A&A 485, 195–198 (2008)
DOI: 10.1051/0004-6361:200809356

Astronomy & Astrophysics

The properties of the putative pulsar associated with IGR J18135−1751/HESS J1813−178 *(Research Note)*

A. J. Dean and A. B. Hill

School of Physics & Astronomy, University of Southampton, UK
e-mail: ajd@astro.soton.ac.uk

Received 7 January 2008 / Accepted 2 April 2008

ABSTRACT

Context. We investigate the possible theoretical properties of the putative pulsar associated with the pulsar wind nebula IGR J18135−1751/HESS J1813−178 based upon recent γ-ray observations and archival multi-wavelength observations.

Aims. We show that when using the standard equations for magnetic dipole radiation with recent soft γ-ray observations leads to deriving an extreme set of parameters (magnetic field, period and spin down rate) for the putative pulsar. Alternative scenarios that generate more typical parameter values are explored.

Methods. The properties of the putative pulsar are calculated assuming that the 20–100 keV luminosity corresponds to 1% of $\dot{E}$, that the source is 4.5 kpc away, and that the pulsar age is 300 yrs. This gives $P = 0.55$ s, $\dot{P} = 3 \times 10^{-11}$ s s^{-1}, and $B = 1.28 \times 10^{14}$ G. This is a very extreme set compared to the population of known pulsars in PWN systems. Using the equations for magnetic dipole losses makes it possible to adjust the initial assumptions to see what is required for a more reasonable set of pulsar parameters.

Results. The current measured properties for IGR J18135−1751/HESS J1813−178 (i.e. luminosity, distance, and age) result in extreme properties of the unseen pulsar within the PWN. The simplest method for achieving more reasonable properties for the pulsar is to decouple the spin-down age of the pulsar from the actual age for the system.

Key words. X-rays: individual: IGR J18135−1751 (HESS J1813−178) – stars: neutron – pulsars: general – gamma rays: observations

1. Introduction

HESS J1813−178 was discovered in the HESS galactic plane survey (Aharonian et al. 2006) and was seen to be one of the more compact TeV sources, with a radius of ∼2′. The source has a hard power law spectrum with $\Gamma \sim 2.09$, and a corresponding flux of $\sim 14.2 \times 10^{-12}$ photons cm^{-2} s^{-1} above 200 GeV. Originally the source was classified as unidentified and located at RA = $18^{h}13^{m}37\overset{s}{.}9$ and Dec = $-17°50'34''$ with a positional accuracy in the range 1–2′. However the study of previously unpublished archival radio data showed the TeV source to be coincident with the faint radio emission from part of the shell structure of a supernova remnant (*SNR* G12.8−0.0), which lies 8′ above the Galactic plane and in the vicinity of the bright star forming region W33 (Brogan et al. 2005). However, no radio pulsar was (or has yet been) found in the vicinity (Helfand et al. 2007).

Likewise a study of previously unpublished ASCA X-ray data revealed a bright non-thermal 2–10 keV X-ray source, AX J1813−178 (Brogan et al. 2005). The ASCA angular resolution does not permit the X-rays to be associated with either the *SNR* shell or a putative compact object near the centre. The X-ray spectrum was found to be quite hard, with the emission extending to 10 keV and a strong cutoff below 2 keV. Typical parameters associated with the X-ray emission are $N_{\rm H} \sim 10^{23}$ cm^{-2}, and $\Gamma \sim 1.83$. The 2–10 keV unabsorbed flux is 7×10^{-12} erg cm^{-2} s^{-1}, corresponding to a 2–10 keV luminosity $L_{\rm X} \sim 1.7 \times 10^{34}$ erg s^{-1}, for a distance of 4.5 kpc to the source as suggested from the measured $N_{\rm H}$ value. The hard power law spectral index is compatible with a pulsar/PWN system, although a careful search in the ASCA high bit-rate GIS data by Brogan et al. (2005) did not detect a pulsed signal between 4 and 8 keV for periods in the range 125 ms to 1000 s. The small angular size of *SNR* G12.8−0.0 ($\phi \sim 2.5'$) suggests youth. At 4.5 kpc the radius will be ∼1.6 pc and, if the *SNR* is still freely expanding with a typical velocity of 5000 km s^{-1}, it will only be a few hundred years old. We may anticipate that the putative pulsar has a period of less than 124 ms, typical of many of the pulsar/PWN X-and γ-ray emitting systems discovered to date (Possenti et al. 2002).

XMM-Newton observations (Funk et al. 2007) have revealed a highly absorbed ($N_{\rm H} \sim 10^{23}$ cm^{-2}) non-thermal point-like object coincident with the ASCA source inside the radio shell and having a faint tail towards the north-east resembling a PWN system. The basic scenario is essentially confirmed by recent *Chandra* observations of HESS J1813−178 (Helfand et al. 2007). The *Chandra* image resolves the ASCA source into diffuse X-ray emission and a point source. The diffuse emission generally fills the radio shell and peaks towards the point source emission, which lies within, but slightly offset from the centroid of the *SNR* by about 20″. Spectra from each morphological region are well characterized by an absorbed power law model associated with non-thermal emission. The best fit photon index for the nebular flux is $\Gamma \sim 1.3$ with $N_{\rm H} \sim 9.8 \times 10^{22}$ cm^{-2}, and the point source having a similar spectrum, also at $\Gamma \sim 1.3$. These values are typical of other energetic young pulsars. For a distance of 4.5 kpc the *Chandra* results correspond to a 2–10 keV luminosities of the putative pulsar and PWN of $L_{\rm PSR} \sim 3.2 \times 10^{33}$ erg s^{-1} and $L_{\rm PWN} \sim 1.4 \times 10^{34}$ erg s^{-1}.

Article published by EDP Sciences

1.1. Gamma-ray observations

Ubertini et al. (2005) report the discovery of a soft γ-ray source IGR J18135−1751, detected by the IBIS telescope on INTEGRAL, coincident with the ASCA and HESS emissions within the errors of the instrument. The source is persistent and has a 20–100 keV luminosity of $L_{S\gamma} \sim 7.2 \times 10^{34}$ erg s^{-1} if situated at 4.5 kpc. Due to the lack of X- and γ-ray variability, the radio morphology and ASCA spectrum the authors interpret this source as a PWN system embedded in its supernova remnant. Using the data set of the recently released 3rd IBIS/ISGRI survey catalogue (Bird et al. 2007), we measure the source flux to be $2.75^{+0.83}_{-0.60} \times 10^{-12}$ erg cm^{-2} s^{-1} corresponding to a source luminosity (at 4.5 kpc) of $L_{S\gamma} \simeq 6.7 \times 10^{34}$ erg s^{-1}. The spectral index of the power law interpretation of the spectrum is well described by $\Gamma = 1.8$. If we look at the luminosities as a function of $\dot{E}$ all PWN seen in the IBIS/ISGRI survey catalogue of Bird et al. (2007) we find a distribution centred on 1% as seen in Fig. 1. Taking the 20–100 keV luminosity to be roughly 1% of the spin down power, then we may expect to find a pulsar in IGR J18135−1751 with $\dot{E} \sim 6.7 \times 10^{36}$ erg s^{-1}.

In discussing the TeV emission the HESS team suggest a model in which the X-rays are produced by synchrotron radiation by electrons in a PWN and the TeV photons arise from Inverse Compton (IC) scattering dust IR photons, the cosmic microwave background and ambient starlight. IC scattering from the Cosmic Microwave Background alone is not sufficient, so that in this context the proximity of HESS J1813−178 to W33 would be a definite advantage. Taking the XMM, INTEGRAL and HESS spectral data, Funk et al. (2007) find that the scenario, in which the VHE and X-ray emitting electrons belong to the same population that originate in a single central object, as suggested by Ubertini et al. (2005) provides a good fit to the spectral energy distribution.

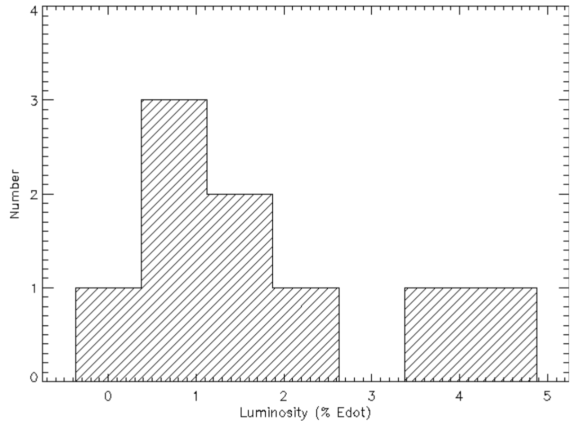

Fig. 1. Histogram of the soft γ-ray (20–100 keV) luminosity as a percentage $\dot{E}$ for the 9 PWN systems detected in the 3rd IBIS/ISGRI survey catalogue of Bird et al. (2007) for which the pulsar characteristics are known.

2. The properties of the putative pulsar

The morphology and spectral emission from the central region of G12.8−0.0 indicate the presence of a pulsar, which is powering the system. *Chandra* currently provides a compelling case that the high-energy emission from G12.8−0.0 is derived from the spin down of a young rotation-powered pulsar, all that remains is the discovery and characterization of the pulsar. If we assume that this pulsar is currently slowing down through the loss of rotational energy at a rate $\dot{E}$ through magnetic dipole radiation, for which the braking index $n = 3$, we can derive expressions relating $\dot{E}$, the period of the pulsar P, the period derivative $\dot{P}$ and the characteristic age τ as follows (Padmanabhan 2001; Bowers & Deeming 1984):

$$\dot{E} = \frac{4\pi^2 I \dot{P}}{P^3} \quad \text{erg s}^{-1} \tag{1}$$

$$B = 3.2 \times 10^{19} (P\dot{P})^{0.5} \quad \text{Gauss} \tag{2}$$

$$\tau = \frac{P}{2\dot{P}} \quad \text{s} \tag{3}$$

where $I \simeq 10^{45}$ g cm^2 is the moment of inertia of the neutron star. Eliminating $\dot{P}$ between Eqs. (1) and (3) we derive:

$$\tau P^2 \dot{E} = 1.9 \times 10^{46} \quad \text{erg s}^2. \tag{4}$$

Thus for a given value of $\dot{E}$ the product of $\tau \times$ P^2 is fixed. The 3rd IBIS/ISGRI survey catalogue of Bird et al. (2007) includes nine pulsar wind nebula systems with measured pulsar properties, although not all are labelled as being such; these include:

- Crab;
- PSR B0540−69.3 (not listed as PWN in Bird et al. 2007);
- Vela Pulsar;
- PSR B1509−58 (not listed as PWN in Bird et al. 2007);
- PSR J1617−5055 (not listed as PWN in Bird et al. 2007);
- IGR J17475−2822 (not listed as PWN in Bird et al. 2007);
- PSR J1811−1926;
- *SNR* 021.5−00.9;
- AX J1846.4−0258.

The luminosity distribution of these systems, as measured by INTEGRAL, in the 20–100 keV band as a percentage of $\dot{E}$ is shown in the histogram shown in Fig. 1. From the histogram it can be seen that an average conversion efficiency of spin down energy into soft γ-rays of $\epsilon \approx 1\%$ is reasonable. Hence for IGR J18135−1751 with a luminosity of $L_{S\gamma} \simeq 6.7 \times 10^{34}$ erg s^{-1} as measured by INTEGRAL leads to a value of $\dot{E} = 6.7 \times 10^{36}$ erg s^{-1}. Taking the distance, d, to this source to be 4.5 kpc, the age of the pulsar to be that of a *SNR* freely expanding at ~5000 km s^{-1} (~300 yr) it is possible to derive the following numerical values for the period, the period derivative and the surface magnetic field B of the pulsar:

$$P = 0.55 \frac{\varepsilon_1^{0.5} I_{45}^{0.5}}{d_{4.5} \tau_{300}^{0.5}} \quad \text{s} \tag{5}$$

$$\dot{P} = 3 \times 10^{-11} \frac{\varepsilon_1^{0.5} I_{45}^{0.5}}{d_{4.5} \tau_{300}^{1.5}} \quad \text{ss}^{-1} \tag{6}$$

$$B = 1.28 \times 10^{14} \frac{\varepsilon_1^{0.5} I_{45}^{0.5}}{d_{4.5} \tau_{300}} \quad \text{Gauss.} \tag{7}$$

Where the subscripts represent the normalization of the parameters. i.e. $\tau_{300} = \tau/(300\ \text{yr})$, $\varepsilon_1 = \varepsilon/(1\%)$, $I_{45} = I/(10^{45}\text{g cm}^2)$, and $d_{4.5} = d/(4.5\ \text{kpc})$.

The values of the parameters P, $\dot{P}$, and B thus derived for a 300 year old pulsar situated at 4.5 kpc constitute an unusual set, making this object a very extreme member of the group of high B field rotation pulsars (Kaspi et al. 2006; Gotthelf 2004; Camilo et al. 2002). The period is very long for such a young pulsar, and the spindown rate extremely high, leading to a unusually high magnetic field attached to the neutron star. The closest known example of a young pulsar/PWN system with a high magnetic field and fast spindown is PSR J1846−0258 in Kes 75 (McBride et al. 2008). The equivalent values for the PSR J1846−0258 system are: $P = 0.326$ s; $\dot{P} = 7.1 \times 10^{-12}$ ss^{-1}; $B = 4.9 \times 10^{13}$; $\tau = 730$ yr and $\dot{E} = 8.1 \times 10^{36}$ erg s^{-1}. The above set of parameters for IGR J18135−1751 are far more extreme, and whilst they may be considered possible, they must be considered unlikely. The situation is exacerbated by the fact that for PSR J1846−0258 the value of the conversion efficiency to soft γ-rays may be extremely high, with ε possibly as high as ~5% (see Fig. 1). Such a high value for IGR J18135−1751 would mean a lower value for $\dot{E}$ making the product of $\tau \times P^2$ even larger, so that for a fixed age of 300 years we require a longer pulsar period and correspondingly larger values for $\dot{P}$ and B.

One approach to generate a more reasonable set of pulsar characteristics is to change the values of the system parameters such as the assumed distance, the age of the pulsar and the conversion efficiency from $\dot{E}$ to observed γ-ray luminosity so as to reduce the pulsar's period and magnetic field parameters to more typical values.

This aim may be achieved through an increase in the value of $\dot{E}$ by assuming a larger distance or a lower value of ε. Alternatively an increase in the age τ of the pulsar will produce a similar effect. Increasing the value of $\dot{E}$ by two orders of magnitude makes the value of $\dot{E} = 6.7 \times 10^{38}$ erg s^{-1}, which is somewhat more than the highest value of known soft γ-ray emitting pulsar/PWN systems (Crab ~4.6×10^{38} erg s^{-1}, and PSR J0540−6919 ~1.48×10^{38} erg s^{-1}). To do this we require that either $\varepsilon = 0.01\%$, making IGR J18135−1751 a Vela-like system (Hoffmann et al. 2007), or the source be removed to an impossible distance of 45 kpc. A change of two orders of magnitude in the value of $\dot{E}$ creates a pulsar system with less extreme characteristics: a period of 55 ms; a period derivative of 3×10^{-12} ss^{-1}; and a magnetic field of 1.28×10^{12} Gauss. However such a configuration itself stretches the current known limits of the pulsar spin down power and couples it with an exceptionally low value of ε, again necessitating a very unusual system. To produce a comparable effect, using the age of the pulsar as a free parameter we have to make the age of the system 30 000 years, definitively decoupling the putative pulsar from *SNR* G12.8−0.0.

Constraints on the distance of the object have been derived from HI absorption measurements as well as the strong absorption found in the X-ray data. (Brogan et al. 2005). G12.8−0.0 lies in the projected vicinity of the W33 region, a complex of HII regions and massive star forming region. The W33 complex has been well studied and its distance has been estimated to be ~4 kpc (See Funk et al. 2007, for a discussion). The $N_{\rm H}$ value (~10^{23} cm^{-2}) is somewhat higher than the total column density in this direction indicating that the X-ray source is embedded in a dense environment and/or possibly located behind W33 making the distance estimate to the source ≳4 kpc. In the context of an age constraint, the small angular size of G12.8−0.0 strongly suggests a young *SNR*, and clearly the estimated age is coupled to the distance value. However, since the swept up mass would be still a small fraction of the ejected mass if the distance is less than ~10 kpc, so that free expansion is justified within this distance range. At greater distances the *SNR* is likely to have entered the Sedov-Taylor phase, for which the age estimate will still dictate a young system, if G12.8−0.0 is expanding into a medium of typical density. See Brogan et al. (2005), who on this basis estimate the age range to be 285–2500 years.

Based on the assumption that the value of ε is close to the 1% observed for other soft -γ−ray emitting pulsar/PWN systems, then it is impossible to obtain a reasonable set of self-consistent parameters, based on a system driven by magnetic dipole energy losses, linking the pulsar period, the period derivative and the magnetic field of the rotating neutron star, without stretching the both distance and age values to the extreme limits based on current estimates. For example taking an extreme age of 2500 years, then an unlikely distance of ~15 kpc is required to provide a reasonable set of values.

All the morphological evidence compiled from observations of *SNR* G12.8−0.0/IGR J18135−1751/HESS J1813−178 points to the presence of a young and energetic pulsar, which is powering a PWN system. The probability of a chance positional coincidence of the hard spectrum X-ray source within the radio shell of the G12.8−0.0 composite *SNR*, at the location of the TeV γ-ray source HESS J1813−178 is extremely low. Using a simple monte-carlo approach this probability can be estimated; if we pessimestically assume that all 45 HESS catalogue sources, 421 INTEGRAL catalogue sources and 265 known SNRs (Green 2006) lie within 5° of the galactic plane, that SNRs are typically 15′ in size and that all HESS and INTEGRAL detections have a poor location accuracy of 3′ then the probability of chance coincidence is 10^{-5}–10^{-6}. However we have seen that if a pulsar was indeed born at the time of this young supernova remnant with a period extremely short compared to its current value then it is extremely difficult to reconcile the properties of the putative pulsar with the likely age and likely distance to the object. Only by evoking an extreme neutron star configuration judged by current observational data or stretching the bounds of both the age and distance is it possible to create a reasonable physical rotating neutron star system.

All the above discussion assumes explicitly that magnetic dipole losses are the source of power for the system and that the associated pulsar was born with a spin period that was considerably faster than the current and unknown value. By decoupling the spin down age of the putative pulsar from the actual age of the system, the dilemma may be resolved. AX J1813−178 /IGR J18135−1751 may be a system containing a pulsar that was created with a spin period not significantly different from the present value. Such a scenario is not unprecedented. The discovery of a 65 millisecond pulsar (PSR J1811−1925) in the supernova remnant G11.2−0.3 with ASCA (Torii et al. 1997) sets a precedent. The object was known to be a composite supernova remnant having an extended shell component and a compact plerionic component. The age of the *SNR* was estimated on the basis of its likely association with the supernova A.D. 386. The discovery of the pulsar and subsequent detailed Chandra X-ray observations (Kaspi et al. 2001) confirmed the morphology of the PWN system with the 65 millisecond energetic young neutron star at its core. Again the inferred spin down age, based on the existing empirical relation between pulsar spin down power and X-ray luminosity led to a characteristic spin down age that was considerably more than 2000 years. Indeed on the basis of radio measurements of $\dot{P}$ for PSR J1811−1925, at ~4.4×10^{-14} ss^{-1} the characteristic spin down age would be placed at more than 20 000 years. The characteristic spin down age has also been found to be inconsistent in the following cases: Pulsar B1951+32 (Migliazzo et al. 2002); Pulsar J0538+2817 (Kramer et al. 2003).

3. Summary and conclusions

All the evidence compiled from observations of *SNR* G12.8−0.0./IGR J18135− 1751/HESS J1813−178 points to the presence of a young and energetic pulsar, which is powering the system. However, if we assume that this as yet undetected pulsar was born within *SNR* G12.8−0.0 with a period that was extremely short compared to the current and unknown value, then it is not possible to reconcile the likely properties of the putative pulsar with the estimated age of the *SNR* without significantly surpassing the physical limits of currently known pulsar/PWN systems or stretching both the age and the distance of the object to or beyond the limits of the accepted values derived from current observational evidence. Such extreme configurations are of course possible, but must be considered unlikely. If, however, we assume that the putative pulsar was born in *SNR* G12.8−0.0 with a period that was close to its current and as yet unmeasured value then the dilemma goes away. The discovery of such a pulsar would be likely to reveal a period of some tens of milliseconds. This is obviously an intriguing and unusual system that will only be understood by future observations and a detection of the putative pulsar.

Acknowledgements. Based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA. We thank Dr A. J. Bird and the INTEGRAL/IBIS survey team for access to and the use of the data products produced in the production of the 3rd IBIS/ISGRI survey.
We acknowledge the funding via PPARC grant PP/C000714/1.

References

Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., Beilicke, M., Benbow, W., & Berge, D. 2006, ApJ, 636, 777
Bird, A. J., Malizia, A., Bazzano, A., Barlow, E. J., & Bassani, L. 2007, ApJS, 170, 175
Bowers, R., & Deeming, T. 1984, Astrophysics I: Stars (Jones & Bartlett), 307
Brogan, C. L., Gaensler, B. M., Gelfand, J. D., et al. 2005, ApJ, 629, L105
Camilo, F., Manchester, R. N., Gaensler, B. M., & Lorimer, D. R. 2002, ApJ, 579, L25
Dean, A. J., et al. 2008, in preparation
Funk, S., Hinton, J. A., Moriguchi, Y., Aharonian, F. A., & Fukui, Y. 2007, A&A, 470, 249
Gotthelf, E. V. 2004, IAUS, 218, 225
Green, D. A. 2006, A Catalogue of Galactic Supernova Remnants (2006 April version), Astrophysics Group, Cavendish Laboratory, Cambridge, UK (available at http://www.mrao.cam.ac.uk/surveys/snrs/)
Helfand, D. J., Gotthelf, E. V., Halpern, J. P., et al. 2007, ApJ, 665, 1297
Hoffmann, A. I. D., Horns, D., & Santangelo, A. 2007, Ap&SS, 309, 215
Kaspi, V. M., Roberts, M. S. E., & Harding, A. K. 2006, csxs.book, 279
Kramer, M., Lyne, A. G., Hobbs, G., et al. 2003, ApJ, 593, L31
Manchester, R. N., Lyne, A. G., Camilo, F., Bell, J. F., & Kaspi, V. M. 2001, MNRAS, 328, 17
McBride, V. A., Dean, A. J., Bazzano, A., Bird, A. J., & Hill, A. B. 2008, A&A, 477, 249
Migliazzo, J. M., Gaensler, B. M., Backer, D. C., et al. 2002, ApJ, 567, L141
Padmanabhan, T. 2001, Theoretical Astrophysics II: Stars and Stellar Systems (Cambridge University Press), 300
Possenti, A., Cerutti, R., Colpi, M., & Mereghetti, S. 2002, A&A, 387, 993
Torii, K., Tsunemi, H., Dotani, T., & Mitsuda, K. 1997, ApJ, 489, L145
Torii, K., Tsunemi, H., Dotani, T., et al. 1999, ApJ, 523, L69
Ubertini, P., Bassani, L., Malizia, A., Bazzano, A., & Bird, A. J. 2005, ApJ, 629, L109