theoretical models of the emission mechanisms. From an understanding of the emission geometry, one can limit the competing models for pulsar emission, and hence understand how pulsars work.

Moran et al. (2013) outlines the study of the phase-averaged linear polarisation of the Crab nebula and pulsar in the optical using archival HST/ACS data. We mapped out the linear polarisation of the inner nebula, and measured the polarisation of the pulsar, inner synchrotron knot, and wisps (Moran et al. 2013, MNRAS, 433, 2564-2575).

The optical linear polarisation of the Vela pulsar was also studied using the HST/ACS. These results not only confirm those originally obtained by Wagner & Seifert (2000) and Mignani et al. (2007) both using the Very Large Telescope (VLT), but are of greater precision. Moreover, as in the case of the Crab, it was found that
the PA of the pulsar is aligned with its proper-motion and spin-axis. The PWN is undetected in polarised light as is the case in unpolarised light, down to a flux limit of 26.8 magnitudes arcsec$^{-2}$. See Moran et al. (2014), MNRAS, 445, 835-844.

Although there are now over 2,300 radio pulsars detected, only 14 have optical counterparts, of which only 5 normal (Crab, Vela, Geminga, PSR B0540–69 and PSR B0656+14) and one anomalous X-ray pulsar (AXP) (4U 0142+61) have been observed to pulsate in the optical. Multi-wavelength studies of neutron stars and pulsars are invaluable in completing their full spectral energy distribution, and thereby enabling one to better understand the processes taking place in their magnetospheres. Such data would allow us to address the following: the expected distribution of plasma within the magnetosphere, the location and mechanism for accelerating the plasma, and the emission mechanisms at various photon energies.

With this in mind, our group is involved in a campaign to search for the optical counterparts to pulsars detected at other wavelengths such as those identified by the Fermi gamma-ray telescope. Mignani et al. (2011), A&A, 533, 101 deals with the search for the optical counterparts to two such pulsars – PSR J1357–6429 and PSR J1048–5832.

We carried out a campaign using several optical facilities (INT, TNG and GTC) to search for the optical counterpart to the X-ray and radio pulsar PSR J0205+6449. Using archival Gemini data we have detected a plausible optical counterpart to this pulsar – see Moran et al. 2013, MNRAS, 436, 401-412.

Moran et al. 2012 and Laurent et al. 2012 (Proceedings of Science, 9th INTEGRAL Workshop) discuss the study of the gamma-ray polarisation of the Crab nebula and pulsar using the INTEGRAL/IBIS Compton mode. In a broader context, a better understanding of the Crab nebula and pulsar system is linked with our understanding of other high-energy astrophysical sources such as active galaxies and gamma-ray bursts. This is because all of these systems involve the release of magnetic energy by a compact object, and the acceleration of particles due to the transfer of this energy.

The thesis concludes with a summary of the main results and outcomes of this
work – see Chapter 5. Future missions and possible future work is also outlined in this chapter.
Chapter 2

Multi-wavelength Observations of Pulsars

A summary of the results of a number of multi-wavelength observations of pulsars is now presented. Studying pulsars across the spectrum gives a much more detailed picture of the processes taking place within their magnetospheres. Such observations allow one to probe the emission geometries of the pulsar and to validate the competing models for the pulsar emission mechanism.

2.0.1 Radio Pulsars

As mentioned previously, the first pulsar was discovered in the radio-band and it is in this regime that discoveries are most fruitful. The radio emission is observed from frequencies in the range of \(~ 100 \text{ MHz–100 GHz}\), thereby requiring a broadband emission process to describe its origin. The radio emission is coherent and highly polarised. Since pulsars are rather weak sources, observations covering a wide bandwidth are needed to maximise sensitivity. The radio signal is affected by the following aberrations as it propagates through the interstellar medium: dispersion and scintillation. Dispersion is due to the frequency dependent nature of the interstellar medium. Radio pulses emitted at higher frequencies travel faster and arrive at the detector earlier than those of lower frequencies. The electron density between our
line of sight and distant sources in the galaxy is not homogenous. These changes in concentration distort and scatter pulses shapes. This results in intensity variations on various timescales and is known as scintillation. These problems can effectively be ignored at optical and higher-energies due to the much higher observing frequencies.

New radio pulsars are found through the detection of dispersed pulses in noisy data. Only a fraction of all known pulsars were strong enough to be detected by their individual pulses. Those still awaiting discovery are very faint and require very sensitive instrumentation and innovative search processes and algorithms. The main group of survey telescopes for radio monitoring and searches of pulsars include Arecibo, Effelsberg, GMRT, Green Bank, Lovell, Nançay, and Westerbork (see Figure 2-1).

A number of pulsars have very faint or no radio emission at all. These are the so called radio-quiet pulsars. The most famous of these being the Geminga pulsar (PSR J0633+1746) (Fichtel et al., 1975). The lack of the detection of radio pulsations from these pulsars may be explained by either an intrinsically low radio luminosity or that the radio beam is narrow and does not cross the observers line of sight, whereas the wider high-energy beam can be observed.

### 2.0.2 Optical Pulsars

Optical pulsars are intrinsically faint (see Table 2.1 and Figure 2-2). They are less efficient than their higher-energy counterparts (efficiency defined as $\eta = L_\nu / \dot{E}$, where $L_\nu$ is the luminosity at a given frequency and $\dot{E}$ is the spin-down luminosity) with $10^{-9}$ against $\approx 10^{-2}$ at $\gamma$-rays. Optical efficiency also decreases with age in contrast to $\gamma$-ray emission (Shearer & Golden, 2001). The Crab pulsar (PSR J0534+2200)
was the first optical pulsar to be detected (Staelin & Reifenstein, 1968; Cocke et al., 1969). However, it took almost a decade before the second optical pulsar, the Vela pulsar (PSR J0835–4510), was discovered (Wallace et al., 1977). The detection rate has now increased thanks to the arrival of the current generation of large telescopes and the improved performance of CCDs. The optical pulse profile is generated by folding the times of arrival of the optical photons with the period predicted by radio timing ephemerides.

Confirmation of an optical detection can also be obtained if the proper motion of the optical counterpart is consistent with that of the radio pulsar measurement e.g. PSR B1929+10 (Pavlov et al., 1996; Mignani et al., 2002) and PSR B0656+14 (Mignani et al., 2000). Other cases exist whereby an optical point source is found at the radio or X-ray position of the pulsar but no optical pulsations or proper motion has been measured e.g. PSR B1509–58 (Caraveo et al., 1994), PSR B0950+08 (Pavlov et al., 1996), PSR B1055–52 (Mignani et al., 1997), PSR B1133+16 (Zharikov & Mignani, 2013), and one millisecond pulsar PSR J0437–4715 (Kargaltsev et al., 2004). To date there are 13 pulsars (see Table 2.2) with either an identified or proposed optical counterpart, of which only 5 have been observed to pulsate: Crab, Vela, Geminga, PSR B0540–69, and PSR B0656+14.

Despite their faintness, it is in the optical regime that it is possible to determine, with reasonable accuracy, all electromagnetic aspects of pulsar radiation – namely flux, spectral distribution, and polarisation. One can readily measure all Stokes parameters for polarisation, and in the optical one is probably seeing a flux which scales linearly with local power density in the observer’s line of sight. Polarisation measurements provide information about the local magnetic field strength and geometry. Such measurements together with numerical models should help determine, through geometrical arguments, the structure of the emission zone for normal pulsars and provide a thorough observational test for the various models of pulsar emission.

Spectral information, for example identifying synchrotron self-absorption and cyclotron features, will give clues to the strength of the magnetic field in the emission zone and thus its height above the neutron star surface. The optical spectra of young
and old pulsars are well fit by power law distributions. Those of middle-aged pulsars also require a black body component produced by the thermal emission from the polar cap or the entire neutron star surface. The optical spectrum does not always match the extrapolation to the components in the X-rays. Moreover, due to the small sample of optical pulsars, a general optical/X-ray correlation has not been established.
Table 2.1: Pulsar observability table based upon the ATNF Pulsar catalog (Manchester et al., 2005) and adapted from Shearer (2008), and Abdo et al. (2013). It shows the top 69 normal, non-binary pulsars according to $\dot{E}/d^2$. Only those pulsars with $\dot{E}/d^2 > 10^{35}$ and those with observed X-ray and $\gamma$-ray emission have been included. No assumptions have been made about the efficiency of optical emission with age, field, period or any of the other normal phenomenological parameters. The predicted magnitude is based upon the transverse light cylinder magnetic field, Luminosity $\propto \dot{E}^{1.6}$ (Shearer & Golden, 2001). The relationship should be treated with caution and is purely phenomenological. The aim here is to give a rough scaling between the different pulsars.

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<th>Period (ms)</th>
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<th>log(E) (erg s$^{-1}$)</th>
<th>log($\dot{E}/d^2$) (erg s$^{-1}$ kpc$^{-2}$)</th>
<th>$N_H$ $10^{22}$ cm$^{-2}$</th>
<th>$A_V$ V Mag.</th>
<th>Pred. Association</th>
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<td>log(E/d(^2)) (erg s(^{-1}) kpc(^{-2}))</td>
<td>N(_H) (10^{22}) cm(^{-2})</td>
<td>(A_V)</td>
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<tr>
<td>J1413–6205</td>
<td>0.1097</td>
<td>21.40</td>
<td>4.80</td>
<td>35.91</td>
<td>33.25</td>
<td>0.40</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>J1429–5911</td>
<td>0.1158</td>
<td>21.80</td>
<td>4.78</td>
<td>35.89</td>
<td>33.21</td>
<td>0.80</td>
<td>-</td>
<td>*</td>
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<tr>
<td>J0734–1559</td>
<td>0.1551</td>
<td>10.30</td>
<td>5.31</td>
<td>35.12</td>
<td>33.09</td>
<td>0.20</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>J1803–2149</td>
<td>0.1063</td>
<td>25.20</td>
<td>4.94</td>
<td>35.81</td>
<td>33.00</td>
<td>0.50</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>J1958+2846</td>
<td>0.2904</td>
<td>18.50</td>
<td>4.34</td>
<td>35.53</td>
<td>33.00</td>
<td>1.22</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>J0622+3749</td>
<td>0.3322</td>
<td>8.30</td>
<td>5.32</td>
<td>34.43</td>
<td>32.59</td>
<td>0.10</td>
<td>-</td>
<td>*</td>
</tr>
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<td>J1620–4927</td>
<td>0.1719</td>
<td>24.10</td>
<td>5.41</td>
<td>34.91</td>
<td>32.15</td>
<td>0.40</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
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<td>0.1767</td>
<td>17.20</td>
<td>5.76</td>
<td>34.54</td>
<td>32.07</td>
<td>0.10</td>
<td>-</td>
<td>*</td>
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<td>8.20</td>
<td>5.73</td>
<td>33.78</td>
<td>31.95</td>
<td>0.08</td>
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</tr>
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<td>15.70</td>
<td>5.74</td>
<td>34.34</td>
<td>31.95</td>
<td>0.40</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>J1846+0919</td>
<td>0.2256</td>
<td>22.00</td>
<td>5.56</td>
<td>34.53</td>
<td>31.85</td>
<td>0.20</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>J1746–3239</td>
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<td>25.30</td>
<td>5.68</td>
<td>34.52</td>
<td>31.71</td>
<td>0.10</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>J1957+5033</td>
<td>0.3748</td>
<td>14.50</td>
<td>5.92</td>
<td>33.70</td>
<td>31.38</td>
<td>0.10</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>J2055+2539</td>
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<td>6.09</td>
<td>33.70</td>
<td>31.33</td>
<td>0.16</td>
<td>-</td>
<td>*</td>
</tr>
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<td>0.2828</td>
<td>14.10</td>
<td>6.40</td>
<td>33.48</td>
<td>31.18</td>
<td>0.10</td>
<td>-</td>
<td>*</td>
</tr>
</tbody>
</table>
Table 2.2: Optical luminosities of all pulsars with identified optical counterparts, those marked in bold have been observed to pulsate. The second and fourth columns list the spin-down age $\tau$ and the rotational energy loss $\dot{E}$, respectively, as listed in the ATNF pulsar data base (Manchester et al., 2005). The distances are taken from Abdo et al. (2010). The optical luminosities are computed from the pulsar magnitudes in the $V$ band, except for PSR J0205+6449(g') and PSR B1509–58 (R), and using the values of the associated interstellar extinction $A_V$ (Mignani, 2011b).

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>log($\tau$) (yr)</th>
<th>d (kpc)</th>
<th>log($\dot{E}$) (erg s$^{-1}$)</th>
<th>log($\dot{E}/d^2$) (erg s$^{-1}$ kpc$^{-2}$)</th>
<th>log $I_{\text{optical}}$ (erg s$^{-1}$)</th>
<th>$m_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab</td>
<td>3.10</td>
<td>2</td>
<td>38.65</td>
<td>38.05</td>
<td>33.15</td>
<td>16.8(V)</td>
</tr>
<tr>
<td>PSR B0540−69</td>
<td>3.22</td>
<td>48.97</td>
<td>38.17</td>
<td>34.79</td>
<td>33.20</td>
<td>22.0(V)</td>
</tr>
<tr>
<td>Vela</td>
<td>4.05</td>
<td>0.29</td>
<td>36.84</td>
<td>37.92</td>
<td>28.13</td>
<td>23.6(V)</td>
</tr>
<tr>
<td>PSR B0656+14</td>
<td>5.05</td>
<td>0.29</td>
<td>34.58</td>
<td>35.66</td>
<td>27.53</td>
<td>25.0(V)</td>
</tr>
<tr>
<td>Geminga</td>
<td>5.53</td>
<td>0.25</td>
<td>34.51</td>
<td>35.71</td>
<td>27.20</td>
<td>25.5(V)</td>
</tr>
<tr>
<td>PSR B1509−58</td>
<td>3.19</td>
<td>4.20</td>
<td>37.25</td>
<td>36.00</td>
<td>30.97</td>
<td>25.7(R)</td>
</tr>
<tr>
<td>PSR B1055−52</td>
<td>5.73</td>
<td>0.72</td>
<td>34.48</td>
<td>34.77</td>
<td>28.20</td>
<td>24.9(V)</td>
</tr>
<tr>
<td>PSR B0950+08</td>
<td>7.24</td>
<td>0.26</td>
<td>32.75</td>
<td>33.92</td>
<td>26.66</td>
<td>27.1(V)</td>
</tr>
<tr>
<td>PSR B1929+10</td>
<td>6.49</td>
<td>0.33</td>
<td>33.59</td>
<td>34.55</td>
<td>27.43</td>
<td>25.6(U)</td>
</tr>
<tr>
<td>PSR B1133+16</td>
<td>6.69</td>
<td>0.35</td>
<td>31.94</td>
<td>32.85</td>
<td>26.51</td>
<td>28.0(V)</td>
</tr>
<tr>
<td>PSR J0108−1431</td>
<td>8.22</td>
<td>0.20</td>
<td>30.76</td>
<td>32.16</td>
<td>26.86</td>
<td>26.4(U)</td>
</tr>
<tr>
<td>PSR J0437−4715</td>
<td>9.20</td>
<td>0.14</td>
<td>34.07</td>
<td>35.78</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PSR J0205+6449</td>
<td>3.73</td>
<td>3.20</td>
<td>37.43</td>
<td>36.42</td>
<td>30.06</td>
<td>27.4(g')</td>
</tr>
</tbody>
</table>
2.0.3 X-ray Pulsars

The X-ray spectra of pulsars show a mixture of thermal and non-thermal processes such as synchrotron radiation. Early X-ray satellites that observed pulsars included *Einstein*, *RXTE*, *BeppoSax* and *ROSAT*. Nowadays *XMM–Newton*, *Chandra* and *NuSTAR* provide the much improved sensitivity and timing accuracy to observe pulsed X-ray emission from normal and millisecond pulsars. The X-ray detected pulsars can be arranged into four groups: Crab-like, Vela-like, middle-aged, and millisecond pulsars. The Crab-like pulsars have double-peaked profiles which are, if detected, similar to the profiles of their optical counterparts. In the case of Vela-like pulsars, their X-ray spectra require more than just simple power laws, and their X-ray pulse profiles are usually misaligned with their radio or \( \gamma \)-ray pulse profiles. The middle-aged pulsars have spectra which show a mixture of thermal and non-thermal emission, and their pulse profiles are energy-dependent. The spectra of the millisecond pulsars can also be fit by power law and/or black body distributions.

2.0.3.1 Pulsar Wind Nebulae

Pulsar wind nebulae (PWNe) are formed when the pulsar wind is confined by the supernova remnant of its progenitor star (Figure 2-3). The time evolution of the wind is therefore complex and is influenced by the properties of the progenitor and the environment in which it exploded. Electrons and positrons are created in the magnetic fields of the pulsar and are then released into the nebula. The electron density through most of the system is assumed to be large enough that magnetohydrodynamical conditions approximately apply. The pulsar wind transfers most of the rotational energy lost by the pulsar into the nebula (Rees & Gunn, 1974). The wind is flowing radiationless until its momentum flux is balanced by the ambient nebula pressure at a termination surface. Here, particle distribution is randomised and the particles begin to lose energy, mainly through synchrotron radiation. To date \( \sim 100 \) PWNe have been detected, mostly at x-ray and TeV energies (Kargaltsev et al., 2013). The Chandra X-ray observatory has detected in excess of 50 PWN, with the Crab,
Figure 2-3: The formation of pulsar wind nebula. Image credit: Aharonian et al. (2012).

Vela, and 3C58 PWNe being the most famous. Figure 2-4 highlights how varied these complex structures can be.
2.0.4 Gamma-ray Pulsars

The gamma-ray emission of pulsars is highly pulsed, beamed and non-thermal. Early studies of the gamma-ray sky were carried out with the SAS–2 and COS–B observatories. The launch of the Compton Gamma-ray Observatory (CGRO) heralded a significant advancement in gamma-ray astrophysics in the 1990s. Prior to the launch of Fermi, there were 7 gamma-ray pulsar detections: Crab, Vela, Geminga, PSR B1055–52, PSR B1509–58, PSR B1706–44, and PSR B1951+32 (Hartman et al., 1999) (see Figure 2-5). One of the instruments aboard the satellite, the Energetic Gamma Ray Experiment Telescope (EGRET), helped to survey the sky and produce a catalogue of 271 gamma-ray sources (E > 100 MeV) (Hartman et al., 1999). Of these sources, about 170 had no known counterparts at other wavelengths. There was good reason to presume that a fraction of these unidentified EGRET sources that did not exhibit flux variability were gamma-ray pulsars, some of which might be detected at other wavelengths. This drove the need for a new generation of space-based

gamma-ray telescopes of even greater sensitivity and angular resolution.
The *Fermi* Gamma-ray Space Telescope (Atwood et al., 2009; Abdo et al., 2010) was launched in 2008 to study high-energy emission throughout the galaxy. It is the most advanced space telescope to study the gamma-ray sky. It has completely revolutionised this field of gamma-ray astronomy through the detection of 1,873 gamma-ray sources (Nolan et al., 2012). This is due to its increased sensitivity and angular resolution. To date, *Fermi* has brought the number of gamma-ray detected pulsars to 117 (Figure 2-6) (Abdo et al., 2013). These are made up of three groups: millisecond pulsars, young radio-loud pulsars, and young radio-quiet pulsars. The double peaked pulse profiles of these pulsars change in appearance at higher energies due to a phase-dependant spectral hardness (Aliu et al., 2008, 2011). This would suggest that, like in the radio, geometry plays an important role.

Figure 2-6: *Fermi* all sky map showing the positions of LAT detected radio-loud, radio-quiet, and millisecond pulsars. Image credit: Second Fermi LAT Catalog of gamma-ray pulsars (Abdo et al., 2013).
2.1 The Crab Nebula and pulsar

The Crab Nebula contains a rotation powered pulsar interacting with a surrounding nebula by means of a relativistic pulsar wind (Figure 2-7). It emits radiation across the entire electromagnetic spectrum from radio up to high-energy $\gamma$-rays. It is home to the brightest known optical pulsar, the Crab pulsar ($V \approx 16.8$). The system is one of the brightest sources in the $\gamma$-ray sky. It is also one of the most densely studied objects in astrophysics as it is one of the prime laboratories to study non-thermal processes.

It is the remnant of the supernova of 1054 AD that was reported by Chinese and Arab astronomers as a new “guest star” in the sky. In 1758, Charles Messier observed the nebulose appearance of the Crab Nebula. He catalogued it as the first source, M1, in the Messier catalogue of nebulose non-cometary objects. However, it was not until the expansion velocity measurements of Edwin Hubble (Hubble, 1928) that the link between the nebula and the supernova of 1054 AD was established, making the Crab the first historical supernova. As mentioned previously, it was the identification of the central star as a pulsar (Staelin & Reifenstein, 1968) that confirmed the hypothesis that pulsars are neutron stars born in the aftermath of supernova explosions (Baade & Zwicky, 1934; Pacini, 1967).

Shklovsky (1953) proposed that the optical radiation of the Crab Nebula was due to synchrotron radiation. This was later confirmed by the work of Dombrovsky (1954) and Vashakidze (1954) who found that the optical radiation from the nebula was polarised. The identification of synchrotron radiation as the source of the optical emission from the nebula implied magnetic fields of the order of $10^{-7}$ T within the nebula. This is in contrast with theoretical estimates because the expansion of the supernova remnant should have weakened these fields. Moreover, the synchrotron electrons would have radiated away all of their energy after 100 years. Hence, the production of synchrotron radiation within the nebula requires a source that can continuously replenish the magnetic fields and inject fresh energetic electrons. This is supplied by the spin-down energy of the pulsar at the centre of the nebula. Assuming
Figure 2-7: Composite image of the Crab Nebula showing showing radio (red), optical (green), and X-ray emission (blue). Image Credit: www.chandra.harvard.edu/photo/2002/0052/more.html. (right) Pulsations in the optical from the Crab pulsar, in the centre of the Crab Nebula. A foreground star is the constant brightness above and to the left of the pulsar. Image credit: National Optical Astronomy Observatories.

A moment of inertia of the neutron star of $I \approx 10^{45}$ g cm$^2$ one finds the spin-down energy $\dot{E} \approx 5 \times 10^{38}$ erg s$^{-1}$ – exactly the energy required to power the nebula. For more detailed reviews of the Crab see Hester (2008) and Buchler & Blandford (2013).

2.1.0.1 Gamma-ray flares

The nebula was thought to be a stable source of gamma-ray emission and was therefore often used to cross-calibrate X-ray and gamma-ray telescopes and to check their stability over time (Weisskopf et al., 2010). However, the nebula emission has been observed to undergo strong flaring in the 100 MeV–10 GeV energy range. The first detections of this activity was by the AGILE (Tavani et al., 2009) satellite in October 2007 and September 2010 (Tavani et al., 2011). During the September 2010 flare the unpulsed flux from the nebula was observed to increase by a factor of 3 compared to the average unpulsed nebular flux. Both the short timescale and luminosity of the flare suggest that it comes from a compact region close to the pulsar. No change in the pulse profile shape of the Crab lightcurve was observed in the gamma-rays, radio, and X-rays. The Fermi collaboration confirmed the flare in September 2010 and also
detected one in February 2009 (Abdo et al., 2011). Since then both AGILE and Fermi have detected two more gamma-ray flares from the Crab Nebula; April 2011 (Buehler et al., 2012) and March 2013 (Mayer et al., 2013). The two leading interpretations of this phenomenon are that gamma-ray emission of the synchrotron component comes from near the termination shock (Lyubarsky & Liverts, 2008; Bednarek & Idec, 2011) or that the particle acceleration takes place in the ac-striped wind of the pulsar via magnetic reconnection (Volpi et al., 2008; Komissarov & Lyutikov, 2011). The observations of such flaring events challenge the emission models of the pulsar wind interaction, particle acceleration processes, our understanding of the Crab Nebula system, and pulsars themselves.

2.1.0.2 Very high-energy emission (TeV)

The emission of pulsars is expected to fall off close to exponentially via \( \nu F_\nu \propto \exp(\varepsilon/\varepsilon_{\text{cut}})^b \) above a cutoff energy \( \varepsilon_{\text{cut}} \). This cutoff is thought to be due to radiation reaction limiting particle acceleration, and/or gamma-ray absorption in the magnetic and photon fields of the pulsar. This is the scenario for the spectra of all the pulsars detected to date at high-energy gamma-rays. In conflict to this, came the recent detection of very-high-energy (VHE) gamma-ray emission from the Crab by the VERITAS and MAGIC collaborations (Aliu et al., 2008, 2011; Aleksic et al., 2011, 2012). The combined high-energy (Fermi-LAT) and VHE data can be described by one power-law function above \( E \approx 4 \) GeV (Figure 2-8). No indication of a spectral cutoff has been found up to photon energies of \( \sim 400 \) GeV. The peaks of the VHE pulses are in phase with the radio ones. Of particular note is that the VHE ones are narrower than the HE ones and the amplitude of the inter pulse exceeds that of the main pulse. This phenomenon is also seen from the radio to hard X-rays (Figure 2-9).

To explain these observations, Lyutikov (2012) argue in favour of an inverse Compton origin for the pulsar VHE emission. Pulsed VHE emission can occur through up-scattering of the photons in particle cascades induced by outer gaps (Aleksić et al., 2011, 2012) or annular gaps (Du et al., 2012). Inverse Compton could also occur in the striped-wind model (Bogovalov & Aharonian, 2000; Kirk et al., 2002). In this
Figure 2-8: Spectral energy distribution of the Crab in gamma-rays. The non-exponential spectral break is inconsistent with curvature radiation as the source of the VHE emission. Image credit: Aliu et al. (2011).

Figure 2-9: The evolution of the pulse profile of the Crab pulsar with energy. The inter pulse increases at low energies becoming the dominant pulse in the hard X-ray band. This phenomenon is repeated from HE to VHE gamma-rays. Image credit: Lyutikov (2012).
case the VHE is created by the up-scatter of pulsed X-ray photons (Aharonian et al., 2012; Pétri, 2012). The absence of a cutoff in the spectrum above $> 100$ GeV implies that $R > R_{LC}$. Hence, curvature radiation is unlikely to be the mechanism for the VHE pulsations since particles can only travel along magnetic fields within the light cylinder. However, the narrowing of the pulses towards VHE domain would not be expected in this model.
Chapter 3

Astronomical Polarimetry

3.1 Background

Polarisation is the preferential direction of oscillation for the electromagnetic vector. It can be thought of as a special “signature” of electromagnetic radiation. It is produced or modified whenever the cylindrical symmetry of the propagating light is broken. It can be induced intrinsically by the radiation process involved (Collett, 1993). Polarisation can also be produced by the propagation of light through a medium which itself has a preferred orientation. An example of this is the passage of light through dust grains aligned by Galactic magnetic fields (Mathewson & Ford, 1971; Axon & Ellis, 1976). All astronomical objects are polarised to some extent. Astronomical polarimetry therefore yields additional information to photometry and spectroscopy alone.

Icelandic spar (Figure 3-1), formerly Iceland crystal is a transparent form of calcite, or crystallised calcium carbonate. It is commonly used to demonstrate the polarisation of light. The discovery of its double-refraction property was crucial in understanding the wave nature of light. Medieval Icelandic texts refer to its use by the Vikings, who called it the “sunstone” and used it for navigational purposes. They could pinpoint the location of the Sun in the sky on cloudy or overcast days to within a few degrees. The first evidence that this technology had been used in seafaring navigation was the recovery of a “sunstone” from the wreck of the Elizabethan ship,
Aldeney, which sank in 1592.

The recorded history of astronomical polarimetry dates back to 1811, when Arago discovered that light reflected off the surface of the moon is polarised. However, it took a long time for polarimetry to make progress towards being an effective tool in astronomy. The period following Arago’s discovery heralded new discoveries in the polarisation properties of materials. Techniques were then developed to utilise these materials in instrumentation for polarimetric observations. The next breakthrough in the history of astronomical polarimetry was the discovery of the phenomenon of interstellar polarisation by Hiltner (1949) and Hall (1949). This marked the point at which astronomical polarimetry truly came of age.

### 3.1.1 Formalisms

The most general state of polarisation is *elliptical polarisation* (Figure 3-2). This occurs when the tip of the electric-field vector traces out an ellipse in the xy plane. Two special cases of polarisation exist: *linear polarisation* and *circular polarisation*. Linear polarisation occurs when the polarisation ellipse collapses into a line i.e. the x and y components of the wave are in phase with one another. Circular polarisation occurs when the ellipse degenerates into a circle i.e. there is a relative phase-shift between the x and y components of the wave. Astronomical observations deal with
Figure 3-2: The polarisation states: linear, circular, and elliptical. Image credit: https://wikispaces.psu.edu/pages/viewpage.action?pageId=55116678.

macroscopic polarisation, whereby the radiation is a superposition of electromagnetic waves, the bulk of which are incoherent. Hence, unpolarised light is often referred to as “natural” light. It has no preferred direction or orientation.

3.1.1.1 Stokes Parameters

The Stokes parameters (G. J. Stokes 1826–1911) describe the source polarisation in terms of the intensity of the electromagnetic radiation. There are four Stokes parameters. The first parameter, I, denotes the total intensity of the radiation. The parameter Q defines a difference in intensities in the x and y plane, and therefore information on linear polarisation. The parameter U also describes linear polarisation. It defines the difference in intensity between the two diagonal components at angles of 45° and 135°, measured anti-clockwise from the positive x-axis (see Figure 3-3). The parameter V denotes circular polarisation.

For macroscopic polarisation, the radiation is formed from a superposition of waves, and the polarisation is to some extent partially averaged out. However, this is not the case for incoherent light. The Stokes parameters are thus related as follows:
\[ I^2 = Q^2 + U^2 + V^2. \]  \hspace{1cm} (3.1)

The fraction of linear polarisation, i.e. the amount of incoming flux that is linearly polarised, is as follows:

\[ P_L = \frac{\sqrt{Q^2 + U^2}}{I} \in [0, 1]. \]  \hspace{1cm} (3.2)

The fraction of circular polarisation, the amount of incoming flux that is circularly polarised, is as follows:

\[ P_C = \frac{V}{I} \in [-1, 1] \]  \hspace{1cm} (3.3)

where -1 denotes clockwise rotation and is referred to as left-handed circular polarisation (LHC), and +1 denotes counterclockwise rotation and is referred to as right-handed circular polarisation (RHC).

The polarisation position angle, measured anti-clockwise from the positive x-axis or eastward from astronomical North, is as follows:

\[ \chi = \frac{1}{2} \atan2 \left( \frac{U}{Q} \right) \in [0, \pi] \]  \hspace{1cm} (3.4)

where \( \atan2 \) represents the quadrant-preserving arc tangent function.
3.2 Polarised Radiation: emission mechanisms and astronomical sources

3.2.1 Synchrotron radiation

Synchrotron radiation is emitted by relativistic electrons gyrating around magnetic field lines. If the magnetic field is in the z direction, the magnetic Lorentz force imposes a circular motion in the xy plane. The electron has a non-zero velocity in the z direction. Therefore, the overall trajectory of the electron has a helical shape. An external, stationary, observer sees the orbit of the electron as an ellipse in projection. Hence, the radiation emitted by a single oscillating charge is elliptically polarised. The amount of linear and circular polarisation observed by an external observer depends on the Lorentz factor, $\gamma$, and the viewing angle, $\phi$, between the line of sight and the plane of the particle motion.

For most astrophysical plasmas, the electron velocities are randomly distributed and roughly isotropically. Therefore, both right-handed and left-handed electron orbits contribute with equal probability. So circular polarisation of the radiation
averages out. Hence, macroscopically the synchrotron radiation becomes linearly polarised.

The polarisation position angle is aligned perpendicular to the magnetic field. The amount of linear polarisation depends on the spectrum of the synchrotron radiation. This in turn depends on the distribution of the electron energies. For mono-energetic electrons the value is 75% (Rybicki & Lightman, 1979). For a power law distribution of electron energies, the number of electrons, \( N \), varies with \( \gamma \) according to \( N \propto \gamma^{-\Gamma} \) with \( \Gamma \) being the energy index, with \( \alpha = \frac{1}{2} (\Gamma - 1) \). The flux density of synchrotron radiation is given by \( S_\nu \propto \nu^{-\alpha} \) (Ginzburg & Syrovatskii, 1965). For an astrophysical plasma with \( \alpha \in [0,1] \), the linear polarisation is in the range 60–80%.

### 3.2.2 Scattering

The scattering of a photon at a free electric charge such as an electron, an atom or a molecule leads to a linear polarisation of the scattered light. Examples include Rayleigh scattering in planetary atmospheres, Mie scattering by large particles, and Thomson scattering and Compton scattering by free electrons. The interstellar medium is composed of dust grains. These grains of dust are about a micrometer in size, roughly corresponding to the wavelengths of visible to infrared light. Again, initially unpolarised incident light becomes linearly polarised on scattering by dust.

### 3.2.3 Magnetic fields

Magnetic fields are everywhere in astronomy. They are found in a variety of scenarios including: molecular clouds in star formation, black holes in active galactic nuclei, pulsars and magnetars. However, their precise impact on many physical systems is still poorly understood. Advanced magnetohydrodynamical (MHD) computer models and simulations have lead to notable progress in addressing this. Precise polarisation measurements can then be used to validate the results of these MHD models.
3.2.3.1 Zeeman Effect

Whenever an emitting or absorbing material is permeated by a magnetic field, its spectral emission or absorption lines experience modifications. Quantum mechanical selection rules demand that the change of magnetic quantum number, $m$, has to obey $\Delta m \in [-1,0,1]$, therefore there are three different transitions possible. This phenomenon was first reported by Zeeman (1897), who noticed such changes in the presence of an external magnetic field. Hence, it is called the Zeeman effect.

3.2.4 Scientific Investigations

3.2.4.1 Pulsars

Strong polarisation is expected when the pulsar optical emission is generated by synchrotron radiation. Shklovsky (1953) suggested that the continuous optical radiation from the Crab Nebula was due to synchrotron radiation. This was later confirmed by Dombrovsky (1954) and Vashakidze (1954) who found that the optical radiation was polarised. The optical to gamma-ray radiation from pulsars can be approximated as synchrotron radiation from collimated beams of electrons. Incoherent synchrotron emission follows a simple relationship between its polarisation profile and underlying geometry. Hence, polarisation measurements of pulsars provide an unique insight into the geometry of their emission regions, and therefore observational constraints on the theoretical models of the emission mechanisms. From an understanding of the emission geometry, one can limit the competing models for pulsar emission, and hence understand how pulsars work – a problem which has eluded astronomers for almost 50 years.

So far, detailed results have only been reported for the Crab pulsar (Weisskopf et al., 1978; Dean et al., 2008; Forot et al., 2008). Although the number of pulsars detected in the optical is growing, only five pulsars have had their optical polarisation measured; Crab (Wampler et al., 1969; Kristian et al., 1970; Smith et al., 1988; Slowikowska et al., 2009; Moran et al., 2013), Vela (Wagner & Seifert, 2000; Mignani et al., 2007), PSR B0540-69 (Middleditch et al., 1987; Chanan & Helfand, 1990;
Wagner & Seifert, 2000; Mignani et al., 2010) PSR B0656+14 (Kern et al., 2003), and PSR B1509-58 (Wagner & Seifert, 2000). Nonetheless, the optical currently remains invaluable for polarimetry in the energy domain above radio photon energies. The Crab pulsar, being the brightest optical pulsar with $V \approx 16.8$ (Nasuti et al., 1996), has had several measurements of its optical polarisation, including both phase-averaged and phase-resolved studies.

The first phase-resolved observations of the optical linear polarisation of the Crab pulsar were those of Wampler et al. (1969), Cocke et al. (1970), and Kristian et al. (1970). Those studies showed that the polarisation position angle changes through each peak in the pulsar lightcurve, and that the degree of polarisation falls and rises within each peak, reaching its minimum value shortly after the pulse peak. These observations were limited to the main and inter pulse phase regions only, because at the time it was thought that the pulsar radiated its optical emission through the pulse peaks only. However, a number of phase-resolved imaging observations of the pulsar (Peterson et al., 1978; Jones et al., 1981; Percival et al., 1993; Golden, Shearer, Redfern, Beskin, Neizvestny & et al., Golden et al.) showed that the optical emission actually persists throughout the pulsar’s entire rotation cycle, at the level of $\sim 1\%$ of the maximum main-pulse intensity.

With this in mind, observations of the optical linear polarisation of the Crab pulsar were made by Jones et al. (1981) and Smith et al. (1988). These results confirmed the previous observations, and were the first studies to reveal the polarisation profile of the pulsar during the bridge and off-pulse phase regions. They also found that the off-pulse region is highly polarised. The degree of polarisation was 70% and $47 \pm 10\%$ for Jones et al. (1981) and Smith et al. (1988), respectively. Słowikowska et al. (2009) report the most detailed phase-resolved observations of the optical linear polarisation of the Crab pulsar (Figure 3-4). Their results are consistent with previous observations albeit with better definition and statistics, and can be explained in the context of the two-pole caustic model (Dyks et al., 2004), the outer-gap model (Romani & Yadigaroglu, 1995; Takata et al., 2007), and the striped-wind model (Pétrit & Kirk, 2005).
Figure 3-4: Phase-resolved optical linear polarisation of the Crab pulsar. Position angle (°) as a function of rotational phase (top panel). Changes in $\theta$ are aligned with the maximum of the main-pulse of the optical light curve (vertical dot-dashed line), and with the radio phase of the main-pulse (vertical solid line). Polarisation degree (%) as a function of rotational phase (bottom panel). The minimum of the polarisation degree is for the radio phase (vertical solid line), and not for the maximum phase of the optical main-pulse (vertical dot-dashed line). Image credit: Fig. 4 of Słowikowska et al. (2009).
3.2.4.2 Active Galactic Nuclei (AGN)

Active galactic nuclei (AGN) are the most luminous persistent sources of radiation in the universe. Their energy source is derived from the accretion of interstellar material onto the central supermassive black hole ($10^6 \text{–} 10^{10} \text{ M}_\odot$) of a galaxy (for a review see Beckmann & Shrader 2012). The energy generated from the accretion process is released in broad-band continuum emission observable from the radio to high-energy $\gamma$-rays. There are two radiation mechanisms involved: synchrotron radiation and inverse Compton scattering. The low energy spectrum of AGN is predominately by synchrotron radiation. Whereas, for the higher energies, it is most likely created by the inverse Compton scattering of the low-energy synchrotron photons.

Since AGN are sources of synchrotron radiation, it follows that their emission is linearly polarised. Polarimetric observations of AGN can be used to probe the geometries of their magnetic fields, their surrounding matter distributions (Saikia & Salter, 1988), and the orientation of and magnetic fields along their jet outflows.

3.2.4.3 Gamma-ray Bursts (GRBs)

Gamma-ray bursts (GRBs) are one of the most energetic transient phenomenon in astrophysics, with luminosities of the order of $10^{46}$ W. They are short, intense bursts of soft gamma-rays (few 100s of Kev) of cosmic origin. The burst durations range from $\approx 0.01 \text{ s}$ to a few 100 s. Based on the burst duration, they are classified into two groups: long duration GRBs and short duration GRBs (for a review see Mészáros 2006).

Long GRBs last few tens of seconds and are linked with type 1b/c supernovae. They are thought to originate from the collapse of massive stars (Wolf-Rayet stars) and the formation of black holes. Short GRBs normally last for less than a second. They are thought to be produced as the result of the merger of compact objects in binary systems – either two neutron stars or a neutron star and stellar mass black hole. Irrespective of the duration, the radiation is collimated into relativistic jets with opening angles of a few degrees. This gives rise to the enormous apparent lumi-
nositics of GRBs. The emission is via a combination of both synchrotron radiation and inverse Compton scattering from relativistic electrons. Synchrotron radiation together with the non-isotropic geometry results in a high fraction of linear polarisation. Measurements of linear polarisation of up to 30% have been reported (Götz et al., 2013; Mundell et al., 2013). Such polarisation measurements can be used to study the nature of the plasma and the magnetic field strengths in GRBs.

Götz et al. (2014) have obtained the most distant polarisation measurement of a GRB. Using the Compton polarimetry mode of the **INTEGRAL/IBIS** they were able to constrain the linear polarisation level of the second peak of GRB 140206A as $>28\%$ at a 90% confidence level. Moreover, through GRB afterglow optical spectroscopy obtained at the **Telescopio Nazionale Galileo (TNG)**, they were able to get a distance measurement of to this GRB of $z=2.739$.

### 3.2.4.4 Solar and Stellar physics

All stars possess magnetic fields of varying strength, ranging from $1–10^4$ G (Schrijver & Zwann, 2000; Berdyugina, 2009). Hot stars with radiative outer layers (spectral class O–A) inherit their magnetic fields from the intergalactic medium from which they formed. The magnetic field of stars with convective outer layers (spectral class F–M) originate from dynamo processes (Berdyugina, 2009). Analysis of stellar magnetic fields enable constraints on solar and stellar dynamo models. Such analysis can be achieved through spectropolarimetry of absorption lines that are affected by Zeeman splitting. The Hanle effect can be used to study the magnetic field of the sun (Berdyugina & Fluri, 2004; Milić & Faurobert, 2012) via spectropolarimetric observations of molecular fluorescent lines such as $\text{C}_2$ and $\text{Mg}$H. Rayleigh and Raman scattering can be used to characterise conditions in stellar atmospheres (Sampoorna et al., 2013).

### 3.2.4.5 Solar & Exo-planetary Systems

Direct imaging of exoplanets can be performed using polarimetric differential imaging (Milli et al., 2013). Normally, exoplanets and disks cannot be imaged directly because
they are enshrouded by the light from their parent star. Polarimetry provides a solution. The light from the central star is essentially unpolarised and the light from the disk is highly polarised. Hence, polarimetry can be used to reduce/remove the light from the central star and directly image disk and exoplanet. Spectropolarimetry can be used to determine the size, shape, and chemical composition of the scattering media.

Polarimetry can also be used to characterise planetary atmospheres. When light is reflected off planetary atmospheres it becomes linearly polarised (Buenzli et al., 2013). The two main processes involved are Rayleigh scattering off molecules and aerosol particles, and relocation and refraction at liquid droplets in clouds. The polarisation signal observed is averaged over multiple light rays. This has the effect of partially averaging out and reducing the degree of linear polarisation. The amount of polarisation depends on the reflection geometry and the chemical composition of the atmosphere. Examples of observed levels of polarisation (at optical wavelengths) integrated over planetary disks are as follows: Venus 5%, Jupiter and Saturn 5–10%, and ≈ 50% Titan.

3.3 Observations

3.3.1 Optical Polarimetry

In the optical regime, polarisation observations require polarising optics placed in front of the detector (normally a CCD) (Tinbergen, 1996). Linearly polarised light can be analysed via the measurement of the intensity of the input light in each polariser. There are three quantities needed to fully characterise the linear polarisation. They are the total intensity, I, the degree of polarisation (fraction of light that is polarised) and the polarisation position angle. The Stokes formalism is the main one used in optical polarimetry. It applies to intensity measurements of photon fluxes. The advantage of this scheme is that it describes all partially polarised polarisation states of light. The Stokes parameters can be thought of as the bridging step between the
raw input data and the final polarisation values.

Another approach is to use a Wollaston prism, which splits incoming light into ordinary and extraordinary linearly polarised rays, and a half wave plate that can turn the plane of linear polarisation. The observation method involves taking two images, each one showing the ordinary and extraordinary ray images of the source; one with the half wave plate turned to a position corresponding to $\phi = 0^\circ/90^\circ$, one with half wave plate turned to a position of $\phi = 45^\circ/135^\circ$. Measurements of circular polarisation require the use of a quarter wave plate which converts circular polarisation into linear polarisation.

Ground based observations are hindered by atmospheric variations since transmission and point spread function change between the multiple observations required to obtain the Stokes parameters. To overcome this problem, two-beam polarimeters (Scarrott et al., 1983) are used in combination with a rotating retarding plate. In this way the complete set of Stokes parameters can be obtained simultaneously. For space-based observations, the stable observational environment eliminates the need for simultaneous acquisition of all Stokes parameters. Instead a set of polarisers of different orientation are used to image the source. The images taken using the various polarisers are combined to obtain the Stokes parameters and hence the polarisation. An example of a space-based instrument for polarimetry in the optical domain is the HST/ACS.

### 3.3.2 X-ray & $\gamma$-ray Polarimetry

Due to their high energies and short wavelengths, optical elements are transparent or absorbent to X-rays and $\gamma$ rays. Therefore polarimetry at these wavelengths is based on the following processes; Bragg diffraction, scattering, and photoelectron tracking.

#### 3.3.2.1 Bragg diffraction

When light with sufficiently short wavelength ($< \text{nm}$) is incident on a crystal, it is reflected by the crystal according to Bragg’s law (Bragg 1890–1971). The reflected
light is linearly polarised, with the component parallel to the surface being the most
dominant. The linear polarisation is measured by rotating the field of view of the in-
strument and observing the resultant sinusoidal profile. Bragg diffraction polarimetry
was the method employed by the *OSO-8* satellite (1975–1978), a space-based X-ray
polarimeter. It yielded the first X-ray polarisation measurements of the Crab Nebula
(Weisskopf et al., 1978).

### 3.3.2.2 Scattering polarimetry

Thomson, Compton scattering, and pair creation of photons are sensitive to the
polarisation of the incident source photons. The photons arrive at a scatter detector.
A fraction of the incident photons will be scattered at right angles into the xy plane
where they are recorded by a calorimeter. In the case of unpolarised sources, the
distribution of scattered photons in the xy plane will be isotropic. For partially
polarised incident light, the photons will be preferentially scattered perpendicular to
the direction of polarisation projected onto the xy plane. This is the method utilised
by the Compton mode of the *INTEGRAL/IBIS* instrument (Forot et al., 2007, 2008).

### 3.3.3 Instrumental Polarisation and Calibration

The polarisation calibration procedure depends on the telescope used. Calibration in-
volves observing a number of polarimetric standards: both unpolarised and polarised
stars. Furthermore, statistical uncertainties and limits need to be taken into account.
In general, polarimetric observations require much higher signal-to-noise (S/N) ratios
than photometric ones. For example, the detection of a weakly polarised signal may
require very high S/N.

For linear polarisation, the statistical uncertainties lead to a bias in the measured
values for the degree of linear polarisation. This is due to instrumental errors which
tend to increase the observed polarisation of a target with respect to its true polari-
sation (see Simmons & Stewart 1985). The effect is negligible when \( \eta = p \times S/N \) is
high (> 10), where \( p \) is the fractional polarisation of the target, and S/N is the target
Figure 3-5: Debias correction. Instrumental errors tend to increase the observed polarisation, P (%), of a target with respect to its true polarisation, P₀ (%) (Fig. 2 of Simmons & Stewart 1985).

Scattered Sun or moon light is linearly polarised. The degree of polarisation is maximum for an angular distance of 90° from the light source. The polarisation is orientated perpendicular to the line of sky connecting the source and the point observed. This phenomenon can be utilised for the calibration of polarimetric observations – for example observations of zenith flat fields at dawn.

### 3.4 Polarimetry Methodology

#### 3.4.1 HST/ACS

The *Hubble Space Telescope* (*HST*) is equipped for polarimetry observations. The *Advanced Camera for Surveys* (*ACS*) is mounted in one of the instrument bays behind the *HST* primary mirror. It has three independent cameras that provide wide-field, high resolution, and ultraviolet imaging capabilities respectively, using a broad assortment of filters designed to address a large range of scientific goals. The *Wide Field*
Channel (WFC) detector, called ACS/WFC, employs a mosaic of two 4096 × 2048 Scientific Imaging Technologies (SITe) CCDs, with a pixel-scale of \( \sim 0.05 \) arcsecond/pixel, covering a nominal FOV \( \sim 202'' \times 202'' \) (Pavlovsky, 2004).

The ACS also has an imaging polarimetric capability. It consists of a set of six filters which are sensitive to linear polarisation; there are three visible polariser filters (POLV) with each set at nominal 60° angles with respect to each other, and three UV polariser filters (POLUV) arranged in a similar manner. The polarisers are normally used in conjunction with a spectral filter which largely defines the spectral bandpass. In this way one can obtain polarisation data in both the continuum and in line emission; and to perform rudimentary spectro-polarimetry. Observers require a minimum of three images of the target in each of the three polariser filters (0°, 60° and 120°). Hence, the intensity changes between the resulting images provide the polarisation information. The data reduction procedure for polarisation data is the same as that for other optical data eg. bias-subtraction, dark-subtraction, and flat-fielding. The polarisation calibration is achieved by combining the set of images (or their counts) in the three filter rotations to produce a set of Stokes I, Q, and U images, or equivalently, a set of images giving the total intensity, degree of polarisation, and polarisation position angle.

3.4.1.1 Calibration and Performance

To compute the polarisation of a target one must measure the counts from the target via aperture photometry. The polarisation “zeropoint” is determined using corrections that are derived from observations of unpolarised standard stars. Corrections \( C(\text{CCD}, \text{POLnXX}, \text{spectral filter}, n) \) are applied to the observed count rate, \( r_{\text{obs}} \), in each of the three polarisers (see equation 3.5). The corrections are given in Table 3.1 and have been scaled such that Stokes I will approximate the count rate seen with no polariser.
Table 3.1: Correction factors $C(\text{CCD}, \text{POLnXX, specfilt, n})$ for the polarisation zeropoint. Table taken from Pavlovsky (2004).

<table>
<thead>
<tr>
<th>CCD</th>
<th>POLnXX</th>
<th>Special Filter</th>
<th>n=0</th>
<th>n=60</th>
<th>n=120</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRC</td>
<td>POLnUV</td>
<td>F330W</td>
<td>1.7302</td>
<td>1.5302</td>
<td>1.6451</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F435W</td>
<td>1.6378</td>
<td>1.4113</td>
<td>1.4762</td>
</tr>
<tr>
<td></td>
<td>POLnV</td>
<td>F475W</td>
<td>1.5651</td>
<td>1.4326</td>
<td>1.3943</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F606W</td>
<td>1.4324</td>
<td>1.3067</td>
<td>1.2902</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F625W</td>
<td>1.0443</td>
<td>0.9788</td>
<td>0.9797</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F658N</td>
<td>1.0614</td>
<td>0.9708</td>
<td>0.9730</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F775W</td>
<td>1.0867</td>
<td>1.0106</td>
<td>1.0442</td>
</tr>
<tr>
<td>WFC</td>
<td>POLnV</td>
<td>F475W</td>
<td>1.4303</td>
<td>1.4717</td>
<td>1.4269</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F606W</td>
<td>1.3314</td>
<td>1.3607</td>
<td>1.3094</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F775W</td>
<td>0.9965</td>
<td>1.0255</td>
<td>1.0071</td>
</tr>
</tbody>
</table>

$$r(n) = C(\text{CCD}, \text{POLnXX, specfilt, n}) \cdot r_{\text{obs}}$$ \hspace{1cm} (3.5)

The Stokes vectors are then calculated using the following formulae:

$$I = \frac{2}{3} [r(0) + r(60) + r(120)]$$ \hspace{1cm} (3.6)

$$Q = \frac{2}{3} [2r(0) - r(60) - r(120)]$$ \hspace{1cm} (3.7)

$$U = \frac{2}{\sqrt{3}} [r(60) - r(120)]$$ \hspace{1cm} (3.8)

where $r(0)$, $r(60)$, and $r(120)$ are the calibrated count rates in the $0^\circ$, $60^\circ$, and $120^\circ$ polarised images respectively (Pavlovsky, 2004).
3.4.2 Computing the degree of linear polarisation of a target

The degree of linear polarisation, P.D. (%), is calculated using the Stokes vectors, and factors which correct for cross-polarisation leakage in the polarising filters (Table 3.1). This correction is useful for the POLUV filters; values for the the parallel and perpendicular transmission coefficients ($T_{\text{par}}$ and $T_{\text{perp}}$) can be found in Fig 5.4 of the ACS Instrument Handbook (Pavlovsky, 2004). These corrections together with the calibration of the source count rates removes the instrumental polarisation of the WFC ($\sim 2\%$) (see equation 3.9).

3.4.3 Computing the polarisation position angle of the E-vector on the sky

The polarisation position angle, P.A. ($^\circ$), is calculated using the Stokes vectors, the roll angle of the HST spacecraft (PA$_V$3 in the data header files), and $\chi$, which contains information about the camera geometry that is derived from the design specifications; for the WFC $\chi = -38.2$ degrees (see equation 3.10).

\[
P.D. = \sqrt{\frac{Q^2 + U^2}{I}} \frac{T_{\text{par}} + T_{\text{perp}}}{T_{\text{par}} - T_{\text{perp}}} \times 100 \quad (3.9)
\]

\[
P.A. = \frac{1}{2} \tan^{-1} \left( \frac{U}{Q} \right) + \text{PA}_V3 + \chi \quad (3.10)
\]

Sparks & Axon (1999) describe a method for determining the errors in the degree of linear polarisation (equation 3.11) and position angle (equation 3.12). The method allows for imperfections in the polarsers. The authors found that the main parameter in experiment design is the product of expected polarisation degree and signal-to-
noise. A good approximation for the case of three perfect polarisers oriented at the optimal 60° relative position angles (like in ACS) is that the error on the polarisation fraction, $P$, (which lies in the range 0 for unpolarised to 1 for fully polarised) is just the inverse of the signal-to-noise per image. One must note that this is an approximation for ideal polarisers with no instrumental polarisation. The polariser filters, especially the UV polariser, have significant leakage of cross-polarised light. The instrumental polarisation of the HRC is in the range 4%–14% in the far-UV, while that of the WFC is $\sim$ 2%.

$$\log \left( \frac{\sigma P}{P} \right) = -0.102 - 0.9898 \log(P \langle S/N \rangle_i) \quad (3.11)$$

$$\log(\sigma_\theta) = 1.514 - 1.068 \log(P \langle S/N \rangle_i) \quad (3.12)$$

The design of the ACS system is far from ideal for polarimetry. This is because the optical systems of both the HRC and WFC contain three tilted mirrors and use tilted CCD detectors. These tilted components will produce significant polarisation effects within the instrument. So in order to obtain accurate results, these effects must be calibrated-out. The two main effects caused by the tilted components are diattenuation and phase retardance. Diattenuation refers to the fact that a tilted component has different reflectivities (or transmissions) for light which is polarised parallel and perpendicular to the plane of the tilt. This can be an important source of instrumental polarisation, and can also alter the position angle of the polarisation E-vector. Phase retardance tends to convert incident linear polarised light into elliptically polarised light. These effects have complex dependencies on the position angle of the polarisation E-vector, and hence are difficult to fully calibrate. For more information about these instrumental effects see Biretta & McMaster (1997) (WFPC2 ISR 97-11) and Biretta et al. (2004) (ACS ISR 04-09).

The instrumental polarisation, which is defined as an instrument’s response to an
unpolarised target, provides a measure of some of these effects. Figure 3-6 shows the instrumental polarisation derived for the WFC through on-orbit observations of unpolarised stars (HST programs 9586 and 9661). Figure 3-7 shows the throughput and performance of the ACS. The HRC instrumental polarisation is approximately 5% at the red end of the spectrum, but rises in the UV to about 14% at the shortest wavelengths. The WFC has an instrumental polarisation around 2% (Figure 3-6). Its IM3 mirror is a proprietary Denton enhance silver coating with an incidence angle of 49°, and the CCD has an incidence angle of 20°.
In order to determine the performance of the ACS as a polarimeter, the ACS team have modelled the complete instrumental effects and the calibration together. This is done so as to quantify the impacts of the remaining uncalibrated systematic errors. They claim that the fractional polarisations will be uncertain at the one-part-in-ten level (e.g. a 20% polarisation has an uncertainty of 2%) for strongly polarised targets; and at about the 1% level for weakly polarised targets. The position angles will have an uncertainty of about 3°. This is in addition to uncertainties which arise from photon statistics (Pavlovsky, 2004). They then checked this calibration against polarised standard stars (∼ 5% polarised) and found it to be reliable within the quoted errors (Cracraft & Sparks, 2007).
3.4.4 INTEGRAL Polarimetry

3.4.4.1 INTEGRAL

The *International Gamma-ray Astrophysics Laboratory (INTEGRAL)* is dedicated to the fine spectroscopy (2.5 keV FWHM @ 1 MeV) and fine imaging (angular resolution: 12′ FWHM) of celestial gamma-ray sources in the energy range 15 keV to 10 MeV. The mission was created as an observatory led by ESA with contributions from Russia (PROTON launcher) and NASA (Deep Space Network ground station). The scientific goals of the mission include the study of gamma-ray bursts, active galactic nuclei, the interstellar medium, the cosmic gamma-ray background, stellar nucleosynthesis, X-ray binaries, neutron stars, and black holes (Winkler et al., 2003).

It has four instruments: an X-ray imager *JEM-X* (Lund et al., 2003) (4–35 keV), a spectrometer *SPI* (Vedrenne et al., 2003) – optimized for high-resolution gamma-ray line spectroscopy (18 keV–8 MeV), an imager *IBIS* (Ubertini et al., 2003) – optimized for high angular resolution imaging (15 keV–10 MeV), and an optical Johnson V-band imager *OMC* (Mas-Hesse et al., 2003) (500–600 nm). All four instruments are co-aligned with overlapping fully coded field-of-views ranging from 4.8° diameter (*JEM-X*), 5° × 5° (*OMC*), to 9° × 9° (*IBIS*) and 16° corner-to-corner (*SPI*). Hence, they observe the same region of sky simultaneously (Figure 3-8) and an observer has the possibility of conducting multi-wavelength studies of their source of interest.

Launched on 17th October 2002, it has been commissioned to operate until 31st December 2016 (subject to a mid-term review in 2014).
3.4.4.2 IBIS Compton Mode

The Imager on Board the INTEGRAL Satellite (IBIS) (Ubertini et al., 2003) is the satellite’s γ-ray imager. It consists of two detectors operating simultaneously: the Integral Soft Gamma-Ray Imager (ISGRI) (Lebrun et al., 2003), a 128×128 cadmium telluride (CdTe) semi-conductor array optimised for low energies (18 keV–1 MeV), and the PIxellated CsIodide Telescope (PICsIT) (Labanti et al., 2003), a 64×64 (CsI) crystal scintillator for higher energies (175 keV–10 MeV). For the design specifications see Table 3.2. It is an example of a coded-aperture Compton telescope. Hence the design has the advantages of a Compton telescope (high-energy response, low background, and wide field-of-view) together with the coded mask’s imaging properties (angular resolution and background subtraction).

The coded mask is based on the Modified Uniformly Redundant Array (MURA) pattern (Figure 3-9). Since diffraction is negligible at γ-ray wavelengths, the angular resolution of the coded-mask telescope is given by $\text{atan}^{-1}(a/D) = 12'$ (FWHM), where
a = the element size (11.2 mm) and D is the distance from the mask and detector plane (3200 mm). The mask is designed such that each source in the field-of-view casts its own unique shadow on the detector. Approximately half the cells in the mask are opaque and half are transparent. The system offers 70% opacity at 1.5 MeV and an off-axis transparency of 60% at 20 keV.

An active Bismuth Germanate Oxide (BGO) scintillator Veto system is used to shield the sides and bottom of the detector. The Veto system is vital to the operation of IBIS because it discriminates against background particles and photons propagating through, or induced within the spacecraft. Figure 3-10 shows the sensitivity of the IBIS Compton mode. It is greater than that of PICsIT for a similar angular resolution. However, unlike PICsIT, it has no major problems with strong backgrounds, allowing one to study photons up to a few MeV in small energy bands. Furthermore, it also allows for polarisation studies of compact objects.

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1Based on in-flight measurements; 3σ detection in $10^5$ s, $\Delta E = E/2$.
2For a 3σ detection in $10^6$ s.
3.4.4.3 Calibration and Performance

The polarisation of celestial sources is measured using the IBIS Compton mode. Photons entering IBIS are Compton scattered in ISGRI, the first detector plane, with a polar angle $\theta$ from their incident direction and at an azimuth $\psi$ from their incident electric vector (see Figure 3-11). The photons are then absorbed in the second detector, PICsIT. Hence, the polarisation of sources can be measured, because these photons are preferentially scattered in a plane at right angle to their incident electric vector. The azimuthal profile $N(\psi)$, in Compton counts recorded per azimuth bin, is:

$$N(\psi) = S \left[ 1 + a_0 \cos(2\psi - 2\psi_0) \right]$$  \hspace{1cm} (3.13)

for a source polarised at an angle $PA = \phi_0 - \pi/2 + n\pi$ and with a polarisation fraction $PF = a_0/a_{100}$. The parameter $a_{100}$ is the amplitude expected for a 100% linearly polarised source. However, the IBIS polarimetric capacity was not calibrated on the ground prior to the launch of the satellite. Forot et al. (2008) estimated $a_{100}$ to be $0.30 \pm 0.02$ for a Crab-like $E^{-2.2}$ spectrum between 200 and 800 keV, using GEANT3 Monte-Carlo simulations of IBIS and its detailed mass model (Laurent...
Table 3.2: *IBIS* technical specifications. Table taken from *IBIS* Observer’s Manual (Bélanger, 2012).

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating energy range</td>
<td>15 keV – 10 MeV</td>
</tr>
<tr>
<td><strong>Continuum sensitivity</strong></td>
<td></td>
</tr>
<tr>
<td>(ph cm(^{-2}) s(^{-1}) keV(^{-1}))</td>
<td>2.85 × 10(^{-6}) @ 100 MeV</td>
</tr>
<tr>
<td></td>
<td>1.6 × 10(^{-6}) @ 1 MeV</td>
</tr>
<tr>
<td><strong>Line sensitivity</strong></td>
<td></td>
</tr>
<tr>
<td>(ph cm(^{-2}) s(^{-1}))</td>
<td>1.9 × 10(^{-5}) @ 100 keV</td>
</tr>
<tr>
<td></td>
<td>3.8 × 10(^{-4}) @ 1 MeV</td>
</tr>
<tr>
<td><strong>Energy Resolution (FWHM)</strong></td>
<td>8% @ 100 keV</td>
</tr>
<tr>
<td></td>
<td>10% @ 1 MeV</td>
</tr>
<tr>
<td><strong>Angular Resolution (FWHM)</strong></td>
<td>12'</td>
</tr>
<tr>
<td><strong>Point source location accuracy</strong></td>
<td>1' for SNR = 30 (ISGRI)</td>
</tr>
<tr>
<td>(90% error radius)</td>
<td>3' for SNR = 10 (ISGRI)</td>
</tr>
<tr>
<td></td>
<td>5–10' for SNR = 10 (PICsIT)</td>
</tr>
<tr>
<td><strong>Timing accuracy</strong></td>
<td>61 µs – 1 hr</td>
</tr>
<tr>
<td><strong>Field of View</strong></td>
<td>8.33° × 8.00° (fully coded)</td>
</tr>
<tr>
<td></td>
<td>29.11° × 29.41° (zero response)</td>
</tr>
</tbody>
</table>

et al., 2003) together with the *GLEPS*\(^3\) package for polarisation.

Events recorded in both detectors within the same time window of 3.8 µs are tagged as Compton events. However, not all of these events result from Compton scattering. Chance coincidences can occur between events independently coming from the source, the sky, or the instrumental background. The majority of the Compton tagged events are due to background events, which are removed using the shadowgram deconvolution (Figure 3-12). About 5% are due to a small fraction of spurious coincidences which must be removed since they induce a false source detection. Only 2% of events come from true Compton events from the source. Compton events that are incompatible with a given source direction can be disregarded from the shadowgram. The most conservative way of removing background events using Compton kinetics is to remove all events whose Compton cones, within the uncertainties, do

\(^3\)GLEPS is a package for handling polarisation in *GEANT3* developed by Mark McConnell at the University of New Hampshire.
Confidence intervals on $a_0$ and $\psi_0$ are not given by the $N(\psi)$ fit to the data as the variables are not independent. They are derived from the probability density distribution of measuring $a$ and $\psi$ from $N_{pt}$ independent data points in $N(\psi)$ over a $\pi$ period, based on Gaussian distributions for the orthogonal Stokes components (Weisskopf et al., 2006):

$$dP(a, \psi) = \frac{N_{pt}S^2}{\pi\sigma_s^2} \exp \left[ -\frac{N_{pt}S^2}{2\sigma_s^2} \left[ a^2 + a_0^2 - 2a_0 a \cos(2\psi - 2\psi_0) \right] \right] a \, da \, d\psi \quad (3.14)$$

where $\sigma_s$ is the error on the profile mean $S$. The errors on each $a$ or $\psi$ dimension are obtained by integrating $dP(a, \psi)$ over the other dimension. The errors in $N(\psi)$ are dominated by statistical fluctuations in the sky background. To improve polarimetric sensitivity, only fully coded observations at off-axis angles $< 5^\circ$ are used.

The polarimetric performance of the IBIS Compton mode was evaluated through a series of tests that searched for a residual modulation of instrumental origin. These tests were carried out using unpolarised sources, on-axis and off-axis radioactive calibration sources, empty fields and spurious samples (Forot et al., 2008). A small modulation is induced due to the non-axisymmetric geometry of the detectors. The modulation fractions from two bright on-axis sources at 392 and 662 keV were measured. This yielded values of $PF = 0.066 \pm 0.013$ and $0.049^{+0.016}_{-0.013}$, respectively, hence the geometry of the detectors induces a small modulation at an angle near $40^\circ$.

Checks for systematics due to the background or the analysis process have also been performed. The polarimetric pattern of a “pseudo source” was computed. It is located $1.5^\circ$ away from the Crab, and also out of the Crab psf yet still within the IBIS field-of-view. This test made use of the same set of observations and analysis software as those for the Crab polarimetric measurements. Since the source is not real, its mean count rate was consistent with zero. The next step was to measure the level of modulation around zero due to potential statistic plus possible systematic fluctuations in the polarimetric pattern. Forot et al. (2008) conclude that the fluctu-
Figure 3-11: Forward scattering of a photon in the IBIS Compton mode. An incident photon (red) is scattered in ISGRI and absorbed in PICsIT (blue). Energy and position measurements at points A and C allow the derivation of the two angles $\theta_{\text{Com}}$ and $\theta_{\text{sca}}$. Image credit: Fig 1. of Forot et al. (2007).

Corrections were consistent with the statistics ones, hence possible systematic fluctuations can be neglected given the statistic level of the observations.

Despite the subtraction of spurious events, a small residual contamination may also modify the shape of the $N(\psi)$. A sample of in-flight spurious events during Crab observations in the energy range 200–800 keV has been analysed. The profile of these events shows a small modulation with a $\text{PF} = 0.15^{+0.04}_{-0.03}$ at an angle of $175.1 \pm 7.8^\circ$. The probability of $\text{PF}$ being greater than 0.15 is $1.2 \times 10^{-3}$ (see Figure 3-13).

For the timing analysis, the times of arrival of the Compton events are referred to the solar system barycentre and phase-folded using the closest in time ephemeris from Jodrell Bank. For more information about the analysis please see Forot et al. (2007, 2008) and Laurent et al. (2012).
Figure 3-12: Shadowgram image. The image of a celestial source can be recovered using deconvolution of the shadowgram with the coded aperture mask. This is shadowgram deconvolution. Image credit: http://imagine.gsfc.nasa.gov/docs/features/exhibit/swift_exhibit.html.

Figure 3-13: Spurious correction. Crab count rates between 200 and 500 keV in different $\Delta \theta$ bins. The total observation time is about 700 ks. Red data points represent all the Compton data (real Compton plus spurious). Blue data represent the spurious contribution, and black data points are derived Compton data. Image credit: Fig. 9 of Forot et al. (2007).
Chapter 4

Scientific Publications

What follows are the 6 scientific publications that make up this thesis.


The optical linear polarisation of the Vela pulsar was also studied using the HST/ACS. These results not only confirm those originally obtained by Wagner & Seifert (2000) and Mignani et al. (2007) both using the Very Large Telescope (VLT), but are of greater precision. Moreover, as in the case of the Crab, it was found that the PA of the pulsar is aligned with its proper-motion and spin-axis. The PWN is undetected in polarised light as is the case in unpolarised light, down to a flux limit of 26.8 magnitudes arcsec$^{-2}$.

For this work I was involved with the data reduction, the photometric/polarimetric measurements, and made the polarisation maps and histograms. I also wrote some of the paper.


We carried out a campaign using several optical facilities (INT, TNG and GTC) to search for the optical counterpart to the X-ray and radio pulsar PSR J0205+6499. Using archival Gemini data we have detected a plausible optical counterpart to this
pulsar.

For this work I did the photometric measurements of the pulsar candidate and made the optical contour plots. I contributed to some of the written sections of the paper.


This work outlines the study of the phase-averaged linear polarisation of the Crab nebula and pulsar in the optical using archival HST/ACS data. We mapped out the linear polarisation of the inner nebula, and measured the polarisation of the pulsar, inner synchrotron knot, and wisps.

For this work I was involved with the data reduction, the photometric/polarimetric measurements, and made the polarisation maps. I also wrote most of the various sections of the paper.

“INTEGRAL/IBIS and optical observations of the Crab nebula/pulsar polarisation” (Moran et al. 2012, Proceedings of “An INTEGRAL view of the high-energy sky (the first 10 years)”)

Compares the phase-averaged optical polarisation of the Crab nebula and pulsar using HST/ACS to the phase-averaged gamma-ray polarisation using the INTEGRAL/IBIS.

For this work I did the polarimetric measurements in the optical with the HST/ACS and in the gamma-ray band with INTEGRAL/IBIS. I also wrote the paper.

“Integral observations of polarization: from the Crab pulsar to Cygnus X-1” (Laurent et al. 2012, Proceedings of “An INTEGRAL view of the high-energy sky (the first 10 years)”)

Discusses the study of the gamma-ray polarisation of the Crab nebula and pulsar and Cygnus X-1 using the INTEGRAL/IBIS Compton mode.

I am listed as co-author due to my participation in the project.
“VLT observations of the two Fermi pulsars PSR J1357−6429 and PSR J1048−5832” (Mignani et al. 2011, A&A, 533, 101)

Our research group is involved in a campaign to search for the optical counterparts to pulsars detected at other wavelengths such as those identified by the Fermi gamma-ray telescope. This paper deals with the search for the counterparts to two such pulsars – PSR J1357−6429 and PSR J1048−5832. Neither pulsar was detected in the optical band.

For this work I cross checked the photometric measurements of the other authors.

Please note that Moran et al. (2012) and Laurent et al. (2012) were both reviewed internally by the scientific organising committee.
HST optical polarimetry of the Vela pulsar and nebula

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ABSTRACT
Polarization measurements of pulsars offer a unique insight into the geometry of the emission regions in the neutron star magnetosphere. Therefore, they provide observational constraints on the different models proposed for the pulsar emission mechanisms. Optical polarization data of the Vela pulsar was obtained from the Hubble Space Telescope (HST) archive. The data, obtained in two filters (F606W, central wavelength = 590.70 nm and F550M, central wavelength = 558.15 nm), consist of a series of observations of the pulsar taken with the HST/Advanced Camera for Surveys and cover a time span of 5 d. These data have been used to carry out the first high spatial resolution and multi-epoch study of the polarization of the pulsar. We produced polarization vector maps of the region surrounding the pulsar and measured the degree of linear polarization (P.D.) and the position angle (P.A.) of the pulsar’s integrated pulse beam. We obtained P.D. = 8.1 ± 0.7 per cent and P.A. = 146.3 ± 2.4, averaged over the time span covered by these observations. These results not only confirm those originally obtained by Wagner & Seifert and Mignani et al., both using the Very Large Telescope, but are of greater precision. Furthermore, we confirm that the P.A. of the pulsar polarization vector is aligned with the direction of the pulsar proper motion. The pulsar wind nebula is undetected in polarized light as is the case in unpolarized light, down to a flux limit of 26.8 mag arcsec−2.


1 INTRODUCTION
Strong polarization is expected when the pulsar optical emission is generated by synchrotron radiation. Shklovsky (1953) suggested that the continuous optical radiation from the Crab nebula was due to synchrotron radiation. This was later confirmed by Dombrovsky (1954) and Vashakidze (1954) who found that the optical radiation was polarized. Incoherent synchrotron emission follows a simple relationship between its polarization profile and underlying geometry. Hence, optical polarization measurements of pulsars provide a unique insight into the geometry of their emission regions, and therefore observational constraints on the theoretical models of the emission mechanisms. From an understanding of the emission geometry, one can limit the competing models for pulsar emission, and hence understand how pulsars work – a problem which has eluded astronomers for almost 50 yr.

Polarimeters are sensitive in the optical, but the majority of pulsars are very faint at these wavelengths with $V \geq 25$ (Shearer 2008). Polarimetry in the very high energy domain, X-ray and $\gamma$-ray, using instruments on board space telescopes, is of limited sensitivity. So far, detailed results have only been reported for the Crab pulsar (Weisskopf et al. 1978; Dean et al. 2008; Forot et al. 2008). Although the number of pulsars detected in the optical is growing (Mignani 2011), only five pulsars have had their optical polarization measured: Crab (Wampler, Scargle & Miller 1969; Kristian et al. 1970; Smith et al. 1988; Słowikowska et al. 2009; Moran et al. 2013), Vela (Wagner & Seifert 2000; Mignani et al. 2007), PSR B0540−69 (Middleditch, Pennypacker & Burns 1987; Chanan & Helfand 1990; Wagner & Seifert 2000; Mignani et al. 2010) PSR B0656+14 (Kern et al. 2003), and PSR B1509−58 (Wagner & Seifert 2000). None the less, the optical currently remains invaluable for polarimetry in the energy domain above radio photon energies. The Crab pulsar, being the brightest optical pulsar with $V \sim 16.8$ (Nasuti et al. 1996), has had several measurements of its optical polarization, both phase-averaged and phase-resolved. Hence, polarization studies of more pulsars are needed to better understand and constrain the polarization properties of pulsars and search for possible correlations with their intrinsic parameters (e.g. age, magnetic field strength).

The Vela pulsar is a young energetic pulsar, with characteristic age $\tau \sim 11$ kyr and spin-down power $E \sim 6.9 \times 10^{35}$ erg s$^{-1}$, associated with the Vela supernova remnant (SNR: Large, Vaughan & Mills 1968). It is the third brightest optical pulsar ($V \sim 23.6$;
Mignani & Caraveo 2001) and is located at a distance of ≈290 pc (Caraveo et al. 2001). It powers the nearest bright X-ray pulsar wind nebula (PWN), a plerion of positrons and electrons that is created by the confinement of the pulsar wind by its surrounding SNR. For detailed reviews of PWNe, see Gaensler & Slane (2006), Kargaltsev & Pavlov (2008), and Kargaltsev, Rangelov & Pavlov (2013). The Vela PWN consists of a double-arc structure (Helfand, Gotthelf & Halpern 2001; Pavlov et al. 2001, 2003) and an X-ray jet (Markwardt & Ogelman 1995), aligned along the axis of symmetry of the arcs. The bilateral structure of the PWN is remarkably similar to that seen by Chandra observations of the Crab nebula (Weisskopf et al. 2000). Radio observations, using the Australian Telescope Compact Array, have revealed a highly polarized (60 per cent) and extended radio nebula with symmetric morphology surrounding the pulsar and X-ray nebula (Dodson et al. 2003a). However, to date no detection of the optical counterpart of the Vela PWN has been reported, despite deep observations with the Hubble Space Telescope (HST) (Mignani et al. 2003).

Here, we present the results of recent polarization observations of the Vela pulsar field carried out with the Advanced Camera for Surveys (ACS) of the HST. The purpose of this work is fourfold. First, we wanted to independently confirm the polarization measurements for the Vela pulsar originally reported by Wagner & Seifert (2000) and Mignani et al. (2007), both obtained with the Very Large Telescope (VLT), and improve their accuracy, obtaining the highest significance polarization measurement of the pulsar.

Secondly, we wanted to check for possible short-term variability of the pulsar polarization, an experiment that can be ideally conducted with the HST being unaffected by the variable polarization background of the Earth’s atmosphere. Thirdly, since we expect that fine structures within the X-ray PWN are strongly polarized in the optical, like for the Crab, we examined the HST/ACS images to search, for the first time, for polarized optical emission from the Vela PWN. Detection of the PWN in the optical, together with the radio and X-ray data, will help establish the properties of the relativistic pulsar wind, including its energetics, magnetic field structure, spatial evolution, and interaction with the ambient medium. As shown, e.g. by the cases of the Crab pulsar (Moran et al. 2013) and PSR B0540—69 (Mignani et al. 2010), it is difficult to determine the polarization for pulsars embedded in highly polarized environments, such as those of the surrounding PWNe and SNRs.

So, in order to determine the Vela pulsar’s polarization profile, we need to know the level of background polarization induced by the surrounding PWN/SNR environment. Therefore, the fourth purpose of this work is to accurately map the polarization of the innermost part of the Vela SNR, around the pulsar position.

Our work will then act as a guideline for future phase-resolved polarization measurements of the Vela pulsar using, e.g. the Galway Astronomical Stokes Polarimeter (GASP). This is an ultra-high-speed, full Stokes, astronomical imaging polarimeter based on the Division of Amplitude Polarimeter and has been designed to resolve extremely rapid variations in objects such as optical pulsars and magnetic cataclysmic variables (Kyne et al. 2010; Collins et al. 2013).

2 OBSERVATIONS AND DATA ANALYSIS

2.1 Observations and data reduction

We downloaded the raw HST/ACS polarization science frames of the Vela pulsar field from the Mikulski Archive for Space Telescopes1 (MAST). The data set is comprised of five observations carried out in five different visits between 2011 February 18 and 23 (Proposal ID: 12240). Observations were obtained using the Wide Field Channel (WFC) detector of the ACS. The WFC employs a mosaic of two $4096 \times 2048$ Scientific Imaging Technologies CCDs, with a pixel scale of $\sim 0.05$ arcsec, covering a nominal field of view (FOV) of $\sim 202 \times 202$ arcsec$^2$ (Pavlovsky 2004). For these observations, with the polarizers in place, the FOV was $\approx 102 \times 102$ arcsec$^2$. The observations were obtained with three different polarizer elements, POL0V, POL60V, and POL120V, corresponding to rotation angles of $0^\circ$, $60^\circ$, and $120^\circ$, respectively. For each epoch, the integrations were split into pairs of exposures of $1299.5$ s each for the POL0V and $1386.5$ s each for the POL60V and POL120V. The filter used was the F606W ($\lambda = 590.70$ nm, $\Delta \lambda = 250.00$ nm) for the integrations with the polarizer. Two $1362.5$ s exposures with the F550M filter ($\lambda = 558.15$ nm, $\Delta \lambda = 54.70$ nm) and no polarizer in place were taken on 2011 February 18. During each observation, HST pointed at the pulsar at about the same spacecraft roll angle ($\sim 205^\circ$), with the pulsar centred at roughly the same CCD position. See Table 1 for a summary of the observations.

For each visit, the raw images, which had already been flat-fielded, were geometrically aligned, combined, and averaged with cosmic ray removal using IRAF (see Fig. 1). We used a total of five field stars and the IRAF task ccmmap and the 2MASS catalogue (Skrutskie et al. 2006) to fit the ACS/WFC astrometry. The pulsar was found at $\alpha = 08^h 35^m 20^s.578 \pm 0^s.004$, $\delta = -45^\circ 10' 34.560 \pm 0'.077$ (the errors denote the rms of the astrometric fit). For each set of observations, the images taken in the different polarizers were analysed using the IMPOL2 software (Walsh 1999), which produces polarization maps (see Fig. 1). In order to increase the number of counts, the size of the cells that we used for the mapping is $\approx 0.8 \times 0.8$ arcsec$^2$.

2.2 Polarization measurements

In order to measure its degree of linear polarization, per each observation, we performed aperture photometry of the pulsar in each of the images taken with the POL0V, POL60V, and POL120V polarizer elements using the IRAF task phot. Since one of our goals was to search for possible short-term variability of the pulsar polarization, we preferred not to co-add all the 10 available exposures in each polarizer element (Table 1) but to work on each observation at once. Moreover, since they were performed with slightly different spacecraft roll angles (by $\sim \pm 1^\circ$) and with the pulsar located at slightly different positions on the CCD (by $\sim \pm 2$ pixels), this approach allowed us to deal with possible systematics affecting the measurement of the pulsar polarization and gave us a better handle on the random error estimates.

As done in Moran et al. (2013), we tested our method by performing aperture photometry on a number of reference stars (see Fig. 1) selected to cover uniformly the ACS/WFC FOV, so as to check for possible systematics, such as the dependence of the linear polarization on the star position on the CCD. The stars are not saturated but bright enough to provide good statistics and sample different brightness ranges to check for a possible dependence of the polarization parameters on the star flux. We also wished to verify the size of the aperture to use for polarimetry. We used images taken

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1 https://archive.stsci.edu/
2 http://www.stscい.org/software/IRAFtools/stecf-iraf/impol
Table 1. Summary of the HST/ACS observations of the Vela SNR taken with the WFC. The filters used were F606W ($\lambda = 590.70$ nm, $\Delta \lambda = 250.00$ nm) and F550M ($\lambda = 558.15$ nm, $\Delta \lambda = 54.70$ nm).

<table>
<thead>
<tr>
<th>Date</th>
<th>Exposure (s)</th>
<th>Filter</th>
<th>Polarizer</th>
<th>Roll angle (PA$_{V3}$) ($^\circ$)</th>
<th>Pulsar position on chip (x, y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 Feb. 18</td>
<td>2 × 1362.5</td>
<td>F550M</td>
<td>CLEAR2L</td>
<td>205.9</td>
<td>1167.83, 1169.08</td>
</tr>
<tr>
<td></td>
<td>2 × 1299.5</td>
<td>F606W</td>
<td>POL0V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 × 1386.5</td>
<td></td>
<td>POL60V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 × 1386.5</td>
<td></td>
<td>POL120V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011 Feb. 19</td>
<td>2 × 1299.5</td>
<td>F606W</td>
<td>POL0V</td>
<td>203.9</td>
<td>1162.19, 1173.87</td>
</tr>
<tr>
<td></td>
<td>2 × 1386.5</td>
<td></td>
<td>POL60V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 × 1386.5</td>
<td></td>
<td>POL120V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011 Feb. 20</td>
<td>2 × 1299.5</td>
<td>F606W</td>
<td>POL0V</td>
<td>203.9</td>
<td>1162.10, 1174.46</td>
</tr>
<tr>
<td></td>
<td>2 × 1386.5</td>
<td></td>
<td>POL60V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 × 1386.5</td>
<td></td>
<td>POL120V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011 Feb. 21</td>
<td>2 × 1299.5</td>
<td>F606W</td>
<td>POL0V</td>
<td>204.9</td>
<td>1165.10, 1171.40</td>
</tr>
<tr>
<td></td>
<td>2 × 1386.5</td>
<td></td>
<td>POL60V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 × 1386.5</td>
<td></td>
<td>POL120V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011 Feb. 23</td>
<td>2 × 1299.5</td>
<td>F606W</td>
<td>POL0V</td>
<td>204.9</td>
<td>1165.29, 1171.90</td>
</tr>
<tr>
<td></td>
<td>2 × 1386.5</td>
<td></td>
<td>POL60V</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 × 1386.5</td>
<td></td>
<td>POL120V</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. HST image of the Vela pulsar field taken with the ACS/WFC on 2011 February 18 with the F606W filter and the POL0V polarizer. The FOV is $\approx 102 \times 102$ arcsec$^2$. The frame has been aligned north–south. The location of the pulsar is marked by the red circle. The reference stars used for analysis are also marked with magenta circles and labelled. The observed polarization vector map is superimposed in black. The legend shows the vector magnitude for 50 percent polarization. Lastly, the Chandra ACIS (1–8 keV) X-ray contours of the Vela X-ray PWN are overlaid in blue (Pavlov et al. 2003).
in Moran et al. (2013). Sparks & Axon (1999) have investigated the achievable accuracies using the assumption of three perfect polarizers oriented at the optimal 60° relative P.A.s (like the ACS/WFC). They found that the important parameter in experiment design is the product of expected fractional polarization and S/N (\(p \times \langle S/N \rangle\)). The error on the fractional polarization, \(\sigma_p\), is just the inverse of the S/N per image. Below are the formulae used for calculating the error in P.D. (equation 1) and P.A. (equation 2; Pavlovsky 2004):

\[
\log \left( \frac{\sigma_p}{p} \right) = -0.102 - 0.9898 \log (p \times \langle S/N \rangle) \\
\log \sigma_\theta = 1.514 - 1.068 \log (p \times \langle S/N \rangle),
\]

where \(\langle S/N \rangle\) is the average target S/N of the three input images, taken with the three different polarizers.

As a guide to our analysis, we also analysed a number of reference stars selected in the pulsar field (see Fig. 1) to confirm the methodology which we used. As in the case of the pulsar, we used an aperture of radius 0.2 arcsec to measure the flux from each star. The sky counts were measured using an annulus of width \(\approx 0.1\) arcsec, located 0.15 arcsec beyond the central aperture. Aperture correction was applied as for the pulsar. We also investigated the effects of photometric losses due to charge transfer efficiency (CTE) in the CCDs of the WFC. The ACS team claim that there is no evidence of photometric losses due to CTE for WFC data taken after 2004 (see Pavlovsky 2004). None the less, we applied the correction for CTE during our analysis is that of bias. This is due to instrumental errors which tend to increase the observed polarization of a target with respect to its true polarization. The effect is negligible when \(\eta = p \times S/N\) is high (>10), where \(p\) is the fractional polarization of the target and S/N is the target signal-to-noise per image. See for example fig. 4 of Sparks & Axon (1999). Since the Vela pulsar is in the high-\(\eta\) regime, the debiasing correction is small and therefore we omit it. However, this is not the case for the reference stars which have low measured polarization (<3 per cent and mostly <2 per cent); consequently the associated errors should be \(\approx 1\) per cent (Simmons & Stewart 1985) and can be considered to be zero, and hence have low \(\eta\). See Section 3.1.

### 3 RESULTS

In this section, we present the measurements of P.D. and P.A. for both the Vela pulsar and each of the reference stars in Fig. 1, obtained per each of the five observing epochs. The values of P.D. and P.A., together with their associated errors, are summarized in Tables 2 and 3 inclusive. For an easier visualization of the results, and to make a trend analysis easier, we have also plotted the values of P.D. and P.A. for both the Vela pulsar and each of the reference stars as a function of time (see Figs 2 and 3).

#### 3.1 The pulsar

As seen from Fig. 1, the Vela pulsar is clearly detected in polarized light, both in the POL0V and with the other polarizer elements. The P.D. values of the POL0V pulsar measured at the different epochs vary from a minimum of 6.6 per cent to a maximum of 10.2 per cent, the latter corresponding to the second observation. The differences between these values are not statistically significant being, in most cases, within \(3\sigma\). The same is true for the P.A. values. We have computed mean P.D. and P.A. values for the Vela pulsar using the values listed in Tables 2 and 3. Using a \(\chi^2\) goodness of fit, we also found no significant variation (at the 95 per cent confidence level) in the polarization of the Vela pulsar during the short time span (5 d) covered by these observations. However, more detailed follow-up observations covering a much longer time span will be needed to determine if there is any longer term variation. The results for the Vela pulsar are P.D. = 8.1 ± 0.6 per cent and P.A. = 146.3 ± 2.4. The values are reported on top of the Vela pulsar panel in Figs 2 and 3 and in Table 4. Not only are these results in good agreement with those of Wagner & Seifert (2000) and Mignani et al. (2007), both obtained using the VLT and the same data set, but they are of greater precision owing to the longer integration time and better spatial resolution of the HST observations, which allowed us to minimize the contamination from the sky background.

As done for the pulsar, we present the mean P.D. and P.A. values for all the reference stars (see Table 4).

#### 3.2 The nebula

The Vela PWN is not detected in polarized optical light in any of the single observations, neither with the POL0V (Fig. 1) nor with any of the other polarizer elements (POL60V, POL120V).
Figure 2. Plots of the P.D. (per cent) of both the Vela pulsar and the reference stars as a function of time. The solid lines are the mean of the P.D. Mean values and rms are reported on top of each panel. The errors for the pulsar are purely statistical, whereas those of the stars are the upper limit (≈1 per cent) imposed by the debiasing correction (Simmons & Stewart 1985).

with the polarized sky background apparently looking uniform. The ACS/WFC polarization map (Fig. 1) shows the variation of the polarization vectors in the pulsar field and in the vicinity of the pulsar itself. Each vector has magnitude equal to the degree of polarization computed over cells of size ≈0.8 × 0.8 arcsec², and its orientation corresponds to the P.A. measured at that point. Such a map allows one to visualize the direction of the magnetic field lines within the region surrounding the pulsar. From Fig. 1, one can see that the pulsar field is significantly polarized, at the level of P.D. ≈10 per cent per cell. However, we cannot see any obvious variation, neither in intensity nor in direction, in the polarization vectors in the vicinity of the pulsar. This is consistent with the fact that the PWN is not detected in polarized light. This is clearly demonstrated in Fig. 1, where we display the ACS/WFC polarization map with superimposed X-ray contours of the PWN in the 1–8 keV energy range as observed by the Chandra-ACIS detector (Pavlov et al. 2003). The figure clearly shows that there is no significant change in the polarization vectors along the main structures of the X-ray PWN, such as the inner and outer arcs and the jets south-east of the pulsar. Unfortunately, owing to the smaller FOV of the ACS/WFC with the polarizer optics in, and the chosen observing strategy, with the Vela pulsar at the centre of the detector, some parts of the region covered by the spatial extent of the X-ray PWN are not fully included in the image or are affected by vignetting at the edge of the detector. In particular, it does not include the region of the bright and long jet protruding north-west of the pulsar position. Thus, we cannot say anything about the jet polarization and whether it is variable, like its X-ray flux and morphology (Durant et al. 2013).

In order to increase our sensitivity to the detection of the PWN in polarized light, we co-added all the 30 available exposures taken...
Figure 3. Plots of the P.A. (°) of both the Vela pulsar and the reference stars as a function of time. The solid lines are the mean of the P.A. Mean values and rms are reported on top of each panel.

in each of the three polarizers (Table 1), corresponding to a total integration time of ≈40 725 s per element. Since the X-ray PWN is extended over scales of tens of arcsec², the possible systematics that might have affected the measurement of the pulsar polarization, such as the slightly different spacecraft roll angle and the pulsar centring on the CCD (see Section 3.1), are much less important here. After co-adding all these exposures, subtracting the field stars, and smoothing with a median filter of 1 arcsec, we found no evidence of the PWN. At the same time, we found no significant difference in the magnitude and orientation of the polarization vectors of the sky background, meaning that its polarization properties do not change on time-scales as short as a few days, as expected.

We use the value of the sky to determine the upper limit of the optical surface brightness of the Vela PWN. For this measurement, we first used a total of 200 cells, each of which was of 1 arcsec² area, and evenly spread across the area coinciding with the central part of the X-ray PWN and well away from field stars. After measuring the flux of the sky in each cell, we took the mean of these 200 measurements, which yielded a value of 23.6 mag arcsec⁻². We then used this mean in conjunction with the standard deviation of the flux measurements to determine the upper limit of the surface brightness of the Vela PWN. The 3σ upper limit of the PWN is 26.8 mag arcsec⁻². Due to the limited FOV of these observations (see Fig. 1), there is no means of determining a background outside the area covered by the PWN. Hence, we note that this is quite a conservative upper limit.

4 DISCUSSION

We have studied the phase-averaged polarization properties of the Vela pulsar using archival HST/ACS data. We have produced polarization vector maps of the ≈102 × 102 arcsec² region directly surrounding the pulsar, covering most of the spatial extent of the X-ray PWN, and measured the degree of linear polarization and the
Table 4. Overall results for the P.D. (per cent) and P.A. (°). The values listed in the table are the mean and standard error of the P.D. and P.A. The last columns give the star magnitude in the F550M filter (mF550M) and the S/N. Photometry errors are purely statistical.

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>P.D. (per cent)</th>
<th>P.A. (°)</th>
<th>mF550M</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar</td>
<td>8.1 ± 0.6</td>
<td>146.3 ± 2.4</td>
<td>23.604 ± 0.018</td>
<td>60</td>
</tr>
<tr>
<td>Star 1</td>
<td>1.1 ± 0.5</td>
<td>135.5 ± 22.4</td>
<td>20.430 ± 0.004</td>
<td>543</td>
</tr>
<tr>
<td>Star 2</td>
<td>1.3 ± 0.2</td>
<td>147.7 ± 10.3</td>
<td>19.600 ± 0.004</td>
<td>1085</td>
</tr>
<tr>
<td>Star 3</td>
<td>2.4 ± 0.4</td>
<td>119.7 ± 3.8</td>
<td>21.034 ± 0.005</td>
<td>362</td>
</tr>
<tr>
<td>Star 4</td>
<td>1.7 ± 0.3</td>
<td>134.9 ± 12.3</td>
<td>19.520 ± 0.004</td>
<td>1085</td>
</tr>
<tr>
<td>Star 5</td>
<td>2.1 ± 0.3</td>
<td>135.3 ± 8.6</td>
<td>19.903 ± 0.004</td>
<td>1085</td>
</tr>
<tr>
<td>Star 6</td>
<td>1.2 ± 0.2</td>
<td>146.1 ± 20.3</td>
<td>19.824 ± 0.004</td>
<td>543</td>
</tr>
<tr>
<td>Star 7</td>
<td>1.8 ± 0.2</td>
<td>129.2 ± 5.8</td>
<td>18.984 ± 0.004</td>
<td>1085</td>
</tr>
<tr>
<td>Star 8</td>
<td>1.5 ± 0.3</td>
<td>121.4 ± 5.0</td>
<td>21.446 ± 0.006</td>
<td>271</td>
</tr>
<tr>
<td>Star 9</td>
<td>1.9 ± 0.2</td>
<td>124.1 ± 1.0</td>
<td>21.374 ± 0.005</td>
<td>271</td>
</tr>
<tr>
<td>Star 10</td>
<td>2.3 ± 0.3</td>
<td>134.5 ± 4.7</td>
<td>19.249 ± 0.004</td>
<td>1085</td>
</tr>
</tbody>
</table>

P.A. of the pulsar’s integrated pulse beam. This work marks the first high spatial resolution multi-epoch study of the variability of the polarization of the pulsar.

The results for the Vela pulsar are P.D. = 8.1 ± 0.6 per cent and P.A. = 146.3 ± 2.4° (see Table 4). These values firmly confirm those of Wagner & Seifert (2000) and Mignani et al. (2007). Both obtained using the same VLT data set but reported with different error estimates [see Mignani et al. (2007) for a discussion of this discrepancy]. However, our measurements are of greater precision than those previously reported owing to the longer integration time and better spatial resolution of the HST observations. Thus, we obtained the first fully independent, and most accurate measurement of the Vela pulsar polarization in the optical. We could see no evidence of significant variation of the pulsar polarization over the 5 d covered by the HST observations (Table 1), suggesting that the optical polarization of pulsars does not vary over short time-scales. This is also the case of the Crab, whose polarization, also measured with the ACS, does not change up to time-scales of a few weeks (Moran et al. 2013). Nothing can be said for PSR B0540—69, the third pulsar for which optical polarization has been measured by the HST (Mignani et al. 2010). Indeed, in that case the polarization measurement was obtained with the WFPC2 and, because of the different instrument observing strategy in polarization mode, the data set did not consist of a series of repeated measurements at each polarizer angle. Monitoring the polarization of these pulsars on a regular time frame would be important to spot possible secular changes. In addition, phase-resolved polarization measurements, so far carried out for the Crab pulsar only (Słowikowska et al. 2009), would be important to track any change in the polarization properties following a glitch, or in coincidence with giant pulses.

As in the case of Mignani et al. (2007), we have found an apparent alignment between the phase-averaged polarization direction of the Vela pulsar (P.A. = 146.3 ± 2.4°), the axis of symmetry of the X-ray arcs and jets observed by Chandra, which are at a P.A. of 310° ± 1.5° (Helfand et al. 2001), and its proper motion vector (301° ± 1.8°) measured with the very long baseline interferometry (Dodson et al. 2003b). This alignment is shown in Fig. 4, where the orientation of these three vectors is compared with the phase-averaged polarization direction measured by Mignani et al. (2007) with the VLT. Interestingly enough, Moran et al. (2013) have found the same scenario for the Crab pulsar. This suggests that the ‘kick’ given to neutron stars at birth, at least in the case of the Crab and Vela pulsars, is directed along the rotation axis (Lai, Chernoff & Cordes 2001), assuming that this is aligned with the proper motion vector. The alternative view is that the apparent alignment is an effect of projection on to the sky plane, and that there is no physical jet along the axis of rotation (Radhakrishnan & Deshpande 2001). More concrete measurements of the optical polarization of pulsars will yield the needed observational restraints on these hypotheses. For the other best candidate, PSR B0540—69, very little can be said because the X-ray structure of the PWN is not clearly resolved by Chandra owing to the Large Magellanic Cloud distance. Moreover, the pulsar has no measured proper motion to compare with (Mignani et al. 2010). Interestingly enough, however, the optical structure of the PWN, which broadly traces that of the X-ray PWN detected by Chandra, shows a possible alignment between its major axis and the pulsar polarization vector. If the PSR B0540—69 PWN has indeed an arc-like structure along its major axis, this would suggest a possible different scenario with respect to both Crab and Vela.

Our improved measurement of the Vela pulsar polarization does not affect the results presented in Mignani et al. (2007) about the comparison with the expectations of various pulsar magnetosphere models. For instance, using the same code as used in Mignani et al. (2007) and the same model parameters, the outer gap model (Romani & Yadigaroglu 1995) still predicts values of the phase-averaged P.D. that are typically much larger than the observed one, unless some depolarization effects are introduced. In particular, our value of P.D., together with its currently associated error, makes it still difficult to set very accurate constraints on the dipole inclination angle α, assuming a realistic viewing angle ζ ∼ 65° compatible with the profile of the pulsar optical light curve (e.g. Gouiffes 1998). This is because the values of the phase-averaged P.D. predicted by the outer gap model are much less dependent on α in the low-polarization regime (see fig. 3 of Mignani et al. 2007). According to our measured P.D. = 8.1 ± 0.6 per cent, we can only say that...
the dipole inclination angle $\alpha$ would be probably close to $\approx 80^\circ$. Similarly, the comparison of our measured P.A. = 146.3 $\pm$ 2.4 with that predicted by the outer gap model would imply, for the same model parameters as before, that the P.A. $\psi_0$ of the pulsar’s projected rotational axis would be $\approx 130^\circ$ (see fig. 4 of Mignani et al. 2007). Modulo 180 $^\circ$, this value is strikingly close to the P.A.s of the axis of symmetry of the X-ray arcs and jets (310 $^\circ$ $\pm$ 1.5; Helfand et al. 2001) and of the proper motion vector (301 $^\circ$ $\pm$ 1.8; Dodson et al. 2003b).

Examining the polarization vector maps (see Fig. 1), one can see that both the levels of linear polarization and P.A.s in the vicinity of the pulsar, including the inner part of the X-ray PWN region, are not much different from those of the rest of the field. In other words, the sky around the pulsar is more or less uniformly polarized. In order to quantify the mean sky polarization properties in the Vela pulsar field, we built the histograms of the distributions of P.D. and P.A., which we show in Figs 5 and 6, respectively. The values represented in the histograms are those extracted from the polarization map (Fig. 1), and are computed over cells of $\approx 0.8 \times 0.8$ arcsec$^2$, evenly distributed in the FOV and far from the regions at the edge of the detector, which are affected by vignetting. From the histogram of the P.D. distribution, we see that, on average, the sky is more strongly polarized than the pulsar, with a peak value of P.D. $\approx 12$ per cent. Furthermore, from the histogram of the P.A. distribution, we also see that the polarization P.A. of the pulsar ($\approx 140^\circ$) is away from the peak of the sky distribution ($\approx 71^\circ$). This shows that the polarization properties of the pulsar are different from those of the rest of the field.

From analysis of the geometry of the HST/ACS pointing (via the header files), we found that the plane of the scattering is perpendicular to the mean of the distribution of polarization P.A.s in the pulsar field ($\approx 71^\circ$) (see Figs 6 and 7). Hence, this, together with the sky brightness ($\approx 23.6$ mag arcsec$^{-2}$), indicates that these observations are affected by zodiacal light. Furthermore, it suggests that the high level of sky polarization is mostly due to zodiacal light rather than the nebula.

The non-detection of the Vela PWN even in deep HST exposures means that it is intrinsically much fainter in the optical than the Crab and PSR B0540–69 PWNe. This can be due to the fact that either the optical brightness of PWNe is not uniquely related to the pulsar spin-down power, with some pulsars injecting larger fractions of their spin-down power in the acceleration of relativistic particles that powers the PWN emission, and/or it is not uniquely related to the PWN X-ray luminosity.

Finally, it is also possible that the low optical surface brightness of the Vela PWN is also affected by the different physical conditions in the ejecta of the surrounding SNR, such as the local density, and/or by the intensity and properties of its magnetic field, which might lead to a different confinement of the pulsar relativistic wind. A better characterization of the SNR environment in the proximity of the pulsar would be crucial to verify this possibility.

5 CONCLUSIONS

We have studied the phase-averaged polarization properties of the Vela pulsar using archival HST/ACS data covering a time span of 5 d. Our work marks the first high spatial resolution multi-epoch study of the polarization properties of the pulsar. We found that the pulsar is polarized, with P.D. $= 8.1 \pm 0.6$ per cent and P.A. $= 146.3 \pm 2.4$, and that its polarization properties do not change significantly over the short time span covered by the HST observations. Our measurement independently confirms those obtained by Wagner & Seifert (2000) and Mignani et al. (2007), using the same VLT data set, but are of greater precision. Thus, we confirm that important...
depolarization factors need to be taken into account to make the measured polarization value consistent with the expectation of most pulsar magnetosphere models, such as the outer gap model. Future phase-resolved optical polarization observations of the Vela pulsar, never performed so far, will bring more information on the geometry of the pulsar emission regions, crucial for a better comparison with theoretical models, together with the development of more advanced simulation codes. For example, McDonald et al. (2011) have developed an inverse mapping approach for determining the emission height of the optical photons from pulsars. It uses the optical Stokes parameters to determine the most likely geometry for emission, including magnetic field inclination angle ($\alpha$), the observer's line-of-sight angle ($\xi$), and emission height.

As in the case of Mignani et al. (2007), we found an apparent alignment between the P.A. of the Vela pulsar phase-averaged polarization vector, the axis of symmetry of the arcs of the X-ray PWN, and the proper motion vector and spin-axis vector, as observed in the Crab PWN (Moran et al. 2013). Whether this characteristic is unique to all young pulsar/PWN systems cannot be determined at the moment, owing to the lack of a sufficiently representative sample, with Vela being only the third young pulsar with a detected X-ray PWN, a measured pulsar proper motion, and a determined phase-averaged polarization direction.

Finally, we present the first and deepest polarized images of the environment surrounding the Vela pulsar. We found that the PWN is undetected in polarized light as is the case in unpolarized light, down to a limit of 26.8 mag arcsec$^{-2}$, not quite as deep as that obtained by Mignani et al. (2003, 28.1 mag arcsec$^{-2}$) with the WFPC2.

The intrinsic faintness of the Vela PWN with respect to the Crab cannot be easily explained in terms of the pulsar energetics and lower surface brightness of the X-ray PWN, assuming that the X-ray and optical PWN brightnesses are uniquely related to each other, but is probably associated with a dramatic spectral turnover of the PWN between the X-rays and the optical.

From a general standpoint, more multiwavelength polarization observations of pulsars, both phase-averaged and phase-resolved, and of their PWNs with existing instruments, such as the HST/ACS and GASP in the optical or INTEGRAL/IBIS in soft $\gamma$-rays, and instruments aboard future X-ray missions such as the Gravity and Extreme Magnetism Small Explorer (Clark et al. 2013) or the X-ray Imaging Polarimetry Explorer (Soffitta et al. 2013) in the X-rays will help to provide the much needed data to constrain current theoretical models of emission from pulsar magnetospheres.

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Optical observations of PSR J0205+6449 – the next optical pulsar?

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ABSTRACT

PSR J0205+6449 is a young (∼5400 yr), Crab-like pulsar detected in radio and at X-ray and γ-ray energies and has the third largest spin-down flux among known rotation-powered pulsars. It also powers a bright synchrotron nebula detected in the optical and X-rays. At a distance of ∼3.2 kpc and with an extinction comparable to the Crab, PSR J0205+6449 is an obvious target for optical observations. We observed PSR J0205+6449 with several optical facilities, including 8 m class ground-based telescopes, such as the Gemini and the Gran Telescopio Canarias. We detected a point source, at a significance of 5.5σ, of magnitude i′ ∼ 25.5, at the centre of the optical synchrotron nebula, coincident with the very accurate Chandra and radio positions of the pulsar. Thus, we discovered a candidate optical counterpart to PSR J0205+6449. The pulsar candidate counterpart is also detected in the g′ (∼27.4) band and weakly in the r′ (∼26.2) band. Its optical spectrum is fitted by a power law with photon index γ0 ∼ 1.9 ± 0.5, proving that the optical emission, if of non-thermal origin, is as expected for a young pulsar. The optical photon index is similar to the X-ray one (ΓX = 1.77 ± 0.03), although the optical fluxes are below the extrapolation of the X-ray power spectrum. This would indicate the presence of a double spectral break between the X-ray and optical energy range, at variance with what is observed for the Crab and Vela pulsars, but similar to the Large Magellanic Cloud pulsar PSR B0540–69.

Key words: pulsars: individual: PSR J0205+6449.

1 INTRODUCTION

PSR J0205+6449 in supernova remnant (SNR) 3C 58 is a young energetic pulsar detected at X-ray, γ-ray and radio wavelengths (Camilo et al. 2002; Murray et al. 2002; Abdo et al. 2009). It has a spin period P = 65 ms and the third highest spin-down energy flux, E/d2 ∼ 2.6 × 1036 erg s−1 kpc−2 (where d is the pulsar distance), after the Crab and Vela pulsars. 3C 58 was thought to be young, associated with supernova SN 1181 (van den Bergh 1978), and consequently should share many of the characteristics of the Crab nebula, including the presence of a young pulsar. Yet its pulsar, PSR J0205+6449, defied detection for over 20 years. It was only about 10 years ago that it was discovered as an X-ray pulsar by Chandra (Murray et al. 2002), while its identification as a radio pulsar came soon after (Camilo et al. 2002). PSR J0205+6449 was also detected in the hard X-rays (Kuiper et al. 2010) by the High Energy X-ray Timing Experiment aboard the Rossi X-ray Timing Explorer (RXTE) and was also one of the first to be identified as a γ-ray pulsar by Fermi (Abdo et al. 2009). PSR J0205+6449 is clearly located within a pulsar wind nebula (PWN), detected in the X-rays (Slane, Helfand & Murray 2002; Slane et al. 2004), optical (Shibanov et al. 2008) and near-infrared (Slane et al. 2008). From the X-ray determined hydrogen column density (Marelli, De Luca & Caraveo 2011; Marelli 2012), and using the Predehl & Schmitt (1995) relation, we can estimate an AV ∼ 2.2–2.5, similar to the Crab pulsar. The distance to PSR J0205+6449, however, is possibly larger than the Crab. H α radio observations give a distance to 3C 58 of 3.2 kpc (Roberts et al. 1993), lower but still consistent with the value of 4.5+1.8−1.2 kpc obtained from the pulsar dispersion measure of 140.7 ± 0.3 cm−3 pc (Camilo et al. 2002) and the electron distribution model of Cordes & Lazio (2002).

If the Crab and 3C 58 SNRs were of the same age, we might also expect similarities between their pulsars. However, PSR J0205+6449 was found to be considerably weaker than the Crab pulsar; its X-ray emission is 1000 times lower than the Crab and its radio emission is 120 times lower. In γ-rays, PSR J0205+6449’s luminosity is about 10% of the Crab
pulsar’s but its efficiency, for an assumed 3.2 kpc distance, is about 0.2–0.3 per cent compared to the Crab’s 0.1 per cent (Abdo et al. 2010) consistent with PSR J0205+6449 being an older pulsar. Some of this discrepancy can be attributed to the mounting evidence that the characteristic age of the pulsar (given by $P$ $\approx$ 5400 yr) is near to its true age (Chevalier 2005; Bietenholz 2006; Gotthelf, Helfand & Newburgh 2007), with the age estimates for the 3C 58 SNR ranging between 3000 and 5100 yr, thus breaking the association between supernova SN 1181 and PSR J0205+6449/3C 58. Recently, however, a re-analysis of the existing H $\alpha$ radio observations (Kothes 2010) suggests a distance as small as 2 kpc for 3C 58 and an age as low as 1100 yr, reopening the debate on its association with SN 1181.

The multiwavelength properties, age and energetics of PSR J0205+6449 combine to make it a likely candidate for optical emission studies. If we assume that the pulsar’s optical luminosity scales with the light cylinder magnetic field $B_{lc}^{6}$ (Shearer & Golden 2001), then we estimate that it should have a visual magnitude in the range 23–25, depending on interstellar absorption and effects of beaming geometry. The first deep observations of 3C 58 (Shearer & Neustroev 2008; Shibanov et al. 2008) showed evidence of an optical nebulosity at the same location as the X-ray counterpart to PSR J0205+6449 but could not resolve the pulsar optical counterpart. The motivation behind this work was to identify a candidate optical counterpart to PSR J0205+6449 using observations taken under the 2009 International Time Programme at the La Palma Observatory (PI: Shearer), combined with observations recently obtained with the 10.4 m Gran Telescopio Canarias (GTC) as well as archival Gemini and Hubble Space Telescope (HST) images. Table 1 reports the summary of the PSR J0205+6449 observations with the different facilities.

### 2.2 Telescopio Nazionale Galileo

On 2009 August 20 and 21, we re-observed the PSR J0205+6449 field with the 3.5 m Italian Telescopio Nazionale Galileo (TNG), also at the La Palma Observatory. We used the DOLORES (Device Optimized for the LOw RESolution) camera, a single-chip E2V CCD with a field of view of 8.6 arcmin $\times$ 8.6 arcmin and a pixel size of 0.252 arcsec. We observed through the standard Johnson $V$ ($\lambda = 5270$ Å; $\Delta \lambda = 980$ Å) and $R$ ($\lambda = 6440$ Å; $\Delta \lambda = 1480$ Å) filters for total integration times of 6060 and 4830 s, respectively. In both cases, the average airmass was around 1.5 and the seeing $\sim$1 arcsec. Observations were performed in dark time. For both the INT and TNG images, we applied standard data reduction (bias subtraction and flat-fielding) using the tools in the IRAF packages MSCRED and CCDRED. The dithered exposures were then aligned, stacked and filtered for cosmic rays so as to produce mosaic images.

### 2.3 Gran Telescopio Canarias

We obtained additional observations of the PSR J0205+6449 field with the GTC at the La Palma Observatory on 2011 September 1 and November 20 as part of the Spanish Time programme (PI: Rea). We observed PSR J0205+6449 with the Optical System for Imaging and low Resolution Integrated Spectroscopy (OSIRIS). The instrument is equipped with a two-chip E2V CCD detector with a nominal field of view of 7.8 arcmin $\times$ 8.5 arcmin, which is actually decreased to 7 arcmin $\times$ 7 arcmin due to the vignetting of one of the two chips. The unbinned pixel size of the CCD is 0.125 arcsec. We took a sequence of dithered exposures in the Sloan Digital Sky Survey (SDSS) $r'$ ($\lambda = 6410$ Å; $\Delta \lambda = 1760$ Å) and $i'$ ($\lambda = 7705$ Å; $\Delta \lambda = 1510$ Å) bands on the first and second nights, respectively, with exposure time of 140 s to minimize the saturation of bright stars in the field and correct for the fringing. The pulsar was positioned at the nominal aim point in chip 2. Observations were performed with an average airmass of 1.25 for both the $r'$ and $i'$ bands. Seeing conditions were $\sim$0.9 and 0.8–1.0 arcsec for the first and second nights, respectively. In both nights, observations were performed in dark time and under clear conditions. For the $i'$-band observations, no valid sky-flats were taken for the night of November 20; therefore, we used closest-in-time sky-flats taken on November 17. As done for the INT and TNG data, we reduced the data using standard tools in the IRAF package CCDRED. We then...
stacked and averaged the single dithered exposures using the task \texttt{drizzle} that also performs the cosmic ray filtering.

2.4 Gemini

Using the Gemini science data archive\(^1\) we identified 34 frames of the PSR J0205+6449 field taken between 2007 August 10 and 2007 October 11 with the Gemini-North telescope in Mauna Kea (Hawaii). Observations were performed using the Gemini Multi-Object Spectrograph (GMOS). At the time of the observations the instrument was still mounting the original three-chip E2V CCD detector that has a field of view of 5.5 arcmin $\times$ 5.5 arcmin, with gaps of 2.8 arcsec between each chip, and a pixel scale of 0.1454 arcsec. Observations were performed through the $g_G$-G0301 ($\lambda = 4750$ Å; $\Delta \lambda = 1540$ Å), $r_G$-G0303 ($\lambda = 6300$ Å; $\Delta \lambda = 1360$ Å) and $i_G$-G0302 ($\lambda = 7800$ Å; $\Delta \lambda = 1440$ Å) filters, very similar to the SDSS filters ($\Delta \lambda = 200$ Å; $\Delta \lambda = 480$ Å). We used the GMOS version 2.3 that applies bias subtraction and flat-field correction and produces distortion-corrected and co-added images. We computed the best position for PSR J0205+6449 using the wavdetect task with wavelet scales ranging from 1 to 16 pixels, spaced by a factor of $\sqrt{2}$ (consistent results were obtained using the \texttt{celldetect} task). To check the accuracy of the \textit{Chandra}/ACIS absolute astrometry, we selected X-ray sources detected at $\gamma$-ray in both observations within 4 arcmin from the aim point, since the accuracy of the \textit{Chandra} astrometry rapidly degrades at large off-axis angles. Then, we cross-correlated their positions with astrometric catalogues. We found four matches with the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006) with offsets of 0.1–0.3 arcsec, in agreement with the expected accuracy of the ACIS absolute astrometry.\(^2\) Three of such sources were also identified in the United States Naval Observatory B1.0 catalogue (Monet et al. 2003), with similar X-ray-to-optical offsets. Based on such coincidences, we could assess that no systematic offsets affect the two astrometric solutions, although it was not possible to improve them.

We computed the best position for PSR J0205+6449 by averaging the coordinates measured in the two observations. The resulting position (2000) is $\alpha = 02^h05^{m}37^s.95$ and $\delta = +64^\circ49'41.6''$ (epoch 2003.31), with a nominal radial uncertainty of 0.375 arcsec at the 90 per cent confidence level. Thus, our re-computed position falls to 0.8 arcsec south of the Slane et al. (2002) one and is more consistent with the Murray et al. (2002) position, which is much closer to the centre of the optical PWN.

While we were close to submit our paper, a \textit{Chandra} position for PSR J0205+6449 was published by Bietenholz et al. (2013), based on the very same data sets and perfectly consistent with ours. Bietenholz et al. (2013) also reported on a new very long baseline interferometry (VLBI) radio position of the pulsar, which is consistent with the \textit{Chandra} one, and on the first measurement of the pulsar proper motion ($\mu_\alpha = 1.4 \pm 0.16$ mas yr$^{-1}$; $\mu_\delta = 0.540 \pm 0.575$ mas yr$^{-1}$). Due to the small angular displacement between the epochs of the \textit{Chandra} and VLBI positions and those of our optical

\[^1\] http://cadcwww.dao.nrc.ca/gsa/
\[^2\] http://archive.stsci.edu/
\[^3\] http://cxc.harvard.edu/cda/
\[^4\] http://cxc.harvard.edu/cal/ASPECT/celmon/
observations, in the following we neglect the effect of the proper motion of the assumed pulsar position. We note that the systematic uncertainty on the radio position of Bietenholz et al. (2013) is only 10 mas (Bietenholz, private communication). Thus, the radius of the radio error circle is dominated by the uncertainty of the astrometric calibration of the optical images (∼0.2 arcsec).

3.2 Optical astrometry

We computed the astrometry calibration of the optical images using the wcs tools suite of programs that automatically match the sky coordinates of stars in the selected reference catalogue with their pixel coordinates computed by SExtractor (Bertin & Arnouts 1996). In order to avoid systematics with the Chandra astrometry (see Section 3.1), we used 2MASS as a reference catalogue. After iterating the matching process and applying a sigma-clipping selection to filter out obvious mismatches, high-proper-motion stars and false detections, a pixel-to-sky coordinate transformation was computed using a polynomial function and we obtained, for the ground-based images, mean residuals of ∼0.2 arcsec in the radial direction, using 50 bright, but non-saturated, 2MASS stars. To this value we added in quadrature the uncertainty σφ = 0.08 arcsec of the image registration on the 2MASS reference frame. This is given by [math]
σφ = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\sigma_i)^2}
\end{math}
where \( N \) is the number of stars used to compute the astrometric solution, \( n = 5 \) is the number of free parameters in the sky-to-image transformation model and \( σ_i \sim 0.2 \) arcsec is the mean absolute position error of 2MASS for stars in the magnitude range \( 15.5 \leq K \leq 13 \) (Skrutskie et al. 2006). After accounting for the 0.015 arcsec uncertainty on the link of 2MASS to the International Celestial Reference Frame (Skrutskie et al. 2006), we ended up with an overall accuracy of ∼0.22 arcsec on the absolute optical astrometry of the ground-based images. For the HST ones, thanks to their much better spatial resolution, we could measure the stars’ relative position with a much better accuracy and obtained mean residuals of ∼0.05 arcsec on the pixel-to-sky coordinate transformation. This corresponds to an overall accuracy of ∼0.1 arcsec on the absolute astrometry of the HST images.

4 DATA ANALYSES AND RESULTS

4.1 Image analyses

The deepest Gemini, GTC and HST stacked images of the PSR J0205+6449 field are shown in Figs 2, 3 and 4, respectively, with the computed Chandra and VLBI (Bietenholz et al. 2013) pulsar positions marked. The optical PWN is visible in all the deepest ground-based images, including the INT and TNG ones, albeit with a different signal-to-noise due to the difference in integration time, observing conditions and telescope/instrument sensitivity. The PWN is also visible in the highest resolution HST WFC3 images (Fig. 4), but only when they are convolved with a median filter of 17 pixels. As a result, this smears the WFC3 resolution to the level of the ground-based optical images and prevents the study of the finer details in the PWN structure. The morphology of the optical PWN is better resolved in the deeper Gemini images (Fig. 1), where its brightness distribution shows a clear central maximum. The nebula features an elongated morphology stretching north to south (NS) with a structure similar to that of the X-ray PWN. However, it extends on a much smaller angular scale (∼6 arcsec) and overlaps only the brightest part of the X-ray PWN. Furthermore, there is no evidence of an optical counterpart of the curved, jet-like X-ray structure protruding west of the pulsar and detected in the Chandra image.

According to our astrometry, the pulsar position is now closer to the centre of the optical PWN. In particular, the pulsar position is consistent with that of the emission maximum of the optical PWN, more clearly detected in the Gemini g′-band image (Fig. 2, top), where the presence of a faint, point-like, object becomes apparent. This is also shown in Fig. 1, where the position of this object is consistent with the centroid of the X-ray contours of the PWN. This object is also detected in the Gemini r′-band image (Fig. 2, bottom) and in the i′-band one (Fig. 2, middle), albeit at lower significance.

Figure 1. High-contrast Gemini images of the PSR J0205+6449 field: g′ (top), r′(middle) and i′(bottom). The Chandra X-ray contours are overlaid in black.
PSR J0205+6449 – the next optical pulsar? 5

Figure 2. High-contrast Gemini images of the PSR J0205+6449 field: $g'$ (top), $r'$ (middle) and $i'$ (bottom). The Slane et al. (2002) and Murray et al. (2002) Chandra error circles of the pulsar are overlaid (in black), together with updated Chandra error circle (this work, blue) and the Green Bank Telescope VLBI radio error circle (Bietenholz et al. 2013, red). The pulsar candidate counterpart is marked by the arrow. We note that the systematic uncertainty on the radio position of Bietenholz et al. (2013) is only 10 mas (Bietenholz, private communication). Thus, the radius of the radio error circle is dominated by the uncertainty of our optical astrometry.

Its independent detection in different images, where it is in different positions of the detector, confirms that the object is not spurious and not produced either by CCD blemishes or artefacts in the data reduction. The object is not detected in the other ground-based images (Fig. 3), owing to their lower sensitivity and the difficulty of resolving the structure of the PWN, and is not detected in the HST images, even after the images had been median filtered (Fig. 4).

Figure 3. GTC images: $r'$ (top) and $i'$ (bottom) images. The Chandra and VLBI positions (Bietenholz et al. 2013) are overlaid in blue and red, respectively.

Figure 4. HST images: F625W (top) and F775W (bottom). The Chandra and VLBI (Bietenholz et al. 2013) positions are overlaid in blue and red, respectively. The PWN is visible but only because these images have been convolved with a median filter of 17 pixels.
Figure 5. High-contrast Gemini images of the PSR J0205+6449 field: $g'$ (top), $r'$ (middle) and $i'$ (bottom). The images were smoothed with a Gaussian filter and optical contours are overlaid. The Chandra and VLBI (Bietenholz et al. 2013) positions of the pulsar are overlaid in blue and red, respectively. The positions of the filamentary structures (knots o1, o2 and o3) observed by Shearer & Nuestroev (2008) are also marked.

Fig. 5 shows the optical contours overlaid upon the Gemini images, with a point-like object recognized on top of the central brightness maximum. The object’s brightness profile is that expected for a star of comparable faintness embedded in a bright nebula. Indeed, its point spread function (PSF) is consistent with that of the Gemini image, after accounting for the low signal-to-noise of the detection, seeing variations during the observations and the stacking of multiple, dithered exposures, which blurs the resulting intensity profile of faint sources. This is shown in Fig. 6, where we plotted the object’s brightness profile in the Gemini $g'$, $r'$ and $i'$ bands. These were obtained from averaging the counts in a slice of 5 pixel width centred on the pulsar’s radio position and aligned along the NS direction, so as to avoid the contribution of the bright star detected east of the nebula. As seen, while the brightness structure of the PWN is clearly that of an extended source, the $g'$- and $i'$-band brightness profiles of the object detected at the PSR J0205+6449 position match reasonably well their respective image PSFs. This is not the case for the $r'$-band brightness profile due to the object’s much lower detection level (3.6$\sigma$).

Deep, high-spatial-resolution observations will better separate the object profile from the surrounding bright PWN and better determine its morphology. In this respect, our case may be similar to that of PSR B0540−69, also embedded in a bright PWN (e.g. De Luca et al. 2007), for which both the morphology and intensity profile of its optical counterpart are also not very well
defined in ground-based non-adaptive optics images (e.g. Caraveo et al. 1992).

Thus, accounting for all caveats, our image analysis suggests that the point-like object detected at the Chandra and VLBI (Bietenholz et al. 2013) positions is a stellar object and, as such, is probably associated with the pulsar. Indeed, the chance coincidence probability that an unrelated point source falls within the radio error circle of PSR J0205+6449 is, after accounting for the accuracy of the optical astrometry, only $\sim 3 \times 10^{-4}$, computed based on the density of stellar objects in the Gemini field $\rho \sim 0.0025$ arcsec$^{-2}$ as $1 - \exp(-\pi\rho r^2)$. We consider such a probability low enough to rule out a chance coincidence association.

We also investigated the possibility that this object is not the pulsar but an emission knot in the PWN. Optical emission knots can be observed in some of the PWNe as the result of a different density of relativistic particles in the nebula caused, for instance, by the formation of shocks at the termination front of the pulsar beam and/or equatorial wind, or turbulent motions in the nebula. An emission knot was seen, e.g., in the PWN around PSR B0540$-$69 (De Luca et al. 2007). However, the knot was much fainter than the pulsar and located far off from the geometrical centre of the PWN, as expected according to its possible formation mechanisms, whereas in the case of PSR J0205+6449 it would be virtually coincident with the pulsar’s position. An emission knot very close to the pulsar ($\sim 0.6$ arcsec) has been seen in the Crab PWN (see Moran et al. 2013 and references therein). However, also in this case the knot is much fainter than the pulsar. Thus, we tend to conclude that it is unlikely that the object detected at the Chandra and VLBI positions is associated with a knot in the PWN, although we cannot completely rule out this possibility. Future observations of the PWN aimed at searching for possible flux variability from this object will help to confirm our conclusion.

Thus, on the basis of the positional coincidence of the object detected in the Gemini images with the accurate Chandra and VLBI coordinates and the centre of symmetry of the optical PWN in the Gemini image, we conclude that it is a plausible optical counterpart to PSR J0205+6449.

4.2 Photometry

We performed aperture photometry of the PSR J0205+6449 candidate counterpart to determine its flux in the Gemini $g'$, $r'$ and $i'$-band images and compare it with the upper limits derived in the INT, TNG, GTC and HST images. We used the IRAF routine daofind to search for and measure the flux of potential point sources detected at the pulsar’s position. In all cases, we used an aperture of diameter comparable with the image PSF, to minimize contamination from the bright PWN. In all cases, we applied the aperture correction computed from the growth curve of a number of unsaturated stars identified in the field. Details on the aperture photometry (aperture size, background annulus, etc.) and the applied aperture correction for each observation are given in the corresponding subsections.

4.2.1 INT and TNG observations

For the photometry calibration of the INT $R$- and TNG $V$- and $R$-band images, we used the set of five secondary photometric standards defined in Shearer & Neustroev (2008) and identified directly in the frames. We matched the measured fluxes of these stars to their tabulated $V$- and $R$-band magnitudes and produced a linear fit (with $\chi^2 = 0.9999$). We verified that the computed photometric zero-points are consistent with those tabulated in the instrument web pages, which are 25.6, 26.2 and 26.3 for the INT $R$, TNG $V$ and TNG $R$ images, respectively. We computed the $3\sigma$ limiting magnitudes of the images using the standard approach described in Newberry (1991). The $3\sigma$ limiting magnitudes for INT $R$, TNG $V$ and TNG $R$ images were 23.5, 24.7 and 24.3, respectively. For both the TNG and INT images, we corrected for the airmass using the average atmospheric extinction terms for the La Palma Observatory from Kidger et al. (2003).

4.2.2 GTC observations

Images of the Landolt standard star fields SA 95, SA 113 and G 158 were taken the same nights as the science observations and used for the photometry calibration. We verified the computed calibration against the photometric zero-points tabulated in the OSIRIS instrument web page, which are 29.2 and 28.8 for the $r'$- and $i'$-band images, respectively. Using the same approach as described above, we placed $3\sigma$ detection limits of 24.4 and 23.0 in the $r'$- and $i'$-band images, respectively. Also in this case, we used the average atmospheric extinction terms from Kidger et al. (2003).

4.2.3 Gemini observations

For the Gemini photometry calibration, we used the average airmasses, the tabulated zero-points and extinction coefficients reported in Jørgensen (2009). We then derived absolute zero-points of 27.9, 28.1 and 27.9 for the $g'$, $r'$ and $i'$ images, respectively. We have cross-checked the photometry calibration against sets of secondary calibration stars identified on the frame and selected from our observations of the field performed with the GTC. Using daofind we detected a source, at the 5.5$\sigma$, 3.6$\sigma$ and 5.5$\sigma$ levels, in the Gemini $g'$-, $r'$- and $i'$-band images, respectively, whose position is consistent with the error circle on the pulsar coordinates obtained from the Chandra and Green Bank Telescope VLBI observations. We then performed aperture photometry on this source. For each band, we used an aperture with a radius equal to 0.5 arcsec. We measured the sky background in an annulus of width 0.3 arcsec located 0.6 arcsec beyond the inner aperture. Both this annulus and the photometric aperture were chosen so as to reduce the contribution of the flux from the nebula. We then applied the computed aperture corrections to our photometry. This yielded magnitudes of $g' = 27.4 \pm 0.2$, $r' = 26.2 \pm 0.3$ and $i' = 25.5 \pm 0.2$ for the candidate pulsar counterpart.

4.2.4 HST observations

We applied the photometric calibration to the HST images by computing the count rate to flux conversion using the updated values of the keywords PHOTFLAM and PHOTPLAM recorded in the image headers following the recipe described in the WFC3 Instrument and Data Handbooks (Rajan & Baggett 2010; Dressel 2012). This yielded photometric zero-points of 25.5 and 24.8. We also applied the charge transfer efficiency and aperture corrections according to the tabulated values in WFC3 Handbooks. The $3\sigma$ detection limits above the sky background are $\sim 26.0$ and $\sim 25.0$ mag in the 625W and 775W images, respectively.

\footnotesize

\begin{itemize}
\item \textsuperscript{6} http://www.ing.iac.es/astronomy/instruments/wfc/
\item \textsuperscript{7} http://www.ing.iac.es/instruments/lrs/
\item \textsuperscript{8} http://www.gemini.edu/sciops/instruments/gmos/
\end{itemize}
Table 2. PSR J0205+6449 coordinates: radio VLBI (Bietenholz et al. 2013), re-computed Chandra X-ray (this work) and candidate optical counterpart (Gemini data). Included are the error circles. The confidence levels are all 90 per cent.

<table>
<thead>
<tr>
<th>Observations</th>
<th>RA (J2000) (h m s)</th>
<th>Dec. (J2000) (° ′ ″)</th>
<th>Error circle (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio VLBI</td>
<td>02 05 37.920</td>
<td>64 49 41.30</td>
<td>0.2</td>
</tr>
<tr>
<td>Chandra</td>
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<td>64 49 41.60</td>
<td>0.4</td>
</tr>
<tr>
<td>Gemini g</td>
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<td>64 49 41.17</td>
<td>0.2</td>
</tr>
<tr>
<td>Gemini r</td>
<td>02 05 37.935</td>
<td>64 49 41.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Gemini i</td>
<td>02 05 37.914</td>
<td>64 49 41.42</td>
<td>0.2</td>
</tr>
</tbody>
</table>

4.2.5 Summary

Table 2 shows the coordinates of the candidate optical counterpart of PSR J0205+6449 detected in the Gemini images. Also shown are the radio VLBI coordinates (Bietenholz et al. 2013) of PSR J0205+6449 and the re-computed X-ray coordinates of the pulsar based upon the re-analysis of archival Chandra observations of 3C 58. We also include the position error circles and confidence levels. The error circles of the optical and X-ray positions, based upon the astrometry, are ~0.2 and ~0.4 arcsec, respectively. The position of the candidate optical counterpart is consistent, within the error circles, with the radio VLBI and re-computed X-ray positions.

Table 3 shows the results of our multiband photometry for all the available image data sets. The listed upper limits are at 3σ. The reported spectral fluxes have been computed from standard formulae after converting the measured magnitudes to the AB system (Oke & Gunn 1983). We used the multiband photometry to determine the slope of the pulsar’s spectrum in the 5000–9000 Å range. To correct our flux measurements for the interstellar extinction towards PSR J0205+6449, we used the value of the hydrogen column density derived from the X-ray spectral fits to the Chandra soft X-ray spectrum and the relation of Predehl & Schmitt (1995).

Marelli (2012) analysed the full Chandra data set and best fitted the soft X-ray spectrum with a two-component model consisting of a power law (PL) (ΓX = 1.77 ± 0.03) plus a blackbody (BB) with temperature kT = 1.88 ± 0.15 MK and an emitting radius RBB = 2.03 ± 0.43 × 10^21 cm for a 3.2 kpc distance. This yields a hydrogen column density NH = 4.5 ± 0.13 × 10^21 cm^-2 and Aν = 2.5 ± 0.07.

5 DISCUSSION

5.1 The pulsar identification

With the identification of PSR J0205+6449, the number of rotation-powered pulsars with either an identified or proposed optical counterpart (Mignani 2011) would amount to 14. For 10 of them, the identification is firmly secured either through the detection of optical pulsations at the radio period, or the tight positional coincidence with the radio position, or from the optical spectrum. The possible identifications of PSR J0108–1431 (Mignani, Pavlov & Kargaltsev 2008) and PSR J1357–6429 (Mignani et al. 2011; Danilenko et al. 2012) are not yet confirmed, while that of PSR B1133+16 (Zharikov et al. 2008) seems now confirmed, albeit still marginally (Zharikov & Mignani 2013). PSR J0205+6449 would be also one of the very few γ-ray pulsars identified in the optical. In particular, it would be, possibly together with PSR J1357–6429, the first identified after the launch of Fermi, whereas most of the others have been identified after their detection by the Compton Gamma Ray Observatory.

One can speculate on whether our candidate counterpart can be identified or not with object o2 of Shearer & Neustroev (2008), tentatively detected as an unresolved emission knot in the nebula in their 4.2 m William Herschel Telescope (WHT) images, which they suggested as a possible pulsar counterpart. The same object was also proposed as the PSR J0205+6449 counterpart by Bietenholz et al. (2013), based on the positional coincidence between its...
coordinates, $\alpha = 02^h05^m37.93$ and $\delta = +64^\circ49'41.4''$ (Shearer & Neustroev 2008), and the updated Chandra and VLBI radio ones (see Fig. 5). However, we note that the flux of object o2 ($R = 24.15$) measured by Shearer & Neustroev (2008) is much fainter than that of our candidate counterpart detected in the Gemini image ($r' = 26.2 \pm 0.3$). This means that, if object o2 were the pulsar’s counterpart, its optical emission must have varied by about an order of magnitude. According to the observed optical emission properties of rotation-powered pulsars, this is an unrealistic scenario. Alternatively, object o2 could have been a variable emission knot in the PWN, undetected in our $R$-band TNG images down to $R \sim 24.3$ (see Table 3) but detected at a much fainter flux level in the Gemini images. However, the possibility that our counterpart is an emission knot in the PWN is unlikely (see our discussion in Section 4.1), although we cannot completely rule it out. Interestingly enough, objects o1 and o3 of Shearer & Neustroev (2008) are also undetected in both the TNG and Gemini images (see Fig. 5). This suggests that, if they also were emission knots in the PWN, they varied in flux by about the same amount as object o2 and, possibly, on the same time-scale. Thus, we are prone to believe that the detection of object o2 in the WHT images of Shearer & Neustroev (2008), which was never confirmed in independent observations, was spurious.

5.2 The pulsar spectrum

We compared our extinction-corrected optical flux measurements of the PSR J0205+6449 candidate counterpart with the low-energy extrapolations of the soft X-ray and $\gamma$-ray spectra measured by Chandra and Fermi, respectively. In the hard X-rays (2.5–54 keV), the RXTE spectrum is described by a flatter PL with photon index $\Gamma_X = 1.06 \pm 0.03$ (Kuiper et al. 2010) which, however, was obtained by fixing the hydrogen column density $N_H = 3.4 \times 10^{21} \text{cm}^{-2}$, lower than derived from the fits to the Chandra spectrum (Marelli et al. 2011; Marelli 2012). We do not include the X-ray spectrum from Kuiper et al. (2010) since it has been computed for the pulsed component only and, as such, it is not directly comparable to the Chandra spectrum and the optical fluxes which are phase-averaged. The $\gamma$-ray spectrum is described by a PL with photon index $\Gamma_\gamma = 2.1 \pm 0.1 \pm 0.2$, where the first and second errors are statistical and systematic, and an exponential cut-off at an energy $E_C = 3.0^{+1.1}_{-0.6}$ GeV (Abdo et al. 2009). The $\gamma$-ray spectral parameters were slightly revised ($\Gamma_\gamma = 2.09 \pm 0.17; E_C = 3.5 \pm 1.4$ GeV) in the first Fermi catalogue of $\gamma$-ray pulsars (Abdo et al. 2010), although they are consistent with the previous ones.

Fig. 7 shows the extinction-corrected optical fluxes of the PSR J0205+6449 candidate counterpart compared with the multiwavelength spectral energy distribution (SED). The Gemini fluxes lie well below the extrapolation of the X-ray PL (Marelli 2012), hinting at the presence of a double break in the optical-to-X-ray spectrum, as observed in other rotation-powered pulsars (Mignani et al. 2010a). In particular, the case of PSR J0205+6449 is similar to that of PSR B0540–69, where a double break is clearly present (Serafinovitch et al. 2004; Mignani et al. 2010a, 2012a). Such a double break in the optical-to-X-ray spectrum would be at variance with what is observed for the Crab and Vela pulsars, where a single break is, instead, required to join the optical and X-ray fluxes. This would suggest a different energy and density distribution of relativistic particles in the neutron star magnetosphere, even for objects of comparable spin-down age. The optical fluxes of the PSR J0205+6449 candidate counterpart can be described by a PL spectrum with photon index $\Gamma_0 = 1.9 \pm 0.5$. This confirms that the optical emission from PSR J0205+6449 would be non-thermal, as expected from its age (Mignani 2011). The value of the photon index of the optical PL would be comparable to those of most rotation-powered pulsars (Mignani, Zharikov & Caraveo 2007; Mignani et al. 2010a; Mignani, Pavlov & Kargaltsev 2010b), for which the average value is $1.45 \pm 0.35$, confirming that there is no obvious evolution as a function of the pulsar’s age. Once again, as in the case of PSR B0540–69 and also for PSR J0205+6449, the value of the optical PL photon index would be compatible with that of the PL component of the Chandra X-ray spectrum ($\Gamma_X = 1.77 \pm 0.03$). Whether or not this suggests that the optical photons are related to the same population of relativistic electrons responsible for the non-thermal $X$-ray emission, perhaps at different altitudes/latitudes in the neutron star’s magnetosphere, is an interesting speculation. One way to address it may be by comparing the X-ray and optical light curves of PSR J0205+6449, which can be measured with the current generation of high-time resolution optical cameras, such as iQueue (Naletto et al. 2009). The optical fluxes are well above the extrapolation of the X-ray PL spectrum (Abdo et al. 2010). This indicates the presence of an additional break in the pulsar spectrum, probably in the soft $\gamma$-rays/hard X-ray part. The discontinuity between the optical and $\gamma$-ray PL spectra is seen in other Fermi pulsars, such as PSR J0007+7303 (Mignani et al. 2013), while for others the available optical upper limits are too high with respect to the extrapolation of the $\gamma$-ray PL extrapolation to constrain the presence of a spectral break (Mignani et al. 2011, 2012b). It is only for PSR J1048–5832 (Razzano et al. 2013) that the optical flux upper limits do not rule out that the optical spectrum is consistent with the extrapolation of the $\gamma$-ray PL. Thus, in general, the connection between the optical and $\gamma$-ray spectra in rotation-powered
pulsars is unclear. Investigating such a connection is important to determine whether the emission in these two energy bands is related, as suggested by the fact that both the pulsar optical and γ-ray luminosities seem to scale with the strength of the magnetic field at the light cylinder (Shearer & Golden 2001).

5.3 The pulsar luminosity

We computed the ratio between the X-ray and optical fluxes of PSR J0205+6449 from the available Chandra and Gemini measurements. The spectral fit of Marelli (2012), based on a PL plus BB model, gives an unabsorbed X-ray flux $F_{X} = (19.7 \pm 0.7) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.3–10 keV energy range for the PL component only, whereas the total X-ray flux is $F_{X} = (21.8 \pm 0.8) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. Hereafter, we assume the total X-ray flux as a reference. On the basis of the Gemini $g'$ detection, and using the same extinction correction as above, we computed the unabsorbed flux of the pulsar in the $g'$ band to be $F_{g'} = 9.43 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$. By assuming a distance of 3.2 kpc, the unabsorbed fluxes give $g'$-band and X-ray luminosities of $L_{g'} = 1.15 \times 10^{30} \text{ erg s}^{-1}$ and $L_X = 2.66 \times 10^{31} \text{ erg s}^{-1}$. This gives an optical-to-X-ray luminosity ratio $L_{g'}/L_X = 4.32 \times 10^{-2}$. Similarly, we computed the unabsorbed optical-to-γ-ray luminosity ratio. As a reference, we assumed the γ-ray flux above 100 MeV measured by Fermi, $F_{\gamma} = (6.64 \pm 0.65) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Abdo et al. 2010). For the assumed distance of 3.2 kpc, the γ-ray luminosity of PSR J0205+6449 is $L_{\gamma} = 8.13 \times 10^{33} \text{ erg s}^{-1}$. This gives a luminosity ratio $L_{g'}/L_{\gamma} = 1.41 \times 10^{-5}$. The computed optical, X-ray and γ-ray luminosities of PSR J0205+6449, together with their ratios, are listed in Table 3, where they are compared with the corresponding values measured for the other γ-ray pulsars identified in the optical. As a reference, for all pulsars we assumed the same pulsar distances as used in Abdo et al. (2010), the unabsorbed X-ray fluxes in the 0.3–10 keV energy range listed in Marelli (2012) and the γ-ray fluxes above 100 MeV listed in Abdo et al. (2010). We computed the optical luminosities according to the observed V-band magnitudes and extinction $A_V$ (Mignani 2011). As seen, PSR J0205+6449 would be the γ-ray pulsar with the second highest optical luminosity after the Crab pulsar, as expected from its low spin-down age ($\tau \sim 5400$ yr). The optical-to-X-ray and optical-to-γ-ray luminosity ratios of PSR J0205+6449 would be consistent with those measured for other young pulsars ($\tau \lesssim 10$ kyr), with the Crab pulsar being that with the highest ratios. However, the luminosity ratios for PSR J0205+6449 would be larger than those of the slightly older Vela pulsar ($\tau \sim 11$ kyr), owing to the fact that the latter is about two orders of magnitude fainter in the optical.

We also computed the ratio between the derived optical luminosity $L_{g'} = 1.15 \times 10^{30} \text{ erg s}^{-1}$ of PSR J0205+6449 and its rotational energy loss $E = 2.7 \times 10^{57} \text{ erg s}^{-1}$. Assuming a 3.2 kpc distance, we obtained $L_{g'}/E = 4.27 \times 10^{-8}$. Again, in Table 4 this value is compared with those of the other γ-ray pulsars identified in the optical domain. Interestingly enough, the optical efficiency for PSR J0205+6449, defined as $\eta_{opt} = L_{opt}/E$, would be lower than for the other young pulsars (Crab and PSR B1509−58) but higher than the Vela pulsar, confirming a trend for a decrease in the optical emission efficiency of young pulsars as a function of the spin-down age. The existence of such a trend has been already proposed (e.g. Zharkov, Shibanov & Komarova 2006), but, so far, the assumption only relied on the computed lower emission efficiency of the Vela pulsar with respect to the other young pulsars Crab, PSR B1509−58 and PSR B0540−69, with the latter ($\eta_{opt} = 1.07 \times 10^{-5}$) not listed in Table 3 because it has not been yet detected in γ-rays. Thus, it has been unclear whether the optical emission efficiency of Vela-like pulsars was indeed intrinsically lower than the Crab-like ones, or Vela stood out as a peculiar case. The probable optical identification of the ~5400-yr-old PSR J0205+6449, which is ideally half way between the two classes, now represents an important piece of evidence in favour of this interpretation. The upper limits on the optical luminosities of Vela-like γ-ray pulsars, such as PSR B1706−44, PSR J1357−6429, PSR J1028−5819, PSR J0007+7303 (Mignani, Caraveo & Bignami 1999; Mignani et al. 2011, 2012b, 2013) and PSR J1048−5832 (Razzano et al. 2013), are consistent with this trend. Of course, the optical identification of some of these pulsars will eventually give the long-sought proof. Such a trend can be interpreted as the result of the secular decrease of the pulsar nonthermal optical luminosity, an effect predicted by Pacini & Salvati (1983) as a result of the pulsar spin-down. We note that the optical emission (non-thermal) efficiency tends to increase again for the middle-aged pulsars (PSR B0656+14 and Geminga).

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10 We note that the value reported in table 3.2 of Marelli (2012) is affected by a typo (Marelli, private communication).
6 SUMMARY AND CONCLUSIONS

We performed multiband optical observations of PSR J0205+6449 with a variety of ground-based facilities, including the 8-m Gemini and 10.4-m GTC telescopes, and the HST. We detected a possible candidate counterpart to the pulsar, with an $\ell$-band magnitude of 25.5 (5.5σ detection), based upon its positional coincidence with the recently measured Chandra and radio coordinates (Bietenholz et al. 2013). Thus, PSR J0205+6449 would possibly be the fourteenth pulsar with either an identified or proposed optical counterpart (Mignani 2011) and the eighth of the $\gamma$-ray pulsars detected by Fermi. The pulsar’s spectrum would be consistent with a PL with photon index $\Gamma_\gamma = 1.9 \pm 0.5$, similar to the X-ray one ($\Gamma_X = 1.77 \pm 0.03$). The multiwavelength SED of PSR J0205+6449 shows that the optical fluxes would lie below and above the extrapolations in the optical domain of the X and $\gamma$-ray PL, respectively, indicating a break in the optical/X-ray region, after that the X/\gamma-ray. The optical luminosity, $L_{opt} = 1.15 \times 10^{36}$ erg s$^{-1}$, would imply an emission efficiency $\eta_{opt} = 4.27 \times 10^{-8}$, higher than the two times older Vela pulsar, confirming a trend for a decrease of the optical emission efficiency with the spin-down age in young pulsars. Due to the presence of a bright point source, confirm the optical identification of PSR J0205+6449 and better study its spectrum. Moreover, monitoring for changes in the flux of the candidate counterpart on a few month/year time-scale would allow one to rule out the possibility that it is an emission knot in the PWN.

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Optical polarimetry of the inner Crab nebula and pulsar

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ABSTRACT
Time-resolved polarization measurements of pulsars offer a unique insight into the geometry of their emission regions. Such measurements provide observational constraints on the different models proposed for the pulsar emission mechanisms. Optical polarization data of the Crab nebula were obtained from the Hubble Space Telescope (HST) archive. The data set consists of a series of observations of the nebula taken with the HST/Advanced Camera for Surveys (ACS). We produced polarization vector maps of the inner nebula and measured, for the first time, the degree of linear polarization (P.D.) and the position angle (P.A.) of the pulsar’s integrated pulse beam, and of its nearby synchrotron knot. This yielded P.D. = 5.2 ± 0.3 per cent and P.A. = 105.1 ± 1.6 for the pulsar, and P.D. = 59.0 ± 1.9 per cent and P.A. = 124.7 ± 1.0° for the synchrotron knot. This is the first high-spatial resolution multi-epoch study of the polarization of the inner nebula and pulsar. None of the main features in the nebula shows evidence of significant polarization evolution in the period covered by these observations. The results for the pulsar are consistent with those obtained by Sliwkowska et al. using the high-time resolution photo-polarimeter – Optical Pulsar Timing Analyzer (OPTIMA), once the constant component (DC) component has been subtracted. Our results clearly prove that the knot is the main source of the DC component.


1 INTRODUCTION

Strong polarization is expected when the pulsar optical emission is generated by synchrotron radiation. Shklovsky (1953) suggested that the continuous optical radiation from the Crab nebula was due to synchrotron radiation. This was later confirmed by Dombrowsky (1954) and Vashakidze (1954) who found that the optical radiation was polarized. Incoherent synchrotron emission follows a simple relationship between its polarization profile and underlying geometry. Hence, optical polarization measurements of pulsars provide a unique insight into the geometry of their emission regions, and therefore observational constraints on the theoretical models of the emission mechanisms. From an understanding of the emission geometry, one can limit the competing models for pulsar emission, and hence understand how pulsars work – a problem which has eluded astronomers for almost 50 years.

Polarimeters are sensitive in the optical, but the majority of pulsars are very faint at these wavelengths with $V \geq 25$ (Shearer 2008). Polarimetry in the very high-energy domain, X-ray and gamma-ray, using instruments on board space telescopes, is of limited sensitivity. So far, detailed results have only been reported for the Crab pulsar (Weisskopf et al. 1978; Dean et al. 2008; Forot et al. 2008). Although the number of pulsars detected in the optical is growing, only five pulsars have had their optical polarization measured: Crab (Wampler, Scargle & Miller 1969; Kristian et al. 1970; Smith et al. 1988; Sliwkowska et al. 2009), Vela (Wagner & Seifert 2000; Mignani et al. 2007), PSR B0540–69 (Middleditch, Pennypacker & Burns 1987; Chanan & Helfand 1990; Wagner & Seifert 2000; Mignani et al. 2010) PSR B0656–58 (Smith et al. 2003) and PSR B1509–58 (Wagner & Seifert 2000). Nonetheless, the optical currently remains invaluable for polarimetry in the energy domain above radio photon energies. The Crab pulsar, being the brightest optical pulsar with $V \approx 16.8$ (Nasuti et al. 1996), has had several measurements of its optical...
polarization, including both phase-averaged and phase-resolved studies.

The first phase-resolved observations of the optical linear polarization of the Crab pulsar were those of Wampler et al. (1969), Cocke et al. (1970) and Kristian et al. (1970). Those studies showed that the polarization position angle (P.A.) changes through each peak in the pulsar light curve, and that the degree of polarization falls and rises within each peak, reaching its minimum value shortly after the pulse peak. These observations were limited to the main and inter pulse phase regions only, because at the time it was thought that the pulsar radiated its optical emission through the pulse peaks only. However, a number of phase-resolved imaging observations of the pulsar (Peterson et al. 1978; Jones, Smith & Wallace 1981; Percival et al. 1993; Golden et al. 2000) showed that the optical emission actually persists throughout the pulsar’s entire rotation cycle, at the level of ∼1 per cent of the maximum main-pulse intensity.

With this in mind, observations of the optical linear polarization of the Crab pulsar were made by Jones et al. (1981) and Smith et al. (1988). These results confirmed the previous observations, and were the first studies to reveal the polarization profile of the pulsar during the bridge and off-pulse phase regions. They also found that the off-pulse region is highly polarized. The degree of polarization was 70 per cent and 47 ± 10 per cent for Jones et al. (1981) and Smith et al. (1988), respectively. Słowikowska et al. (2009) report the most detailed phase-resolved observations of the optical linear polarization of the Crab pulsar. Their results are consistent with previous observations albeit with better definition and statistics, and can be explained in the context of the two-pole caustic model (Dyks, Harding & Rudak 2004), the outer-gap model (Romani & Kirk 2005), the striped-wind model (Pétri et al. 2008), and the Counter wisp located 8.3 arcsec SE of the pulsar (Scargle 1969; Hester et al. 1995; Weisskopf et al. 2000). A bright knot of synchrotron emission is located 0.65 arcsec SE of the pulsar.

Detailed observations of the inner nebula, in the optical and X-rays, have revealed a torus structure, that is bisected by oppositely directed jets, knots and a series of highly variable synchrotron wisps (Scargle 1969; Hester et al. 1995; Weisskopf et al. 2000). A bright knot of synchrotron emission is located 0.65 arcsec SE of the pulsar. It is highly polarized and is slightly variable in both its location and its brightness (Hester et al. 1995, 2002; Hester 2008). Komissarov & Lyutikov (2011) proposed that it is radiation from an oblique termination shock in the pulsar wind nebula. In this model, the Earth line of sight is tangent to the flow at the position of the knot, hence the intensity is Doppler boosted for synchrotron emission in the mildly relativistic post-shock flow. The results of their relativistic magnetohydrodynamic (MHD) simulations show that the knot is highly variable and can dominate the gamma-ray synchrotron emission. It has been suggested that this knot is responsible for the highly polarized off-pulse emission seen in time-resolved observations in the optical (Slowikowska et al. 2009, 2013) and gamma-rays (Forot et al. 2008). The knot has no counterpart to the NW of the pulsar, but there is a faint second knot located 3.8 arcsec SE of the pulsar, the so-called outer knot.

The wisps consist of Wisp 1, a Thin wisp located 1.8 arcsec NW of the pulsar, and the Counter wisp located 8.3 arcsec SE of the pulsar. Wisp 1, located 7.3 arcsec NW of the pulsar, breaks into three separate and distinct components: 1-A, 1-B and 1-C (Scargle 1969). However, one must note that this does not represent the constant configuration of the wisps. The wisps are interpreted as magnetic flux tubes that undergo unstable synchrotron cooling (Hester 1998). A number of follow-up observations of the inner nebula have confirmed the presence of the wisps (Hester et al. 1995; Bietenholz et al. 2004). The NW wisps are more prominent than the SE wisps due to Doppler beaming of the flow. Schweizer et al. (2013) studied the behaviour of the wisps NW of the pulsar in both the optical and X-rays. They observed that the wisps form and move off from the region associated with the termination shock of the pulsar wind, roughly once per year. Moreover, they found that the precise locations of the NW wisps in the optical and X-rays are similar but not exactly coincident, with X-ray wisps located closer to the pulsar. This would suggest that the optical and X-ray wisps are not produced by the same particle distribution. In terms of MHD models, they found that the optical wisps are more strongly Doppler-boosted than the X-ray wisps. For a more detailed review of the Crab nebula see Hester (2008).

The first optical linear polarization maps of the Crab nebula were produced by Oort & Walraven (1956), Hiltner (1957) and Wolter (1957). X-ray observations of the linear polarization of the nebula, in the range 2.6–5.2 keV, yield polarization of 19 per cent at a P.A. of 152–156° within a radius of 3° of the pulsar (Weisskopf et al. 1978). These results are in agreement with the optical measurements of the polarization, which give polarization of 19 per cent at a P.A. of 162° for the central nebular region within a radius of ∼0.5 arcmin (Oort & Walraven 1956). Dean et al. (2008) measured the polarization of the Crab nebula and pulsar in the off-pulse phase using the International Gamma-ray Astrophysics Laboratory/Spectrometer on INTEGRAL (INTEGRAL/IBIS) telescope, and showed that the polarization E-vector (124° ± 11°) is aligned with the spin-axis of the neutron star (Kaplan et al. 2008; 110 ± 2 ± 9°, where the first uncertainty is the measurement uncertainty and the second is from the reference frame uncertainty). This result was later confirmed by Forot et al. (2008), in the off-pulse phase region using the INTEGRAL/Imager on-Board the INTEGRAL Satellite (IBIS) telescope (120.6 ± 8.5°, and has also been seen in optical observations (Smith et al. 1988; Słowikowska et al. 2009). The SPI and IBIS measurements both encompass the entire nebula and pulsar, and so are dominated by nebular emission. As with the optical observations (Smith et al. 1988; Słowikowska et al. 2009), they found the off-pulse region to be highly polarized.

The purpose of this work is two fold. First, we want to check the polarization of the pulsar, knot and wisps for variability. It is difficult to determine the polarization for objects embedded in a strong nebular background. So, in order to determine the Crab pulsar’s polarization profile, we need to know the level of background polarization. Therefore, the second purpose of this work is to accurately map the polarization of the inner Crab nebula. This will then act as a guideline for future time-resolved polarization measurements of the Crab pulsar using the Galway Astronomical Stokes Polarimeter (GASP). This is an ultra-high-speed, full Stokes, astronomical imaging polarimeter based on the Division of Amplitude Polarimeter (DOAP). It has been designed to resolve extremely rapid variations in objects such as optical pulsars and magnetic cataclysmic variables (Kyne et al. 2010).

2 OBSERVATIONS AND ANALYSIS

The raw Hubble Space Telescope/Advanced Camera for Surveys (HST/ACS) polarization science frames of the Crab nebula were obtained from the Mikulski Archive for Space Telescopes (MAST). The data set consists of 13 observations of the nebula taken in three different polarisers (0°, 60° and 120°) between 2003 August and 2005 December (Proposal ID: 9787) (see Table 1). The Wide Field Camera (WFC) detector, called ACS/WFC, employs a mosaic of two 4096 × 2048 Scientific Imaging Technologies (SITe) CCDs, with a pixel-scale of ∼0.05 arcsec pixel−1, covering a nominal field of view (FOV) ∼202 × 202 arcsec² (Pavlowsky et al. 2004).
Table 1. Summary of the HST/ACS observations of the Crab nebula. The filters used were F606W ($\lambda = 590.70$ nm, $\Delta \lambda = 250.00$ nm) and F550M ($\lambda = 558.15$ nm, $\Delta \lambda = 54.70$ nm).

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<th>Roll-angle (PA, $\circ$)</th>
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<td>1279.52 871.13</td>
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<td>1267.44 851.24</td>
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<td>POL120V</td>
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For these observations, with the polarisers in place, the FOV was $\approx 102 \times 102$ arcsec$^2$. The filter used was F606W ($\lambda = 590.70$ nm, $\Delta \lambda = 250.00$ nm). The raw images, which had already been flat-fielded, were geometrically aligned, combined and averaged with cosmic ray removal using IRAF (see Fig. 1). We used a total of five field stars and the IRAF task CCMAP and the 2MASS catalogue to fit the astrometry. The pulsar was found at $\alpha = 05^h34^m31.930 \pm 0.001$, $\delta = +22\,00^\circ51'999\,0 \pm 0.110$, whilst the synchrotron knot, located 0.65 arcsec SE of the pulsar (Hester et al. 1995) is found at $\alpha = 05^h34^m31.980 \pm 0.001$, $\delta = +22\,00^\circ51'630 \pm 0.110$ (the errors denote the rms of the astrometric fit). For each set of observations, the images taken in the different polarisers were analysed.
Figure 1. HST/ACS image of the inner Crab nebula (2005 Sept 06, FOV ≈ 102 × 102 arcsec², F606W, POL0V). The location of the pulsar and inner knot is marked by the circle.

Figure 2. Polarization vector map of the inner Crab nebula superimposed on the nebula (2005 Sept 06, FOV ≈ 102 × 102 arcsec²). The location of the pulsar and inner knot is marked by the circle. The legend shows the vector magnitude for 50 per cent polarization.

Figure 3. Polarized flux map of the inner Crab nebula (2005 Sept 06, FOV ≈ 102 × 102 arcsec²) with the stars for analysis marked. The location of the pulsar and inner knot is marked by the circle.

epoch. Gilliland (2004) describes the well-behaved response of the ACS, and shows that electrons are conserved after saturation. The response of the ACS CCDs remains linear up to and beyond the point of saturation provided one uses a gain value that samples the full well depth. For ACS this is a gain equal to 2 e−1/ADU, which is the gain setting used for these observations. Over a range of almost 4 magnitudes, photometry remains linear to <1 per cent. One can perform aperture photometry of isolated point sources by summing over all the pixels that were bled into (Pavlovsky et al. 2004). We tested this method by performing aperture photometry on the pulsar and Trimble 28. We used images taken at the same epoch as the polarimetric observations (2005 September to December) in the F550M filter (λ = 558.15 nm, Δλ = 54.70 nm) but with no polarizer in place. We computed the visual magnitudes of both targets and found that the values are consistent with those of Sandberg & Sollerman (2009), once the different pass bands are taken into account.

We used an aperture of radius 0.25 arcsec to measure the flux from the pulsar. The sky counts were measured using an annulus of width ≈0.1 arcsec, located 0.15 arcsec beyond the central aperture. We added to this flux the flux from the pixels that were bled into. An aperture of radius 0.15 arcsec was used to measure the flux from the synchrotron knot. The sky counts were measured in a region close to the pulsar and knot.

The Stokes parameters were then calculated using the following formulae:

\[ I = \frac{2}{3} [r(0) + r(60) + r(120)] \] (1)

\[ Q = \frac{2}{3} [2r(0) - r(60) - r(120)] \] (2)

\[ U = \frac{2}{\sqrt{3}} [r(60) - r(120)] \] (3)

where \( r(0) \), \( r(60) \) and \( r(120) \) are the calibrated count rates in the 0, 60 and 120° polarized images, respectively (Pavlovsky et al. 2004).
2.1 Computing the degree of linear polarization of a target

The degree of linear polarization (P.D.) is calculated using the Stokes parameters, and factors which correct for cross-polarization leakage in the polarizing filters. This correction is useful for the POLUV filters; values for the parallel and perpendicular transmission coefficients (T_{par} and T_{perp}) can be found in fig. 5.4 of the ACS Instrument Handbook (Pavlovsky et al. 2004). These corrections together with the calibration of the source count rates removes the instrumental polarization of the WFC (~2 per cent) (see equation 4).

\[ P.D. = \frac{\sqrt{Q^2 + U^2}}{I} \times 100 \]  

(4)

P.A. = \frac{1}{2} \tan^{-1}\left( \frac{U}{Q} \right) + PA_{V3} + \chi.  

(5)

An important property of polarization that needs to be considered during analysis is that of bias. This is due to instrumental errors which tend to increase the observed polarization of a target from its true polarization. The effect is negligible when \( p = p \times S/N \) is high (>0.1), where \( p \) is the fractional polarization of the target, and S/N is the signal-to-noise ratio per image. See for example fig. 4 of Sparks & Axon (1999). Since the targets are in the high \( \eta \) regime, the debiasing correction is small and therefore we omit it. We note that for stars 3 and 4, which have low \( \eta \) values, there will be a systematic overestimate of the polarization [see Simmons & Stewart (1984) and Sparks & Axon (1999)]. However, as these have a polarization consistent with zero, no further analysis was performed on them to remove bias.

Naghizadeh-Khouei & Clarke (1993) investigated the statistical behaviour of the P.A. of linear polarization using both numerical integrations and data simulations. They found that the distribution of the angle is essentially Gaussian for \( \eta > 0 \). Hence, we used the formae of Serkowski (1958, 1962) for our error analysis. We propagated the errors in the count rates to obtain errors for the Stokes parameters \( I, Q \) and \( U \). Finally, the errors in the Stokes parameters were propagated through the equations for the errors in the degree of polarization (equation 6) and P.A. (equation 7). As negative polarization is impossible, we used asymmetric error bars for stars 3 and 4. Below are the formulae used for calculating the errors in the degree of polarization and P.A.:

\[ \sigma_{P.D.} = \sqrt{\sigma_I^2 + \sigma_Q^2 + \sigma_U^2} \]  

(6)

\[ \sigma_{P.A.} = 28.65 \frac{\sigma_{P.D.}}{P.D.} \]  

(7)

where \( \sigma_I, \sigma_Q \) and \( \sigma_U \) are the errors in Stokes parameters \( I, Q \) and \( U \), respectively. These errors take into account those introduced by instrumentation and systematics.

The polarization of the synchrotron wisps was also studied (see Tables 2 and 3). To measure the total flux of each wisp, we summed the flux from a series of apertures (\( r \approx 0.3 \) arcsec) placed along the extent of each wisp. We adopt the standard nomenclature as discussed by Scargle (1969), who noted their temporal variability and strong polarization (see Fig. 4). We have accounted for their temporal motion in our analysis. For the sky background subtraction we use the same region of the nebula as used for the knot. Since the contribution of zodiacal and scattered light to the background is low, we therefore ignore the effect of the background polarization in our analysis.

As a guide to our analysis, a number of fore/background stars in the nebula (see Fig. 3) were also analysed to confirm the methodology which we used, and to cross-check for any systematics. Stars 3 and 4 are not saturated in each frame per epoch, but stars 1, 2 and Trimble 28 are saturated. Therefore we employed the same photometric method as used for the pulsar. We used an aperture of radius 0.35 arcsec to measure the flux from each star. The sky counts were measured using an annulus of width \( \approx 0.1 \) arcsec, located 0.15 arcsec beyond the central aperture. We have found that all of the stars are consistent, within the errors, with unpolarized sources.

We have omitted the results of the analysis of the 2003 August data set. The sky background is highly variable in one of the raw images. This then causes errors when one calculates the polarization of the wisps and plots the polarization maps for this epoch. We also note that for the 2005 December data set that the roll-angle of the spacecraft was significantly different to other observations. For this data set the diffraction spike from the pulsar crosses the knot. Furthermore, we note that for the 14th December data set the full Moon was 9° away from the pulsar. This might have introduced spurious background levels which would have impacted upon the polarization of the faint extended sources such as the wisps.

Table 2. P.D. (per cent) of the Crab pulsar, synchrotron knot and wisps as a function of time. Wisp 1-A is unresolved from 2005 Sept 06 to 2005 Oct 12 inclusive.

<table>
<thead>
<tr>
<th>Date</th>
<th>Crab</th>
<th>Knot</th>
<th>Wisp 1-A</th>
<th>Wisp 1-B</th>
<th>Wisp 1-C</th>
<th>Thin Wisp</th>
<th>Counter Wisp</th>
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</thead>
<tbody>
<tr>
<td>2005 Sept 06</td>
<td>4.9 ± 1.0</td>
<td>59.4 ± 7.3</td>
<td>41.7 ± 3.8</td>
<td>32.1 ± 4.5</td>
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<tr>
<td>2005 Sept 15</td>
<td>5.0 ± 1.0</td>
<td>60.0 ± 7.0</td>
<td>45.0 ± 4.0</td>
<td>34.5 ± 4.6</td>
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<tr>
<td>2005 Sept 25</td>
<td>5.4 ± 1.0</td>
<td>62.1 ± 7.1</td>
<td>44.2 ± 4.3</td>
<td>40.7 ± 4.7</td>
<td>38.5 ± 4.7</td>
<td>40.1 ± 5.1</td>
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</tr>
<tr>
<td>2005 Oct 02</td>
<td>4.9 ± 1.0</td>
<td>62.4 ± 6.9</td>
<td>41.3 ± 4.5</td>
<td>39.7 ± 4.7</td>
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<tr>
<td>2005 Oct 12</td>
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<td>60.3 ± 6.6</td>
<td>43.4 ± 4.5</td>
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Table 3. Polarization P.A.s (◦) of the Crab pulsar, synchrotron knot and wisps as a function of time. Wisp 1-A is unresolved from 2005 Sep 06 to 2005 Oct 12 inclusive.

<table>
<thead>
<tr>
<th>Date</th>
<th>Crab</th>
<th>Knot</th>
<th>Wisp 1-A</th>
<th>Wisp 1-B</th>
<th>Wisp 1-C</th>
<th>Thin Wisp</th>
<th>Counter Wisp</th>
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<td>125.6 ± 3.3</td>
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<td>125.0 ± 3.0</td>
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<tr>
<td>2005 Nov 08</td>
<td>106.5 ± 5.7</td>
<td>125.4 ± 2.9</td>
<td>123.4 ± 3.0</td>
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<td>127.1 ± 4.1</td>
<td>130.7 ± 3.9</td>
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<td>2005 Nov 16</td>
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<td>120.0 ± 3.3</td>
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<td>2005 Dec 14</td>
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We have investigated the effects of photometric losses due to charge transfer efficiency (CTE) in the CCDs of the WFC. The effect reduces the apparent brightness of sources, and it requires a photometric correction to restore the measured integrated counts to their ‘true’ value. The ACS team claims that there is no evidence of photometric losses due to CTE for WFC data taken after 2004. Nonetheless, we applied the correction for CTE (see equation 8) to our photometry and found that it does not change the results of the polarimetry. Below is the formula for the correction for CTE loss.

\[
Y_{\text{CTE}} = 10^4 \times \text{Sky}^B \times \text{Flux}^C \times \frac{Y}{2048} \times \frac{\text{MJD} - 52333}{365},
\]

where MJD is the modified Julian date of the observation, and reflects the linear degradation of the CCD with time. The parameters A, B and C are found in table 6.1 of the ACS Instrument Handbook (Pavlovsky et al. 2004).

In order to determine the performance of the ACS as a polarimeter, the ACS team have modelled the complete instrumental effects and the calibration together. This is done so as to quantify the impacts of the remaining uncalibrated systematic errors. They claim that the fractional polarizations will be uncertain at the one-part-in-ten level (e.g. a 20 per cent polarization has an uncertainty of 2 per cent) for strongly polarized targets; and at about the 1 per cent level for weakly polarized targets. The P.A.s will have an uncertainty of about 3 ◦. This is in addition to uncertainties which arise from photon statistics (Pavlovsky et al. 2004). They then checked this calibration against polarized standard stars (5 per cent polarized) and found it to be reliable within the quoted errors (Cracraft & Sparks 2007).

2.3 Photometry and morphology of the knot in unpolarized light

We also retrieved from the MAST archive a series of 12 ACS/WFC data sets, collected through the F550M filter (\(\lambda = 558.15 \text{ nm}, \Delta \lambda = 54.70 \text{ nm}\)) at the same epoch as the polarimetric observations (from 2005 September 6 to 2005 December 14). Each observation consists of a sequence of two images collected in a single orbit, to
Table 5. Polarization P.A. (◦) of Trimble 28 and the background stars as a function of time.

<table>
<thead>
<tr>
<th>Date</th>
<th>Trimble 28</th>
<th>Star 1</th>
<th>Star 2</th>
<th>Star 3</th>
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<td>116.3 ± 18.5</td>
<td>149.5 ± 25.8</td>
<td>177.0 ± 28.1</td>
<td>139.3 ± 49.5</td>
<td>146.6 ± 50.7</td>
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<tr>
<td>2005 Sept 15</td>
<td>170.8 ± 17.6</td>
<td>145.3 ± 15.9</td>
<td>174.4 ± 22.2</td>
<td>138.7 ± 31.4</td>
<td>136.2 ± 30.7</td>
</tr>
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<td>2005 Sept 25</td>
<td>159.4 ± 11.1</td>
<td>148.2 ± 12.6</td>
<td>124.2 ± 25.2</td>
<td>145.7 ± 30.5</td>
<td>144.4 ± 32.0</td>
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<td>178.5 ± 16.3</td>
<td>151.1 ± 19.4</td>
<td>1.0 ± 20.5</td>
<td>125.9 ± 47.0</td>
<td>148.1 ± 36.9</td>
</tr>
<tr>
<td>2005 Oct 12</td>
<td>74.8 ± 20.5</td>
<td>151.1 ± 18.6</td>
<td>97.6 ± 27.1</td>
<td>148.9 ± 39.7</td>
<td>145.8 ± 47.1</td>
</tr>
<tr>
<td>2005 Oct 22</td>
<td>152.4 ± 8.0</td>
<td>147.4 ± 15.4</td>
<td>138.8 ± 17.1</td>
<td>148.8 ± 28.3</td>
<td>148.6 ± 24.5</td>
</tr>
<tr>
<td>2005 Oct 30</td>
<td>140.0 ± 24.9</td>
<td>153.8 ± 26.3</td>
<td>136.7 ± 17.9</td>
<td>150.8 ± 41.0</td>
<td>142.2 ± 38.3</td>
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<tr>
<td>2005 Nov 08</td>
<td>155.6 ± 15.1</td>
<td>151.3 ± 16.5</td>
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<td>149.0 ± 24.5</td>
<td>139.5 ± 29.0</td>
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<tr>
<td>2005 Nov 16</td>
<td>156.8 ± 12.0</td>
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<td>116.3 ± 15.7</td>
<td>140.2 ± 38.7</td>
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<td>142.6 ± 12.2</td>
<td>153.8 ± 19.9</td>
<td>136.6 ± 17.0</td>
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<td>149.6 ± 30.9</td>
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<tr>
<td>2005 Dec 05</td>
<td>135.5 ± 10.4</td>
<td>132.4 ± 17.3</td>
<td>144.2 ± 22.2</td>
<td>146.4 ± 37.4</td>
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<td>2005 Dec 14</td>
<td>144.1 ± 10.1</td>
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<td>164.9 ± 17.0</td>
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<td>149.1 ± 69.2</td>
</tr>
</tbody>
</table>

allow for cosmic ray rejection. We retrieved pipeline-calibrated, drizzled images from the archive. Total exposure times range from 1950 s to 2300 s per epoch (see Table 1). We superimposed the images on the first-epoch one by using the coordinates of 30 non-saturated field sources as a reference grid. The rms accuracy was better than 0.07 pixels per coordinate. We performed multi-epoch photometry of the knot with the SExtractor software (Bertin & Arnouts 1996). We used an implementation of the Kron method (Kron 1980), which measures the flux of an object within an optimized elliptical aperture, evaluated using the second moments of the object’s brightness distribution. The parameters of the Kron ellipse (centre, semi-axes and orientation) also yield a measure of the object coordinates and morphology, which is useful for the case of the knot, which is possibly variable in both position and shape as a function of time. The measured count rate was converted to flux using the standard ACS photometric calibration tabulated in the image headers. Correction for CTE losses proved to have a negligible effect.

Since the knot is a diffuse source located very close to a much brighter and saturated point source (the Crab pulsar), particular care was devoted to estimate systematic errors possibly affecting the flux measurements. To this aim, we performed simulations with the ESO/MIDAS software,3 adding to the ACS images a ‘synthetic knot’. A two-dimensional Gaussian function was used to generate the artificial source, setting one of the symmetry axes aligned to the pulsar spin-axis. The synthetic knot was positioned to the NW of the pulsar, along the direction of the pulsar spin-axis, at an angular distance comparable to that of the true knot. By varying the flux and the position of the artificial source we evaluated the uncertainty on the flux measurement to be ∼2.5 per cent.

We also measured the fluxes of a sample of non-saturated stars in the field as a further assessment of the stability of photometry in the variable background of the Crab nebula (see Fig. 3).

3 RESULTS

Included here are the measurements of the degree of polarization and P.A. of each target per epoch (see Tables 2–5 inclusive). We have plotted the degree of polarization and P.A. for each target as a function of time (see Figs 5 and 6). Using a χ² goodness-of-fit, we found no significant variation (at the 95 per cent confidence level) in the polarization of the pulsar, knot and wisps over the 3 month period of these observations. As a final comparison, we present the mean values. These are the values obtained from using the weighted mean and error of the degree of polarization and P.A. (see Table 6). Stars 3 and 4 have asymmetric error bars. Hence, we use the method of Barlow (2004) for calculating the weighted mean for asymmetric error bars. As can be seen from Figs 5 and 6 and Table 6, the 2005 December data set shows evidence of a possible variation of the knot polarization at the 2σ level. This variation is due neither to a known systematic effect nor to the contribution of the diffraction spikes from the pulsar (see Section 2.2), which only affect the knot’s flux by <2 per cent. Future polarimetry observations on a longer time-span will help us to address the possible knot variability. Similarly, we note that the polarization of Wisps 1-A and 1-B also shows a possible variation at the 2σ level in the 2005 December data set. As discussed in Section 2.2, this may be partially ascribed to the enhanced Moon contribution to the background. This possible variation may be also ascribed to the unresolved contribution of the bright torus in the nebula, to which Wisps 1-A and B have moved closest in the 2005 December observations.

The polarization maps (Figs 2 and 7) show the variation of the polarization throughout the inner nebula and particularly in the vicinity of the pulsar itself. Each vector has magnitude equal to the degree of polarization, and its orientation is the P.A. at that point. Such maps allow one to visualize the direction of the magnetic field lines within the nebula. One can distinctly see the overall structure of the inner nebula, the degree of polarization of the knots and the synchrotron emission. In particular, the filaments are unpolarized and the structures that are visible in polarized light (Fig. 3) do not map exactly the continuum (Fig. 1).

The F550M band images were used to study with high accuracy possible displacements of the knot. The light curve of the knot is shown in Fig. 8, compared to the one of the reference stars. The knot is seen to brighten by ∼40 per cent on a 60-d time-scale, then to fade to its initial flux level. Reference stars, conversely, do not display any significant variability. Focusing on the knot, we note that changes in flux are accompanied by shifts in position, the knot centroid being closer to the pulsar when the feature is brighter (the displacement between maximum and minimum flux is 0.075 ± 0.025 arcsec). There is no statistically significant evidence of a change in the full width at half-maximum of the knot as a function of time. We checked our photometric results by repeating

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2 Single, calibrated ACS images were combined using the MULTIDRIZZLE software, which also produces a mosaic image of the two ACS chips and applies a correction for the geometric distortions of the camera.

3 http://www.eso.org/sci/software/esomidas/
Figure 5. Plots of the P.D. (per cent) of the sources as a function of time. The solid lines are the weighted mean of the degree of polarization.

Figure 6. Plots of the polarization P.A. (°) of the sources as a function of time. The solid lines are the weighted mean of the P.A.
Table 6. Overall results for the P.D. (per cent) and P.A. (◦). These are the weighted mean and error of the degree of polarization and P.A.

<table>
<thead>
<tr>
<th>Source</th>
<th>P.D. (per cent)</th>
<th>P.A. (◦)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar</td>
<td>5.2 ± 0.3</td>
<td>105.1 ± 1.6</td>
</tr>
<tr>
<td>Synchrotron knot</td>
<td>59.0 ± 1.9</td>
<td>124.7 ± 1.0</td>
</tr>
<tr>
<td>Wisp 1-A</td>
<td>39.8 ± 1.6</td>
<td>124.7 ± 1.2</td>
</tr>
<tr>
<td>Wisp 1-B</td>
<td>43.0 ± 1.3</td>
<td>127.4 ± 0.9</td>
</tr>
<tr>
<td>Wisp 1-C</td>
<td>38.5 ± 1.3</td>
<td>128.8 ± 1.0</td>
</tr>
<tr>
<td>Thin Wisp</td>
<td>36.7 ± 1.4</td>
<td>127.1 ± 1.0</td>
</tr>
<tr>
<td>Counter Wisp</td>
<td>40.6 ± 1.5</td>
<td>130.3 ± 1.1</td>
</tr>
<tr>
<td>Trimble 28</td>
<td>1.6 ± 0.2</td>
<td>147.5 ± 3.7</td>
</tr>
<tr>
<td>Star 1</td>
<td>2.3 ± 0.4</td>
<td>147.7 ± 5.2</td>
</tr>
<tr>
<td>Star 2</td>
<td>1.2 ± 0.3</td>
<td>128.3 ± 5.9</td>
</tr>
<tr>
<td>Star 3</td>
<td>1.6 ± 0.7</td>
<td>144.0 ± 10.2</td>
</tr>
<tr>
<td>Star 4</td>
<td>2.2 ± 1.0</td>
<td>144.8 ± 9.9</td>
</tr>
</tbody>
</table>

Figure 7. Polarization vector map of the vicinity of the Crab pulsar superimposed on the nebula (2005 Nov. 25, FOV ≈25 × 33 arcsec²). The location of the pulsar and inner knot is marked by the circle. The legend shows the vector magnitude for 50 per cent polarization.

the analysis with simple aperture photometry, using an aperture of 0.15 arcsec positioned on the knot centroid (as measured in each epoch). Such an exercise yielded consistent results (~40 per cent brightening in two months), confirming the significant variability in flux.

4 DISCUSSION

We have studied the phase-averaged polarization properties of the Crab pulsar and its nearby synchrotron knot using archival HST/ACS data. We note that the data set analysed in this paper has previously been used by Hester (2008) to examine the morphology and structure of the polarized components of the inner nebula. However, we have produced polarization vector maps of the inner nebula and measured, for the first time, the P.D. and the P.A. of the pulsar’s integrated pulse beam, and of its nearby synchrotron knot. Furthermore, this work marks the first high-spatial resolution multi-epoch study of the variability of the polarization of the inner nebula and pulsar.

The results for the Crab pulsar are P.D. = 5.2 ± 0.3 per cent, and P.A. = 105.1 ± 1.6 (see Table 6). These values are in good agreement with those of Słowikowska et al. (2009) using the high time resolution photo-polarimeter – Optical Pulsar Timing Analyzer (OPTIMA)4 (Kanbach et al. 2008), once the constant component (DC) is subtracted. They measure phase-averaged values of P.D. = 9.8 ± 0.1 per cent, and P.A. = 109.5 ± 0.2, which is not DC subtracted and includes the emission from the inner knot due to the OPTIMA aperture. They measure values of P.D. = 5.4 per cent, and P.A. = 96.4 after DC subtraction, and it is this latter measurement that agrees with our own. The optical polarization of the Crab pulsar has also been measured by Wampler et al. (1969) (P.D. = 6.5 ± 0.9 per cent, P.A. = 107.0 ± 6.0), and Kristian et al. (1970) (P.D. = 6.8 ± 0.5 per cent, P.A. = 98.0 ± 3.0).

We note that the polarization of the inner knot (59.0 ± 1.9 per cent) is a factor of 2 larger than the off-pulse polarization of 33 per cent obtained from OPTIMA observations (Słowikowska et al. 2009) and consistent with the older measurements of Jones et al. (1981) (70 per cent) and Smith et al. (1988) (47 ± 10 per cent). This discrepancy is partially due to the uncertainty of determining

4 http://www.mpe.mpg.de/OPTIMA
the phase interval bracketing the minimum of the Crab’s light curve, hence the contribution of the DC component (see fig. 5 of Słowikowska et al. 2009). It could also be partially due to uncertainties in the estimate of the sky background in the OPTIMA data and/or the contribution from the sky and pulsar ‘off-pulse’ flux. Golden et al. (2000) give the unpulsed pulsar flux to be 0.02 mJy compared to 0.03 mJy from the knot (this work). We estimate the contribution from the sky for OPTIMA data to be equivalent to 0.04 mJy based on the pupil size of 2.35 arcsec and a 21 magnitude arcsec$^{-2}$ sky background. This would be sufficient to explain the difference. Two-dimensional phase-resolved polarization observations will allow us to better quantify the knot contribution to the DC component.

X-ray observations of the nebula taken by Chandra (Weisskopf et al. 2000) reveal a torus with bipolar jets emanating outwards from SE and NW of the pulsar. Ng & Romani (2006) found that the axis of symmetry of the jet is roughly aligned with the pulsar’s proper motion vector. The Crab torus, bisecting the synchrotron wisps, can be traced back to the knot of synchrotron emission seen $\approx 0.65$ arcsec SE of the pulsar. Our measurement of the polarization P.A. of the synchrotron knot, P.A. = 124.7 $\pm$ 1.0, agrees with the Crab torus P.A. = 126.3 $\pm$ 0.03 (Ng & Romani 2004). We also found evidence for an apparent alignment between the pulsar polarization P.A. (105.1 $\pm$ 1.6) and proper motion vector (Kaplan et al. 2008; 110 $\pm$ 2 9$'$) (see Fig. 9). Mignani et al. (2007) have found the same scenario for the Vela pulsar. Those authors found an apparent alignment between the polarization P.A. of the pulsar, the axis of symmetry of the X-ray arcs and jets (Chandra; Pavlov et al. 2001; Helfand, Gotthelf & Halpern 2001), and the pulsars proper motion vector. This suggests that the ‘kick’ given to neutron stars at birth is directed along the rotation axis (Lai, Chernoff & Cordes 2001). The alternative view is that the apparent alignment is an effect of projection on to the sky plane, and that there is no physical jet along the axis of rotation (Radhakrishnan & Deshpande 2001). More concrete measurements of the optical polarization of pulsars will yield the needed observational restraints on these hypotheses.

As mentioned previously, the polarization of the wisps was also studied. Our photometry accounts for the outward motion of the wisps. From the analysis of the wisps in each epoch, we find that the wisps show variation in both location and brightness on time-scales of a few weeks. We found that all of these wisps have similar values of degree of polarization ($\sim$40 per cent) and P.A. equal to that of the synchrotron knot ($\sim$125$'$). Hence, as with the synchrotron knot, they are aligned with the spin-axis of the pulsar. Also, Wisps 1-A is not visible in the frames from 2005 September to 2005 October 12 inclusive, and may be merged with Wisp 1-B during this period. Examining the polarization vectors maps, one can see that the P.A. of the wisps are different to those of the rest of the nebula, where the P.A. are aligned NS (Figs 2 and 7). Fig. 10 is a histogram of the distribution of the polarization P.A. of the inner nebula. The P.A. were extracted from the values in the polarization map. From this histogram we see that the polarization P.A. of the pulsar environment ($\sim$125$'$) is away from the peak of the nebula distribution ($\sim$165$'$). This means that the polarization properties of the structures close to the pulsar are different from those of the rest of the inner nebula.

As discussed earlier, using a $\chi^2$ goodness of fit, we found no significant variation (at the 95 per cent confidence level) in the polarization of the pulsar, knot and wisps over a 3 month period. The knot is variable in flux but fairly constant in polarization. This variation in flux may be explained in terms of an increased plasma density in the vicinity of the knot. Whereas the wisps have constant flux and constant polarization over this period of time. This would suggest that the magnetic fields within the nebula are uniform over time. However, more detailed follow-up observations will be needed to determine if there is any longer term variation.

5 CONCLUSIONS

We have studied the phase-averaged polarization properties of the Crab pulsar and its nearby synchrotron knot using archival

![Figure 9. The pulsar region with the synchrotron knot located $\approx 0.65$ arcsec SE of the pulsar (2005 Sept. 06, FOV $\approx 2 \times 2$ arcsec$^2$). The vectors included are as follows: spin-axis vector (SA) (124 $\pm$ 0.1) (Ng & Romani 2004), proper motion vector (PM) (110 $\pm$ 2 9$'$) (Kaplan et al. 2008), and the polarization P.A. of the pulsar (105:1 $\pm$ 1:6) and synchrotron knot (124:7 $\pm$ 1:0) from the HST/ACS data. Also included are the phase-averaged OPTIMA measurements of the polarization P.A. of the synchrotron knot (119:8 $\pm$ 0:8) and pulsar (109:5 $\pm$ 0:2) (Słowikowska et al. 2009), and the phase-averaged INTEGRAL/IBIS measurement of the polarization P.A. during the off-pulse and bridge emission (OP+B) phases (122:0 $\pm$ 7:7) (Forot et al. 2008).]
Optical polarimetry of the inner Crab nebula

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ACKNOWLEDGEMENTS

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Dean J. et al., 2008, Sci, 321, 1183

HST/ACS data. This marks the first high-spatial resolution multi-epoch study of the polarization of the inner nebula and pulsar. We found an apparent alignment between the polarization P.A. of the pulsar and the pulsar’s proper motion vector. We confirm that the inner knot is responsible for the highly polarized off-pulse emission seen in observations in the optical. We found that the inner knot is variable in position, and brightness over the period of these observations. These are the first quantified measurements of such a variation. We note that we found evidence of a possible variation of the knot polarization (at 2σ) which is due neither to a known systematic effect nor to the spike contribution. Future observations will help to address this point. We have also measured the polarization of the wisps in the inner nebula, and found no significant variation in their polarization over this 3 month period of observations.

Polarization measurements give a unique insight into the geometry of the pulsar emission regions. More multi-wavelength polarization observations of pulsars, both phase-averaged and phase-resolved, with instruments such as HST/ACS and GASP (optical), and INTEGRAL/IBIS (gamma-ray), will help to provide the much needed data to constrain the theoretical models.

For example, McDonald et al. (2011) have developed an inverse mapping approach for determining the emission height of the optical photons from pulsars. It uses the optical Stokes parameters to determine the most likely geometry for emission, including: magnetic field inclination angle (α), the observers-line-of-sight angle (χ) and emission height.
Walsh J., 1999, The ST-ECF Newsletter, Issue Number 26

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.
INTEGRAL/IBIS and optical observations of the Crab nebula/pulsar polarisation

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Previous INTEGRAL/IBIS observations have shown that the gamma-ray radiation of the Crab Nebula is highly polarised and remarkably aligned along the axis of rotation of the pulsar [4]. Their study was based on the first four years of operation of the satellite. Here we present an analysis based upon nearly ten years of operation. This new analysis allows a better characterisation of the polarisation fraction and position angle, as well as a measure of spectral energy distribution of the polarised component. These results are then compared to the known optical polarisation of the pulsar and nearby synchrotron knot. In the future we shall compare the gamma-ray polarisation with the phase-resolved optical polarisation using instruments such as GASP [10].
1. Introduction

Polarisation measurements of pulsars provide an unique insight into the geometry of their emission region, and therefore observational constraints on the theoretical models of the emission mechanism. From an understanding of the emission geometry, one can limit the competing models for pulsar emission, and hence understand how pulsars work - a problem which has eluded astronomers for almost 50 years. Here we present the preliminary results of a multi-wavelength campaign, whereby we study the polarisation of the Crab Nebula and pulsar using both the INTEGRAL/IBIS Compton mode (gamma-ray) and archival HST/ACS data (optical).

2. INTEGRAL/IBIS Polarisation via Compton Mode

The work presented here is a continuation of the work of [4]. Those authors studied the polarisation of the Crab Nebula and pulsar using the first four years of operation of the INTEGRAL satellite. We use the same procedure and software for our analysis of the data from 2007 September to 2012 April. The polarisation of celestial sources is measured using the IBIS Compton mode. Photons entering IBIS (Imager on Board the INTEGRAL Satellite) are Compton scattered in ISGRI (Integral Soft Gamma-Ray Imager), the first detector plane, at a polar angle $\theta$ from their incident direction and at an azimuth $\psi$ from their incident electric vector. The photons are then absorbed in the second detector, PICsIT (Pixellated CsI Telescope). Hence, the polarisation of sources can be measured, since the scattering azimuth is related to the polarisation direction. Events recorded in both detectors within the same time window of 3.8 $\mu$s are tagged as Compton events. However, not all of these events result from Compton scattering. Chance coincidences can occur between events independently coming from the source, the sky, or the instrumental background. The majority of the Compton tagged events are due to the background events, which are removed using the shadowgram deconvolution. IBIS is an example of a coded-aperture Compton telescope. The design provides high-energy response, low background, and a wide field-of-view. Moreover, utilising the imaging properties of the coded mask, a high angular resolution and background subtraction is achieved (see Figure 1). For the timing analysis, the times of arrival of the Compton events are referred to the solar system barycentre and phase-folded using an ephemeris from Jodrell Bank. We have used the pulsar phase intervals of [9]: P1 (main pulse), P2 (inter pulse), B (Bridge emission), and OP (off-pulse emission) (see Figure 2). For more information about the analysis see [3] and the paper by Laurent et al. in these proceedings.

3. Optical Polarisation Studies

Strong polarisation is expected when the pulsar optical emission is generated by synchrotron radiation. [15] suggested that the continuous optical radiation from the Crab Nebula was due to synchrotron radiation. This was later confirmed by [2] and [17] who found that the optical radiation was polarised. Archival HST/ACS polarisation science frames of the Crab Nebula were obtained from the Mikulski Archive for Space Telescopes (MAST). The data comprises of a series of observations of the nebula with the HST/ACS taken in three different polarisers ($0^\circ$, $60^\circ$ & $120^\circ$) between 2003 August and 2005 December. The raw images, which had already been
flat-fielded, were geometrically aligned, combined and averaged with cosmic-ray removal using IRAF. For each set of observations, the images were analysed by the IMPOL software [18], which produces polarisation vector maps. In order to determine the polarimetry, aperture photometry was performed on the pulsar and synchrotron knot in each image using the IRAF task phot (see ACS Data Handbook [14]). This work is intended to accurately map the polarisation of the Crab Nebula, and act as a guideline for future time-resolved polarisation measurements of the Crab pulsar using the Galway Astronomical Stokes Polarimeter (GASP). This is an ultra-high-speed, full Stokes, astronomical imaging polarimeter based on the Division of Amplitude Polarimeter (DOAP). It has been designed to resolve extremely rapid variations in objects such as optical pulsars and magnetic cataclysmic variables.

4. Conclusion

We have measured the polarisation of the Crab Nebula and pulsar using the INTEGRAL/IBIS Compton mode. Our results are consistent with those of [4]. They found that the off-pulse emission is highly polarised, and that the polarisation is aligned with the axis of rotation of the pulsar (124±0.1°) [12]. We have also examined the phase-averaged optical polarisation of the Crab pulsar and its synchrotron knot using archival HST/ACS data. The results of the optical polarimetry of the Crab pulsar are in good agreement with those of [16] using OPTIMA, [19], and [8]. We see that the knot is strongly polarised and we suggest that it is responsible for the highly polarised off-pulse emission. Our measurement of the polarisation PA of the synchrotron knot, PA = 126.86±0.23°, agrees with the Crab torus PA = 126.31±0.03° [12]. We also found evidence for an apparent alignment between the pulsar polarisation PA (105.97±2.00°) and proper motion vector ([7]; 290±2±9° or 110±2±9°) (see Figure 4). Looking at the gamma-ray data, we again see evidence of an alignment between the polarisation position angle of the pulsar and it’s rotation axis. Furthermore, we have compared our results to those obtained at other wavelengths (see Table 1).

The optical polarisation maps show the variation of the polarisation throughout the inner nebula and particularly in the vicinity of the pulsar itself. One can distinctly see the overall structure of the inner nebula, the degree of polarisation of the knots and the synchrotron emission (see Figures 3 & 4). The first optical polarisation maps of the Crab Nebula were those of [13], [6] and [21].

In November 2012 we used GASP to measure both the linear and circular optical polarisation from the Crab pulsar, on time-scales of ≈1 millisecond. The analysis of these observations are still ongoing. Polarisation measurements give an unique insight into the geometry of the pulsar emission region (see [11]). More multi-wavelength polarisation observations of pulsars will help to provide the much needed data to constrain the theoretical models, and hence solve the emission-model problem.

Acknowledgments

Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts.
We thank Jeremy Walsh, ESO, for the use of his polarimetry software IMPOL to produce the polarisation maps. PM is grateful for his PhD funding from the Irish Research Council, and also thanks the French Embassy in Ireland for helping to fund this research project.

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INTEGRAL/IBIS and optical observations of the Crab nebula/pulsar polarisation

Paul Moran

Figure 1: Deconvolved significance map of the Crab Nebula and pulsar using the Compton mode, 200–800 keV, 1 Ms.

Figure 2: Left: Compton mode lightcurve of the Crab pulsar, 200–600 keV, 2.6 Ms. Right: Azimuthal profile of the Crab Nebula and pulsar, 200–800 keV, 2.6 Ms.

<table>
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<tr>
<th>Source</th>
<th>Polarisation Degree (%)</th>
<th>Position Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ-ray (SPI) [1]</td>
<td>OP</td>
<td>46 ± 10</td>
</tr>
<tr>
<td>γ-ray (IBIS) [4]</td>
<td>OP</td>
<td>&gt; 72</td>
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<tr>
<td>γ-ray (IBIS) [4]</td>
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<td>&gt; 88</td>
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<td>42 ± 30</td>
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<td>Total</td>
<td>47 ± 19</td>
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<tr>
<td>γ-ray (IBIS) (this work)</td>
<td>Total</td>
<td>58 ± 7</td>
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<td>X-ray (OSO 8) (2.6–5.2 keV) [20]</td>
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<td>19.22 ± 0.92</td>
</tr>
</tbody>
</table>

Table 1: List of multi-wavelength polarisation studies of the Crab Nebula and pulsar. For gamma-ray phase selections OP, B, P1, and P2 see text and [9].
Figure 3: Left: HST/ACS image of the Crab Nebula (1.76′×1.7′, 2005 Sep 06). Right: Polarisation vector map of the Crab Nebula superimposed on the nebula. The legend shows the vector magnitude for 50% polarisation. The location of the pulsar and knot is marked by the red circle.

Figure 4: Left: Polarisation vector map of the vicinity of the Crab pulsar and wisp region superimposed on the nebula. The legend shows the vector magnitude for 50% polarisation. The location of the pulsar and knot is marked by the red circle. Right: Close up of the Crab pulsar region with the synchrotron knot located ≈ 0.65″ SE of the pulsar. The vectors included are as follows: spin-axis vector (SA) (124 ± 0.1°) (Ng & Romani 2004), proper motion vector (PM) (110 ± 2 ± 9°) (Kaplan et al. 2008), and the polarisation position angles of the pulsar (105.97 ± 2.00°) and synchrotron knot (126.86 ± 0.23°). Also, included is the INTEGRAL/IBIS measurement of the position angle during the off-pulse and bridge emission phases (OP+B) (122.0 ± 7.7°) (Forot et al. 2008).
Integral observations of polarization: from the Crab pulsar to Cygnus X-1

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In complement to spectro-imaging observations, $\gamma$-ray polarimetry provides a unique insight into the geometry and magnetic configuration of compact $\gamma$-ray sources, such as neutron stars or black holes. Due to the unprecedented spectral and timing capabilities of Integral, and thanks to its coded mask imaging techniques, which efficiently suppresses most of the background contribution, we have measured linearly polarized emission from the brightest cosmic high energy sources with the two telescopes IBIS and SPI. We were able to measure for the first time, at energies above 200 keV, a clear polarization signal from different types of $\gamma$-ray sources such as the Crab pulsar and nebula, the black hole candidate Cygnus X-1, and Gamma-Ray Bursts. These observations have enabled us to put strong constraints on the physical process at work in these sources, and the achieved sensitivity opens a new window for polarimetric studies in the soft $\gamma$-ray regime.
1. Introduction

Whereas difficult, γ-ray polarimetry has been possible with Compton telescopes since the 1970s. Photons that are Compton scattered between two detectors follow an azimuthal distribution around the source direction that allows to quantify the degree and direction of linear polarization because these photons are preferentially scattered in a plane at right angle to their incident electric vector. This measure was unsuccessful up to recently because of intrinsic asymmetries in the detector response and of non-uniformities in the large background signals. These defaults induce pseudo polarimetric signals, even from an unpolarized source, that limit the sensitivity to any detection. Thanks to their imaging capacities, however, the IBIS [1] and SPI [2] telescopes on board the Integral satellite are well suited for polarimetry studies, between 200 keV and 5 MeV. In this paper, we will describe the polarimetry methods developed, and present evidence for the detection of polarization from the Crab nebula, Gamma-Ray Bursts, and Cygnus X–1 at energies above 200 keV.

2. Polarimetry with the Integral/IBIS Compton mode

Photons entering the INTEGRAL/IBIS telescope may be Compton scattered in the first detector plane, ISGRI [3], at a polar angle $\theta$ from their incident direction and at an azimuth $\psi$ from their incident electric vector. They are then absorbed in the second detector, PiCsIT [4]. The azimuthal profile $N(\psi)$, in Compton counts recorded per azimuth bin, follows:

$$N(\psi) = S[1 + a_0 \cos(2\psi - 2\psi_0)]$$

for a source polarized at an angle $PA = \psi_0 - \pi/2 + n\pi$ and with a polarization fraction $PF = a_0/a_{100}$. The $a_{100}$ amplitude is expected for a 100% polarized source. Unfortunately, the IBIS and SPI polarimetric capacities have not been calibrated on ground, due to the tight planning of the INTEGRAL project before launch. For IBIS, we have then evaluated $a_{100}$ to be $0.30 \pm 0.02$ for a Crab-like $E^{-2.2}$ spectrum between 200 and 800 keV, using GEANT3 Monte-Carlo simulations with the GLEPS package for polarization.

Events recorded in ISGRI and PiCsIT within the same time window of 3.8 $\mu$s are tagged as 'Compton' events, but do not all result from Compton scattering. Chance coincidences can occur between ISGRI and PiCsIT events independently coming from the source, the sky, or the instrumental background. These coincidences are generally called spurious events. Most of the 'Compton'-tagged events are due to background events that will be removed by the shadowgram deconvolution; 5% are due to a small fraction of spurious coincidences that must be removed with high accuracy because they induce a false source detection in the sky image; 2% come from true Compton events from the source.

The procedure we used to subtract the spurious events contribution and measure the polarization is described in Forot et al. [5]. Confidence intervals on $a_0$ and $\psi_0$ are not given by the $N(\psi)$

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1Integral is an ESA project with instruments and science data center funded by ESA member states with the participation of Russia and USA. ISGRI has been realized and maintained in flight by CEA/Irfu with the support of CNES.

2GLEPS is a package for handling polarization in Geant 3 developed by Dr. Mark McConnell at University of New Hampshire, USA.
fit to the data since the variables are not independent. They have been derived from the probability density distribution of measuring $a$ and $ψ$ from $N_{pt}$ independent data points in $N(ψ)$ over a $π$ period, based on Gaussian distributions for the orthogonal Stokes components [6]:

$$dP(a, ψ) = \frac{N_{pt}}{π \sigma_S^2} \exp\left[-\frac{N_{pt}}{2} \frac{S^2}{\sigma_S^2} \left[a^2 + a_0^2 - 2aa_0 \cos(2ψ - 2ψ_0)\right]\right] a \, da \, dψ$$ \hspace{1cm} (2.2)

$σ_S$ notes the error on the profile mean $S$. The errors on each $a$ or $ψ$ dimension are obtained by integrating $dP(a, ψ)$ over the other dimension.

### 3. Polarimetry with the SPI telescope

The SPI telescope onboard Integral is able to measure $γ$-ray sources polarization through an analysis of its “multiple events”. Indeed, these events are generated when a photon makes several energy deposits in two or more SPI germanium detectors, and are mostly due to Compton scattering in different detectors. They can thus be used to measure polarimetry, on the same basis as what is done for the IBIS/Compton mode. However, due to the SPI imaging complexity, it is merely impossible to measure this polarization directly, and one has to rely on heavy Monte-Carlo simulations to look for a polarized signal in the data. This search is done by computing, for each pointing and a given source spectrum, overall SPI simulations for 100% polarized sources with $18$ given position angles spanning from $0^\circ$ to $180^\circ$ and also using an unpolarized source. Simulation results for a given polarization fraction and angle are then given by [7]:

$$G4(a, ψ) = a \, G4(ψ) + (1. - a) \, G4(0)$$ \hspace{1cm} (3.1)

where $G4(ψ)$ and $G4(0)$ are the results of GEANT-4 simulations for beams with 100% polarization, polarization angle $ψ$, and for unpolarized beams, respectively. The simulated count rates for both cases are then compared with a $χ^2$ statistics with the observed distribution. Polarized angle and fraction are thus determined by the simulation giving the lowest $χ^2$. This method was first described by Dean et al. [8], and then improved in the recent Jourdain et al. paper on Cygnus X-1 [7].

### 4. Crab observations

The first studies of the Crab polarization at hard X-ray energies by Integral have been published by Dean et al. [8] and Forot et al. [9]. In this last paper, we use Integral observations of the Crab nebula between 2003 and 2007 for a total of 1.2 Ms. The pulsed lightcurve in the 200-800 keV band has been constructed with the Jodrell Bank ephemerides of the pulsar. We have considered four phase intervals for polarimetry studies: the two main peaks, the off-pulse interval and the bridge interval, dominated by the nebular emission. The interval boundaries were taken from [10] and were not adapted to enhance a possible signal. Table 1 and Fig. 1 show the results and illustrate the contrast between the modulation obtained for the nebular emission versus the flat profile of the pulsed emission.

There is indeed no significant indication of polarization in the pulsed peaks. The chance probability of a random fluctuation reaches 33.5 % and the signal shows no modulation at the 95 % confidence level over all angles. This behaviour is consistent with the radio and optical data where
Figure 1: Azimuthal profile, modulation angle, PA, and fraction, PF, measured in the IBIS Compton mode for the Crab data between 200 and 800 keV, in the off-pulse (top), off-pulse and bridge (middle), and two-peak (bottom) phase intervals. The error bars for the profile are at one sigma. The 68%, 95%, and 99% confidence regions are shaded from dark to light gray. The SPI result [8] is indicated in the top figure by a cross.
PF drops below 10% as the angle largely flips within each peak [11]. Conversely, the chance is low that the modulation seen in the off-pulse emission above 200 keV be of random origin. The \( P(a,\psi) \) probability density yields a probability of \( 2 \times 10^{-3} \) that a random fluctuation produces an amplitude \( a_0 \) larger than the recorded one. Adding the bridge and off-pulse data strengthens the signal and gives a chance probability of \( 10^{-3} \) that an unpolarized source produce this modulation (see table 1). The off-pulse-and-bridge emission is polarized at an angle of \( 122.0^\circ \pm 7.7^\circ \) which is fully consistent with the north-to-east angle \( \psi = 124^\circ \pm 0.1^\circ \) of the pulsar rotation axis projected on the skyplane.

We have pursued this study of the Crab pulsar and nebula polarization using the 2007 to 2012 Integral/IBIS data. The results we found for the whole pulsar period are shown on the last row of Table 1 and are consistent with those obtained in the Forot et al. paper (see P. Moran et al., [12] for details).

### 5. Observation of variable polarization from Gamma Ray Bursts

The IBIS and SPI telescopes on board the INTEGRAL satellite have also been used to measure the polarization of the prompt \( \gamma \)-ray emission of long and bright gamma-ray bursts (GRB) in the 200 – 800 keV energy band. Two bright GRBs have been studied so far by Integral/IBIS: GRB 041219A and GRB 061122. For GRB 041219A, characterized by a two peaked light curve, Götz et al. [13] found a variable degree of polarization ranging from less than 4% over the first peak to 43 ± 25% for the whole second peak. Time resolved analysis of both peaks indicates a high degree of polarization, and the null average polarization in the first peak can be explained by the rapid variations observed in the polarization angle and degree. The azimuthal distributions of the GRB flux for the different time intervals are reported in figure 2.

These results are consistent with the SPI analysis which reported a high polarization level (68% with \( \psi = 70^\circ \pm 12^\circ \) [14]) observed during the brightest part of GRB041219A, corresponding to the P8 time interval in figure 2, when IBIS measured a polarization angle \( \psi = 88^\circ \pm 12^\circ \). Finally, using a recent determination [15] of the GRB distance, and measuring the polarization properties of the emitted photons in two adjacent energy range, Laurent et al. [16] were able to increase by 4 orders of magnitude the existing constraint on Lorentz invariance violations (LIV), arising from

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### Table 1: Polarization angle and fraction with respect to the Crab pulsar phase \( \phi \)

<table>
<thead>
<tr>
<th>phase interval</th>
<th>polarization angle</th>
<th>polarization fraction</th>
<th>chance probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_1 ) and ( P_2 )(IBIS)</td>
<td>( 70^\circ \pm 20^\circ )</td>
<td>( 0.42^{+0.30}_{-0.16} )</td>
<td>33.5%</td>
</tr>
<tr>
<td>OP(IBIS)</td>
<td>( 120.6^\circ \pm 8.5^\circ )</td>
<td>( &gt; 0.72^a )</td>
<td>0.26%</td>
</tr>
<tr>
<td>OP(SPI)</td>
<td>( 123^\circ \pm 11^\circ )</td>
<td>( 0.46 \pm 0.1 )</td>
<td></td>
</tr>
<tr>
<td>OP and B(IBIS)</td>
<td>( 122.0^\circ \pm 7.7^\circ )</td>
<td>( &gt; 0.88^a )</td>
<td>0.10%</td>
</tr>
<tr>
<td>all(IBIS, 2003 – 2007)</td>
<td>( 100^\circ \pm 11^\circ )</td>
<td>( 0.47^{+0.19}_{-0.13} )</td>
<td>2.8%</td>
</tr>
<tr>
<td>all(IBIS, 2007 – 2012)</td>
<td>( 85^\circ \pm 10^\circ )</td>
<td>( 0.58 \pm 0.07 )</td>
<td></td>
</tr>
</tbody>
</table>

\( a \): The lower limits for the polarization fraction are given at the 95% confidence level.
Figure 2: Polarigrams of the different GRB 041219A time intervals that have been analyzed. For comparison purposes, the curves have been normalized to their average flux level. For a definition of the time intervals see \[13\].

Vacuum birefringence. The study of GRB 041219A and GRB 061122 polarization with Integral is described in more details in \[17\].

6. Observation of the Cygnus X–1 polarized high energy component

Cygnus X–1 is probably the best known black hole (BH) X-ray binary in our Galaxy. It is located around 1.9 kpc away from the Earth, and forms a binary system together with a high mass blue O star. It radiates mainly in the X-ray and soft gamma-ray domain and its X-ray luminosity is thought to come from accretion of matter from the companion onto the BH through the formation of an accretion disk. Finally, a compact radio jet is ejected from the vicinity of the BH, with a kinetic power similar to the source’s bolometric X-ray luminosity (see \[18\] and references therein). The spectral measurements of the INTEGRAL/IBIS/Compton observations of Cygnus X-1 are shown in Figure 3 \[18\], where the X-ray/gamma-ray spectrum as obtained with the standard Integral/IBIS pipeline is presented. Two high energy components are clearly seen, a cutoff power law component between 20 and 400 keV, reminiscent of a Compton-scattering induced spectrum, and a power law
spectrum at higher energies of up to 2 MeV. These two components are signatures of two different high energy emission processes in the source, whose locations have not yet been constrained.

Thanks to polarization measurements, we are now able to better understand this gamma-ray emission geometry. Indeed, the signal measured in the first energy band for which a polarimetry study could be performed (250-400 keV), appeared to be consistent with a non-polarized signal with an upper limit of 20% for the polarization fraction $PF$ (shown in Figure 3). This result agrees with what is expected from a zone where Compton multiple scattering dominates. In contrast to the low polarization in the 250-400 keV band, the signal from the 400-2000 keV band in which the hard tail dominates is highly polarized ($PF = 67 \pm 30\%$, see Figure 3). This result is no longer consistent with domination of Compton scattering, and such a high polarization fraction is more likely the signature of synchrotron emission, e.g., from the jet already observed in the radio band.

A similar spectral dependence of the polarization signal from Cygnus X-1 has been recently observed by the SPI telescope [7]. IBIS and SPI are thus now consistently measuring a highly polarized signal above 400 keV at a polarization angle $\psi = 40^\circ \pm 8^\circ$, that is 60$^\circ$ away from the compact radio jet position ($-21^\circ : -24^\circ$ [19]).

Following these results, we aim to study in the near future with Integral the variation of the polarimetric signal with the different Cygnus X-1 spectral states, using the spectral state determination described in [20], and to use Integral long term observations to measure possibly polarized signals from other bright Black Hole candidates, such as GX 339-4, GRS 1915+105 or Sw J1745-26.

7. Conclusions

The measurement of polarization in hard-X rays/soft-$\gamma$ rays is a powerful tool to investigate the emission mechanisms and geometry of high-energy astrophysical sources. We have shown that fundamental physics questions can also be addressed. By these pioneering observations, Integral is a pathfinder and we hope that next generation dedicated polarimeters (e.g. POLAR [21], Astro-H/SGD [22], etc.) will complement the Integral discoveries.

References

Figure 3: Spectra and polarigrams observed by the Integral/IBIS telescope from Cygnus X–1.

[12] Moran, P. et al., 2012, these proceeding
[17] Gotz D., et al., 2012, these proceedings
[20] Grindberg, V. et al., 2012, these proceedings
VLT observations of the two Fermi pulsars PSR J1357—6429 and PSR J1048—5832*

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ABSTRACT

Context. Optical observations of pulsars are crucial to study the neutron star properties, from the structure and composition of the interior, to the properties and geometry of the magnetosphere. Historically, X and γ-ray observations have paved the way to the pulsar optical identifications. The launch of the Fermi Gamma-ray Space Telescope opened new perspectives in the optical-to-γ-ray studies of neutron stars, with the detection of more than 80 γ-ray pulsars.

Aims. Here, we aim to search for optical emission from two Fermi pulsars which are interesting targets on the basis of their spin-down age, energetics, and distance. PSR J1357—6429 is a Vela-like pulsar (P = 166.1 ms; τ = 7.31 kyr), at a distance of ∼ 2.4 kpc, with a rotational energy loss rate of ∼ 3 × 10^34 erg s^-1. PSR J1048—5832 is also a Vela-like (P=123.6 ms; τ = 20.3 kyr) pulsar at a distance of ∼ 2.7 kpc and with a ∼ 2 × 10^36 erg s^-1. The two pulsars and their pulsar wind nebulae (PWNe) are also detected in X-rays by Chandra and XMM-Newton.

Methods. No deep optical observations of these two pulsars have been reported so far. We used multi-band optical images (V, R, I) taken with the Very Large Telescope (VLT) and available in the European Southern Observatory (ESO) archive to search for, or put tight constraints to, their optical emission.

Results. We re-assessed the positions of the two pulsars from the analyses of all the available Chandra observations and the comparison with the published radio coordinates. For PSR J1357—6429, this yielded a tentative proper motion μ ≈ 0′′.17 ± 0′′.055 yr^-1 (70′′ ± 15′′ position angle). We did not detect candidate counterparts to PSR J1357—6429 and PSR J1048—5832 down to V ~ 26.6 and R ~ 26.6, respectively, although for the former we found a possible evidence for a faint, unresolved object at the Chandra position. Our limits imply an efficiency in converting spin-down power into optical luminosity ≤ 7 × 10^-7 and ≤ 6 × 10^-6, respectively, possibly close to that of the Vela pulsar.

Conclusions. Observations with the Hubble Space Telescope (HST) are required to identify PSR J1357—6429 against nearby field stars. Due to the large extinction (A_V ~ 5) and the presence of a molecular cloud complex, near-infrared observations of PSR J1048—5832 are better suited to spot its candidate counterpart.

Key words. Optical: stars; neutron stars: individual: PSR J1357—6429, PSR J1048—5832

1. Introduction

Optical observations of rotation-powered pulsars are important to complete the picture of their multi-wavelength phenomenology and play a major role in studying the intrinsic properties of neutron stars, from the interior structure and composition, to the atmosphere and magnetosphere properties, as well as in understanding their formation and evolution (see, e.g. Mignani 2010a,b).

More than 40 years have gone by since the optical identification of the Crab pulsar. Since then, only 10 pulsars have been firmly identified in the optical (Mignani 2009a; 2011), mostly with the Hubble Space Telescope (HST) and the telescopes of the European Southern Observatory (ESO), like the Very Large Telescope (VLT), which have played a fundamental role in pulsar optical astronomy (Mignani 2010c; 2009b). Together with those in the radio band, high-energy observations play a pivotal role in
paving the way to the optical identification of pulsars. In particular, 5 out of the 7 γ-ray pulsars detected by NASA’s Compton Gamma-ray Observatory (CGRO) satellite (see, e.g. Thompson 2008) have also been detected in the optical, suggesting that γ-ray detections indicate promising candidates for optical observations, since the emission at both energies seems to correlate with the strength of the magnetic field at the light cylinder (Shearer & Golden 2001; Shearer et al. 2010). The launch of NASA’s Fermi Gamma-ray Space Telescope in June 2008 represents a revolution in γ-ray observations of pulsars. The Large Area Telescope (LAT; Atwood et al. 2009) has detected more than 80 γ-ray pulsars (Ray & Saz-Parkinson 2010; Caraveo 2010). While in the X-rays systematic observations of Fermi pulsars are performed (e.g., Marelli et al. 2011), for most of them no deep optical observations have been carried out so far (Mignani et al. in preparation). An exploratory survey in the Northern hemisphere has been carried out with 2.5m/4m-class telescopes at the La Palma Observatory but no pulsar has been detected down to V ≈ 23–26 (Shearer et al. 2011, in preparation), while in the Southern hemisphere a dedicated survey with the VLT is in progress (Mignani et al. 2011). In addition, VLT observations of three Fermi pulsars, PSR J1357−6429, PSR J1048−5832, and the m binary pulsar PSR J0613−0200 (Abdo et al. 2010) are available in the public ESO archive. Unfortunately, for the last one an incorrect windowing of the detector cut the pulsar position out of the field-of-view.

PSR J1357−6429 is a young (τ ~ 7.3 kyr) Vela-like pulsar discovered in radio (Camilo et al. 2004) during the 1347 MHz Parkes multi-beam survey of the galactic plane. Its period (P = 166.1 ns) and period derivative (˙P = 3.60 × 10^{-13}s^{-1}) yield a rotational energy loss rate Ė ~ 3.1 × 10^{36}ergs^{-1} and a magnetic field B = 7.83 × 10^{12}G. The pulsar dispersion measure (DM = 127.2 ± 0.5 cm^{-3}pc; Camilo et al. 2004) yields a distance of 2.4 ± 0.6 kpc, according to the NE2001 Galactic electron density models of Cordes & Lazio (2002). X-ray emission at 2–10 keV from PSR J1357−6429 has been discovered by our group (Esposito et al. 2007) from Chandra and XMM-Newton observations. The pulsar X-ray emission appeared point-like, with no obvious evidence of a pulsar wind nebula (PWN). No pulsations were detected down to a 3σ upper limit of 30% on the pulsed fraction (2–10 keV). However, based on the same Chandra and XMM-Newton data sets Zavlin (2007) claimed evidence of a compact PWN and of X-ray pulsations, both of which are now confirmed by new Chandra and XMM-Newton observations (Lemoine-Goumard et al. 2011; Chang et al. 2011). PSR J1357−6429 has been possibly detected as a γ-ray pulsar at ≳ 100 MeV by the Astrorivelatore Gamma ad Immaginii LEGgero (AGILE) with a detection significance of 4.7σ (Pelizzoni et al. 2009). Recently, it has also been detected by Fermi (Lemoine-Goumard et al. 2011), while its associated pulsar wind nebula (PWN) has been detected at TeV energies by HESS (Abramowski et al. 2011). PSR J1048−5832 is also a young (20.3 kyr), Vela-like radio pulsar, discovered during a 1420 MHz radio survey of the galactic plane (Johnston et al. 1992). The pulsar period (P = 123.6 ms) and period derivative (˙P = 9.63 × 10^{-14}s^{-1}) yield a rotational energy loss rate Ė ~ 2 × 10^{36}ergs^{-1} and a magnetic field B = 3.49 × 10^{12} G. The DM (129 ± 0.1 cm^{-3}pc; Wang et al. 2001) puts the pulsar at a distance of 2.7 ± 0.35 kpc. In the X-rays, PSR J1048−5832 was observed with the Röntgen Satellite (ROSAT) at 0.1–2.4 keV (Becker & Trümper 1997) and, soon after, with the Advanced Satellite for Cosmolgy and Astrophysics (ASCA) by Pivovaroff et al. (2000), who found possible evidence of extended X-ray emission associated with a PWN. More recent observations with Chandra (Gonzalez et al. 2006) confirmed the existence of the PWN although they failed to detect pulsed X-ray emission, with a conservative 3σ upper limit of 53% on the pulsed fraction (0.5–10.0 keV). In γ-rays, PSR J1048−5832 was associated with the source 3EG J1048−5048 (Kaspi et al. 2000), detected by the EGRET instrument aboard CGRO, both on the basis of a spatial coincidence with the γ-ray source error box and of the tentative detection of γ-ray pulsations. Recently, these were clearly detected at ≥ 0.1 GeV by Fermi (Abdo et al. 2009), with a double-peaked light-curve.

Here, we report on the results of an archival VLT survey for Fermi pulsars. This paper is organised as follows: observations, data reduction and analysis are described in Sect. 2, while results are presented and discussed in Sect. 3 and 4, respectively. Conclusions follow.

2. Observations and data reduction

2.1. Observation description

Optical images of the PSR J1357−6429 and PSR J1048−5832 fields were obtained with the VLT Antu telescope at the ESO Paranal observatory between April 2009 and February 2010 (see Tab. 1 for a summary of the observations) and are available in the public ESO archive 1. Observations were performed in service mode with the FOcal Reducer/low dispersion Spectrograph (FORS2; Appenzeller et al. 1998), a multi-mode camera for imaging and long-slit/multi-object spectroscopy (MOS). FORS2 was equipped with its red-sensitive MIT detector, a mosaic of two 2k × 4k CCDs optimised for wavelengths longer than 6000 Å. In its standard resolution mode, the detector has a pixel size of 0”25 (2 × 2 binning) which corresponds to a projected field-of-view of 8”3 × 8”3 over the CCD mosaic. However, due to vignetting, the effective sky coverage of the two detectors is smaller than the projected detector field-of-view and it is larger for the upper CCD chip. Observations were performed with the standard low gain, fast read-out mode and in high-resolution mode (0”125/pixel) for PSR J1357−6429 and in standard resolution mode (0”25/pixel) for PSR J1048−5832. In both cases, the target was positioned in

1 www.eso.org/archive
Table 1. Summary of the available pulsar observations, reporting the exposure times in s (T), the number of exposures (N), the average airmass sec(z) during the sequence of N exposures, the associated average image quality (IQ), and its rms (in parentheses).

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>Date</th>
<th>Filter</th>
<th>T (s)</th>
<th>N</th>
<th>sec(z)</th>
<th>IQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR J1357−6429</td>
<td>2009-04-04</td>
<td>vHIGH</td>
<td>580</td>
<td>5</td>
<td>1.35</td>
<td>0.62 (0.03)</td>
</tr>
<tr>
<td></td>
<td>2009-04-04</td>
<td>R_SPEC</td>
<td>580</td>
<td>5</td>
<td>1.44</td>
<td>0.58 (0.03)</td>
</tr>
<tr>
<td></td>
<td>2009-04-22</td>
<td>vHIGH</td>
<td>590</td>
<td>20</td>
<td>1.35</td>
<td>0.65 (0.03)</td>
</tr>
<tr>
<td></td>
<td>2009-04-24</td>
<td>R_SPEC</td>
<td>590</td>
<td>10</td>
<td>1.35</td>
<td>0.59 (0.04)</td>
</tr>
<tr>
<td></td>
<td>2009-04-25</td>
<td>I_BESS</td>
<td>200</td>
<td>8</td>
<td>1.31</td>
<td>0.57 (0.04)</td>
</tr>
<tr>
<td>PSR J1048−5832</td>
<td>2010-01-11</td>
<td>vHIGH</td>
<td>750</td>
<td>4</td>
<td>1.21</td>
<td>0.69 (0.04)</td>
</tr>
<tr>
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<td>2010-01-13</td>
<td>vHIGH</td>
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<td>8</td>
<td>1.23</td>
<td>0.56 (0.03)</td>
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<tr>
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<td>750</td>
<td>4</td>
<td>1.21</td>
<td>0.79 (0.04)</td>
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<td>1.22</td>
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</tbody>
</table>

the upper CCD chip. For PSR J1357−6429, bright stars close to the pulsar position have been masked using the FORS2 MOS slitlets as occuling bars. Different filters were used: vHIGH (λ = 5570 Å; Δλ = 1235 Å), R_SPEC (λ = 6550 Å; Δλ = 1650 Å), and I_BESS (λ = 7680 Å; Δλ = 1380 Å). To allow for cosmic ray removal and minimise saturation of bright stars in the field, sequences of short exposures (from 200 to 750 s) were obtained per each target and per each filter. The total integration time was 14700 s (vHIGH), 8800 s (R_SPEC), and 1600 s (I_BESS) for PSR J1357−6429 and of 24000 s (vHIGH) for PSR J1048−5832. Exposures were taken in dark time and under photometric conditions, with an airmass mostly below 1.3 and sub-arcsecond image quality, as measured directly on the images by fitting the full-width at half maximum (FWHM) of unsaturated field stars.

2.2. Data reduction and astrometry

We reduced the data through standard packages in IRAF for bias subtraction, and flat-field correction using the closest-in-time bias and twilight flat-fields frames available in the ESO archive. Per each band, we aligned and averaged the processed science images using the IRAF task drizzle applying a 3σ filter on the single pixel average to filter out residual hot and cold pixels and cosmic ray hits. Since all exposures have been taken with sub-arcsec image quality, we did not apply any selection prior to the image stacking. We applied the photometric calibration by using the extinction-corrected night zero points computed by the FORS2 pipeline and available through the instrument data quality control database. To register the pulsar positions on the FORS2 frames as precisely as possible, we re-computed their astrometric solution which is, by default, based on the coordinates of the guide star used for the telescope pointing. Since most stars from the Guide Star Catalogue 2 (GSC-2; Lasker et al. 2008) are saturated in the stacked images, we used shorter exposures (10−15 s) of the fields taken with the same instrument configurations as those in Tab. 1 and available in the VLT archive. We measured the star centroids through Gaussian fitting using the Graphical Astronomy and Image Analysis (GAIA) tool4 and used the code ASTROM5 to compute the pixel-to-sky coordinate transformation through an high-order polynomial, which accounts for the CCD distortions. For both pulsar fields, the rms of the astrometric fits was σr ∼ 0′′1 in the radial direction. To this value we added in quadrature the uncertainty σr = 0′′1 of the registration of the FORS2 image on the GSC2 reference frames, σr = (3/Na)σGSC2, where σGSC2 = 0′′3 is the mean positional error of the GSC2 coordinates and Na is the number of stars used to compute the astrometric solution (Lattanzi et al. 1997). After accounting for the ∼ 0′′15 accuracy of the link of the GSC2 coordinates to the International Celestial Reference Frame (ICRF), we thus estimate that the overall (1σ) uncertainty of our FORS2 astrometry is δr ∼ 0′′2.

2.3. The problem of position: radio vs. X-rays

As a reference for our astrometry, we started from the most recently published radio positions of the two pulsars. Moreover, they both have precise X-ray positions obtained with Chandra. The published radio and X-ray coordinates of PSR J1357−6429 and PSR J1048−5832 are summarised in Table 2. We note that the Chandra position of PSR J1357−6429 (Zavlin 2007) is quite different from that derived from the radio-interferometry observations performed with the Australia Telescope Compact Array (ATCA) by Camilo et al. (2004). Since this apparent inconsistency hampers the correct pulsar localisation on

4 See star-www.dur.ac.uk/~pdraper/gaia/gaia.html
5 www.starlink.rl.ac.uk/star/docs/sun5.htx/sun5.html
the FORS2 images, hence the search for its optical counterpart, we independently checked all the available sets of coordinates. For PSR J1357–6429, multiple Chandra observations are available. Thus, we could use them to check the internal consistency of the Chandra astrometry. Firstly, we re-computed the X-ray position from the analysis of the two, independent Chandra/HRC observations (Esposito et al. 2007; Zavlin 2007) and we found values consistent with that published in Zavlin (2007). The pulsar has been recently observed also with the ACIS instrument (OBS-ID=10880; MJD=55112.28). We downloaded the data from the public Chandra archive and we found that the pulsar coordinates are also consistent, within the nominal Chandra position uncertainty of 0′′6 (90% confidence level), with those obtained with the HRC. We then averaged the three sets of coordinates, which yields: α = 13h57m02.60 and δ = −64°29′29″.80 with a radial error of ∼0″.38. This implies a difference of 1″.23 ± 0″.4 between the Chandra and radio-interferometry position. Then, we verified the Chandra absolute astrometry by matching the positions of serendipitous X-ray sources detected in the Chandra/ACIS image with those of their putative counterparts detected in the 2MASS catalogue (Skrutskie et al. 2006). Since the accuracy of the Chandra astrometry rapidly degrades at large off-axis angles, we restricted our search to within 4′ from the centre of the ACIS field-of-view. In particular, we found 2MASS matches for 4 X-ray sources in the PSR J1357–6429 field. Although the uncertainty on the computed bore-sight correction does not yield any significant improvement on the absolute Chandra astrometry, the source match does not show evidence of possible offsets between the optical and X-ray reference frames (both tied to the ICRF). Thus, we conclude that the Chandra coordinates are not affected by systematics. Similarly, we verified the published radio-interferometry position of PSR J1357–6429 against the radio-timing position obtained through more recent observations performed by the Fermi Pulsar Timing Consortium (Smith et al. 2008) and we found that they are consistent, although the latter is probably affected by the pulsar timing noise and has a much larger uncertainty.

In principle, the observed difference between the Chandra and the radio-interferometry positions of PSR J1357–6429 can be, at least partially, due to its yet unknown proper motion. The time span between the epochs of the Chandra and the ATCA observations is ∼7.17 yrs. This would imply a proper motion μ = 0′.17 ± 0′.055 yr−1 along a position angle θ = 70° ± 15°. We note that the Chandra observations of PSR J1357–6429 are distributed over a time span of ∼3.9 yrs. Then, for the assumed single-epoch Chandra radial position uncertainty of 0′′.6, they would be sensitive only to a proper motion of ≥0′′.55 yr−1 (3σ), i.e. larger than inferred from the comparison between the average Chandra position and the radio one. At the DM distance of ∼2.4 kpc, the inferred proper motion would imply a transverse velocities of 2100±700 km s−1. This value is high but, after accounting for the associated uncertainty, it is not unheard of for a neutron star, as shown by the Guitar Nebula pulsar PSR B2224+65, whose transverse velocity could be as high as 1600 km s−1 (e.g., Chatterjee & Cordes 2004). Thus, the computed difference between the Chandra and radio positions of PSR J1357–6429 might, indeed, result in its first proper motion measurement. A similar case is that of the pulsar PSR J1018–1431, for which the comparison between its Chandra and ATCA radio-interferometry positions also yielded a first evidence of a 3σ proper motion (Pavlov et al. 2009), soon after confirmed by VLBI observations (Deller et al. 2009). As in that case, future radio-interferometry observations will be crucial to confirm our tentative proper motion measurement of PSR J1357–6429.

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(1) Camilo et al. (2004); (2) Zavlin (2007); (3) This work; (4) Wang et al. (2000); (5) Stappers et al. (1999); (6) Gonzalez et al. (2006)
that obtained by the Fermi Pulsar Timing Consortium and we found no obvious difference. The time span between the epochs of the Chandra and the radio-timing observations of PSR J1048–5832 is ~ 5.39 yrs, which would imply a proper motion of 0.76±0.24 yr⁻¹. At the DM distance of ~ 2.7 kpc, this corresponds to a transverse velocity of 10250±3250 km s⁻¹, which is much larger than the most extreme values derived from the known radio pulsar velocity distribution (e.g., Hobbs et al. 2005). Thus, the apparent inconsistency between the Chandra and radio-timing positions cannot be explained by the pulsar proper motion, but by a genuine difference in the astrometry of either of the two observations. In this respect, we note that the radio-timing position of Wang et al. (2000) is also inconsistent with the radio-interferometry one of Stappers et al. (1999), which suggests that the former might be affected by systematics and has to be taken with caution. Indeed, such an inconsistency was also noted by Wang et al. (2000) who attributed it to the effect of timing noise following period irregularities after a glitch. We note that if we assume the radio-interferometry position of PSR J1048–5832 as a first-epoch reference, the more recent Chandra position would imply a proper motion μ ≲ 0.138 yr⁻¹ (1σ) along an unconstrained position angle.

Although the origin of the inconsistency between the Chandra and radio positions of the two pulsars is still debatable, and addressing it fully is beyond the goals of this work, we tend to favour the former and more recent ones. Thus, in the following we assume them as a reference. However, not to overlook any potential candidate counterpart, we also prudently evaluate any object detected in the VLT images at, or close to, the radio positions of the two pulsars.

3. Data analysis and results

The computed positions of PSR J1357–6429 and PSR J1048–5832 are shown in Fig. 1, overlaid on the stacked V-band FORS2 images of the two pulsars. The overall uncertainties on the pulsar positions account for the absolute error on the reference Chandra and radio coordinates (Table 2) and the accuracy of our astrometry recalibration of the FORS2 images (0.′2). However, to conservatively account for the unknown pulsar proper motions, in the following we extended our search radius up to 3 times the estimated 1σ uncertainties.

3.1. PSR J1357–6429

The radio position of PSR J1357–6429 (Fig. 1, left panel) falls at ~ 0.′65 from that of a relatively bright field star (Star A; V = 21.8 ± 0.06), i.e. at an angular distance equal to the ~ 2–3 σ radio position uncertainty. To quantitatively assess the significance of the association, we estimated the chance coincidence probability that an unrelated field object falls within a radius of 0.′65 from the computed pulsar radio position. This probability can be computed as P = 1 − exp(−πσ²), where μ is the measured object density in the FORS2 upper CCD field-of-view (accounting for areas affected by vignetting and the areas masked by the occultation bars, see Sect. 2.1) and r is the matching radius (0.′65). The density of star-like objects (ellipticity e < 0.2) with magnitude V ~ 22 in the field-of-view is μ ~ 0.005/sq. arcsec. This yields an estimated chance coincidence probability P ~ 9 × 10⁻³, not statistically compelling yet.

In order to qualitatively verify the reliability of such an association, we compared the brightness of Star A with that expected from the pulsar, PSR J1357–6429 has a rotational energy loss $\dot{E} = 3.1 \times 10^{36}$ erg s⁻¹. If we assume an efficiency in converting spin-down power into optical luminosity $\eta_{\text{opt}} \equiv \frac{L_{\text{opt}}}{\dot{E}}$ comparable to that of, e.g. the ~ 11 kyr old Vela pulsar, we would expect an optical luminosity for PSR J1357–6429 lower by only a factor of ~ 2, after scaling for the Vela rotational energy loss ($\dot{E} \sim 6.9 \times 10^{36}$ erg s⁻¹). At the PSR J1357–6429 distance (2.4 ± 0.6 kpc) and for the corresponding interstellar extinction (A_V = 2.5±1.7), computed from the $N_H = 0.4^{+0.3}_{-0.2} \times 10^{22}$ cm⁻² obtained from the spectral fits to the XMM-Newton spectrum (Esposito et al. 2007) using the relation of Predehl & Schmitt (1995) and the extinction coefficients of Fitzpatrick (1999), we then derive an expected magnitude in the range V ~ 29.5–33.4, accounting for both the distance and interstellar extinction uncertainties. Obviously, these values are not within reach for any current 10m-class telescope. On the other hand, if PSR J1357–6429 had an efficiency comparable to that of the younger (τ ~ 1 kyr) and more energetic ($\dot{E} \sim 4.6 \times 10^{38}$ erg s⁻¹) Crab pulsar, the same scaling as above would yield an expected magnitude of V ~ 21.1–24.9. Thus, if Star A were the pulsar’s optical counterpart, PSR J1357–6429 would have an emission efficiency either comparable or up to ~ 15 times larger than the Crab. Thus, the association would not be impossible, in principle, at least based on the pulsar’s energetics and an assumed Crab-like optical emission efficiency. However, we note that pulsar optical emission efficiencies have been computed for less than 10 objects and their dependance on the pulsar parameters, such as their spin-down age, is yet unclear. Therefore, we followed an independent approach to estimate the expected pulsar’s brightness using as a reference the relation between the non-thermal X-ray and optical luminosities measured for pulsars with identified X-ray/optical counterparts (e.g., Zharikov et al. 2004; 2006). In this case, taking into account the rather large uncertainty affecting this relation, as well as the uncertainty on the X-ray spectral parameters of PSR J1357–6429 (Esposito et al. 2007), hence on the non-thermal X-ray luminosity, we end up with an expected magnitude in the range V ~ 26.2–31.2, i.e. much fainter than that of star A. As a further test, we also compared the colours of Star A (V = 21.80±0.06; R = 20.65±0.03; I = 19.75±0.03) with those of field stars, as measured on the short exposures to avoid problems in background subtraction for stars close to the occulting bars, saturation problems, and to homo-
Fig. 1. VLT/FORS2 observations of PSR J1357−6429 (left) and PSR J1048−5832 (right) taken in the \(v_{\text{HIGH}}\) filter, with integration times of 14700 and 24000 s, respectively. North to the top, East to the left. Image cutouts are 30\('\)\(''\) \(\times\) 30\('\)\(''\) in size. The circles marks the pulsar radio (T=timing; I=interferometric) and Chandra positions derived according to our astrometry re-calibration (Sect 2.2). Their radius account for the absolute error on the reference X-ray/radio coordinates (Table 2) and the accuracy of our optical astrometry (0.2\('\)\(''\)). The radius of the error circles is \(\sim 0.43\) and \(\sim 0.25\) for the Chandra and radio-interferometry coordinates of PSR J1357−6429, respectively, and \(\sim 1.58\), \(\sim 0.22\), and \(\sim 1.22\), for the Chandra, radio-interferometry, and radio-timing coordinates of PSR J1048−5832, respectively. The white areas in the left panel correspond to the edges of the occulting bars used in the FORS2 frame to mask bright stars close to the pulsar position. The clumpy white structure in the right panel is part of an extended nebula detected in the PSR J1048−5832 field (see Sect. 3.2). In both panels, the square (10\('\)\(''\) \(\times\) 10\('\)\(''\)) corresponds to the area shown in Fig. 3.

genevously cover the unmasked FORS2 field–of–view. The two \(V-(V-R)\) and \(V-(V-I)\) colour-magnitude diagrams (CMDs) are shown in Fig. 2. As seen, the location of Star A in both CMDs is along the sequence of field stars, implying that it has no peculiar colours and that its association with the pulsar is unlikely. For instance, for a flat power-law spectrum \(F_\nu \propto \nu^{-\alpha}\), like that of, e.g. the Vela pulsar (Mignani et al. 2007), we would expect a \((V-R) \approx 0.2\) and a \((V-I) \approx 0.1\), once accounting for the interstellar extinction towards PSR J1357−6429, which are obviously off the main sequence in both CMDs. Thus, on the basis of the comparison with the optical emission efficiency of pulsars with known optical counterparts, their relative X-ray–to–optical brightness, and the colours of Star A, we consider it unlikely that it is the pulsar’s counterpart.

We then searched for possible counterparts at our revised Chandra position. We note that this overlaps with an apparent enhancement over the sky background noticed in the co-added I-band image (Fig. 3, left). However, it is difficult to determine whether such an enhancement is due to a background fluctuation, perhaps produced by the superposition of the PSF wings of the two adjacent stars detected southwest (Star A) and northeast (Star B) of the Chandra position and of the bright masked star southeast of them, or it is associated with a real source. Unfortunately, the difficulties in the PSF subtraction of the two stars, with Star A possible blended with a fainter star and Star B at the edge of occulting bar and partially blended with a bright star, do not allow us to better resolve the background enhancement. If associated with a point source, such an enhancement would correspond to a magnitude \(I \approx 24.6\). Interestingly enough, such an enhancement is recognisable only in the I-band image and not in the longer-integration \(R\) and \(V\)-band ones. This would suggest that either it is not associated with a real object or, if it is, that the object’s spectrum is either quite red and/or affected by an interstellar extinction probably larger than measured in the pulsar’s direction. To verify the presence of an object at the Chandra position, we inspected the single I-band images. However, their short integration time (200 s) makes it difficult to recognise any obvious systematic flux enhancement at the expected location. We also smoothed the images using a Gaussian filter over 3 \(\times\) 3 pixel cells, but this did not yield to a clearer detection. Thus, it is difficult to prove that the background enhancement seen at the pulsar Chandra position in the
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Fig. 2. Observed (not extinction-corrected) colour-magnitude diagrams of all the objects detected in the PSR J1357–6429 field. The two objects detected closest to the radio (Star A) and Chandra (Star B) pulsar positions (Fig. 1) are marked in red, with magnitudes $V = 21.8 \pm 0.06$ and $V = 23.05 \pm 0.13$, respectively. The photometry errors are purely statistical and do not account for the systematic uncertainties on the absolute flux calibrations.

$I$-band image is unambiguously associated with a real object. Higher spatial resolution observations with the HST would be crucial to resolve this putative object against the noisy background produced by the PSF of Stars A and B and confirm it as a candidate optical counterpart to PSR J1357–6429.

No other possible counterpart is detected within the computed pulsar Chandra error circle (Fig.3, left). Star B is at $\sim 1''4$, i.e. $\approx 3\sigma$ from the best-estimate Chandra position. Moreover, both its fluxes ($V = 23.05 \pm 0.13; R = 21.86 \pm 0.07; I = 20.5 \pm 0.05$) and colours (Fig. 2) are comparable with those of Star A, already ruled out as a candidate counterpart (see above). Thus, assuming that PSR J1357–6429 is not detected in the FORS2 images we computed the pulsar flux upper limits in the $VRI$ bands. Following a standard approach (e.g., Newberry 1991), we determined the number of counts corresponding to a $3\sigma$ detection limit in a photometry aperture of $1''$ diameter (8 pixels) from the standard deviation of the background sampled within the Chandra error circle. After applying the aperture correction, computed from the measured PSF of a number of relatively bright but unsaturated stars in the field, we then derived $3\sigma$ upper limits of $V \sim 27$ and $R \sim 26.8$ at the Chandra position, while in the $I$ band we conservatively assumed a flux of $I \approx 24.6$ measured above as our upper limit estimate.

3.2. PSR J1048–5832

The field of PSR J1048–5832 shows large extended structures where both the sky brightness and the star density are much lower then in the rest of the field. These structures are present in the single FORS2 raw frames taken days apart so that they are not an artefact due to, e.g., an incorrect flat fielding or to the unreported presence of clouds at the moment of the observations. We have checked the $R$-band images of the Digitised Sky Survey (DSS) and we found that the same structures are visible with the same extent and position as seen in the FORS2 images, which proves that they are real and not due to any instrumental or atmospheric effects. We used the DSS to investigate the presence of such structures on scales as large as $40' \times 40'$ and we found that they apparently connected to other similar structures extending on a sort of regular pattern. We have also checked the 2MASS $JHK$-band images which, instead, do not show either evidence of such structures or of under-density of stars at their expected locations. Thus, we conclude that they are most likely dense molecular clouds along the plane of the Milky Way, possibly part of the CH$_3$OH maser associations in nearby star-forming regions (e.g. Goedhart et al. 2004).

Although no counterpart to PSR J1048–5832 has been yet proposed in the literature, we note that an observing program

7 Confirming the detection of a Fermi gamma-ray pulsar in the optical, PI Sollerman, 386.D-0585(A).
date counterpart, presumably in the same data set used in this work. This prompted us to prudently screen each object detected close to the published positions of PSR J1048−5832. In particular, we note that its radio-timing position (Fig. 1, right panel) falls close to a $V \sim 24$ object (Star C), even detected in the short 15s exposures used for the image astrometry, right on the edge of the radio error circle ($\sim 1''22$). Again, based on position alone we can not rule out that Star C is associated with the pulsar. However, the probability of chance coincidence with field objects of magnitude $V \gtrsim 24$ is $P \sim 0.04$, i.e. certainly not low enough to statistically claim an association. In addition, such an association is problematic from the point of view of the pulsar's energetics. As done in Sect. 3.1, we compared the brightness of Star C with that expected for the pulsar. By assuming an optical efficiency comparable to that of the Vela pulsar, PSR J1048−5832's rotational energy loss ($E \sim 2 \times 10^{36}$ erg s$^{-1}$) would then imply only a factor of $\sim 3$ lower optical luminosity. Following the same analysis as for PSR J1357−6429 (see Sectn. 3.1), at the PSR J1048−5832 distance (2.7±0.35 kpc) and for the corresponding interstellar extinction ($A_V = 5_{-1.1}^{+2.2}$), derived from the $N_H = 0.9_{-0.2}^{+0.4} \times 10^{22}$ cm$^{-2}$ (Marelli et al. 2011), we determine an expected magnitude $V \sim 33.3-37$, accounting for both the distance and interstellar extinction uncertainties. Similarly, assuming more optimistically an emission efficiency comparable to that of the Crab pulsar, we derive an expected magnitude of $V \sim 25-28.7$. This means that, if Star C were indeed the PSR J1048−5832 optical counterpart, the pulsar should have an emission efficiency $\sim 2-80$ times larger than the Crab. On the other hand, by using the relation between the X-ray and optical luminosity (Zharikov et al. 2004; 2006) as done in Sectn. 3.1, we obtain a magnitude in the range $V \sim 29-34$. Thus, Star C cannot be the pulsar optical counterpart.

Then, we searched for a possible counterpart at the pulsar Chandra position. No object is detected within, or close to, the Chandra (0''55) error circle apart from a faint object (Star D; $V \sim 26.7$) visible $\sim 1''6$ southwest of it (Fig. 3, right). However, the offset is about 3 times the 1$\sigma$ uncertainty on the pulsar position. Thus, we deem the association unlikely both on the basis of the loose positional coincidence and on statistical grounds, with a chance coincidence probability $P \sim 0.08$. Moreover, the lack of colour information makes it impossible to constrain the nature of this object. Therefore, we conclude that PSR J1048−5832 is not detected in the FORS2 image.

Following the same procedure as used in Sect. 3.1, we determined the number of counts corresponding to a 3$\sigma$ detection limit in a 1'' photometry aperture (4 pixel) from the standard deviation of the background sampled within the Chandra error circle. After applying the aperture correction, this yield to a 3$\sigma$ detection limit of $V \sim 27.6$.

### 3.3. Search for the optical PWNe

In order to verify the possible presence of PWNe in the optical, we have over plotted the X-ray contours of
Fig. 4. Zooms of the PSR J1357−6429 (left) and PSR J1048−5832 (right) FORS2 V-band images. The blue contours correspond to the isophotes underlying the structure of the PWNe observed by Chandra in the 0.5–4 keV range. In both cases, a smoothing with a Gaussian kernel of 1″ has been applied. The contours have logarithmic spacing, with a factor of 2 step in surface brightness.

Fig. 4. Corresponds to the isophotes underlying the structure of the PWNe observed by Chandra in the 0.5–4 keV range. In the case of PSR J1357−6429, any upper limit of the optical surface brightness of the PWN is hampered by the covered area.

4. Discussion

We compared our optical flux upper limits in the V band with the pulsars’ rotational energy loss rates. For PSR J1357−6429, our upper limit of $V \sim 27$ corresponds to an optical luminosity upper limit $L_{\text{opt}} \sim 0.6\text{–}21.6 \times 10^{29}$ erg s$^{-1}$, for a distance $d = 2.4 \pm 0.6$ kpc and for an interstellar extinction $A_V = 2.2^{+1.7}_{-1}$, after accounting for their associated uncertainties. This implies an emission efficiency upper limit $\eta_{\text{opt}} \sim 0.2\text{–}7 \times 10^{-7}$. This value is at least a factor of 5 lower than the Crab pulsar and, possibly, closer to that of the Vela pulsar. On the other hand, for PSR J1048−5832 our upper limit of $V \sim 27.6$ implies (for $d = 2.7 \pm 0.35$ kpc and $A_V = 5^{+2.2}_{-1}$) upper limits of $L_{\text{opt}} \sim 0.4\text{–}12.5 \times 10^{30}$ erg s$^{-1}$ and $\eta_{\text{opt}} \sim 1.8\text{–}62.5 \times 10^{-7}$. In principle, this does not rule out an optical emission efficiency comparable to that of the Crab pulsar, although the pulsar spin-down age (20.3 kyr) might suggest, also in this case, a Vela-like emission efficiency. An optical emission efficiency $\eta_{\text{opt}} \lesssim 10^{-7}\text{–}10^{-6}$ has been measured also from the upper limit on the optical emission of PSR B1706−44, the only other Vela-like pulsar for which VLT observations are available (e.g. Mignani et al. 1999). This would confirm that Vela-like pulsars are intrinsically less efficient emitters in the optical than Crab-like pulsars, possibly even less efficient than middle-aged and old pulsars, like PSR B0656+14, Geminga, PSR B1055−52, PSR B1929+10, and PSR B0950+08. The measurement of such a low emission efficiency in the optical band for Vela-like pulsars...
Upper limits on the extinction-corrected optical fluxes of PSR J1357–6429 (left) and PSR J1048–5832 (right) compared with the low-energy extrapolations of the X-ray (solid black) and γ-ray (solid blue) spectral models which best fit the XMM-Newton, Chandra (Esposito et al. 2007; Marelli et al. 2011), and Fermi (Lemoine-Goumard et al. 2011; Abdo et al. 2009) data. The plotted optical flux upper limits are corrected for interstellar extinction based upon the best-fit value of the \( N_H \). The dotted lines in the left panel correspond to the PL and BB components to the model X-ray spectrum. In both panels, the yellow and blue-shaded areas (left to right) indicate the 1σ uncertainty on the extrapolations of the X and γ-ray PLs, respectively. The vertical red dashed lines mark the uncertainty on the extinction-corrected optical flux upper limits, computed around the best-fit value of the \( N_H \). For PSR J1357–6429, we neglected the uncertainties on the extrapolation of the BB component, whose contribution in the optical band is negligible.

Fig. 5. Upper limits on the extinction-corrected optical fluxes of PSR J1357–6429 (left) and PSR J1048–5832 (right) compared with the low-energy extrapolations of the X-ray (solid black) and γ-ray (solid blue) spectral models which best fit the XMM-Newton, Chandra (Esposito et al. 2007; Marelli et al. 2011), and Fermi (Lemoine-Goumard et al. 2011; Abdo et al. 2009) data. The plotted optical flux upper limits are corrected for interstellar extinction based upon the best-fit value of the \( N_H \). The dotted lines in the left panel correspond to the PL and BB components to the model X-ray spectrum. In both panels, the yellow and blue-shaded areas (left to right) indicate the 1σ uncertainty on the extrapolations of the X and γ-ray PLs, respectively. The vertical red dashed lines mark the uncertainty on the extinction-corrected optical flux upper limits, computed around the best-fit value of the \( N_H \). For PSR J1357–6429, we neglected the uncertainties on the extrapolation of the BB component, whose contribution in the optical band is negligible.

We compared the flux upper limits of PSR J1357–6429 and PSR J1048–5832 with the extrapolations in the optical domain of the X and γ-ray spectra. For PSR J1357–6429, we assumed the X-ray spectral model of Esposito et al. (2007), a power-law (PL) with photon index \( \Gamma_X = 1.4 \pm 0.5 \) plus a blackbody (BB) with temperature \( kT = 0.16^{+0.09}_{-0.04} \) keV (\( N_H = 0.4^{+0.3}_{-0.2} \times 10^{22} \) cm\(^{-2}\)), and the γ-ray spectral model of Lemoine-Goumard et al. (2011), a PL with photon index \( \Gamma_\gamma = 1.54 \pm 0.41 \) and exponential cut-off at \( \sim 0.8 \) GeV. For PSR J1048–5832, we assumed the X-ray spectral model of Marelli et al. (2011), a PL with photon index \( \Gamma_X = 2.4 \pm 0.5 \) (\( N_H = 0.9^{+0.4}_{-0.2} \times 10^{22} \) cm\(^{-2}\)), and the γ-ray spectral model of Abdo et al. (2009), a PL with photon index \( \Gamma_\gamma = 1.38 \pm 0.13 \) and exponential cut-off at \( \sim 2.3 \) GeV. Our optical flux upper limits are corrected for interstellar extinction based upon the \( N_H \) derived from the fit to the X-ray spectra. The multi-wavelength spectral energy distributions (SEDs) of the two pulsars are shown in Fig. 5, where we accounted for both the 1σ uncertainty on the extrapolations of the X and γ-ray PL and the uncertainty on the extinction-corrected flux upper limits. In the case of PSR J1357–6429 (Fig. 5, left) we see that the optical flux upper limits can be compatible with the extrapolation of the X-ray PL. Thus, it is possible that the expected optical PL spectrum indeed follows the extrapolation of the X-ray one, a case so far observed only for PSR B1509–58 among all the optically-identified pulsars (see, e.g. Mignani et al. 2010a). The optical flux upper limits are also compatible, with the possible exception of the R-band one, with the extrapolation of the γ-ray PL, which does not allow us to prove that there is a break in the optical/γ-ray spectrum, as observed in other pulsars. Indeed, a possible consistency between the γ-ray and optical PL spectra has been found so far for a minority of cases only (Mignani et al., in preparation) like, e.g. the middle-aged pulsar PSR B1055–52 (Mignani et al. 2010b). To summarise, we can not rule out that a single model can describe the optical–to–γ-ray magnetospheric emission of PSR J1357–6429. The multi-wavelength SED is different in the case of PSR J1048–5832 (Fig. 5, right), for which the optical V-band upper limit is compatible with the extrapolation of the steep X-ray PL only for the largest values of the \( N_H \) but is well above the extrapolation of the flat γ-ray one. This does not rule out that there is a break in the optical/X-ray PL spectrum, as observed in most pulsars (Mignani et al. 2010a), and that the optical spectrum follows the extrapolation of the γ-ray PL. Interestingly enough, at variance with the case of PSR J1357–6429, no single model can describe the optical–to–γ-ray magnetospheric emission of PSR J1048–5832.

Thus, the comparison between the multi-wavelength SEDs of these two Vela-like pulsars suggests that the occurrence of spectral breaks might not correlate with the pulsar’s age. Of course, the uncertainty on the spectral parameters of PSR J1357–6429, especially in the γ-ray band, makes it difficult to draw any conclusion. As new data are taken by Fermi, it will be possible to better constrain the value of the pulsar’s γ-ray photon index and
verify the possible absence of spectral breaks and its dissimilarity with PSR J1048–5832.

5. Summary and conclusions

We used archival VLT/FORS2 observations to perform the first deep optical investigations of the two Fermi pulsars PSR J1357–6429 and PSR J1048–5832. We reassessed the positions of the two pulsars from the analyses of all the available Chandra observations and the comparison with the published radio positions. For PSR J1357–6429, this yielded a tentative proper motion $\mu = 0\rlap{.}’17 \pm 0\rlap{.}’055$ yr$^{-1}$ (70° ± 15° position angle), which needs to be confirmed by future radio-interferometry observations. For PSR J1048–5832, we concluded that its radio-timing position is either wrong or affected by large uncertainties due to timing irregularities. For both pulsars, none of the objects detected around the Chandra positions can be considered viable candidate counterparts on the basis of their relatively large optical flux, $\gtrsim 3\sigma$ offset from the pulsar position, and lack of peculiar colours with respect to the field stars.

For PSR J1357–6429, we found a marginal evidence of a flux enhancement over the background at the edge of the Chandra error circle, which might be due to the presence of a faint source ($I \approx 24.6$). However, the local crowding, with two relatively bright stars within a radius of $\sim 1\rlap{.}’5$ from the Chandra position, and the lack of detections in the V and R-bands, make it problematic to determine whether such an enhancement is due to a background fluctuation, perhaps produced by the PSF wings of the two stars, or it is associated with a real source and hence to a putative pulsar counterpart. Assuming that PSR J1357–6429 is not detected in the VLT images, we determined $3\sigma$ upper limit on its optical brightness of $V \sim 27$. This implies an optical emission efficiency $\eta_{\text{opt}} \lesssim 7 \times 10^{-7}$, at least a factor of 5 lower than the Crab pulsar and, possibly, more compatible with that of the Vela pulsar. For PSR J1048–5832, our $3\sigma$ upper limit of $V \sim 27.6$ implies an optical emission efficiency $\eta_{\text{opt}} \lesssim 6 \times 10^{-6}$, which is still compatible with a Crab-like optical emission efficiency. Finally, in both cases we did not find evidence for possible optical counterparts of the PWNe detected in X-rays by Chandra, with the search complicated by the field crowding and the partial occultation at the pulsar position for PSR J1357–6429, and by the presence of the molecular cloud complex for PSR J1048–5832.

The VLT observations presented here are close to the sensitivity limits achievable with 10m-class telescopes under sub-arcsec seeing conditions. In the case of PSR J1357–6429, deep, high spatial resolution images with the HST are probably required to firmly claim an object detection from the flux enhancement seen at the Chandra position. Moreover, if our tentative proper motion measurement is confirmed by future radio-interferometry observations, the pulsar will be close to occultation by the nearby Star B in mid 2012 and it will remain occulted for the following 10 years. Thus, prompt HST follow-up observations in the I-band are the only way to achieve the optical identification of PSR J1357–6429. In the case of PSR J1048–5832, the large interstellar extinction ($A_V \sim 5$) and the presence of the molecular cloud complex in the field hamper observations in the optical/near-ultraviolet. Deep observations in the near-infrared, either with the HST or with adaptive optic device at 10m-class telescopes, might represent a better opportunity to spot a candidate counterpart to the pulsar.

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Chapter 5

Conclusions & Future Work

This thesis describes the results of a multi-wavelength and polarimetric study of a number of rotation-powered pulsars: namely, the Crab, Vela, and PSR J0205+6449. Polarisation studies of pulsars are just one example of obtaining insight into the geometry of their emission regions. Such studies provide observational constraints on the various theoretical models of the pulsar emission mechanism. Hence, it is possible to limit the competing models and find the model that best matches observations. A comparison of the optical light curves to the radio, X-ray, and $\gamma$-ray ones is also important to locate different emission regions in the neutron star magnetosphere.

The phase-averaged optical linear polarisation of the Crab nebula and pulsar was measured using observations from the HST/ACS. These findings were then compared to the results of hard-X-ray/ soft-$\gamma$-ray polarisation observations of the system using INTEGRAL/IBIS. In both cases it was found that the polarisation position angle (PA) of the pulsar is aligned with its proper-motion and spin-axis vectors. The optical polarisation of the entire inner nebula was mapped out and the polarisation of the inner synchrotron knot and wisps were determined. From this analysis, the knot has been confirmed as the source of the highly polarised off-pulse emission seen in phase-resolved studies in the optical and $\gamma$-ray bands. No variation, at the 95% significance level, was found in the polarisation of these sources over the period of the HST/ACS observations. We also found that the inner knot is variable in position,
and brightness (40% enhancement) over the 3 month period of the HST/ACS observations. These are the first quantified measurements of such a variation. We note that we found evidence of a possible variation of the knot polarisation (at 2σ). Future observations will help to address this point.

Porth et al. (2014) have modelled the synchrotron radiation from the Crab nebula using magnetohydrodynamic (MHD) simulations. The observed polarisation fraction of the knot is 0.58±0.01, which agrees well with the early off-pulse polarisation observations of Jones et al. (1981), Smith et al. (1988), and moreover, those that are reported in Moran et al. (2013). The time lapse of their simulations show that the knot is variable in shape, position and flux over a period of one month. For the knot flux, its standard deviation is about 10%. However, between 50.3 and 50.8 years, it increases systematically by 35%. This enhancement is comparable to the ∼ 40% brightening that we report in Moran et al. (2013). Moreover, as the knot position approaches the pulsar, its optical flux tends to increase.

A more thorough analysis of the INTEGRAL/IBIS polarimetric observations of the Crab nebula and pulsar will be carried out in the coming months. The aim is to study both the phase-averaged and phase-resolved components, and monitor the system for any possible variability over the past 7 years of dedicated observations. The emission from the Crab nebula is variable on all time scales. Both the AGILE and Fermi missions have reported brief enhancements in the gamma-ray flux from the nebula – the so called gamma-ray flares. A monitoring campaign will help us to identify any “smoking-gun” or “signature” of the flaring, for instance a change in polarisation during or after a period of flaring.

The phase-averaged optical linear polarisation of the Vela pulsar was also studied using the HST/ACS. These results not only confirm those originally obtained by Wagner & Seifert (2000) and Mignani et al. (2007) both using the Very Large Telescope (VLT), but are of greater precision. Moreover, as in the case of the Crab, it was found that the PA of the pulsar is aligned with its proper-motion and spin-axis. The PWN is undetected in polarised light as is the case in unpolarised light, down to a flux limit of 26.8 magnitudes arcsec⁻².
Polarisation measurements give a unique insight into the geometry of the pulsar emission regions. More multi-wavelength polarisation observations of pulsars, both phase-averaged and phase-resolved analysis, and of their PWNe, with existing instruments such as HST/ACS and GASP (optical), and INTEGRAL/IBIS (gamma-ray), and instruments aboard future X-ray missions such as the Gravity and Extreme Magnetism Small Explorer (GEMS; Ghosh et al. 2013) or the X-ray Imaging Polarimetry Explorer (XIPE; Soffitta et al. 2013), and the ASTRO-H/Soft Gamma-ray Detector (SGD) (Takahashi et al., 2012; Tajima et al., 2010), will help to provide the much needed data to constrain the theoretical models. For example, McDonald et al. (2011) have developed an inverse mapping approach for determining the emission height of the optical photons from pulsars. It uses the optical Stokes parameters to determine the most likely geometry for emission, including: magnetic-field inclination angle ($\alpha$), the observers line-of-sight angle ($\chi$) and emission height.

The other objective of this work was to search for the optical counterparts to pulsars detected at other wavelengths. Such detections enable one to probe the geometry of the neutron star magnetosphere. They also facilitate statistical analysis when trying to search for correlations between optical and X-ray luminosities, and therefore constraining emission theories. To this extent, we used ground-based observations using facilities such as WHT, GTC, INT, and TNG. We used VLT data to search for the optical counterparts to two pulsars, PSR J1357–6429 and PSR J1048–5832, both of which were detected by the Fermi gamma-ray telescope. Unfortunately, the optical counterparts of these pulsars were not detected.

However, a plausible optical counterpart to one particular pulsar, PSR J0205+6449, was detected using archival observations from Gemini-North. We performed multi-band optical observations of PSR J0205+6449 with a variety of ground and space-based facilities, including the 8 m Gemini and 10.4 m GTC telescopes, and the HST. We detected a possible candidate counterpart to the pulsar, based upon its positional coincidence with the recently measured Chandra and radio coordinates (Bietenholz et al., 2013). It has an optical spectral energy distribution (SED) that is pulsar like, and a visual magnitude, $i' = 25.5$ (5.5σ detection), that is consistent with that esti-
mated via its $\gamma$-ray luminosity and distance ($\sim 3$ kpc). Thus, PSR J0205+6449 would possibly be the fourteenth pulsar with either an identified or proposed optical counterpart (Mignani 2011) and the eighth of the $\gamma$-ray pulsars detected by Fermi. The pulsar’s spectrum would be consistent with a PL with photon index $\Gamma_O = 1.9 \pm 0.5$, similar to the X-ray one ($\Gamma_X = 1.77 \pm 0.03$).

The multi-wavelength SED of PSR J0205+6449 shows that the optical fluxes would lie below and above the extrapolations in the optical domain of the X-ray and $\gamma$-ray PL, respectively, indicating a break in the optical/X-ray region, similar to that in the X/$\gamma$-ray. The optical luminosity, $L_{\text{opt}} = 1.15 \times 10^{-30}$ erg s$^{-1}$, would imply an emission efficiency $\eta_{\text{opt}} = 4.27 \times 10^{-8}$, higher than the two times older Vela pulsar, confirming a trend for a decrease of the optical emission efficiency with the spin-down age in young pulsars. Due to the presence of a bright PWN, deeper high-spatial resolution observations with the HST are better suited to resolve the presence of a point source, confirm the optical identification of PSR J0205+6449, and better study its spectrum. Moreover, monitoring for changes in the flux of the candidate counterpart on a few month/year time-scale would allow one to rule out the possibility that it is an emission knot in the PWN.

The Square Kilometer Array (SKA) (Cordes, 2006; Lazio, 2008) is a radio telescope currently under development. It will have a total collecting area of approximately one square kilometre, and operate over a wide range of frequencies. It will address such topics as the early universe, high-energy astrophysics, and astrobiology. Its size will make it 50 times more sensitive than any other radio instrument. By having receiving stations extending out to a distance of 3,000 km from a concentrated core, it will make use of radio astronomy’s ability to obtain the highest resolution images in all astronomy. Construction of the SKA is scheduled to begin in 2018 for initial observations by 2020 and full operation by 2025.

The Australian Square Kilometer Array Pathfinder (ASKAP) is a 36 element array of 12 m antennas with a 30-square-degree field-of-view. It will be built at the proposed SKA site in Western Australia. Stairs et al. (2011) have conducted a design study
for pulsar observations with *ASKAP*, planning both timing and search observations.

Despite having a lower point-source sensitivity than *Parkes*, *ASKAP* can achieve good S/N on millisecond pulsars with sufficiently long integration times. It could also be integrated into the *International Pulsar Timing Array Project*. Whilst millisecond pulsars are being monitored, the rest of the 30-square-degree *ASKAP* field-of-view can be used to monitor pulsars, and in particular the Galactic Plane, where there are regions where 20 or more pulsars are accessible at once. The *SKA* should find about 15,000 new pulsars and provide tests of General Relativity through timing studies of neutron star–neutron star or neutron star–black hole binaries.

The next generation of ground-based optical telescopes, the so called “Extremely Large Telescopes” are still in the planning stage but designs and sites have already been chosen. These include the *Giant Magellan Telescope* (*GMT*) (a 7×8.4m array), the *Thirty Meter Telescope* (*TMT*), and the 39 m *European Extremely Large Telescope* (*E-ELT*) (McPherson et al., 2012). The European Southern Observatory’s (ESO) *E-ELT* will be the largest optical-NIR telescope in the world and will gather 13 times more light than the largest existing optical telescopes. The *E-ELT* will be able to correct for atmospheric effects through adaptive optics. Hence, it will be fully adaptive and diffraction-limited, and therefore able to produce images that are 16 times sharper than those from the *HST*. It will enable studies of planets around other stars, the first galaxies, super-massive black holes, and facilitate investigations of dark matter and dark energy. Groundbreaking on the chosen site, Cerra Armazones, Chile, has already begun. *E-ELT* will commence operations as an integrated part of the Paranal Observatory in 2024.

With its awesome light gathering capabilities, and the advances in the technologies for detector physics (e.g. *MKIDS*), a HTRA instrument on *E-ELT* would allow the detection of optical pulsars down to a visual magnitude of $m_V \approx 30$, and perhaps enable high-time resolution of pulsars down to 28 magnitudes. This should lead to the detection of $\sim 100$ new identifications of isolated neutron stars. Furthermore, it will enable studies of neutron star atmospheres, probe neutron star magnetospheres, and resolve debris discs, all of which currently challenge telescopes such as the *VLT*.
(Shearer et al., 2010; Mignani, 2011a). Pulsar timing with the E-ELT is the only way to investigate giant optical pulses and study their link with the giant radio pulses, and hence the link between incoherent and coherent radiation. Polarimetry with the E-ELT would enable measurements of the polarisation of neutron star atmospheres, mapping of the magnetic fields of PWNe and SNRs, and facilitate tests of the emission models of neutron star magnetospheres.

The Cherenkov Telescope Array (CTA), with arrays planned for northern Argentina and southern Australia or Africa, will allow a better scan of both the northern and southern hemispheres than is currently possible with HESS and VERITAS. Its superior sensitivity will enable the detection and characterisation of VHE emission from the brightest rotation-powered pulsars other than the Crab. The consortium foresees a factor of 5–10 improvement in sensitivity above 0.1 TeV (de Oña-Wilhelmi et al., 2013).

CTA will explore the energy range form 10 GeV to 100 GeV. As the largest and most efficient population of VHE γ-ray sources, observations of PWNe is one of the prime goals of the CTA mission. Most VHE PWNe have large angular sizes $\sim 1.2^\circ$. The current generation of Cherenkov Telescopes have FOVs of about $5^\circ$ which has enabled imaging of the whole halos of PWNe and lead to the dramatic increase in detections of PWNe. An angular resolution of $5''$ per axis should be achievable for CTA which should be sufficient for such observations. Not much is known about the behaviour of pulsars above 10 GeV where the performance of the Fermi LAT is less effective. CTA observations of pulsars would offer the chance to examine the most extreme energetic processes in pulsar magnetospheres and outside their light cylinders. Therefore, the VHE regime will greatly help in constructing a concrete electrodynamic theory of pulsar emission.
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