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Pulsars – Extreme Cosmic Lighthouses

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Abstract
Pulsars are ancient, fast-rotating, highly-magnetised neutron stars that radiate across the electromagnetic spectrum. New discoveries by the *Fermi* Large Area Telescope (LAT) in the gamma-ray band since 2008, combined with the quality of new multi-frequency data, have caused a revolution in the field of gamma-ray rotation-powered pulsars. There are still many unsolved mysteries regarding the magnetospheric conditions in these stars – even after 50 years of research! This paper will relate several thoughts surrounding this field from a personal perspective that has taken shape over the past 15 years.

Keywords
Pulsars — Gamma rays

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> *"Great finishes have small beginnings;*
> *never despise a humble beginning."*
> *– Rajiv Chelladurai*

Contents

1. Introduction

Pulsars (pulsating stars) were first discovered in 1967 by Dame Jocelyn Bell-Burnell [57]. Pulsed emission from these stars are perhaps best intuitively understood via the analogy of pulsars being cosmic lighthouses that send beams of radiation into the unknown, being visible only to those observers that happen to be in their line of sight. Pulsars have been observed to pulsate across the electromagnetic spectrum. Their light curves vary with energy and time (i.e., they may change shape for different pulsar rotations), but radio light curves averaged over many pulsar rotations are usually quite stable. Their spectra (distribution of photons vs. frequency or energy) span a very wide range in energy, making these rotating neutron stars true multi-frequency objects.

Pulsars are extreme objects. Their magnetic fields exceed that of the Earth by factors of 10^8 – 10^{16}; they have 500 000 times more mass, yet have a radius one thousandth of that of the Earth, implying a density that is 10^{14} times larger than that of our planet. Their interior mostly consists of superfluid neutrons. The regularity of their pulses rival the stability of atomic clocks. They are laboratories of fundamental physics, including pair formation, photon splitting, relativistic plasmas, non-thermal and thermal emission processes, and even potential indicators of gravitational waves.

Pulsars come in various flavours and form part of several classes of astrophysical systems [64]. A young pulsar may be surrounded by a wind of relativistic particles and magnetic field and is referred to as a pulsar wind nebula (PWN); these systems are sometimes associated with supernova remnants. Older pulsars typically manifest themselves by their millisecond pulsations, and many occur in a binary system that includes a companion star or they may be isolated stars. These ancient pulsars also occur abundantly in globular clusters and may collectively account for some of the gamma-ray and X-ray emission detected from these conglomerations of stars. Magnetars (anomalous X-ray pulsars and soft gamma-ray repeaters probably fall in this class) are characterised by exquisitely large magnetic fields and derive their energy from the decay of these fields, while accretion-powered pulsars tap the energy released by infalling matter from the companion; on the other hand, rotation-powered pulsars convert rotational energy of the neutron star itself into radiation and particle acceleration. Pulsars may also be named after the band in which they have been observed, e.g., X-ray or radio pulsars. Rotating Radio Transients (RRATs) emit infrequent flashes of radio emission at regular intervals.

The era before the launch of the *Fermi* Large Area Telescope (LAT) was characterised by a mere 7 gamma-ray pulsars that were detected at high confidence [105]. However, after ten years in orbit and continuously scanning the full sky in the high-energy band from ~ 20 MeV[1] to over 300 GeV [14], the *Fermi* LAT has now detected over 200[2] gamma-ray pulsars[3]. This incredible increase in pulsar number enables us to perform population studies, as well as scrutinise temporal and spectral properties of individual objects at an ever increasing level of detail.

In this paper, I initiate the discussion by listing some open questions (Section 2), summarise the status of gamma-ray observations (Section 3), describe the basic theoretical framework of gamma-ray pulsar physics (Section 4 and 5), and then focus on some new theoretical developments in the field (Section 6) before summarising our group's particular contribution to this field (Section 7) and providing a future outlook (Section 8). I end with some thoughts of a more philosophical nature (Section 9). For a more technical companion article from which some of the material below has been derived, refer to Venter *et al.* [116].

2. Open Questions After 50 Years of Research

One should acknowledge both the immense progress that has been made as well as (some of) the remaining open questions in the field (cf. [113]):

- How and where exactly is rotational energy converted into emission and particle winds?
- In a plasma-filled magnetosphere, deviations or "gaps" are expected to form to allow particle acceleration. How are these closed and sustained?
- What is the exact microphysics (including

[1] The electronvolt (eV) is a unit of energy that is equal to 1.602×10^{-19} J; 1 MeV = 1 million eV, and 1 GeV = 1 billion eV.

[2] At the time of writing, there are 234 publicly-announced *Fermi* pulsars, including > 100 millisecond pulsars (MSPs).

[3] https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

spatial properties and energetics) of electron-positron pair formation in the magnetosphere?

- What is the role of the current sheet that forms beyond the light cylinder (see Section 4)?
- What is the magnetospheric structure? How much does this deviate from a dipolar structure? Is it universal?
- What effects the change from a magnetically-dominated environment close to the pulsar to a particle-dominated one farther away?
- How does the evolutionary sequence of pulsars come about?
- How do we explain the transient phenomena we see in pulsars?
- What exactly is the nature of the neutron star interior (equation of state)?
- What is the role of general relativity and quantum effects in pulsars?
- How is radio emission generated?

Each of these broad questions may lead to many detailed ones in many subfields of pulsar research. However, being able to ask good questions and attempting to answer them is a hallmark of scientific maturation.

3. Observational Properties of Gamma-ray Pulsars

As a response to the open questions raised in the previous section, I now discuss some observational properties of pulsars to give us some firm ground on which to base our theories. I will focus on the gamma-ray band.

Prior to the launch of the *Fermi* LAT, we observed that [105]:

1. Pulsar light curves are energy-dependent, i.e., their shapes change with energy.
2. Gamma-ray pulsar light curves typically exhibit a double-peaked morphology.
3. The leading pulse typically fades in brightness relative to the trailing pulse as energy is increased.
4. Gamma-ray pulsars seem to be relatively young (compared with the full radio population) and to possess large spin-down power $\dot{E}_{\rm rot} = I\Omega\dot{\Omega} = -4\pi^2 I\dot{P}/P^3$, with I the moment of inertia, Ω the angular speed, and $\dot{\Omega}$ its time derivative.
5. The inferred gamma-ray luminosities of young pulsars follow the trend $L_\gamma \propto \dot{E}_{\rm rot}^{1/2}$.
6. The radiative power in the GeV gamma-ray band (or sometimes soft gamma-ray band, 100 keV – 1 MeV) dominates the multi-frequency spectrum.
7. The spectra are typically quite hard and typically exhibit spectral cutoffs $E_{\rm cut}$ around a few GeV. In the *Compton Gamma-Ray Observatory (CGRO)* era, the GeV spectrum of the Vela pulsar was consistent with expectations of both the near-surface polar cap (PC) and high-altitude outer gap (OG) models (See Section 5).
8. No pulsed TeV emission from pulsars could be detected [96].
9. The *Fermi* (formerly *GLAST*) Mission was expected to find tens to hundreds [45, 46, 119] of gamma-ray pulsars, both radio-loud and radio-quiet, aided by its potential for blind period searches using gamma-ray data only. Only very few MSPs were expected to be seen in gamma rays.

The *Fermi* LAT has confirmed all these basic observational trends (as for number 7, *Fermi* has shown that the emission must originate in the outer magnetosphere, from OGs, SGs or the current sheet), and also confirmed the detection of the 7 high-confidence *CGRO* pulsars (the Crab, Vela, B1509−58, B1706−44, B1951+32, Geminga, and B1055−52) as well as the 3 pulsars detected at lower significance (B1046−58, B0656+14, and J0218+4232),

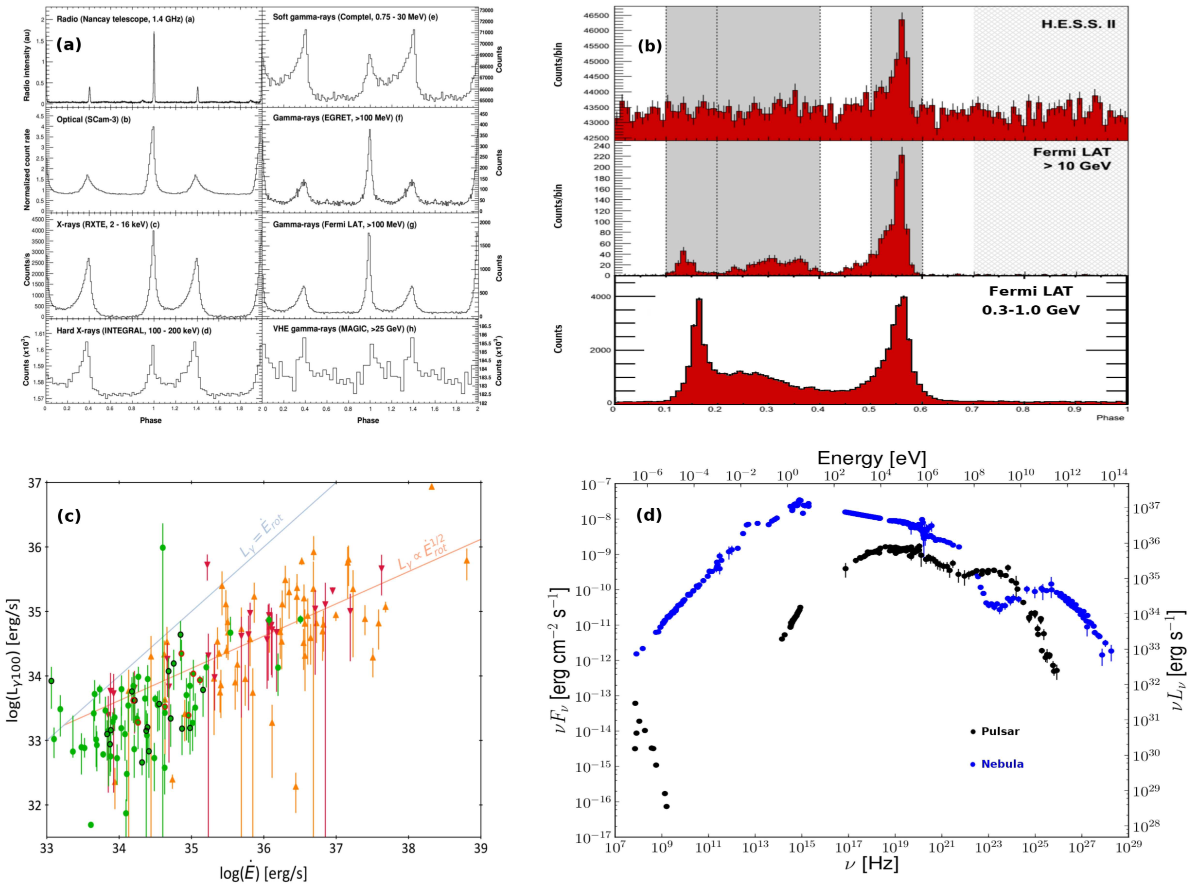

Figure 1. A selection of typical observational signatures of pulsars. *Panel (a):* Multi-frequency and subband evolution of the light curves of the Crab pulsar [2]. *Panel (b):* Disappearance of the Vela pulsar's first peak with energy as seen by *Fermi* [3] and H.E.S.S. [1]. *Panel (c):* Updated plot of L_γ vs. $\dot{E}_{\rm rot}$ for old and young pulsars, exibiting two distinct trends: $L_\gamma \propto \dot{E}_{\rm rot}^{1/2}$ for young pulsars (orange and red dots), while $L_\gamma \propto \dot{E}_{\rm rot}$ for MSPs (green dots) [49]. *Panel (d):* Broad spectral energy distribution of the Crab pulsar (black) and nebula (blue), with the GeV pulsar component showing the typical flat spectrum and exponential cutoff [25]. From Venter *et al.* [116].

in addition to more than 200 new gamma-ray pulsar detections. More comprehensively, *Fermi* has shown that (cf. Abdo *et al.* [6], Figure 1):

1. Pulsar light curve shapes not only change for different energy domains, but also within different subbands of the gamma-ray range (e.g., Abdo *et al.* [3]).

2. Gamma-ray pulsar light curves often exhibit a double-peaked morphology, although there are more complex profiles (e.g., triple peaks and broad or sharp single peaks) as well; furthermore, the radio pulse may be either leading the gamma-ray pulse in phase, be aligned with the gamma-ray peaks, or trailing the gamma-ray pulse [58]. There is an inverse trend between the gamma-ray peak separation Δ and the radio-to-gamma phase lag δ [6], as first noted [92] in the context of outer-magnetosphere models with caustic pulses, but which is also predicted in later models involving the current sheet or the beginning of the striped wind [61, 77] (Section 5).

3. For most gamma-ray pulsars, the first peak

fades in brightness relative to the second peak with increasing energy, with the Vela and Crab pulsars providing prime examples [3, 7], although about $\sim 30\%$ of the light curves show the reverse behaviour [23, 90]. The main peak positions seem to remain more or less the same as the energy increases (the third peak of Vela is an exception and migrates in phase with an increase in energy [3]), while the pulse widths become narrower [7, 1].

4. Gamma-ray pulsars represent the most energetic subpopulation of pulsars in terms of $\dot{E}_{\rm rot}$. At the highest spin-down powers (e.g., PSR B1509−58), the spectrum may cut off in the $1-100$ MeV range [67].

5. The inferred gamma-ray luminosity L_γ of young pulsars follow the trend $L_\gamma \propto \dot{E}_{\rm rot}^{1/2}$, while MSPs seem to follow the trend $L_\gamma \propto \dot{E}_{\rm rot}$ (see Figure 1; Abdo *et al.* [6]), although there is large scatter in the latter case, which may be partly explained by uncertain distances, variations in equation of state (since $\dot{E}_{\rm rot} \propto I$), or different beam and pulsar geometries [50, 51, 63]. Thus pulsars become increasingly more efficient gamma-ray emitters as they age (converting a larger fraction of $\dot{E}_{\rm rot}$ into L_γ [6]; cf. Figure 1) even though the MSPs have smaller $\dot{E}_{\rm rot}$.

6. The GeV power is typically still the dominant component of the multi-frequency spectrum (for all but the youngest Crab-like pulsars).

7. The gamma-ray spectra are quite hard and exhibit spectral cutoff energies $E_{\rm cut}$ in a very narrow band around a few GeV [6] (the soft-gamma-ray pulsars are exceptions, with spectral (sub-exponential) cutoffs and dominant radiative power occurring in the MeV band [67]). A key result from the *Fermi* Mission was favouring a sub-exponential spectral cutoff over a super-exponential one in the case of the Vela pulsar at a significance of 16σ, indicating that gamma-ray emission must come from the outer magnetosphere in order to escape pair production or photon splitting in the intense B-field near the stellar surface to be able to reach the observer (e.g., [101]).

8. Pulsed TeV emission from pulsars may be uncommon or intrinsically faint, and therefore rather hard to detect given the current and near-future telescope capabilities. Yet, three pulsars have now been detected at tens to hundreds of GeV, and even up to TeV energies: the Crab, Vela, and Geminga [9, 1, 71].

9. The *Fermi* crop of > 230 pulsar discoveries is diverse: there are radio-loud vs. radio-faint ones, young pulsars vs. MSPs, and pulsars in evolving binary systems (redback and black widow systems [91]) vs. isolated ones [99]. Surprisingly, MSPs turn out to be a substantial sub-class of gamma-ray pulsars, being energetic emitters of GeV emission [27, 49]. Furthermore, blind period searches directly in the gamma-ray data [95, 88], also using distributed volunteer (crowd) computing [35], have made an enormous impact.

10. Young pulsars occur near the Galactic Plane, while old MSPs are detected at all latitudes, because of the closer distance of these fainter objects and also because old MSPs have had time to evolve to larger scale heights above the Galactic Plane due to their large velocities [6].

11. The photon spectral index Γ softens with larger $\dot{E}_{\rm rot}$ values [6], possibly indicating an increase in pair production or the onset of a synchrotron radiation (SR) component in more energetic pulsars.

12. Radio-quiet gamma-ray MSPs seem to be quite rare (there are a handful of candidates, around a dozen [36], out of a population of > 100 detected ones), which may be attributed to MSPs having very wide gamma-ray *and* radio beams owing to their relatively compact magnetospheres (since $R_{\rm LC} \sim P$).

13. Surprising variability was detected in the wind of the Crab pulsar [103, 4] (i.e., "Crab flares"), while the pulsed emission remained stable. Another type of variability was found in PSR J2021+4026 [8], which exhibited changes in gamma-ray flux, light curve morphology, and spectrum coincident with an abrupt step change in spin-down power.

4. Basic Theoretical Framework

The open questions and observational behaviour of pulsars discussed in the two previous sections guide us toward formulating and formalising our current understanding of pulsars. The first step is a basic theoretical framework that may be refined as more data and insight become available.

4.1 A Rotating Conductor in a Static Magnetic Field (The Unipolar Inductor)

A number of authors have pointed out the similarity between the physics of a unipolar inductor and a pulsar that is an aligned rotator (having aligned magnetic and spin axes).

Let us consider a conducting disc spinning in a static B-field [73]. Electrons in the disc move with a net velocity $\vec{v} = \vec{\Omega} \times \vec{r}$ and experience a Lorentz force $\vec{F} = -e\vec{v} \times \vec{B}/c$ in the surrounding B-field, with c the speed of light in vacuum and e the electron charge. Electrons move toward the axis, leading to a steady configuration in which the total Lorentz force on the electrons vanishes. Similarly, for the aligned rotator in the force-free (FF) limit (plasma-filled, co-rotating magnetosphere and neglecting particle inertia), one finds [44]

$$\vec{E} + \frac{\vec{\Omega} \times \vec{r} \times \vec{B}}{c} = 0, \tag{1}$$

implying $\vec{E} \cdot \vec{B} = 0$. This sets up a potential difference between the axis and rim (or for a pulsar, on the stellar surface between the pole and edge of the PC, which delineates the open B-field line region of the magnetosphere):

$$\Delta V = -\int_0^a \vec{E} \cdot d\vec{s} = \frac{\Omega \Phi_{\rm B}}{2\pi} = -\frac{B_0 \Omega a^2}{2c}, \tag{2}$$

with $\Phi_{\rm B}$ the magnetic flux, B_0 the B-field, and a the disc radius. There is a component $E_{||}$ of the electric field parallel to the local B-field (nearly a radial electric field) associated with this potential drop, which pulls primary charges from the stellar surface and eventually fills the magnetosphere with plasma via ensuing gamma-ray emission and a cascade of secondary e^+/e^- pair production (Section 5), creating an FF magnetosphere. Using Gauss' law as well as the electric field that occurs in such an FF magnetosphere where $\vec{E} \cdot \vec{B} = 0$, we find the so-called Goldreich-Julian charge density [44]

$$\rho_{\rm GJ} = \frac{\vec{\nabla} \cdot \vec{E}}{4\pi} \approx \frac{\vec{\Omega} \cdot \vec{B}}{2\pi c}. \tag{3}$$

The radius where the corotation speed $|\vec{v}_{\rm rot}| = |\vec{\Omega} \times \vec{r}| = c$, is

$$R_{\rm LC} = \frac{c}{\Omega} \propto P. \tag{4}$$

This is the so-called "light cylinder radius" that sets the typical spatial scale for the pulsar magnetosphere. The last open field line tangent to the light cylinder defines the PC, the rim of which lies at a polar angle $\Theta_{\rm PC} \sim (\Omega R/c)^{1/2}$, with R the stellar radius.

4.2 The Braking (Spin-down) Model

Pulsars are born as remnants of supernova explosions following the gravitational collapse of a massive star [15]. For a stellar core that rotates more or less rigidly and assuming that the angular momentum is conserved during collapse, the final angular speed will be

$$\Omega_f \sim \Omega_i \left(\frac{R_i}{R_f}\right)^2, \tag{5}$$

with R and and "i" and "f" indicating the initial and final values. Inserting typical values of $R_i \sim 10^{11}$ cm and $R_f \sim 10^6$ cm into the above equation yields an increase in angular speed by a factor of $\sim 10^{10}$ and rotational periods in the millisecond to second range. If the stellar interior is fully conductive, magnetic flux will also be conserved during collapse, implying

$$B_f \sim B_i \left(\frac{R_i}{R_f}\right)^2. \tag{6}$$

This relation yields typical surface B-fields of $B_0 \sim 10^{12}$ G.

Rotational energy is the reservoir that is tapped and converted into electromagnetic (fields, pulsed emission) and particle (pulsar wind) energy. An isolated neutron star will thus "spin down" and rotate slower (i.e., $\dot{P} > 0$). An estimate for the surface polar B-field strength may be obtained by equating the rate of slowing down and the magnetic-dipole radiation loss rate[4] for a star in vacuum [75]:

$$\begin{aligned} \dot{E}_{\rm rot} &\equiv \frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = I\Omega\dot{\Omega} \\ &= L_{\rm md} = -\frac{2}{3c^3}\mu^2 \sin^2\alpha\,\Omega^4, \end{aligned} \tag{7}$$

with $L_{\rm md}$ the loss rate due to magneto-dipole radiation, $I \sim MR^2$, $\mu \equiv B_0R^3/2$ the magnetic moment, B_0 the B-field at the pole, and α the angle between the magnetic and spin axes. Thus, if one assumes that $\mu \sin\alpha \approx$ const., the general "braking" or "spin-down" law may be written as

$$\dot{\Omega} \propto -\Omega^n, \tag{8}$$

with n the braking index that may be obtained by differentiating the above equation with respect to time (for constant $n \neq 1$):

$$n = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2} = 2 - \frac{P\ddot{P}}{\dot{P}^2}, \tag{9}$$

with $\ddot{\Omega}$ and $\ddot{P}$ the second derivate of the angular speed and period, and $n = 3$ for a dipolar B-field. By inserting typical values of $I \sim 10^{45}$ g cm^2, $R \sim 10^6$ cm and $\alpha \sim 90^\circ$ into Eq. (7) one obtains an estimate for the surface B-field at the pole:

$$B_0 \sim 6 \times 10^{19} P^{1/2}\dot{P}^{1/2} \text{ G}. \tag{10}$$

Assuming the B-field is dipolar, one may adopt an r^{-3} dependence and calculate the poloidal field at the light cylinder (the toroidal field starts to dominate beyond $R_{\rm LC}$ and has an r^{-1} dependence):

$$B_{\rm LC} = B_0\left(\frac{R}{R_{\rm LC}}\right)^3 \propto P^{-5/2}\dot{P}^{1/2}. \tag{11}$$

By assuming that $\mu_\perp \equiv \mu \sin\alpha$ remains roughly constant, and so does n, the characteristic or "rotational" age $\tau_{\rm c}$ can be derived upon integration of Equation (8) and substitution of $\Omega^{n-1} = \dot{\Omega}/(k\Omega)$, with k a constant:

$$\begin{aligned} \tau_{\rm c} &= -\frac{\Omega}{(n-1)\dot{\Omega}}\left[1 - \left(\frac{\Omega}{\Omega_0}\right)^{n-1}\right] \\ &\approx -\frac{\Omega}{(n-1)\dot{\Omega}} \equiv \frac{P}{(n-1)\dot{P}}, \end{aligned} \tag{12}$$

when $\Omega_0 \gg \Omega$.

The PC voltage may be written as (by substituting $a = R\sin\Theta_{\rm PC}$ into Eq. [2])

$$-\Delta V_{\rm PC} = \frac{B_0\Omega^2R^3}{2c^2} \sim |L_{\rm md}|^{1/2}. \tag{13}$$

The Goldreich-Julian current is (Eq. [3])

$$I_{\rm GJ} \sim 2\rho_{\rm GJ}cA \sim |L_{\rm md}|^{1/2}, \tag{14}$$

with $A = \pi R^2 \sin^2\Theta_{\rm PC}$ the area of one PC. The total electromagnetic power is thus

$$L = \Delta V_{\rm PC} I_{\rm GJ} \sim |L_{\rm md}|. \tag{15}$$

If one accepts a constant ΔV as a threshold condition for pair production in young pulsars [52], one expects the gamma-ray luminosity to behave as (assuming $\dot{E}_{\rm rot} \sim L_{\rm md}$; Eq. [7])

$$L_\gamma \sim \Delta V_0 I_{\rm GJ} \sim \dot{E}_{\rm rot}^{1/2}, \tag{16}$$

since $\Delta V = \Delta V_0 =$ constant in this case. On the other hand, if older pulsars have pair-starved magnetospheres, their gamma-ray luminosity may behave as

$$L_\gamma \sim \Delta V_{\rm PC} I_{\rm GJ} \sim \dot{E}_{\rm rot}. \tag{17}$$

Using the above expressions for $\dot{E}_{\rm rot}$, $B_{\rm LC}$, B_0, and $\tau_{\rm c}$, a $\dot{P}P$-diagram may be constructed to categorise the various pulsar species we observe (Figure 2), although one should be aware of a number of simplified assumptions that have been employed.

[4] The spin-down due to Poynting flux leaving an FF (plasma-filled) magnetosphere is similar to the vacuum case of magneto-dipole losses, but with the $\sin^2\alpha$ term replaced by $1+\sin^2\alpha$ [100].

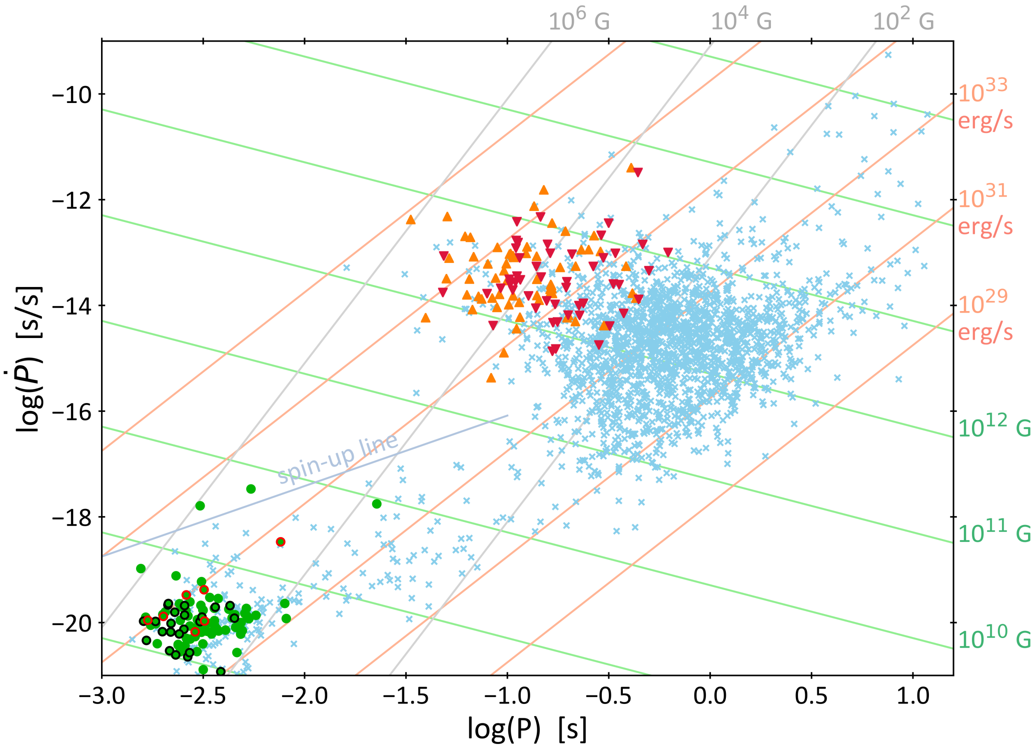

Figure 2. Plot [49] of pulsar period (P) vs. period time derivative ($\dot{P}$) of gamma-ray and radio pulsars, with 53 radio-loud and gamma-loud young pulsars (orange upward triangles), 37 radio-faint and gamma-loud young pulsars (red downward triangles), 71 radio-loud and gamma-loud MSPs (green filled circles, circled in black and red when in black-widow and redback systems, respectively), and 2 256 other radio pulsars (light blue crosses). Recently discovered MSPs, with no $\dot{P}$ measurement yet, are plotted as squares at $\dot{P}$ near 10^{-21}. Lines of constant spin-down power (brown; (Eq. [7])) and polar B-field strength (green; Eq. [10]) are given for a magnetic dipole in vacuum and a stellar moment of inertia of 1.4×10^{45} g cm^{-2} applicable to a 1.4 solar mass neutron star with a 12 km radius. Lines of constant B-field strength at the light cylinder (Eq. [11]) radius are shown in grey. The bluish-grey line marks the spin-up rate expected from mass transfer at the Eddington rate from a stellar companion in a binary system. From Venter *et al.* [116].

5. Standard Emission Models

In a seminal paper, Goldreich and Julian [44] invoked an aligned-rotator model and provided an "existence proof" for a plasma-filled pulsar magnetosphere (as opposed to a vacuum one): the rotationally-induced electric field vastly dominates gravity (and particle inertia) near the stellar surface, ripping charges from the crust and accelerating these primary charges along the nearby B-field lines. Their model provided a measure for the local charge density that would characterise such a magnetosphere. However, their model did not allow for particle acceleration, as all local electric fields would be screened by the ubiquitous plasma.

In PC [38] and slot gap (SG) [11] models, primary particles originating from the stellar surface emit curvature radiation (CR) as they are constrained to move along curved B-field lines. The gamma-ray photons undergo magnetic (one-photon) pair creation in which energy is converted to matter, and this leads to a cascade of electron-positron pairs that fill the surrounding magnetosphere and screen the local electric field $E_{||}$ that is parallel to the local B-field. However, there remain regions (just above the stellar surface in PC models, before the pair formation front develops at a fraction of R in altitude; and along the last closed field lines in SG models where $E_{||}$ vanishes and the pair formation mean free path becomes infinite) where the plasma is not dense enough to shield $E_{||}$, and particle acceleration can take place. In OG models [34, 93], particle outflow above the null-charge surface (where $\vec{\Omega} \perp \vec{B}$ and $\rho_{\rm GJ} = 0$) creates gaps where acceleration and two-photon pair production (light converted to electron-positron plasma) may take place. Pair-starved polar cap (PSPC) models have been studied in the context of suppressed pair production in older pulsars [53]. Annular and core gap models [89, 40] invoke gaps between critical field lines (lines that intersect the null-charge surface at the light cylinder) and last-closed field lines. All of these models may be categorised as "local gap models" that enforce local deviations from large plasma densities, but are agnostic regarding the global current flow patterns.

In the interum period leading up to the development of global emission models, geometric two-pole caustic (TPC) [16, 41, 42] and OG [111, 118] light curve models were used to constrain emission gap and pulsar geometries (inclination and observer angles α and ζ). Such geometric models do not contain any knowledge of the $E_{||}$ distribution and thus one can not calculate a spectrum or energy-dependent light curves from such models. These rather assume a constant emissivity per unit length in the corotating frame along certain B-field lines, with photons being emitted tangentially to the local field lines in the corotating frame. Aberration plus time-of-flight delays are included, leading to photons bunching in phase to form so-called caustics of bright emission. These caustics result in sharp peaks as the asymmetric beam sweeps past the observer. Although these models had reasonable success in reproducing gamma-ray light curves [58, 87, 111, 112], they pointed to the fact that a more general model is needed of which the various geometric models may be particular incarnations [113].

In addition to the local gap models interior to the light cylinder, work has also been done on "striped-wind" models, where dissipation takes place in the current sheet that forms near the equator beyond the light cylinder (e.g., [77, 78]). The notion of the current sheet emerges in the context of FF B-field models. In contrast to the rotating vacuum dipole solution obtained by Deutsch [39], which has been used in several pulsar light curve models as a first approximation (e.g., [42, 111]), the FF solution assumes that there is dense enough plasma everywhere so that $E_{||}$ may be screened throughout the magnetosphere. This leads to the "pulsar equation" that has been solved for the aligned-rotator case [37]. The FF field has also been obtained for the oblique case [100], and additionally using full magnetohydrodynamics (MHD) [65, 104].

However, both vacuum or plasma-filled (FF) pulsar magnetospheres can only be extreme approximations to reality, since the first possesses no charges to radiate the pulsed emission we observe, while the latter permits no electric fields $E_{||}$ that can accelerate charges to high enough energies to radiate gamma-ray emission. Dissipative magnetosphere MHD solutions [60, 61, 70] seek to obtain more realistic solutions by including a macroscopic conductivity σ as a free parameter, and therefore allowing charges, currents, and acceleration to occur in the pulsar magnetosphere. The question of how σ comes about must be closely linked to how injection and pair formation rates differ in different regions in the magnetosphere. Particle-in-cell (PIC) codes study such microphysical questions, but are subject to computational limits as well as particular assumptions pertaining to model implementation. See Venter [115] and references therein for a more detailed overview of the above models.

6. New Theoretical Developments

6.1 Dissipative Magnetic Fields (MHD Models)

Dissipative models have been developed [60, 61, 70] allowing solutions that transition from the vacuum to FF case (from zero to formally infinite σ).

Kalapotharakos *et al.* [61] found that the observed inverse correlation between the phase separation of the two main gamma-ray peaks, Δ, and the radio-to-gamma phase lag, δ (the "$\Delta - \delta$ trend") could only be reproduced for a spatially-dependent macroscopic σ: FF conditions should exist interior to the light cylinder, and a large but finite σ outside. These models are referred to as FIDO models – FF inside, Dissipative Outside. Brambilla et al. [23] found a tentative correlation between σ and $\dot{E}_{\rm rot}$ as well as an anti-correlation between σ and age $\tau_{\rm c}$. These trends are expected if one identifies higher σ with more efficient screening of $E_{||}$ by pairs (which possibly happens in younger, more energetic pulsars). Kalapotharakos *et al.* [62] refined their FIDO model and could infer $E_{||}$ using *Fermi*-measured spectra, showing that $E_{||}$ decreases with $\dot{E}_{\rm rot}$ but saturates at low $\dot{E}_{\rm rot}$. This model thus provides a tantalising macroscopic description of pulsars that may guide kinetic codes attempting to uncover the microphysics that support the required macroscopic charge and current densities.

6.2 Particle-in-Cell Codes

The application of kinetic PIC codes to pulsar magnetospheres marks a mini-revolution in theoretical studies of neutron stars. This technique can model the magnetosphere from first principles, in contrast to the approaches described above. It is important to resolve both the temporal and spatial scales of the problem (plasma frequency and skin depth) to avoid numerical instability and numerical plasma heating [24]. Correcting for the effect of too low a B-field on the radiative properties is also important to fully capture the emission physics [63].

Previous works [18, 19, 33, 28, 29, 30, 31, 83, 84, 85, 63] focused on dealing self-consistently with the pulsar electrodynamics including global current closure, the contribution of charges of different sign to the current, dissipative processes, electromagnetic emission, and the effects of pair production and general relativity (see Venter [115] for a more detailed summary). Several aspects, including the importance of (spatial) particle injection properties (which was found to critically depend on general relativity), as well as a renewed focus on the current sheet and Y-point (a region of merging field lines close to the light cylinder, where the inner magnetospheric lines transition to a equatorial current sheet [106]) as important dissipative regions (including the study of plasma instabilities and magnetic reconnection) came to the fore.

A recent example of PIC modelling is afforded by the work of Brambilla *et al.* [24] that focused on the dependence of magnetospheric properties on particle injection rate. As the injection rate was increased (i.e., equivalent to a macroscopic σ being increased), $E_{||}$ was gradually (but never completely) screened and the FF current structure was attained. By studying particle trajectories, they could probe some details of the current composition (Figure 3), elucidating and justifying the FIDO macroscopic assumptions and electrodynamical (or spatial accelerator) constraints derived from the gamma-ray data [63]. Future studies should keep reaching to allow for higher particle energies to simulate the radiative physics more realistically. Alternative assumptions of pair production should lead to distinct observational characteristics, which may be probed by future X-ray missions.

Another example is that of Philippov *et al.* [86] who included one-photon and two-photon pair production as well as General Relativistic frame-dragging effects in their PIC code, finding that that latter substantially increases the number of open field lines that can sustain pair production. They allow for electron and ion extraction from the stellar surface and assume the gamma-ray emission is due to SR. Interestingly, non-stationary pair creation is found to occurred above the PC and also in the return current layer and current sheet. These detailed simulations are also providing important hints as to how the different species of particles make up the global current flow patterns. In this model, SR produced by mostly positrons accelerated via relativistic magnetic reconnection in the current sheet and close to the Y-point, dominated the gamma-ray waveband emission.

PIC codes are starting to address very interest-

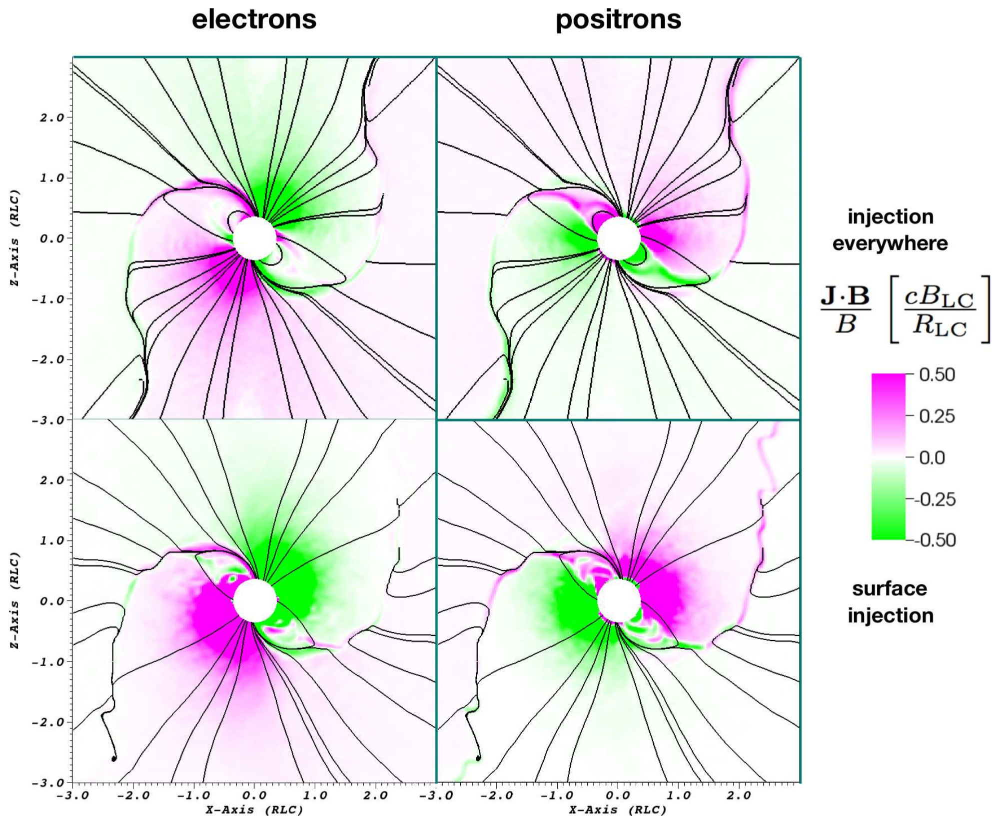

Figure 3. The electron and positron components of the current density for magnetospheres close to being FF, as predicted by the PIC model of Brambilla *et al.* [24]. One can see that the electrons and positrons both flowed out in the PC regions. The labels distinguish the cases where pair injection took place only at the surface vs. everywhere in the magnetosphere.

ing, detailed questions about current flow and emission properties of pulsars, while also raising new questions pertaining to the specific properties of pair production. The latter is fundamentally linked to the particle energetics and radiative output of a pulsar.

6.3 Other Ideas: Multipolar Fields and Polarisation

A number of authors have pointed out the need for offset-dipole or multipolar B-fields beyond the usual assumption of a dipolar rotator (e.g., [10, 13, 32, 94]), as also motivated by observations [21, 22, 43, 68]. Harding & Muslimov [54, 55] found that introduction of a modest azimuthally asymmetric distortion in the B-field (the “offset-PC model”, cf. Barnard *et al.* [17]), which may be due to B-field-line sweepback near the light cylinder or non-symmetric currents within the star, can significantly increase $E_{||}$ on one side of the PC. This, combined with a smaller B- field line radius of curvature, leads to larger pair multiplicity and a significant extension of pair spectra to lower energies, thus providing a mechanism for pair creation even in (old) pulsars that have previously been thought to be pair-starved.

Pétri studied offset-dipole B-fields in vacuum in a series of papers. He presented analytical solutions in closed form in flat vacuum spacetime for the retarded point quadrupole, hexapole, and octopole as generalisations of the retarded point dipole, emphasising the effect of B-field topology on emitted Poynting flux, braking index, PC geometry, and caustic beam structure [79]. He next provided analytical solutions for a displaced dipolar field, and computed the $\dot{E}_{\rm rot}$ and the torque exerted on the pulsar's crust, pointing out that gamma-ray light curve and polarisation modelling may help constrain the magnetic topology [80]. In a dedicated paper, polarisation properties in an off-centre dipole field were studied by extending the well-known rotating vector model to a form appropriate for this topology, called the decentred rotating vector model (DRVM) [81]. Finally, Pétri [82] generalised multipolar field expressions to include the effect of strong gravity by computing general-relativistic extensions of the Deutsch solution [39], including spacetime curvature and frame-dragging effects (both numerically and analytically, but approximately in the latter case).

Gralla *et al.* [48] studied oblique rotators, including general-relativistic effects and multipole components and focusing on the near-field charge and current flow. They derived a general analytic formula for the PC shape and charge-current distribution as a function of the stellar mass, radius, rotation rate, moment of inertia, and B-field. For combined dipole and quadrupole components, thin annular PCs were obtained. These results may be important for PC heating and resulting X-ray thermal emission calculations, as well as neutron star mass and radius measurements by, e.g., the *NICER* Mission [12], and for pair production physics.

In addition to explaining spectral, light curve, and population features, models should also be able to describe the polarisation signatures that have been or may be seen in pulsars (e.g., [59, 76, 102]). Thus, polarisation studies provide an additional constraint on B-field structure, obliquity and viewing angle, and magnetospheric emission physics while also aiding in model scrutiny and discrimination. Dyks *et al.* [42] studied the effect of Special Relativity on gamma-ray pulsar light curves and polarisation in the TPC, OG, and PC models using a retarded vacuum B-field geometry [39]. They found that the TPC could qualitatively reproduce the optical polarisation measurements of the Crab pulsar [98]. Cerutti *et al.* [30] calculated Stokes parameters using their 3D PIC code. They studied gamma-ray SR originating in the current sheet and found that this emission is mildly polarised, also showing a clear anti-correlation between flux and degree of linear polarisation as a signature of caustic emission. Harding & Kalapotharakos [56] calculated multi-frequency polarisation characteristics of pulsar emission invoking emission from the outer FF magnetosphere and current sheet. They assumed that optical to hard X-ray emission is produced by SR from electron-positron pairs and gamma-ray emission is due to either CR or SR from primary electrons. Large swings in position angle coupled with strong depolarisation dips occurred near the light curve peak phases in all energy bands. The SR polarisation characteristics were found to be very sensitive to the photon emission radius. A sharp increase in polarisation degree together with a change in position angle at the transition between X-ray and gamma-ray spectral components, if detected in future, would confirm CR as the gamma-ray emission mechanism.

7. Local Contributions to the Pulsar Research Field

In this short section, I would like to acknowledge the many and varied contributions of my group and collaborators to this field by listing several projects that we have been directly involved in over the years:

- Spectral modelling of gamma-ray MSPs [108].
- Geometric modeling of pulsar light curves in both the radio and gamma-ray band [111, 112, 58, 72].
- Combining light curve and polarisation modelling to infer pulsar geometries (inclination and observer angles) [97].
- Developing a statistical method to rigorously combine dual-band light curve data and obtain sensible model parameter constraints [20].
- Studying the effect of an offset-dipole magnetic field and associated electric field on light curve structure [17].

- Modelling the energy-dependent gamma-ray light curves of Vela invoking CR (Barnard *et al.*, *in prep*).
- Modelling the pulsed TeV emission of the Vela pulsar (Harding *et al.*, *accepted*).
- Applying the rotating vector model to a white-dwarf pulsar system to constrain its geometry (Du Plessis *et al.*, *submitted*).
- Using population synthesis, pair production and transport models to predict the contribution of pulsars to the detected local cosmic-ray electron flux [26, 114].
- Modelling the expected modulated emission originating at intrabinary shocks of so-called "spider binary" pulsars in which the pulsar wind heats and sometimes ablates the companion star [117].
- Modelling the collective emission from a population of MSPs in a globular cluster [110, 66, 74].
- Modelling the spectral and spatial properties of PWNe [109, 107].

8. Conclusion

One notices that a huge amount of effort and time have been spent during the last five decades to uncover the inner workings of a pulsar. Below, I paraphrase some remarks I have heard being made by colleagues during the past years that capture this lively debate, struggle, and enduring mystery:

- "A pulsar is a (sometimes) rapidly-rotating, (sometimes) highly magnetic, (sometimes) stable, (sometimes) spinning-down, (sometimes) cooling, (sometimes) observable neutron star."
- "We should scrap all theoretical pulsar models and start over."
- "I am not married to any particular model."
- "The past decades' local models were wrong. The gamma-ray emission mechanism is SR, NOT CR. Particles are accelerated by magnetic reconnection, NOT electrostatic fields. This all happens in the current sheet, NOT inside the light cylinder."
- "All roads lead to the current sheet."
- "Pulsar physics would be a matter of solving a simple circuit – the problem lies in the connecting wires (plasma)!"
- "Look at the old papers; everything that could be tried, have been tried."

The *Fermi* LAT has had an enormous impact on pulsar science, providing renewed impetus for theoretical development. Some of the standard ideas have been confirmed, while the data necessitate new directions to be pursued, including the effect of general relativity on pair production and PC shapes, studying multipolar fields, and making predictions for polarisation signatures expected for different emission mechanisms. Continued development of our technological capabilities, theoretical model development, computational advances, and better data acquisition should aid us in pushing the boundaries of our understanding of the pulsar phenomenon.

9. Final Thoughts

I would like to end by raising a few questions and making a few remarks of a broader nature.

- *Knowability:* What are the limits of our knowledge? What do we know for certain? Are our answers unique? Is the extrapolation of physical laws justifiable? I believe these questions imply that we should approach our science and knowledge with honesty and humility.
- *Social Aspects:* Science is in essence collaborative. This raises issues such as politics, worldviews, competition, collective understanding, interdependence, and false idolising of people. I believe one should respect

one's peers and leaders, within reasonable bounds, and not fear to be contradicted.

- *Opportunities:* Science affords incredible opportunities to the individual to meet talented people, see beautiful places, to be stimulated by novel ideas, acquire sought-after skills, and to challenge one's own abilities. Thus, there is enormous scope for personal growth.

- *Why do we do science?* It is the thrill of discovery, the opportunity for growth and self-realisation, a very unique and logical way of thinking... Science provides a special pair of glasses through which to view the world (but not the only way), and it may be viewed as part of our "Culture Assignment" (Genesis 3:15). It is a vehicle that thrusts one into a circle of unique people and allow one to touch their lives – to influence and be influenced. It is also a powerful means to affect social good.

- *Describing Nature:* Using the language of mathematics coupled with scientific investigation, one observes tremendous complexity, order, beauty, symmetry, geometry, and harmony that, in my personal view, point to a Master Creator Who has embedded an even more mysterious creation inside of us – that of longing to know Him (Ecclesiastes 3:11 AMP).

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About the Author

Christo, son of Japie and Huegene Venter, was born in Humansdorp, Eastern Cape, South Africa on 14 May 1980. He matriculated from Potchefstroom Gimnasium in 1998 with 8 distinctions and the highest average in the North-West Province. He graduated with a B.Sc. (*cum laude*) in 2002 and thereafter joined the Centre for Space Research (CSR) of the North-West University, Potchefstroom Campus. He obtained his M.Sc. (*cum laude*) and Ph.D. (first class) in 2004 and 2008, under supervision of the late prof. Okkie de Jager[5], a renowned researcher in Gamma-ray Astrophysics.

Christo was appointed Physics lecturer in 2005, and was promoted to senior lecturer in 2008, to associate professor in 2014 and to full professor in 2017. He successfully applied for a NASA Postdoctoral Program (NPP) Fellowship, and spent 2009 at the Goddard Space Flight Center in Maryland, USA as a postdoc working under supervision of a world leader in gamma-ray pulsar modelling, Dr Alice K. Harding.

Professional and research affiliations include membership of the High Energy Stereoscopic System (H.E.S.S.), Cherenkov Telescope Array (CTA), SA-GAMMA Consortium, *Fermi* LAT, Neutron star Interior Composition Explorer (NICER), Transients and Pulsars with MeerKAT (TRAPUM) Experiment, South African Council for Natural Scientific Professions (SACNASP), Golden Key International Honour Society, South African Institute of Physics (SAIP), African Astronomical Society (AfAS), International Astronomical Union (IAU), and the Suid-Afrikaanse Akademie vir Wetenskap en Kuns (SAAWK).

Christo was awarded the coveted President's Award (P-rating) by the National Research Foundation (NRF) in 2013 for his outstanding research and the promise of becoming a future world leader in his field. He is co-author of 20 peer-reviewed papers, 30 peer-reviewed proceedings articles, 21 conference proceedings articles, 161 H.E.S.S. papers, and 24 *Fermi* papers. NASA ADS lists nearly 16 000 citations to

[5] I believe the following quotes may be applicable to my two mentors in Astrophysics, prof. De Jager (1961 – 2010) and Dr Harding:

"*Remember when you leave this Earth, you can take with you nothing that you have received, only what you have given – a heart enriched by honest service, love, sacrifice and courage"* (St Francis of Assisi).

"*Someone is sitting in the shade today because someone planted a tree long ago* (Warren Buffet)."

these papers, giving an h-index of 68 (11 for non-Collaboration papers). He has attended 44 international and 21 local conferences and has been invited to give 9 plenary and 5 popular talks. He has supervised 6 M.Sc. students, 4 Ph.D. students, collaborated with 2 postdocs, and acted as examiner for 1 Master's and 2 PhD theses. He also acted as external moderator for the University of Johannesburg and University of Namibia, as well as refereeing 31 proceedings and journal articles. He acted as a judge at science fairs, served on organisational committees for international conferences, and has also served as treasurer and later co-chair of the Astrophysics and Space Science Division of the SAIP, and chair of the South African National Committee of the IAU.
Christo is married to Cathrine. In his free time, he likes to play piano, sing in a choir, or do oil painting. He humbly acknowledges God's abundant blessings on his life.

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