INTEGRAL observations of TeV plerions

Abstract Amongst the sources seen in very high gamma-rays several are associated with Pulsar Wind Nebulae (“TeV plerions”). The study of hard X-ray/soft gamma-ray emission is providing an important insight into the energetic particle population present in these objects. The unpulsed emission from pulsar/pulsar wind nebula systems in the energy range accessible to the INTEGRAL satellite is mainly synchrotron emission from energetic and fast cooling electrons close to their acceleration site. Our analyses of public INTEGRAL data of known TeV plerions detected by ground based Cherenkov telescopes indicate a deeper link between these TeV plerions and INTEGRAL detected pulsar wind nebulae. The newly discovered TeV plerion in the northern wing of the Kookaburra region (G313.3+0.6 powered by the middle aged PSR J1420-6048) is found to have a previously unknown INTEGRAL counterpart which is besides the Vela pulsar the only middle aged pulsar detected with INTEGRAL. We do not find an INTEGRAL counterpart of the TeV plerion associated with the X-ray PWN “Rabbit” G313.3+0.1 which is possibly powered by a young pulsar.

Keywords INTEGRAL observations Rotation powered pulsar wind nebulae (RPWN) TeV plerions individuals objects: PSR J1513-5908, PSR J0835-4510, PSR J1420-6048, G313.3+0.6, G313.3+0.1

1 Introduction - What are Rotation powered pulsar wind nebulae (RPWN)?

Rotation powered pulsar wind nebulae (RPWN) contain an isolated neutron star that drives a relativistic wind of particles into the ambient medium fueling an extended nonthermal emission region.

The rotational energy of the neutron star is partially transformed into a highly relativistic wind of particles that is driven into the ambient medium which (for middle aged RPWN) is potentially modified by the reverse shock of the supernova remnant ejecta [1]. A relativistic standing shock forms at a distance of typically $10^{16}$ – $10^{17}$ cm to the central object and is believed to be the site of particle acceleration. Among the possible ways of accelerating particles, the well-known Fermi acceleration mechanism has been considered to be a good candidate to explain the broad band power law distribution of the pair plasma in the downstream region.

2 Particle acceleration in RPWN

The ultrarelativistic wind with bulk Lorentz factors of about $\gamma = 10^4$ – $10^6$ terminates in a standing shock. The details of Fermi-type shock acceleration in relativistic shocks has become recently a matter of controversy. While initial calculations [2,3,4] indicated an efficient acceleration of particles following a universal power law type distribution, recent calculations have revealed substantial difficulties in accelerating particles to form a power law type particle distribution [5,6]. Moreover, detailed particle in cell distributions of shocks forming in flows with different magnetization have not been found to show any acceleration at all [7]. While the issue is currently not settled, it appears worthwhile to consider alternative mechanisms to explain the acceleration of particles in ultrarelativistic shocks. An interesting alternative has been proposed by Hoshino et al. [8], and Arons & Tavani [9] in which in the downstream region gyrating, reflecting ions dissipate energy in magnetosonic waves which are absorbed by the pair-plasma to form a power law type spectrum. An important prediction of this model is that the maximum energy achievable in this type of acceleration is given by $\gamma m_i c^2 = Z$, where $m_i$ indicates the mass and $Z$ the charge of the ions.

3 Hard X-ray emission from RPWN:
In situ tracer of particle acceleration

While the archetypal RPWN, the Crab nebula is a well studied example of a young ($t \sim 10$ kyrs) RPWN which is sufficiently bright to measure the emitted power over an extremely wide energy range, similar detailed energy spectra for middle aged RPWN ($t \sim 10$ kyrs) have not been obtained. The hard X-ray band (20 – 100 keV) and the gamma-ray band (0.1 – 100 MeV) are crucial observational windows to explore the acceleration of particles: In this energy range, we expect predominantly synchrotron emission of accelerated electrons. Moreover, the life-time of the electrons emitting in the hard X-ray band is rather limited

$$t_{1/2} = 8 \times 10^3 \text{ yrs} \left(B_4 \right)^{3/2} \left(\varepsilon = 20 \text{ keV} \right)^{-1/2}$$

with $B = B_4 \times 10^4$ G. In general, we expect unpulsed hard X-rays to be emitted only in a very confined volume close to the acceleration site.

4 INTEGRAL observations of TeV plerions

The INTEGRAL instruments have been used to observe regularly a large fraction of the Galactic disk. A rather small fraction of a few per cent of the sources detected by the INTEGRAL satellite have been identified to be young and middle-aged RPWN (see Tab. 1). We have analysed part of the archival data focussing on RPWN which have been detected as TeV plerions. In addition to already known INTEGRAL sources, we find evidence for hard X-ray emission from the newly discovered “Kookaburra” TeV plerion G313.3+0.6.

Here we present results from two mosaic images assembled of public INTEGRAL observations. Both mosaics were generated using the standard INTEGRAL offline analysis package OSA 5.0. The mosaic centered on the region of the “Kookaburra” incorporates all public INTEGRAL data up to a maximal distance of 10’ from the source position of the Kookaburra region. While Fig. 5 shows this region, Fig. 1 is a section of the same mosaic showing PSR J1513-5908, which due to the large FOV of INTEGRAL is also in this mosaic. But there are more public data for this pulsar available in the archive. The total exposure time for this mosaic is about 940 ksec. The other mosaic (Fig. 3) uses all public INTEGRAL data available for a maximal distance of 4.5’ from the position of the Vela pulsar. The total exposure time for this mosaic is 1.3 Msec.

4.1 PSR J1513-5908 (MSH 15-52)

One of the young RPWNs with only an age of about 1500 years is the powerful pulsar PSR J1513-5908 associated with the MSH 15-52 supernova remnant. The 150 ms pulsar PSR J1513-5908 is seen in the X-ray, gamma-ray and radio energy band. Fig. 1 shows the INTEGRAL mosaic for the region around PSR J1513-5908. For comparison the VHE image for this region is shown in Fig. 2. It is interesting to note, that the emission seen by INTEGRAL is possibly spatially resolved with INTEGRAL to be extended (see also Terrier et al., these proceedings).

4.2 PSR J0835-4510 (Vela)

The signal in the INTEGRAL IBIS (ISGRI) image of the Vela pulsars about 44.2 $\sigma$ (Fig. 3). Most of the emission above 20 – 60 keV is unpulsed (Hermsen et al., priv. communication). Fig. 4 shows the Vela pulsar seen with H.E.S.S. No indication for an extended emission in hard X-rays from the Vela X region is apparent (see also Horns et al.,
Table 1  Some parameters of Pulsars seen with INTEGRAL and H.E.S.S. PSR J0534+2200 and PSR J1513-5908 are young pulsars, PSR J0835-4510 and PSR J1420-6048 are middle-aged pulsars. All values except VHE and X-ray luminosities from Manchester et al. (2005) [10]. The VHE luminosities are calculated based on the power law values given in the following references: \(^{a}\) Masterson et al. 2005 [11], \(^{b}\) Aharonian et al. 2005a [12], \(^{c}\) Aharonian et al. 2006a [13], \(^{d}\) Aharonian et al. 2006b [14]. The X-ray luminosities - except for PSR J1420-6048 - are based on the power law values given in the latest INTEGRAL Reference Catalogue Version 26 [17]. Only a estimation for the X-ray flux and thus for the X-ray luminosity is possible due to the faint detection. The second VHE source in the Kookaburra region, G313.3+0.1, is not seen with INTEGRAL and therefore not listed in the table.

| Name                      | PSR J0534+2200 (Crab Nebula) | PSR J1513-5908 (MSH 15-52) | PSR J0835-4510 | PSR J1420-6048 (G313.3+0.6) |
|---------------------------|-------------------------------|-----------------------------|----------------|-----------------------------|
| \(P\) [ms]               | 33                            | 151                         | 89             | 68                          |
| \(\dot{P}\) [s/s]        | \(4.23 \times 10^{-3}\)      | \(1.54 \times 10^{-2}\)    | \(1.25 \times 10^{-3}\) | \(8.82 \times 10^{-4}\)   |
| \(\log_{10} E\) [erg/s] | 38.7                          | 37.2                        | 36.8           | 37                          |
| \(\tau\) [kyrs]         | 1.24                          | 1.55                        | 11.37          | 13                          |
| distance / [kpc]         | 2.0                           | 4.4                         | 0.29           | 7.69                        |
| \(\log_{10} L_{\text{VHE}}\) [erg/s] | \(34.4 (\text{a})\) | \(34.6 (\text{b})\) | \(32.9 (\text{c})\) | \(34.9 (\text{d})\) |
| \(\log_{10} L_{\text{X}}\) [erg/s] | \(36.6\) | \(35.2\) | \(32.7\) | \(34.6 (\text{a})\) |
| \(\text{(1TeV - 10TeV)}\) |                 |                             |                |                             |
| \(\text{(20 - 40keV)}\)  |                 |                             |                |                             |

Fig. 3  Vela pulsar seen with INTEGRAL. The significance mosaic for the energy band between 20 - 40 keV has an exposure time of 1.3 Msec. The scale is truncated below 0 and above 10 \(\sigma\).

Fig. 4  PSR J0835-4510 seen with H.E.S.S. (Figure from [13].) PSR J0835-4510 is located at position I. The white contours belong to the X-ray emission observed by ROSAT.

these proceedings). Combining spectral data of the ASCA satellite with the non-detection, we conclude that there exists a spectral cut-off in the energy range between 10 - 20 keV.

4.3 PSR J1420-6048 (Kookaburra)

The discovery of the TeV emission, associated with the two radio wings of the Kookaburra complex with H.E.S.S. [12], confirms their non-thermal nature and establishes their connection with the two X-ray pulsar wind nebulae candidates (Fig. 6). As an explanation for the Very High Energy gamma-rays inverse Compton scattering of accelerated electrons on the Cosmic Microwave Background is assumed. The INTEGRAL mosaic for the energy range of 20 - 40 keV shows a faint signal of 5\(\sigma\) at the position of the PSR J1420-6048. The pulsar PSR J1420-6048 belongs to the class of middle-aged pulsars where the RPWN interacts with the reverse shock of supernova remnant. Interestingly, there is no INTEGRAL counterpart to the “Rabbit” RPWN candidate [15, 16]. This object is presumably powered by a young (as yet not clearly detected pulsar). While the two TeV plerions show a similar morphology and energy spectrum, their X-ray properties appears to be very different.
are presumably tracing the on-going particle acceleration at the relativistic standing shock. In the frame of ion induced acceleration, the observed hard X-ray spectrum constrains the bulk Lorenz factor of the relativistic wind and its composition.

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References

1. Blondin, J. M., R. A. Chevalier, & D. M. Frierson: Pulsar Wind Nebulae in Evolved Supernova Remnants. ApJ 563, 806 (2001)
2. Kirk, J. & Schneider, P.: On the acceleration of charged particles at relativistic shock fronts. A&A 315, 425 (1987)
3. Achterberg, A., et al.: Particle acceleration by ultrarelativistic shocks: theory and simulations. MNRAS 328, 393 (2001)
4. Ostrowski, M.: Monte Carlo simulations of energetic particle transport in weakly inhomogeneous magnetic fields. I - Particle acceleration in relativistic shock waves with oblique magnetic fields. MNRAS 249, 551 (1991)
5. Niemiec, J. & Ostrowski, M.: Cosmic Ray Acceleration at Ultrarelativistic Shock Waves: Effects of a “Realistic” Magnetic Field Structure. ApJ 641, 984 (2006)
6. Lemoine, M., Pelletier, G., & Revenu, B.: On the Efficiency of Fermi Acceleration at Relativistic Shocks. ApJ 645L, 129L (2006)
7. Spitkovsky, A.: Simulations of relativistic collisionless shocks: shock structure and particle acceleration. MNRAS 249, 551 (1991)
8. Hoshino, M. et al.: Relativistic magnetosonic shock waves in synchrotron sources - Shock structure and nonthermal acceleration of positrons. ApJ 390, 454 (1992)
9. Arons, J. & Tavani, M.: Relativistic particle acceleration in plerions. ApJS, 90, 797 (1994)
10. Manchester, R.N., Hobbs, G.B., Teoh, A. et al.: The Australia Telescope National Facility Pulsar Catalogue. ApJ 129, 1993 (2005)
11. Masterson, C. et al. (for H.E.S.S. Collaboration): Observations of the Crab nebula with H.E.S.S. In: F.A. Aharonian, H.J. Völk, & D. Horns (ed.) AIP Conf. Proc. 745, High Energy Gamma-Ray Astronomy, Heidelberg (Germany), 26-30 July 2004, 617-621. American Institute of Physics, New York (2005)
12. Aharonian, F. et al. (H.E.S.S. Collaboration): Discovery of extended VHE gamma-ray emission from the asymmetric pulsar wind nebula in MSH 15-52 with HESS. A&A 435, L17 (2005a)
13. Aharonian, F. et al. (H.E.S.S. Collaboration): First detection of a VHE gamma-ray spectral maximum from a cosmic source: HESS discovery of the Vela X nebula. A&A 448, L43 (2006a)
14. Aharonian, F. et al. (H.E.S.S. Collaboration): Discovery of the two wings of the Kookaburra complex in VHE gamma -rays with H.E.S.S. accepted for publication in A&A, astro-ph/0606311 (2006b)
15. Roberts, M.S.E. et al.: The Rabbit: A Potential Radio Counterpart of GeV 11417-6100. ApJ 515, 712–720 (1999)
16. Ng, C.-Y. et al.: Two Pulsar Wind Nebulae: Chandra/XMM-Newton Imaging of GeV 11417-6100. ApJ 627, 904–909 (2005)
17. Bird, A. J. et al.: The Second IBIS/ISGRI Soft Gamma-Ray Survey Catalog. ApJ 636, 765B (2006)
18. Horns, D., Aharonian, F., Santangelo, A. et al.: Nucleonic gamma-ray production in Vela X. A&A 451, L51 (2006)