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Discovery of the candidate pulsar wind nebula HESS J1718-385 in very-high-energy gamma-rays

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Abstract: Motivated by recent detections of pulsar wind nebulae in very-high-energy (VHE) gamma rays, a systematic search for VHE gamma-ray sources associated with energetic pulsars was performed, using data obtained with the H.E.S.S. (High Energy Stereoscopic System) instrument. The search for VHE gamma-ray sources near the pulsar PSR J1718-3825 revealed the new VHE gamma-ray source HESS J1718-385. We report on the results from the HESS data analysis of this source and on possible associations with the pulsar and at other wavelengths. We investigate the energy spectrum of HESS J1718-385 that shows a clear peak. This is only the second time a VHE gamma-ray spectral maximum from a cosmic source was observed, the first being the Vela X pulsar wind nebula.

Introduction

It has long been known that pulsars can drive powerful winds of highly relativistic particles. Confinement of these winds leads to the formation of strong shocks, which may accelerate particles to $\sim$PeV energies.

The best studied example of a pulsar wind nebula (PWN) is the Crab nebula, which exhibits strong non-thermal emission across most of the electromagnetic spectrum from radio to $>$50 TeV γ-rays [1]. More recently, VHE γ-ray emission has been detected from the Vela X PWN [2], which is an order of magnitude older ($\sim$11 kyr) than the Crab nebula, and its nebula is significantly offset from the pulsar position, both in X-rays and VHE γ-rays. Offset nebulae in both X-rays and VHE γ-rays have also been observed in the Kookaburra Complex [3] and for the PWN associated with the γ-ray source HESS J1825$-$137 [4, 5]. The latter source appears much brighter and more extended in VHE γ-rays than in keV X-rays. This suggests that searches at TeV energies are a powerful tool for detecting PWNe.

Motivated by these detections, a systematic search for VHE γ-ray sources associated with high spin-down energy loss rate pulsars was performed, using data obtained with the H.E.S.S. instrument. The VHE γ-ray data set used in the search includes all data used in the H.E.S.S. Galactic plane survey [6], an extension of the survey to $-60^\circ < l < -30^\circ$, dedicated observations of Galactic targets and re-observations of H.E.S.S. survey sources. It spans Galactic longitudes $-60^\circ < l < 30^\circ$ and Galactic latitudes $-2^\circ < b < 2^\circ$, a region covered with high sensitivity in the survey. These data are being searched for VHE emission from pulsars from the Parkes Multibeam Pulsar Survey [7]. The search for a possible γ-ray excess is done in a circular region with radius $\theta = 0.22^\circ$ (as in [6]) around each pulsar position, sufficient to encompass a large fraction of a possible PWN. The statistical significance of the resulting associations of the VHE γ-ray source with the pulsar is evaluated by repeating the procedure for randomly generated pulsar samples, modelled after the above-mentioned parent population.

In this search, it is found that pulsars with high spin-down energy loss rates are on a statistical basis accompanied by VHE emission. The search for VHE γ-ray emission near the pulsar PSR J1718−3825 revealed the new VHE γ-ray source HESS J1718−385. This paper deals with the results from the HESS data analysis of HESS J1718−385 and with its possible associations with PSR J1718−3825 and other objects seen in radio and X-ray wavelengths.

H.E.S.S. Observations and Analysis

The data on HESS J1718−385 are composed primarily from dedicated observations of the supernova remnant RX J1713.7−3946 [8], which is located at about 1.6° south-west of HESS J1718−385. After passing the H.E.S.S. standard data quality criteria based on hardware and weather conditions, the data set for HESS J1718−385 has a total live time of ∼82 hours. The standard H.E.S.S. analysis scheme [9] is applied to the data, including optical efficiency corrections. In this analysis, *hard cuts* are applied, which include a rather tight cut on the shower image brightness of 200 photo-electrons and are suitable for extended, hard-spectrum sources such as PWN. These cuts also improve the angular resolution and therefore suppress contamination from the nearby RX J1713.7−3946. To produce a sky map, the background at each test position in the sky is derived from a ring surrounding this position with a mean radius of 1° and a width scaled to provide a background area that is about 7 times larger than the area of the on-source region.

For spectral studies, only observations in which the camera centre is offset by less than 2° from the best-fit source position are used to reduce systematic effects due to reconstructed γ-ray directions falling close to edge of the field of view. The remaining live time of the data sample is ∼73 hours. The spectral significance is calculated by counting events within a circle of radius 0.2° from the best-fit position, chosen to enclose the whole emission region while reducing systematic effects arising from morphology assumptions. The proximity of the strong source makes it necessary to choose the background data from off-source observations (matched to the zenith angle and offset distribution of the on-source data) instead of from areas in the same field of view. For a more detailed description of methods for background estimation, see [10].

Results

The detection significance from the search for VHE γ-ray emission within 0.22° of the location of PSR J1718−3825 is 7.9σ. A very conservative estimate of the number of trials involved ([6]) leads to a corrected significance of 6.2σ.

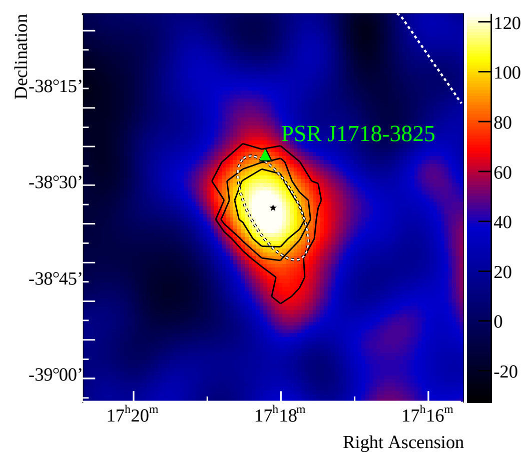

Figure 1: An image of the VHE γ-ray excess counts of HESS J1718−385, smoothed with a Gaussian of width 0.06°. The colour scale is set such that the blue/red transition occurs at approximately the 3σ significance level. The black contours are the 4, 5 and 6σ significance contours. The position of the pulsar PSR J1718−3825 is marked with a green triangle and the Galactic plane is shown as a white dotted line. The best-fit position for the γ-ray source is marked with a black star and the fit ellipse with a dashed line.

Figure 1 shows the smoothed excess count map of the 1° × 1° region around HESS J1718−385. A two-dimensional Gaussian brightness profile, folded with the H.E.S.S. point-spread function, is fit to the distribution before smoothing. Its parameters are the width in two dimensions and the orientation angle, defined counter-clockwise from North. The intrinsic widths (with the effect of the point-spread function removed) for the fit are $9' \pm 2'$ and $4' \pm 1'$ and the orientation angle is ∼33°. The best-fit position for the centre of the excess is RA = $17^{\rm h}18^{\rm m}7^{\rm s} \pm 5^s$, Dec = $-38°33' \pm 2'$ (epoch J2000). H.E.S.S. has a systematic pointing error of $\sim 20''$.

For the spectral analysis, a statistical significance of 6.8σ (with 343 excess counts) is derived. Figure 2 shows the measured spectral energy distribution for HESS J1718−385 (in $E^2\, dN/dE$ representation).

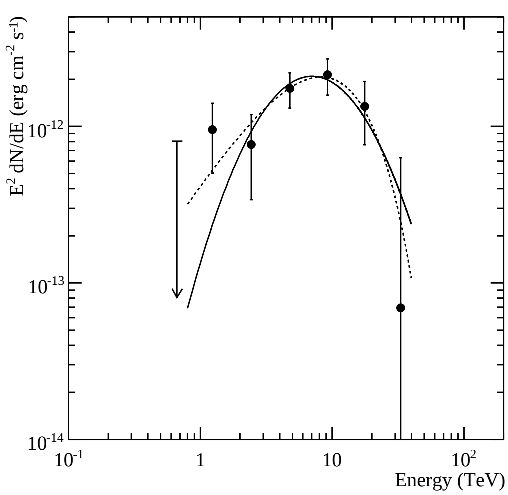

Figure 2: The energy spectrum of HESS J1718−385, which is fit by a curved profile (solid line). Alternatively, the fit of an exponentially cut-off power law is shown (dashed line, refer to the text for details on both fits). The first point in the spectrum lacks statistics due to lower exposure at small zenith angles and is plotted as an upper limit with at a confidence level of 2σ.

The spectrum is fit by a curved profile (shown as the solid line):

$$\frac{dN}{dE} = N_0 \left(\frac{E_{\rm p}}{1\,{\rm TeV}}\right)^{-2} \left(\frac{E}{E_{\rm p}}\right)^{\beta\cdot\ln(E/E_{\rm p})-2} \quad (1)$$

The peak energy $E_{\rm p}$ is $(7 \pm 1_{\rm stat} \pm 1_{\rm sys})$ TeV, the differential flux normalisation $N_0 = (1.3 \pm 0.3_{\rm stat} \pm 0.5_{\rm sys}) \times 10^{-12}$ TeV^{-1} cm^{-2} s^{-1} and $\beta = -0.7 \pm 0.3_{\rm stat} \pm 0.4_{\rm sys}$. This fit has a $\chi^2/d.o.f.$ of $3.2/3$. The integral flux between $1 - 10$ TeV is about 2 % of the flux of the Crab nebula in the same energy range [9].

Alternatively, fitting the spectrum by an exponentially cut-off power law ($dN/dE = N_0 E^{-\Gamma} e^{-E/E_{\rm cut}}$) gives $N_0 = (3.0 \pm 1.9_{\rm stat} \pm 0.9_{\rm sys}) \times 10^{-13}$ TeV^{-1} cm^{-2} s^{-1}, photon index $\Gamma = 0.7 \pm 0.6_{\rm stat} \pm 0.2_{\rm sys}$ and a cut-off in the spectrum at an energy of $E_{\rm cut} = (6 \pm 3_{\rm stat} \pm 1_{\rm sys})$ TeV. This fit, which is shown as a dashed line in Figure 2, has a $\chi^2/d.o.f.$ of $1.6/3$.

Both the curved and exponentially cut-off power law profiles fit the data well; the former has the advantage of showing explicitly the peak energy of the spectrum, which has to date only been resolved in one other VHE source, Vela X [2].

Possible Associations

The γ-ray source HESS J1718−385 is located ∼0.14° south of the pulsar PSR J1718−3825. PSR J1718−3825 appears to be a Vela-like pulsar, as it is of comparable age, 90 kyr, and has a similar spin period, 75 ms. From the spectral fit of a curved profile, the energy flux of HESS J1718−385 between (1 – 10) TeV is estimated to 2.9×10^{-12} erg cm^{-2}s^{-1}. With a distance of ∼4 kpc and a spin-down luminosity of $\dot{E} = 1.3 \times 10^{36}$ erg s^{-1}, PSR J1718−3825 is energetic enough to power HESS J1718−385, with an implied efficiency of $\epsilon_\gamma \equiv L_\gamma/\dot{E} = 0.5\,\%$.

As can be seen in Figure 3, no obvious X-ray counterpart is visible for HESS J1718−385. There is diffuse extended radio emission, which is partially coincident with the VHE emission. However, this emission seems to be correlated with thermal dust emission visible in the IRAS Sky Survey Atlas [13], suggesting that the radio emission is thermal and is thus not likely associated with a possible PWN. The brightest part of this diffuse feature is catalogued as PMN J1717−3846 [14]. From the point of view of positional coincidence, energetics, and lack of other counterparts, the association of HESS J1718−385 with PSR J1718−3825

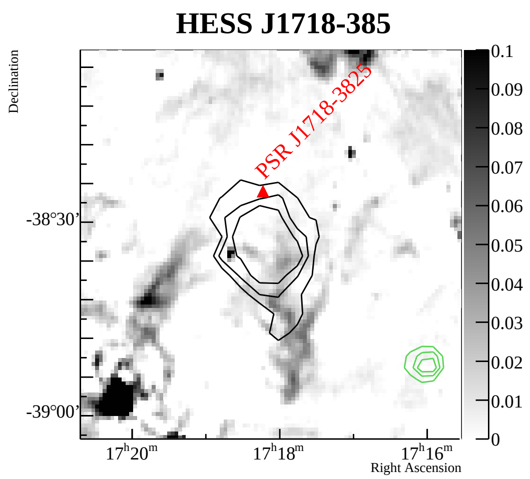

Figure 3: Radio image from the Molonglo Galactic Plane Survey at 843 MHz [11] (in Jy/beam). The H.E.S.S. significance contours are overlaid in black and the pulsar position is marked with a red triangle. Adaptively smoothed ROSAT hard-band X-ray contours are shown in green [12].

seems plausible. To confirm this, additional evidence from spectral and morphological studies in VHE γ-rays and from data at other wavelengths is needed.

HESS J1718−385 may well represent the first VHE γ-ray PWN found in a systematic search for pulsar associations, despite the present lack of a PWN detection in other wave bands. The remarkable similarity between HESS J1718−385 and other known VHE PWNe, together with the lack of other probable counterparts, gives additional confidence. The detection of an X-ray PWN would provide confirmation.

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