Pulsar Wind Nebulae in the SKA era

J. D. Gelfand[*][ab]**, R. P. Breton**[cf]**, C.-Y. Ng**[d]**, J. W. T. Hessels**[e]**, B. Stappers**[f]**, M. S. E. Roberts**[a]**, A. Possenti**[g]

[a]*New York University Abu Dhabi, PO Box 129188, Abu Dhabi, United Arab Emirates; E-mail:* joseph.gelfand@nyu.edu, mallory.roberts@nyu.edu

[b]*Center for Cosmology and Particle Physics, New York University, Meyer Hall of Physics, 4 Washington Place, New York, NY 10003*

[c]*School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom; E-mail:* rene.breton@manchester.ac.uk

[d]*Department of Physics, The University of Hong Kong, Pokfulam Road, Hong Kong; E-mail:* ncy@bohr.physics.hku.hk

[e]*ASTRON, Postbus 2, 7990 AA Dwingeloo, The Netherlands / University of Amsterdam; E-mail:* hessels@astron.nl

[f]*The School of Physics and Astronomy, The University of Manchester, Manchester, United Kingdom; E-mail:* ben.stappers@manchester.ac.uk

[g]*Astronomical Observatory of Cagliari, Selargius, Italy; E-mail:* possenti@oa-cagliari.inaf.it

Neutron stars lose the bulk of their rotational energy in the form of a pulsar wind: an ultra-relativistic outflow of predominantly electrons and positrons. This pulsar wind significantly impacts the environment and possible binary companion of the neutron star, and studying the resultant pulsar wind nebulae is critical for understanding the formation of neutron stars and millisecond pulsars, the physics of the neutron star magnetosphere, the acceleration of leptons up to PeV energies, and how these particles impact the interstellar medium. With the SKA1 and the SKA2, it could be possible to study literally hundreds of PWNe in detail, critical for understanding the many open questions in the topics listed above.

---

[*]Speaker.

1. Introduction

Roughly every 100 years, a neutron star is born in the Milky Way (e.g., Faucher-Giguère & Kaspi 2006). The rotational energy of a neutron star powers a highly relativistic, magnetized outflow called a "pulsar wind" (e.g., Goldreich & Julian 1969), which creates a "pulsar wind nebula" (PWN) as it expands into its surroundings. The properties of the PWN depend on how this wind is generated inside the neutron star's magnetosphere, how PeV and higher energy particles are generated inside this outflow, and the wind's interaction with its surroundings.

This is true for neutron stars young and old, isolated and in binaries. When the neutron star is young ($\lesssim 10^4 - 10^5$ years old), it is still inside the supernova remnant (SNR) created by the progenitor explosion, and the expansion of the PWN inside the SNR creates a "composite SNR" (Helfand & Becker 1987). As described in §2, not only do such systems allow us to study the generation and properties of the pulsar wind for the most energetic neutron stars, they can be used to determine the neutron star's initial spin period and the mass and initial kinetic energy of the supernova ejecta – important quantities for understanding how neutron stars are formed in these explosions. As described in §3, in binary systems the PWN is produced by the interaction between the neutron star's pulsar wind and its companion. By studying such PWNe, one can measure the properties of the pulsar wind under very different conditions than in composite SNRs and gain valuable insight into the last stages of the formation of millisecond pulsars (MSPs). Last, but not least, as described in §4, older neutron stars moving supersonically through the interstellar medium (ISM) also produce PWNe. Studying these PWNe is important for understanding the magnetic field structure of the pulsar, and how it interacts with its surroundings.

Therefore, PWNe play an important role in many areas of astrophysics – from the explosion mechanism of core-collapse supernovae to the physics of magnetized plasmas to the acceleration of particles in many different physical conditions. As described in §5, the significant improvements in collecting area and observing capabilities promised by the SKA1 and SKA 2 has the potential to revolutionize this field by increasing the number of well-studied PWNe by $\sim 10 - 100\times$, allowing for the statistical studies needed to answer the above questions.

2. Composite Supernova Remnants

When the pulsar wind leaves the neutron star magnetosphere, it is thought to be a primarily equatorial outflow comprised of regions of alternating magnetic field polarity whose energy is mainly in the form of magnetic fields (e.g., Bogovalov 1999). The confinement of the pulsar wind by the surrounding medium creates a "termination shock," where the "cold" pulsar wind is converted to a "hot" outflow (e.g., Kennel & Coroniti 1984). The PWN is then formed by the expansion of the shocked, now particle dominated, pulsar wind into the surrounding medium. The significant fraction of Galactic TeV γ-ray sources associated with PWNe ($\sim 40\%$; Wakely & Horan 2008) requires that these objects produce extremely high energy particles. While observations support this general picture, many basic questions remain unanswered: How is the pulsar wind generated in the magnetosphere? What is responsible for converting the pulsar wind from a magnetically dominated to a particle dominated outflow? How are particles accelerated in these objects?
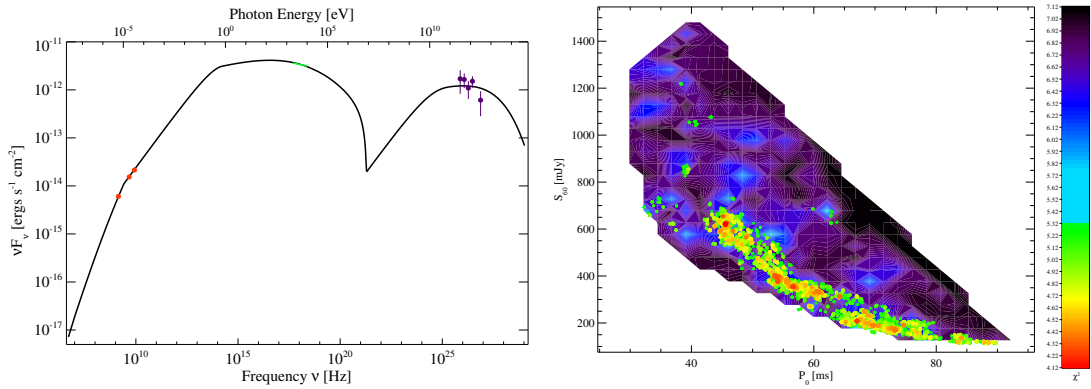
Figure 1: *Left*: Broadband SED of PWN G54.1+0.3 overlaid with the best fit model SED. *Right*: The model-predicted 60 MHz flux density S_{60} of G54.1+0.3 as a function of the initial spin period P_0 of the central pulsar. The color bar indicates the χ^2 of the model fit to the observed data, with red (lower χ^2) indicating a better fit (Gelfand et al. submitted).

Answering these questions requires studying, in detail, the PWNe produced by the youngest, and most energetic, neutron stars. Understanding how particles are created in the neutron star's magnetosphere requires measuring the total number of particles produced by a pulsar over its lifetime. This is possible only for pulsars whose PWN is detected at both radio and γ-ray energies (e.g., de Jager 2007; Gelfand et al. submitted). Currently, only ~ 10 pulsars meet these criteria (e.g., Roberts 2004), with the SKA and the Cerenkov Telescope Array (CTA), this number could increase by a factor of $\sim 5-10\times$ (§5). Ions in the pulsar wind can explain both the high acceleration efficiency of PWNe (e.g., Amato & Arons 2006) and the detection of variable "wisps" near the termination shock of several PWNe (e.g., Spitkovsky & Arons 2004), as can magnetic reconnection in the pulsar wind before (e.g., Kirk & Skjæraasen 2003), at (e.g., Lyubarsky 2003), or after the termination shock (e.g., Porth et al. 2013). Distinguishing between these models requires sensitive measurements of a PWN's radio polarization structure and spectrum (e.g., Olmi et al. 2014). Currently, this is possible for maybe a handful of PWNe – too few to draw any strong conclusions. With the SKA, it should be possible for dozens (§5).

As mentioned in §1, when a neutron star is young and most energetic, it is likely inside the SNR produced by the progenitor explosion. In this case, the evolution of a PWN is sensitive to the initial spin period of the central neutron star as well as the mass and initial kinetic energy of the supernova ejecta (e.g., Chevalier 2005; Gelfand et al. 2009). This can be done using models for the evolution of a PWN inside a SNR (Figure 1, e.g., Gelfand et al. submitted), but requires measuring the current spin-down luminosity and characteristic age of the central neutron star, the radio, X-ray, and γ-ray spectrum of the PWN, and the radius of the surrounding SNR. Currently, only ~ 10 composite SNRs meet this criteria (e.g., Bucciantini et al. 2011; Torres et al. 2014), since only $\sim 50\%$ of all PWNe are associated with a pulsar (e.g., Roberts 2004), $< 50\%$ of these are associated with a SNR, and many of the remaining PWNe detected at γ-ray energies (e.g., Ferrand & Safi-Harb 2012) are undetected in the radio. Even worse, a precise estimate of the initial spin-period requires measuring the braking index of the central pulsar (e.g., Gelfand et al. 2014), currently accomplished for < 5 sources. As described in §5, the SKA could increase this number by $\sim 5-10\times$, enabling one to directly test different models for the formation of neutron stars in

core-collapse supernovae (e.g., Watts & Andersson 2002; Blondin & Mezzacappa 2007).

Lastly, as mentioned above, PWNe dominate the luminous TeV γ-ray population of the Milky Way (Carrigan et al. 2013), with TeV PWNe typically associated with pulsars whose characteristic ages are $t_{ch} \lesssim 10^5$ years (Wakely & Horan 2008). Therefore, the majority of these pulsars, and PWNe, will be inside the SNR of their progenitor explosion even if this SNR is not detected. With the SKA1 and SKA2, we will determine if this is true for the considerable number of currently unidentified Milky Way TeV sources, by discovering a coincident "young" radio pulsar, diffuse, flat spectrum radio emission characteristic of a PWN, and/or a surrounding steep-spectrum shell suggestive of a SNR. Additionally, the SKA1 and SKA2 will discover PWNe around energetic pulsars whose radio beams do *not* point towards the Earth. For all these objects, the flux densities measured by SKA1-LOW will allow us to estimate their initial periods even if pulsed emission is not detected.

3. Neutron Star Binaries

If a neutron star is in a binary system, the highly relativistic "pulsar wind" powered by its rotational energy will interact with its companion. The interaction between the neutron star's pulsar wind and its stellar companion leads to an intrabinary shock which possibly accelerates particles to high energies (e.g., Bogdanov et al. 2011), filling the system with plasma. Evidence for plasma production in pulsar binaries has been observed from high-mass X-ray binaries (e.g., Moldón et al. 2014) to "black widow" and "redback" systems (e.g., Roberts et al. 2014), where the pulsar wind actually ablates material from the companion star (Figure 2, e.g., Fruchter et al. 1988). Studying the intrabinary plasma probes the pulsar wind much closer to the neutron star magnetosphere (Pétri & Dubus 2011) than the systems described in §2, where extremely different conditions may prevail. In fact, analysis of one binary pulsar system suggests the wind is strongly magnetized in this regime (Bogdanov et al. 2011), while the study of the PWNe described in §2 require a weakly magnetized wind further from the neutron star. If correct, this places strong constraints on models for magnetic reconnection in the pulsar wind (§2), the currently leading theory for particle acceleration in these systems (e.g. Kirk & Skjæraasen 2003).

Typically, such studies require detecting orbitally-modulated non-thermal X-ray emission from the binary (e.g., Bogdanov et al. 2011), not achievable with a radio telescope like the SKA. However, as described in §5, the collecting area of the SKA2 could increase by $> 10\times$ the number of binary pulsars – providing much needed targets for these X-ray studies. Additionally, inhomogeneities and/or free-free absorption in the cloud of plasma generated at the intrabinary shock is believed to be responsible for the "eclipses" in the pulsed radio emission (Fig. 2) observed from ~ 50 binaries pulsars (Roberts 2013; Freire 2013). By simultaneously measuring the pulsed and unpulsed continuum radio flux of these systems, it is possible to determine the density, geometry, and filling factor of this plasma as well as the structure of its magnetic field – especially if there are simultaneous or contemporaneous γ-ray observations. With the SKA1 and SKA2, we expect to make such measurements for ~ 300 eclipsing binaries (§5), allowing one to determine how the properties of the plasma produced in this interaction depend on the characteristics of the neutron star and binary system (e.g., neutron star spin-down luminosity, binary separation, companion mass and radius).
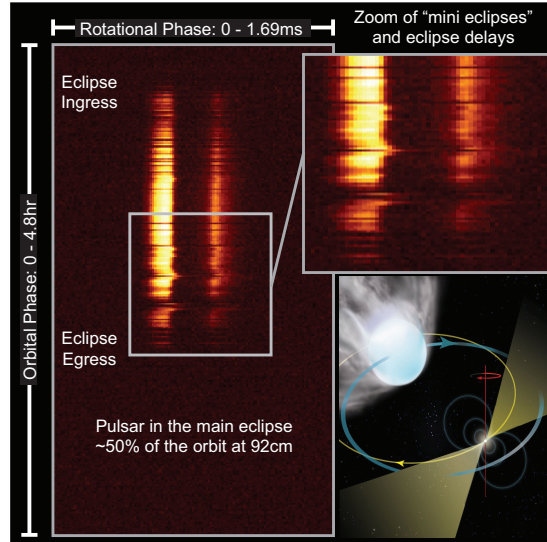
Figure 2: Eclipses in the pulsed radio emission from PSR J1023+0038 (Hessels, priv. comm.) as well as an artist's impression of the cloud of plasma resulting from the ablation of its low-mass companion by its pulsar wind (Bill Saxton, NRAO).

Lastly, the recent discovery of several millisecond pulsars (MSPs) / low mass X-ray binaries (LMXBs) transitioning between an "accretion"-dominated phase where no radio pulsations are detected and a MSP phase which shows no evidence for accretion (e.g., Archibald et al. 2009; Bassa et al. 2014; Papitto et al. 2013; Stappers et al. 2014) promises important insight into the formation of MSPs as well as understanding accretion onto magnetized neutron stars. Since studies of intermittent pulsars strongly suggest that the emission of radio pulses is connected to their loss of rotational energy (e.g., Young et al. 2013; Li et al. 2014), the physical mechanism responsible for generating a pulsar wind likely plays an important role in this transition. Only by studying the radio and higher energy (X-ray, γ-ray) properties of such systems will it be possible to understand the interplay between accretion and a neutron star's magnetosphere. As described in §5, the potential multi-beam and high-frequency capabilities of the SKA are critical for understanding the physics of these transitions which may comprise the final stage in the formation of a MSP (though some systems might be stuck transitioning back-and-forth to a LMXB state).

4. Isolated Pulsars in the Interstellar Medium

The pulsar winds of isolated, older neutron stars will also significantly impact their surrounding. In this case, the pulsar wind is confined by the ram pressure created by the neutron star's supersonic motion. The morphology (e.g., Vigelius et al. 2007) and the magnetic field structure (e.g., Bucciantini et al. 2005) of such PWNe are sensitive to the density structure of the ISM, the speed and direction of the neutron star's spatial velocity, and the geometry of its pulsar wind. Additionally, X-ray observations suggest such PWNe efficiently inject high-energy particles into the surrounding ISM, often in directions misaligned with the neutron star's proper motion (e.g., Bandiera (2008); De Luca et al. (2013); Marelli et al. (2013); Pavan et al. (2014)).

Understanding the structure of these pulsar winds, and how high energy particles escape the PWN, requires mapping the polarized radio emission for a range of neutron star and ISM properties. Currently, this is possible for $\lesssim 5 - 10$ systems, but even this small sample shows significant diversity in their magnetic field structure – for example, the "Frying Pan" (G315.9$-$0.0) PWN has
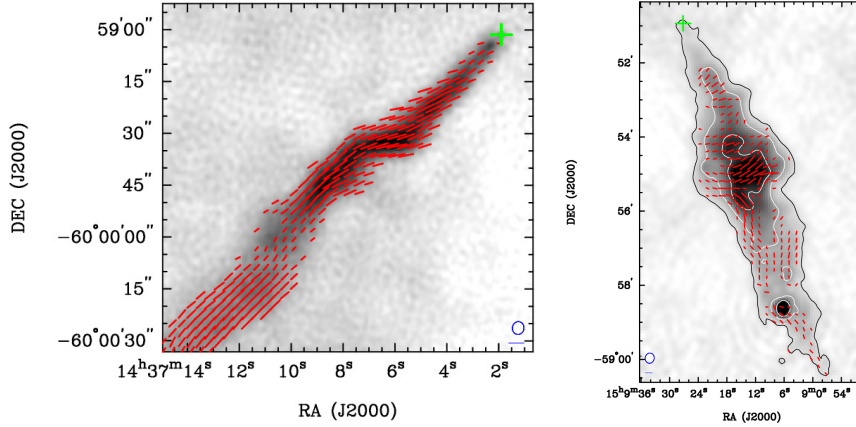
Figure 3: The radio nebulae G315.9−0.0 (*left*; Ng et al. 2012) and G319.9−0.7 (*right*; Ng et al. 2010. The location of the associated pulsars are indicated by the green crosses, while the polarization $\vec{B}$-vector is shown by the red lines.

a magnetic field aligned with the pulsar's proper motion (Ng et al. 2012), while the magnetic field of G319.9−0.7 has a helical structure Ng et al. (2010) (Figure 3) – suggesting a dependence on the flow conditions, pulsar speed, and/or misalignment between the pulsar rotation axis and proper motion. Understanding the relationship between these different physical parameters requires measuring the magnetic field structure of many more PWN which, as described in §5, will become possible with the SKA.

5. Requirements for SKA1 and SKA2

Thanks to the considerable improvement in sensitivity promised by the SKA1 and the SKA2, these instruments should be capable of measuring the radio morphology, spectrum, and polarization properties of ~ 100 PWNe – a significant improvement over the ~ 10 for which such measurements exist, and increase the number of eclipsing binary pulsars from ~ 50 to ~ 300. Such sample sizes are needed to determine how a neutron star's spin-down luminosity, age, and environment affects the evolution of its PWN. Additionally, the SKA1 and especially SKA2 will be able to measure properties of a PWN never before possible. These studies depend less on the collecting area of the SKA1, and therefore are more immune to a 50% reduction of its capabilities, but on the configuration and capabilities of its telescopes as described below:

Discover pulsars: Currently, $\sim 40 - 50\%$ of PWN candidates are unassociated with a pulsar in any waveband (Roberts 2004), problematic for the analyses discussed in §2 and §4. While beaming explains some of the missing pulsars, for many PWNe it likely results from the limitations of current observatories. The large collecting area of the SKA1-LOW should increase the number of pulsars detected in nearby PWN, but the high dispersion measure (DM) and scattering timescales expected for pulsars on the far side of the Milky Way require that the SKA1-MID also be able to detect pulsars.

Monitor a PWN's pulsed and unpulsed radio emission: Monitoring the timing properties of young, isolated pulsars is needed to measure their braking indices which, as described in §2, is critical for estimating their initial spin period. For eclipsing binary pulsars, monitoring the pulsed

emission allows one to detect changes in the orbital phase and length of radio eclipses changes, and monitoring the pulsed emission of MSP/LMXB is critical for determining if the pulsed radio emission disappears before or after the resumption of accretion onto the neutron star (§3). Both the SKA1-LOW and SKA1-MID require these capabilities since the possible presence of dense plasma in these systems will result in frequency dependent behavior. Additionally, observations of young PWNe every few months are required to measure the variability of "wisps" near the termination shock, critical for determining if ions are present in the pulsar wind (§2). Since these wisps are only a few arcseconds in size (e.g., Bietenholz et al. 2004), this is best done with the higher frequencies of SKA1-MID.

Conduct pulsar gating and VLBI observations: While all pulsars are believed to generate a PWN, radio PWNe are detected around $< 10\%$ of young, energetic pulsars. One possibility is that the radio PWN is masked in continuum observations by the pulsar's pulsed emission. With pulsar gating, it is possible to image the region when the pulsar is "off", making it possible to detect faint radio PWNe (Gaensler et al. 1998). This is particularly important for SKA1-LOW, due to its lower angular resolution and increased brightness of the pulsar relative to the PWN. Pulsar gating of eclipsing binary pulsars allows simultaneous measurements of its pulsed and unpulsed flux, critical for determining the eclipsing mechanism (§3), and significantly improves measurements of a pulsar's parallax and proper motion in VLBI observations – important for measuring the initial spin periods of young pulsars in composite SNRs (e.g., Gelfand et al. submitted) and interpreting the morphology of "bow shock" PWNe (§4).

Observe PWNe across a broad range of frequencies: The broadband radio spectrum of a PWN inside a SNR is expected to have numerous features (e.g., Gelfand et al. 2009). The minimum particle energy injected at the termination shock will result in a "break" at low ($\nu \lesssim 1$ GHz) frequencies, and measuring its flux density below this break is critical for estimating the initial spin period of the central neutron star (e.g., Gelfand et al. submitted; Figure 1). Ions in the pulsar wind and/or magnetic reconnection downstream of the termination shock (§2) is expected to lead to broad "bumps" in the spectrum at higher frequencies ($\nu \gtrsim 10$ GHz; Olmi et al. 2014). Continuous frequency coverage between the different SKA1 and SKA2 observing bands would improve measurements of curvature in the PWN's radio spectrum.

Detect emission on large angular scales: The non-detection of many TeV PWNe at radio wavelengths (e.g., Ferrand & Safi-Harb 2012) and SNRs around young pulsars / PWNe (e.g., Roberts 2004) likely results from the large angular size ($\sim 30' - \lesssim 1°$) and low radio surface brightness of these objects. Current radio interferometers do not have the short baselines needed to detect emission on these angular scales, and single-dish telescopes do not have the sensitivity needed to detect this emission over the Galactic background. While SKA1-LOW and SKA1-MID will have the needed sensitivity, a dense core is required to detect emission on the needed angular scales.instantaneous SKA1-LOW single beam

Measure the polarization properties of PWNe: Last, but not least, mapping the magnetic field structure of young (§2) and old (§4) PWNe requires spatially resolved measurements of their polarized intensity and direction at multiple frequencies to both correct for foreground Faraday rotation

and detect changes in its rotation measure (e.g., Ng et al. 2010). Furthermore, measuring changes in the DM during the "eclipse" of a binary pulsar (e.g., Archibald et al. 2013) are important for measuring the density and magnetic field structure of the intervening plasma (§3). These observations require high polarization purity of both SKA1-LOW and SKA1-MID, and sensitivity to polarized emission over a small bandwidth or at higher ($\nu > 1$ GHz) frequencies to avoid bandwidth depolarization, especially for SKA1-MID. Furthermore, since a PWN's radio emission can be highly linearly polarized, an all-sky polarization survey with the SKA1-SUR could identify new PWNe, particularly around older, isolated pulsars.

References

Amato, E. & Arons, J. 2006, ApJ, 653, 325

Archibald, A. M. et al.. 2013, ArXiv e-prints: 1311.5161

—. 2009, Science, 324, 1411

Bandiera, R. 2008, A&A, 490, L3

Bassa, C. G. et al.. 2014, MNRAS, 441, 1825

Bietenholz, M. F. et al.. 2004, ApJ, 615, 794

Blondin, J. M. & Mezzacappa, A. 2007, Nature, 445, 58

Bogdanov, S. et al.. 2011, ApJ, 742, 97

Bogovalov, S. V. 1999, A&A, 349, 1017

Bucciantini, N. et al.. 2005, A&A, 434, 189

—. 2011, MNRAS, 410, 381

Carrigan, S. et al.. 2013, ArXiv e-prints: 1307.4690

Chevalier, R. A. 2005, ApJ, 619, 839

de Jager, O. C. 2007, ApJ, 658, 1177

De Luca, A. et al.. 2013, ApJ, 765, L19

Faucher-Giguère, C.-A. & Kaspi, V. M. 2006, ApJ, 643, 332

Ferrand, G. & Safi-Harb, S. 2012, Advances in Space Research, 49, 1313

Freire, P. 2013, http://www.naic.edu/ pfreire/GCpsr.html

Fruchter, A. S. et al.. 1988, Nature, 333, 237

Gaensler, B. M. et al.. 1998, MmSAI, 69, 813

Gelfand, J. D. et al.. 2014, Astronomische Nachrichten, 335, 318

—. submitted, ApJ

—. 2009, ApJ, 703, 2051

Goldreich, P. & Julian, W. H. 1969, ApJ, 157, 869

Helfand, D. J. & Becker, R. H. 1987, ApJ, 314, 203

Kennel, C. F. & Coroniti, F. V. 1984, ApJ, 283, 694

Kirk, J. G. & Skjæraasen, O. 2003, ApJ, 591, 366

Li, L. et al.. 2014, ApJ, 788, 16

Lyubarsky, Y. E. 2003, MNRAS, 345, 153

Marelli, M. et al.. 2013, ApJ, 765, 36

Moldón, J. et al.. 2014, International Journal of Modern Physics Conference Series, 28, 60173

Ng, C.-Y. et al.. 2012, ApJ, 746, 105

—. 2010, ApJ, 712, 596

Olmi, B. et al.. 2014, MNRAS, 438, 1518

Papitto, A. et al.. 2013, Nature, 501, 517

Pavan, L. et al.. 2014, A&A, 562, A122

Pétri, J. & Dubus, G. 2011, MNRAS, 417, 532

Porth, O. et al.. 2013, MNRAS, 431, L48

Roberts, M. S. E. 2004, http://www.physics.mcgill.ca/ pulsar/pwncat.html

Roberts, M. S. E. 2013, in IAU Symposium, Vol. 291, IAU Symposium, ed. J. van Leeuwen, 127–132

Roberts, M. S. E. et al.. 2014, Astronomische Nachrichten, 335, 313

Spitkovsky, A. & Arons, J. 2004, ApJ, 603, 669

Stappers, B. W. et al.. 2014, ApJ, 790, 39

Torres, D. F. et al.. 2014, Journal of High Energy Astrophysics, 1, 31

Vigelius, M. et al.. 2007, MNRAS, 374, 793

Wakely, S. P. & Horan, D. 2008, International Cosmic Ray Conference, 3, 1341

Watts, A. L. & Andersson, N. 2002, MNRAS, 333, 943

Young, N. J. et al.. 2013, MNRAS, 429, 2569