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Energy Dependent Morphology in the PWN candidate HESS J1825–137

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Abstract: Observations with H.E.S.S. revealed a new source of very high-energy (VHE) gamma-rays above 100 GeV – HESS J1825–137 – extending mainly to the south of the energetic pulsar PSR B1823–13. A detailed spectral and morphological analysis of HESS J1825–137 reveals for the first time in VHE gamma-ray astronomy a steepening of the energy spectrum with increasing distance from the pulsar. This behaviour can be understood by invoking radiative cooling of the IC-Compton gamma-ray emitting electrons during their propagation. In this scenario the vastly different sizes between the VHE gamma-ray emitting region and the X-ray PWN associated with PSR B1823–13 can be naturally explained by different cooling timescales for the radiating electron populations. If this scenario is correct, HESS J1825–137 can serve as a prototype for a whole class of asymmetric PWN in which the X-rays are extended over a much smaller angular scales than the gamma-rays and can help understanding recent detections of X-ray PWN in systems such as HESS J1640–465 and HESS J1813–178. The future GLAST satellite will probe lower electron energies shedding further light on cooling and diffusion processes in this source.

Introduction

The pulsar PSR B1823–13 and its surrounding X-ray pulsar wind nebula (PWN) G18.0–0.2 is a system that has been studied by H.E.S.S. in very high-energy gamma-rays above 200 GeV in unprecedented detail [1]. PWNe seem to constitute a significant fraction of the population of identified Galactic VHE gamma-ray sources detected by H.E.S.S. [2] and as also suggested by a statistical assessment of the correlation between Galactic VHE γ-ray sources and energetic pulsars (see Carrigan et al., these proceedings). The gamma-ray emission in these objects is typically thought to be generated by Inverse Compton scattering of relativistic electrons accelerated in the termination shock of the PWN.

Considering the population of VHE gamma-ray PWNe, HESS J1825–137 is probably thus far the best example of the emerging class of so-called *offset Pulsar Wind nebulae* in which an extended VHE gamma-ray emission surrounding an energetic pulsar is offset into one direction of the pulsar. This offset is generally thought to arise from dense molecular material in one direction of the pulsar that prevents an symmetric expansion of the PWN (see e.g. [3] for a hydro-dynamical simulation and discussion of this effect).

As one of the best studied objects in VHE gamma-rays with an observation time of nearly 70 hours, HESS J1825–137 has been used as a template for the association of asymmetric PWN in VHE γ-rays and X-rays [2, 4]. In HESS J1825–137 the claimed association between the VHE γ-ray source and the X-ray PWN rests on the following properties of the source:

- Same morphology (i.e. asymmetric extension to the south) in both bands but X-ray nebula much smaller (~ 5") than γ-ray ($\sim 0.5°$) emission region

- Spectral steepening of the VHE gamma-ray source away from the pulsar (i.e. decrease of gamma-ray extension with increasing energy). Interestingly the maximum of the VHE γ-ray emission is not coincident with the pulsar position but is shifted $\sim 17'$ to the south-west.

The vastly different sizes of the emission region in the two wavebands prevents at first glance a direct identification as a counterpart, since the morphology can not be matched between X-rays and gamma-rays. As will be explained in the following, the different sizes can be explained in a time-dependent leptonic model by different cooling timescales of the X-ray and of the VHE gamma-ray emitting regions. Caution should however be used, if such an association serves as a template for other unidentified H.E.S.S. VHE gamma-ray sources with an energetic pulsar in the vicinity, in cases in which no X-ray PWN has been detected so far.

Observational data

CO-Observations performed in the composite survey [5] show a dense molecular cloud in the distance band between 3.5 and 4 kpc to the north of PSR B1823–13 (located at $\sim$ 4 kpc) [6]. This cloud seems to support the picture of an offset PWN and could explain why the X-ray and VHE emission is shifted to the south of the pulsar. Given the relatively high gamma-ray flux and the rather large distance of the system of 4 kpc (in comparison to the Crab), the required gamma-ray luminosity $L_\gamma \sim 3 \times 10^{35}$ erg/s is comparable to the Crab luminosity. The spin-down luminosity of the pulsar is, however, two orders of magnitude lower than the Crab spin-down luminosity. Assuming the distance of $\sim$ 4 kpc is correct this shows that the efficiency of converting spin-down power to gamma-ray luminosity must be much higher than in the Crab Nebula, not unexpected, given the large magnetic field in the Crab Nebula. Detailed time-dependent modelling of the source shows indeed that (especially below $\sim$ 1TeV) the energy injection into the system must have been about an order of magnitude higher in the past. Potentially the spin-down power of the pulsar was significantly higher in the early stage of the pulsar evolution. For the lower energy end of the H.E.S.S. spectrum and for modest magnetic fields of a few μG as suggested by the large VHE gamma-ray flux, the electron lifetimes become comparable to the pulsar age and therefore "relic" electrons released in the early history of the pulsar can survive until today and provide the required luminosity. It should
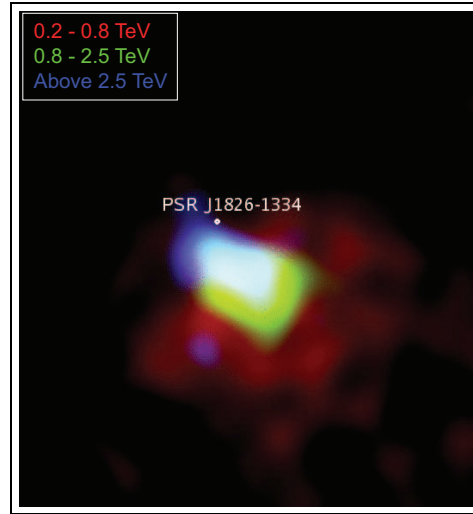

Figure 1: Three-colour image showing the gamma-ray emission in different energy bands (red: 0.2-0.8 TeV, green 0.8-2.5 TeV and blue: above 2.5 TeV). The different gamma-ray energy bands show a shrinking with increasing energy away from the pulsar PSR B1823–13.

be noted that to this date no sensitive X-ray observation of the region coinciding with the peak of the VHE gamma-ray emission has been performed and a low surface-brightness extension to the south of the X-ray PWN found by Gaensler et al. [7] remains an interesting possiblility that should eventually be tested.

Energy dependent morphology

Given the large data set with nearly 20,000 γ-ray excess events, a spatially resolved spectral analysis of HESS J1825–137 could be performed. For the the first time VHE γ-ray astronomy an energy dependent morphology (see Figure 1) was established [1] in which the size of the emission region decreases with increasing energy. This shrinking size with increasing energy is equivalent to the statement of a steepening of the spectral index away from the pulsar. The spectrum in HESS J1825–137 changes from a rather hard photon index $\sim$ 2 close to the pulsar to a softer value of $\sim$ 2.5 at a distance of $1°$ away from the pulsar.

Figure 2 shows the surface brightness as a function of the distance from the pulsar for different energy bands. Two clear trends are apparent in this figure: a) the peak of the surface brightness shifts to lower energies (as already suggested by the steepening of the energy spectrum away from the pulsar) b) at low energies the surface brightness is nearly independent of the distance whereas at the higher energies the surface brightness drops rapidly with increasing distance from the pulsar. The right panel of Figure 2 shows the derived radius R_{50} corresponding to the 50% containment of the surface brightness. This radius R_{50} drops with increasing energy as already apparent in Figure 1.

The steepening of the energy spectrum away from a central pulsar is a property commonly observed in X-ray studies of PWNe other than the Crab. For most of these system the total change in the photon index is close to ~ 0.5 similar to what is seen in HESS J1825–137. It should be noted that the results shown here represent the first unambiguous detection of a spectral steepening at a fixed electron energy (since the synchrotron emission seen in X-rays depends on the magnetic field) in a PWN system. Spectral variation with distance from the pulsar could result from (1) energy loss of particles during propagation, with radiative cooling of electrons as the main loss mechanism, from (2) energy dependent diffusion or convection speeds, and from (3) variation of the shape of the injection spectrum with age of the pulsar. Concerning (1): Loss mechanisms include amongst others adiabatic expansion, ionisation loss, bremsstrahlung, synchrotron losses and inverse Compton losses. Only synchrotron and IC losses can result in a electron lifetime that decreases with increasing energy. A source decreasing source size with increasing energy is therefore generally seen as indicative of electrons as the radiating particles.

For continuous injection and short radiative lifetimes of the electrons (in comparison to the age of the source), the spectral index of the electrons changes by one unit as a result of the cooling, yielding in a change of 0.5 in the the photon index. This matches roughly what is seen in HESS J1825–137 when comparing the inner and the outer nebula. The lower energy gamma-rays (i.e. below ~ 0.6 TeV) correspond to mostly un-cooled low energy electrons (i.e. the spectral index consistent

with the injection spectral index). At these low energies the electron lifetime becomes comparable to the age of the source and the size is rather independent of the energy. At higher energies the cooling break takes effect and the source size shrinks with increasing energy as expected from electron cooling. The XMM-Newton X-ray emitting electrons typically have much higher energies (~ 100 TeV) than the γ-ray emitting electrons (~ 10 TeV), assuming a typical magnetic field of 5 μG. The synchrotron cooling lifetime of X-ray emitting electrons is therefore expected to be much smaller, resulting in a smaller spatial extension in X-rays.

For systems like HESS J1825–137 a detailed study in X-rays trying to detect the low surface brightness nebula in the soft X-ray band would be very beneficial, is however very hard to achieve given the absorption of soft X-rays. The upcoming GLAST-satellite will observe this object in a thus far rather unexplored energy regime especially above ~ 10 GeV, where the angular resolution of the instrument becomes comparable to the angular resolution of the ground-based instrument. In this energy range GLAST will probe even lower energy electrons and it will be interesting to compare the sizes of the GLAST and the H.E.S.S. emission region. The H.E.S.S. results have shown that a wealth of detail exists in gamma-rays at an angular scale of $\sim 0.1°$. Future instruments like CTA or AGIS might improve this angular resolution even further.
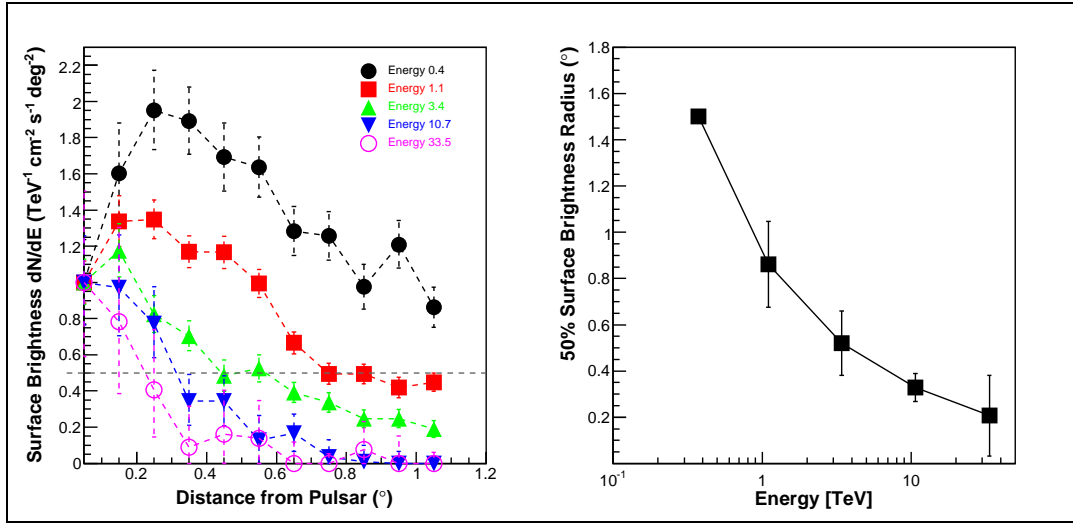
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Figure 2: **Left:** Surface brightness as a function of distance from the pulsar for different energy bands (derived from Figure 4 in Aharonian et al [1]. The surface brightness is defined as the differential gamma-ray flux at a given energy scaled by the area of the extraction region and normalised by the flux for that energy at the pulsar position r = 0. **Right:** Distance from the pulsar at which the surface brightness drops to 50% of the flux at the pulsar position. The error bars are derived by fitting the falling points of the left plot, varying the fit parameters within the errors and recalculating the 50% containment radius.

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