Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Nuclear and Particle Physics Proceedings 00 (2018) 1–??

Nuclear and Particle Physics Proceedings

Neutron Stars as Particles' Accelerators

Patrizia A. Caraveo

INAF-IASF, Via E. Bassini, 15 - 20133 Milano - Italy

INFN, Sezione di Pavia, Via U. Bassi 6 - 27100 Pavia - Italy

Abstract

According to standard theoretical interpretations, in neutron stars' magnetospheres particles are accelerated along the magnetic field lines where the highly-magnetized surrounding offers the ideal conditions to make them radiate high-energy gamma-rays (E ≥ 100 MeV) that bear the timing signature of their parent neutron star. Moreover, the accelerated particles (mostly electrons and positrons) can either move outward, to propagate into space, or be funnelled back, towards the star surface. While particles impinging on the neutron star surface generate hot spots, detectable in X-rays, outgoing ones could light-up the neutron star surroundings giving rise to extended features, visible both in X-and in Very-High-Energy (VHE) gamma-rays (E ≥ 100 GeV) .
By combining gamma-ray light curves and spectra with the X-ray emission, both thermal (from the hot spots) and non thermal (from somewhere in the magnetosphere) we can try to map the emission geography within the light cylinder. Moreover, we can trace the particles' propagation outside the neutron stars' magnetospheres through their synchrotron emission, responsible for X-ray extended features, and their VHE gamma-rays inverse Compton emission, which give rise to extended sources, whose shapes, however, appear different from that of the corresponding X-ray ones since they are produced by particles of different energies.

Keywords: Neutron stars; pulsars; acceleration; gamma-ray emission; hot spots; Pulsar Wind Nebulae

1. Introduction

Isolated neutron stars (INSs) are natural particle accelerators. Their, presumably dipolar, rapidly rotating magnetic fields, naturally inclined with respect to the star rotation axis, induce electric fields ideally suited to accelerate particles already present in the stars' magnetospheres or extracted from the crusts. Following the seminal paper of Goldreich & Julian (1969) and Sturrock (1971), a lot has been done to work out the details of such an acceleration, focusing on its most likely location(s) inside the INS magnetosphere and on its efficiency. Traditionally, two classes of models have been developed: on one side the polar cap ones(Ruderman & Sutherland 1975; Harding & Daugherty; 1998, Rudak & Dyck 1999), where the acceleration takes place near the star surface, just above the magnetic pole; on the other hand , the outer gap ones (Romani 1996), where the acceleration is taking place in the outer magnetosphere, not far from the light cylinder. Later, the slot gap model, extending from the polar cap to the light cylinder, has been added as a third alternative (Muslinov & Harding 2003; Harding, 2005). Including special relativity effects in the slop gap model, Dyck & Rudak (2003) developed e two-pole caustic model. In parallel, locations outside the light cylinder have also been considered such as in the striped wind model propose by Coroniti (1990) and, more recently, by Petri (2012). Notwhistanding important differences between models, the interaction between accelerated particles (typically electrons) and the star magnetic field results in the production of high energy gamma-rays which, in turn, are not able to escape the highly magnetic environment and are converted into electron positron pairs. This initiates a cascade rapidly filling the magnetosphere with energetic particles which, interacting with the magnetic field, are responsible for the vast majority of the INSs' multiwavelength phenomenology.

We can trace the path of the accelerated particles through their X and gamma-ray emissions which are produced in different locations ranging from the INS surface to its magnetosphere to elongated jet-like features protruding into the interstellar medium.

2. An overview

INSs are mainly studied through their non thermal radio emission. Radio searches have been highly successful and the current radio catalog list more than 2500 pulsars[1].

In spite of the sheer number of objects and their very diverse phenomenology, INS radio emission accounts for a negligible fraction of the star rotational energy loss. A far more important fraction of the star energy reservoir goes into high-energy radiation, mainly in high-energy gamma-rays. While the number of objects shrinks to about 1% of the radio ones [2], in gamma rays the INSs' luminosity can reach a sizeable fraction of the total rotational energy loss (Caraveo 2014).

The rich INSs' phenomenology encompasses also X and optical emissions, as well as VHE gamma-ray one. While the numbers of INSs seen in X-ray is slightly lower than that of the gamma-ray ones (Becker 2009; Marelli, 2012), in optical we are down to about dozen objects (Mignani et al. 2004; Mignani 2011) and in VHE gamma-rays only Crab and Vela have been detected as pulsating sources (Aliu et al. 2008; Aliu et al, 2011; Djannati-Atai et al. 2017) while few dozens have been seen to power their pulsar wind nebulae in VHE gamma-rays (Carrigan et al. 2013; Klepser et al. 2013; Acero et al. 2013).

In the optical, as well as in X-rays, aged neutron stars exhibit both thermal and non-thermal emissions. Indeed, when non-thermal emission somewhat weakens with age, the thermal one begins to emerge to tell the story of the cooling crust of the neutron star.
INS thermal emission, however, is not totally unrelated to the magnetospheric particle acceleration. Depending on their electric charge, particles move in different directions along the magnetic field lines. While those moving outward try to escape the INS magnetosphere, those moving inward hit the star and heat its crust at well defined spots, that, under the assumption of a dipolar magnetic field, should coincide with its polar caps (return currents, see e.g. Ruderman & Sutherland 1975; Arons & Scharlemann 1979). Thus, thermal emission could be of use to trace non-thermal phenomena.

The escaping particles, on the other side, are part of the neutron stars' relativistic wind which is supposed to account for the bulk of their observed rotational energy loss.

Such relativistic wind can be traced through its interaction with the interstellar medium (ISM), both in the immediate surroundings of the stars, where the INS magnetic field is still important, or farther away, where the wind radiation pressure is counterbalanced by the shocked ISM. An important player to determine the shape and the phenomenology of the resulting Pulsar Wind Nebula (PWN) is the actual neutron star speed. INSs are known to be high velocity objects and, plunging supersonically through the ISM, they can give rise to a rich bow shocks phenomenology seen in the radio, optical and X-ray domains (e.g. Chatterjee & Cordes, 2002, Kargaltsev et al., 2015). Modelling the electron spectrum at the termination shock, allows Vorster et al (2013)to make proediction on the PWNs' non-thermal radiation.

3. Particles in the magnetosphere: Gamma-ray emission

Isolated Neutron Stars have been the first identified sources in the field of high-energy gamma-ray astronomy. At first, in the 70, there were only the Crab and Vela pulsars. Although few in number, they were crucial to establish the very concept of gamma-ray source. Moreover, they opened a significant space for discovery both from the theoretical and from the phenomenological sides. The need to explain their copious gamma-ray emission fostered break-through developments in understanding the structure and the physics of their magnetosphere. In parallel, the 20 year long chase for Geminga (Bignami & Caraveo, 1996) unveiled the existence of a radio-quiet, gamma-ray emitting, isolated neutron star, adding a new dimension to the INS family. Today we are living through an extraordinary time of discovery. The current generation of gamma-ray detectors have boosted the detections of gamma-ray emitting neutron stars passing the 200 mark, and counting (the second pulsar catalog, encompassing 117 objects, has been published in Abdo et al. (2013), while an up to date list of Fermi detected gamma-ray pulsars can be seen at the site given in footnote n.2). The gamma-ray emitting neutron star population exhibits a comparable number

[1] http://www.atnf.csiro.au/research/pulsar/psrcat/

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

of radio-loud and radio-quiet young INSs (with a somewhat higher number of radio quiet objects) with an astonishing, and unexpected, contribution from millisecond pulsars (MSPs), both isolated and in binary systems, whose number has been steadily growing making them the most numerous representatives of the gamma-ray emitting INS family (Caraveo, 2014)

A gamma-ray pulsar is characterized by both its light curve and its spectrum. Of course these are not independent variables since the photons energy distribution determine the shape of the light curve at different energies. However, on average, gamma-ray pulsars' spectra tend to be quite similar and can be described by a power law with an exponential cut off at few GeV. The cut-off parameter b is compatible with b=1 and rules out hyper-exponential absorption which could have been the signature of attenuation due to the interaction of high-energy gamma-ray photons with the strong pulsar magnetic field one would expect at low altitude. Thus, the lack of hyper-exponential absorption points to high latitude emission. This finding is strengthened by the detection of pulsed photons up to tens of GeV, an emission that must arise at R> 3.8 R_{NS} (from Baring 2004).

Thus, Fermi pulsar spectra point to emission regions in the outer magnetosphere, near to the light cylinder. A similar hint comes from the inspection of the gamma-ray pulsars' light-curves. Indeed , one immediately realizes that the majority of the pulsars (70% of the young pulsars and 60% of the MSPs) have two peaks (in short, P1-the one nearest to the radio pulse- and P2) and the ratio P2/P1 increases with energy, pointing to a harder second peak. Many double peaked pulsars display a crescent type light curve with significant emission between the two peaks (Abdo et al. 2013).

Such wealth of information on pulsars light curves represent a new challenge for theoreticians who try to constrain pulsars geometry as well as the relevant magnetospheric physics. Starting from the location(s) of the emitting region(s), namely polar cap (PC), outer gap (OG) and slot gap (SG) or its variation two-pole caustic (TPC), in a dipole geometry, one can build an atlas of predicted gamma-ray curves to be compared to the observed ones. In general, OG models yield better fits, but they are not able to account for all the detected pulsars. Lower altitude emission is preferred by a sizable minority of pulsars, especially those MSPs with aligned radio and gamma-light curves. However, with gamma-ray light-curves and spectra similar to those of young pulsars, also for MSPs the emission regions should be far from the neutron star surface. Although young pulsars and millisecond ones have vastly different B field at the star surface, the value of the B field at the light cylinder is similar pointing to a region were similar conditions naturally arise.

The detection of the Crab pulsar at E ≥ 100 GeV by Magic and Veritas (Aliu et al. 2008, 2011; Aleksic et al. 2012) is well above any reasonable extrapolation of the Fermi LAT best spectral fit, pointing to a different emission mechanism, possibly located beyond the light cylinder as discussed by Petri (2012) and by Aharonian et al. (2014). Although far from completely understood, the gamma-ray pulsar panorama seems to point to emission region in the outer magnetosphere, far from the pulsar surface.

4. Particles hitting the Star surface: Hot spots

The presence of hot spots on the surface of INSs has been long suspected on the basis of their overall X-ray spectral shape requiring more than a simple black-body to describe the data. Although all INSs should have hot spots, in order to be able to detect (and characterize) their thermal emission, copious harvest of time-tagged photons is needed. Thus, only INSs which have been the targets of long X-ray observations have yielded robust evidence for the presence of hot spots. Following the compilation of Marelli (2012), the sample of the "spotted", pulsating, young INSs encompasses about a dozen objects. Usually, to fit the X-ray spectra of such INSs two black-body curves, characterized by different temperatures and emitting areas, are needed. A slightly colder black-body, covering the majority of the INS surface, provides the bulk of the X-ray luminosity while a hotter one, covering a smaller surface, is needed to obtain a satisfactory spectral fit.

In the following I will focus on few cases where hot spots have been clearly detected through phase resolved spectroscopy. Contrary to expectations, the dimensions of such spots, as computed from their X-ray flux, vary by more than 1 order of magnitude, casting doubts on their simplistic polar cap interpretation.

Long XMM-Newton observations of Geminga, PSR B0656+14 and PSR B1055-52, three middle-aged, rather similar INSs, have shown that
a) the spectra are varying significantly throughout the rotational phase
b) the hot blackbody contribution is the most dramatically variable spectral component (De Luca et al. 2005).
The emitting radii, computed on the basis of the phase-resolved spectral fits, vary as a function of the pulsar rotational phase. Selecting the phase interval of maximum emission, and taking into account the pulsar distance values, their dimensions are : 60 m for Geminga, 460 m for PSR B1055-52 and 1,800 m for PSR B0656+14.

While for PSR B0656+14 the modulation in the emitting radius wrt. the average value is <10%, in the case of PSR B1055-52 we see a 100% modulation, since the hot blackbody component is not seen in 4 out of 10 phase intervals. A similar, 100% modulation is observed also for Geminga, although in this case the hot blackbody component disappears in just one phase interval.
Also PSR J0007+7303, a radio quiet INS inside the SNR CTA-1 (Abdo et al., 2008), known as "next Geminga" (Halpern et al. 2004) when it was an unidentified EGRET source, shows a 100% modulation for its thermal X-ray emission (Caraveo et al. 2010). Its phase resolved spectral analysis has unveiled a clear variation as a function of the pulsar' rotational phase. Such variation can indeed be ascribed to a thermal component coming from a hot spot of 600 m radius, while no emission from the bulk of the INS surface, presumably cooler (and larger) has been detected.

It is natural to interpret such marked variations as an effect of the star rotation, which alternatively brings into view or hides one or more hot spots on the star surface. As outlined above, such hot spots arise when charged particles, accelerated in the magnetosphere, fall back to the polar caps along magnetic field lines. Straight estimates of neutron star polar cap sizes, based on a simple "centred" dipole magnetic field geometry (polar cap radius $R_{PC} = R\sqrt{\frac{R\Omega}{c}}$), where R is the neutron star radius, Ω is the angular frequency and c is the speed of light), predict very similar radii for the four neutron stars, characterized by similar periods (233 m for PSR B0656+14, 257 m for PSR J0007+7303, 297 m for Geminga, 326 m for PSR B1055-52, assuming a standard neutron star radius of 10 km). The observed radii are instead markedly different, with values ranging from $\sim$ 60 m for Geminga to $\sim$2 km for PSR B0656+14 (see De Luca et al. 2005 for a detailed discussion). A different situation is found for PSR J0007+7303 wich sports a 600 m hot spot, roughly the double than its theoretical polar cap, but lack the accompanying emission the entire surface of any reasonable INS.
Indeed, the tiny dimension of Geminga's hot spot points to a grazing incidence angle of our line of sight. Such inclination of the polar cap wrt our line-of sight could explain the lack of radio emission, traditionally located above the polar cap.

5. Particles escaping in the ISM: Tails, Jets, Nebulae

When the particle wind from a fast moving INS interacts with the surrounding ISM, it gives rise to complex structures, globally named "Pulsar Wind Nebulae" (PWNe) where $\sim 10^{-5} - 10^{-3}$ of the INS $\dot{E}_{rot}$ is converted into electromagnetic radiation (for reviews see Gaensler & Slane, 2006, and Kargaltsev et al. 2015). The study of PWNe may therefore give insights into aspects of the neutron star physics which would be otherwise very difficult to access, such as the geometry and energetics of the particle wind and, ultimately, the configuration of the INS magnetosphere and the mechanisms of particle acceleration. Moreover, PWNe may probe the surrounding medium, allowing one to measure its density and its ionisation state.

A basic classification of PWNe rests on the nature of the external pressure confining the neutron star wind (e.g. Pellizzoni et al. 2005). For young INSs (< few 10^4 y) the pressure of the surrounding supernova ejecta is effective and a "static PWN" is formed. For older systems (> 10^5 y) the neutron star, after escaping the eventually faded supernova remnant, moves through the unperturbed ISM and the wind is confined by ram pressure to form a "Bow-shock" PWN.

Static PWNe (Slane 2005, for a review) usually show complex morphologies. Striking features such as tori and/or jets (as in the Crab and Vela cases), typically seen in X-rays (Kargaltsev & Pavlov, 2008), reflect anisotropies of the particle wind emitted by the energetic, central INS and provide important constrains on the geometry of the system. A remarkable axial symmetry, observed in several cases, is assumed to trace the rotational axis of the central INS. For the Crab and Vela PWNe, such an axis of symmetry was found to be coincident with the accurately measured direction of the INS proper motion (Caraveo & Mignani 1999; Caraveo et al. 2001). This provided evidence for an alignment between the rotational axis and the proper motion of the two neutron stars, with possible important implications for the understanding of supernova explosion mechanisms (Lai et al. 2001). The alignment between spin axis and space velocity, directly observed only for Crab and Vela, is now assumed as a standard property of INSs (Ng & Romani 2004).

Bow-shocks (for a review see Pellizzoni et al. 2005, Gaensler et al 2004) have a remarkably simpler, "velocity-driven" morphology. They are seen frequently in H_α as arc-shaped structures tracing the forward shock, where the neutral ISM is suddenly excited. In other cases, X-ray emission (and/or radio emission on larger scales) is seen, with a cometary shape elongated behind the neutron star, due to synchrotron radiation from the shocked INS particles downstream. According to the lower energetics of the central, older INS, bow shocks are typically fainter than static PWNe and proximity is a key parameter for their observation. However, for typical nebular magnetic field intensities (B between 1 and 100 microG), synchrotron photons with energy about 1 keV are produced by electrons with Lorentz factor in the range (0.3 – 3) 10^8. For electrons with Lorenz factor 10 times lower, synchrotron emission falls in the infrared, optical and UV frequencies. However, such electrons can produce photons with energies up to tens of TeV via inverse Compton scattering of the ambient photon field. The Cosmic Background Radiation, the dust-scattered light, and the starlight provide the target photons for inverse Compton scattering, with typical photon energies around $10^{-3}-10^{-2}$ eV, and 1 eV, respectively. In the Thompson regime, photons with energy about 1 TeV are produced by electrons with Lorentz factor in the range (0.1 – 3) 10^7. Due to their different energies, the cooling time of the X-ray electrons is smaller than the one of the gamma-ray electrons. Thus, the X-ray emission traces the recent history of the nebula, whereas the gamma-ray emission traces a longer history, possibly up to the pulsar birth (Mattana et al. 2009). This is why PWNe are such prominent, extended sources in the VHE sky as shown by the H.E.S.S. Galactic Plane Survey (Carrigan et al., 2013; Klepser et al., 2013; Donath et al. 2017)

6. Geminga as a test case

The observational evidence on the presence of high energy electrons/positrons in the magnetosphere of Geminga is manyfold. First, the gamma-ray light-curve whose > 100 MeV photons (Abdo et al. 2010) could not have been produced without high energy particles and magnetic fields.
Next, deep and repeated X-ray observations which yielded both
a) the evidence for the presence of minute hot spot(s) varying throughout the pulsar phase (Caraveo et al. 2004)
b) the detection of elongated tails, trailing the pulsar in its supersonic motion through the ISM and perfectly aligned with the proper motion direction (Caraveo et al. 2003; De Luca et al. 2006; Pavlov et al. 2010; Posselt et al. 2017). The flat spectral shape of the tails' X-ray photons suggests a synchrotron origin which, combined with the typical magnetic field present in a shocked ISM, implies the presence of $\sim 10^{14}$ eV electrons/positrons, i.e. of particle at the upper limit of the energy range achievable for an INS like Geminga. Moreover, the lifetime of such electrons (or, more precisely, the time it takes for them to lose half of their energy) in the bow-shock magnetic field is $\sim$ 800 years. On the other hand, Geminga's proper motion (170 mas/year, Bignami et al. 1993) allows one to compute the time taken by the pulsar and its bow shock to transit over the apparent length of the X-ray structures in the sky (3' from the central source). Such a time is close to 1,000 years. Thus, Geminga's tails remain visible for a time comparable to the electron synchrotron X-ray emission life time after the pulsar passage. The comet-like structure seen by Chandra (De Luca et al, 2006, Pavlov et al, 2010) is as luminous as the larger and fainter tails and its spectrum is equally hard. Recent analysis of a series of Chandra observations have unveiled intriguing hints of variability, especially in the short, comet-like trail (Posselt et al. 2017)

Hot spot(s), elongated, faint tails and short, brighter trail have roughly the same luminosity, corresponding to $\sim 10^{-6}$ of its $\dot{E}_{rot}$.

We note that the morphology and hard spectrum of the Trail is reminescent of the jet-like collimated outflows structures seen in the cases of Crab and Vela (Helfand et al., 2001, Pavlov et al. 2003, Willingale et al., 2001, Mori et al. 2004) and associated to the neutron stars spin axis direction. In particular, the small Geminga's Trail can be compared to the "inner counterjet" of the Vela PSR (Pavlov et al. 2003), characterized by a similar spectrum (photon index ~1.2) and efficiency ($L_X \sim 10^{-6}\dot{E}$). The projected angle between Geminga proper motion and its backward jet is virtually null, which implies that also the pulsar spin axis should be nearly aligned with them. Geminga would thus be the third observed neutron star having its rotational axis aligned with its space velocity, after the cases of the Crab and Vela.
The whole scenario, encompassing both the large Tails and the small Trail, could therefore fit in the frame of an anisotropic wind geometry. It includes jet structures along the spin axis and relativistic shocks in the direction of the magnetic axis where most of the wind pressure is concentrated due to the near radial outflow from magnetosphere open zones.

At variance with Crab and Vela, Geminga is not detected by the current generation of VHE Cherenkov telescopes. However, climbing up in energy to reach the TeV domain, both Milagro (Abdo et al. 2007) and HAWC (Abeysekara et al. 2017) reported faint TeV emission from an extended source whose position is compatible with Geminga, although the extension is definitely much larger that that of the X-ray nebula.

7. Conclusions

The particle acceleration going on in an INS magnetosphere can now be traced from end-to-end. While gamma ray emission probes directly the particle population in the magnetosphere, using the current generation of X-ray observatories we are now able to follow the destiny of the particles traveling up and down the magnetic field lines through the study of hot spots on the star surface and of PWNe. The same process responsible for the copious gamma-ray emission of INSs would thus also be responsible for the appearance of the X-ray emissions from the hot spots on their surface and extended features in their surroundings. Moreover, the escaping particles are seen to power extended sources of very high-energy gamma-rays which, indeed, represent the majority of the sources detected by H.E.S.S. along the Galactic plane. Such number will significantly grow when the Cherenkov Telescope Array (Actis et al. 2011) will become operational at the beginning of the next decade. With better angular resolution and wider energy coverage than the current experiments, CTA will undoubtedly improve our knowledge of INSs as particles' accelerators.

References

[1] Abdo, A. A., et al.(Milagro Collaboration), 2007, Ap.J. 664, L91
[2] Abdo, A. A., et al.(Fermi Lat Collaboration), 2008, Science, 322, 1218
[3] Abdo, A.A., et al. (Fermi Lat Collaboration), 2010, Ap.J. 720,272
[4] Abdo, A.A., et al. (Fermi Lat Collaboration), 2013, Ap.J. Suppl. 208, 17
[5] Abeysekara, A. u., et al.(HAWC Collaboration), 2017, Science 6365, 911
[6] Acero, F., et al. (Fermi Lat Collaboration), 2013, Ap.J. 773, 77
[7] Actis et al (CTA Collaboration) 2011 Experim. Astr. 32, 193
[8] Aharonian, F. A., Bogovalov, S. V., Khangulyan, D. 2014, Nature 482,507
[9] Aliu, E., et al. (Magic Collaboration), 2008, Science, 322, 1221
[10] Aliu, E., et al (Veritas Collaboration), 2011, Science, 334, 69
[11] Aleksic J. et al,(Magic Collaboration), 2012, A&A, 540,69
[12] Arons, J. & Scharlemann, E.T., 1979, Ap.J. 231, 854
[13] Baring, M., 2004, Adv. Space Res. 33,552
[14] Becker. W., 2009 Neutron Stars and Pulsars, Astrophysics and Space Science Library, Springer Volume 357, 91
[15] Bignami, G.F. Caraveo, P.A. & Mereghetti, S., 1993, Nature, 361,704
[16] Bignami, G.F. & Caraveo, P.A. 1996, Ann.Rev. Astron. Astrophys. 34,331
[17] Caraveo, P.A. 2014, Ann.Rev. Astron. Astrophys. 52, 211
[18] Caraveo, P. A., De Luca, A., Marelli, M., Bignami, G. F., Ray, P. S., Saz Parkinson, P. M., Kanbach, G. 2010, ApJ 725, L6
[19] Caraveo, P.A., De Luca, A., Mereghetti, S., Pellizzoni, A., Bignami, G.F., 2004, Science 305, 376
[20] Caraveo, P.A., Bignami, G.F., De Luca, A., et al., 2003, Science 301, 1345
[21] Caraveo, P.A., De Luca, A., Mignani, R.P., Bignami, G.F., 2001, Ap.J. 561, 930
[22] Caraveo, P.A., Mignani, R.P., 1999, A&A 344, 367
[23] Carrigan, S. et al. for the H.E.S.S. collaboration, 2013, Proceedings of the 33rd International Cosmic Ray Conference (ICRC2013), Rio de Janeiro (Brazil, arXiv:1307.4690
[24] Chatterjee, S. & Cordes, J. M., 2002, Ap.J. 575, 407
[25] Coroniti, F.V., 1990, Ap.J. 349, 538
[26] De Luca, A. et al. 2005 Ap.J., 623, 1051
[27] De Luca, A. et al. 2006 A&A, 445, L9
[28] Donath, A. et al for the H.E.S.S. collaboration, 2017, AIP Conf. Proc. 1792, 040001
[29] Djannati-Atai, A., et al. for the H.E.S.S. collaboration, 2017, AIP Conf. Proc. 1792, 040028
[30] Dyks, J. and B. Rudak, 2003, Ap.J., 598, 1201
[31] Gaensler, B.M., van der Swaluw, E., Camilo, F., et al., 2004, Ap.J. 616, 383
[32] Gaensler, B.M. & Slane, P. O., 2006, Ann.Rev. Astron. Astrophys. 44,17
[33] Goldreich, P. Julian, W.H., 1969, Ap.J.,157, 869
[34] Halpern, J. P., Gotthelf, E. V., Camilo, F., Helfand, D. J., & Ransom, S. M. 2004, Ap.J., 612, 398
[35] Harding, A. K. and J. K. Daugherty, 1998, Adv. Space Res. 21, 251
[36] Harding, A. K. 2005, Proceedings of the 22nd Texas Symposium on Relativistic Astrophysics at Stanford University, Stanford, 2004, edited by P. Chen et al., eConf C041213
[37] Helfand, D.J., Gotthelf, E.V., Halpern, J.P., 2001, Ap.J. 556, 380
[38] Kargaltsev, O., Cerutti, B., Lyubarsky, Y., Striani, E. 2015 Space Science Reviews, 191, 391
[39] Kargaltsev, O., Pavlov, G. G., 2008, AIP Conference Proceedings, 983, 171
[40] Klepser, S. et al. for the H.E.S.S. collaboration, 2013 Proceedings of the 33rd International Cosmic Ray Conference (ICRC2013), Rio de Janeiro (Brazil)arXiv:1307.7905
[41] Lai, D., Chernoff, D.F., Cordes, J.M., 2001, Ap.J. 549, 1111
[42] Marelli, M., 2012 Ph.D. Thesis, arXiv:1205.1748
[43] Mattana, et al., 2009, Ap.J., 694, 12
[44] Mignani, R. P., de Luca, A., Caraveo, P. A., 2004, IAU Symposium no. 218 Ed.s Fernando Camilo and Bryan M. Gaensler. Astronomical Society of the Pacific, 2004,391
[45] Mignani, R. P., 2011, Advances in Space Research, 47, 1281
[46] Mori et al., 2004, ApJ, 609, 186
[47] Muslimov, A. G. and A. K. Harding, 2003, Ap. J. 588, 430
[48] Ng, C.-Y.,& Romani, R.W., 2004, Ap.J. 601, 479
[49] Pavlov, G.G., Teter, M.A., Kargaltsev, O., Sanwal, D., 2003, ApJ 591, 1157
[50] Pavlov, G. G., Bhattacharyya, S., Zavlin, V. E., 2010, Ap.J. 715, 66
[51] Pellizzoni, A., Mattana, F., De Luca, A., et al., 2005, "High Energy Gamma-Ray Astronomy", eds. F.A. Aharonian, H.J.Vlk, D.Horns, AIP Conference Proceedings, 745, p.371
[52] Petri, J., 2012, Mon. Not. R. Astron. Soc. 424, 2023
[53] Posselt, B., et al, 2017, Ap.J., 835, 66
[54] Romani, R. W.,1996, Ap. J 470, 469
[55] Rudak, B. and J. Dyks, 1999, Mon. Not. R. Astron. Soc. 303, 477.
[56] Ruderman, M. A. & P. G. Sutherland 1975 Ap. J 196, 51
[57] Slane, P., 2005, Adv.Sp.Res. 35, 1092
[58] Stappers, B.W., Gaensler, B.M., Kaspi, V.M., van der Klis, M., Lewin, W.H.G., 2003, Science 299, 1372
[59] Sturrock, P. A., 1971 Ap. J. 164, 529
[60] Vorster, M. J., Tibolla, O., Ferreira, S. E. S., Kaufmann, S., 2013, Ap.J. 773, 139
[61] Willingale et al., 2001, A&A, 365, L212