Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 2 (OG part 1), pages 831–834

ID 1091

30TH INTERNATIONAL COSMIC RAY CONFERENCE

New VHE emitting middle-age pulsar wind nebula candidates in the extended H.E.S.S. Galactic plane survey data

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Abstract: The H.E.S.S. 2004-2005 survey of the Galactic Plane at energies above 200 GeV had revealed a number of pulsar wind nebulae candidates, including the remarkable source HESS J1825-137. Spatially resolved spectral measurements of this source gave the first evidence of an energy-dependent morphology which was interpreted as being due to the cooling of relic electrons cumulated throughout pulsar's history. Also for a few number of sources the asymmetry of the pulsar with respect to the nebula could be attributed to an asymmetric reverse shock from the associated supernova remnant due to inhomogeneities in the interstellar matter. Subsequently a class of large offset and relic nebulae emerged as an outstanding new type of VHE γ-ray source.
We discuss here the cases of such nebulae in the extended H.E.S.S. Galactic Plane survey data through an energetic criterion taking into account earlier epochs of pulsar injection as well as through investigation of CO data to search for inhomogeneities.

Introduction

During 2004-2006 H.E.S.S. (High energy stereoscopic system) performed a Survey of the inner part of the Galaxy [1] where its excellent capability allowed to mark a breakthrough in the field of Pulsar wind nebula (PWN) study : for the first time the morphological structure of many PWN was resolved in the γ-ray band and many of them appears to belong to the middle-age Vela-like pulsar class.
HESS J1825-137 is the archetypal example of this population. For this source, a detailed spectral and morphological analysis [2] revealed for the first time in γ-ray a steepening of the energy spectrum with increasing distance from the pulsar. This fact was interpreted as due to the radiative cooling of the emitting electrons during their propagation. Indeed very high energy (VHE) Inverse Compton (IC) flux typically provide information on lower energy electrons than those of the keV synchrotron flux and imply a larger life-time for IC emittors. For the middle-age PWN, electrons emitting at TeV energies consist of cooled particles cumulated during few tenth of kyrs (called relic electrons thereafter). HESS J1825-137 can also be taken as a prototype by its asymmetrical configuration with respect to the pulsar, a morphological characteristic observed in many of the middle-age candidates. The similar morphology of HESS J1825-137 to that of the X-ray nebula G18.0-0.7 [3] suggested an asymmetric reverse shock to have happened in the 10 first kyrs of the pulsar life, consisting of the interaction of a supernova remnant (SNR) with an inhomogeneous surrounding material implying different colliding times of the reverse shock with the PWN, and resulting in a one-sided morphology [4]. To examine this hypothesis, [5] probed the interstellar matter density near G18.0-0.7 through ^{12}CO line emissions. Two molecular structures were discovered and their characteristics were found compatible with the observed offset of the VHE nebula HESS J1825$-$137 within the framework of the simulations by [6].
Here, we propose to extend this study to the large set of asymmetric middle-age PWN candidates found in the 2004-2007 H.E.S.S. data. In one first step, the association between the TeV sources and

the pulsars will be tested by the calculation of a new energy criterion. It will result in the first catalogue of middle-age PWN at VHE γ-ray. For the selected candidates which exhibit an asymmetric shape, the pulsar configuration with respect to the H_2 density profile and the high energy emissions will be considered and compared to the numerical model of [6], as it has been done in [5].

Build a catalogue of PWN candidates

Method

During the first part of the H.E.S.S. scan of the Galactic Plane, we buit a list of six VHE sources for which the spectral and morphological characteristics together with the proximity of an energetic pulsar placed them as potential PWN candidates. With the extended scan performed during 2006-2007, 3 new sources have been added to the list : HESS J1718-385 and HESS J1809-193 [7], and HESS J1912+101 [8]. All the sources of this list have ages between few to few hundred of kyrs (middle-age class) and the high energetic pulsars are closer that 7 kpc from us.

To evaluate the likelihood of an association between the TeV sources and the nearby pulsars, the power available for γ-ray production must be assessed. Since pulsar's rotational energy $\dot{\mathrm{E}}$ is the source for most of the emission seen from PWNe, it is used to consider the actual spin evolution of pulsars with respect to the PWN flux. But since the sources we consider have middle-ages, and given the fact that TeV electrons emittors are cooled particles in the nebula, we must consider also the earlier stages of the system if we want to get a true estimation of the TeV flux (contraty the X-ray nebulae for which the actual $\dot{\mathrm{E}}$ is relevant).

Our solution is to take into account the electrons injected by the pulsar in the nebula along the pulsar life-time, and the radiative losses dominated by the synchrotron component. The model assumes a power law electron injection spectrum with index of 2.02 and a fixed minimum energy $E_{\min}$= 1 TeV. The maximum energy is constrained by the acceleration condition that the gyroradius must not exceed the terminal shock radius and the normalization is determined by $\dot{\mathrm{E}}$ at each time and by the ratio between particles and field σ defined in [9] and fixed at 0.003 (similar to Crab Nebula's). The time evolution of the spin down power of the pulsar is written $\dot{E}(t) = \frac{\dot{E}_o}{(1+t/\tau_o)^2}$, with $\dot{E}_o$, the initial spin down power of the pulsar, τ_o the characteristic pulsar time scale (we fix it at the standard value of 400 years) and a breaking index of 3. The total injected energy by the pulsar during the time dt is:

$$\mathrm{dW} = \frac{1}{\sigma+1}\,\dot{\mathrm{E}}(\mathrm{t})\mathrm{dt} \tag{1}$$

The synchrotron losses are calculated with a typical average magnetic field of 5 μG :

$$\mathrm{dP_{losses}} = \mathrm{k.E^2.B^2dt} \tag{2}$$

The energetic balance for the electrons in the nebula can then be written at each time :

$$\mathrm{dU} = \mathrm{dW} - \mathrm{dP_{losses}} \tag{3}$$

After integration of this equation over the pulsar life-time, we obtain the actual total electron spectrum in the nebula. These electrons produce Inverse Compton photons that can be seen in the γ-ray band. We use an average value for the targets density of 0.25 $\mathrm{eV.cm^{-3}}$ for the CMB and 0.5 $\mathrm{eV.cm^{-3}}$ for the star and dust light. We define as ϵ an equivalent percentage of the ratio between the measured and predicted (this calculation) flux and propose to use it as an energetic criterion to estimate the credibility of an association between the VHE sources and corresponding pulsars.

Results

Table 1 shows the complete selected sources list, with the corresponding pulsars characteristics, the measured and predicted γ-ray luminosity and the γ-ray efficiency. A 30$\%$ efficiency criterion of acceptance looks reasonable, since it gives the insurance that the pulsar generated enough power to reproduce the observed flux, even if the conversion efficiency at the shock radius is low. Using this criterion, a first class of 9 good candidates appears clearly in the upper part of the table, whereas the two last sources are definitely rejected. All the selected candidates are extended and have a spectral index between 2 and 2.5, in good agreement with the known X-ray nebula. Six of them have an X-ray nebula detected but only one has a counterpart

in radio (mostly due to the faint radio emission of such extended object).
One of the most remarkable characteristic of these sources is that almost all of them show an asymmetric shape. We now propose to investigate possible reasons of this asymmetry by exploring the Interstellar medium (ISM).

Search for inhomogeneity in the ISM

Data and Method

The ^{12}CO observations used here are taken from the Composite CO Survey from [10]. This survey compiles observations from 37 individual surveys with a resolution of 0.2° and a FWHM velocity resolution of 2 km.s^{-1} [10].
As a first step, clouds are searched for through the scan of the CO intensity in the (l, b) plane as a function of the radial velocity in the vicinity of the associated pulsar. If some structures are detected, the average CO velocity profiles are made in the line of sight of these structures and they are extracted by detecting CO pics. We take the fit (gaussian) centroid of the ^{12}CO peak to establish the kinematic distance to the clouds using the empirical Galactic rotation curve models [11]. Only molecular clouds with a compatible distance with the pulsar are selected. In order to compare the compatibility of the interstellar matter distribution with the one by [6], we analyze the average gradient of molecular matter along the vector defined from the pulsar position, in the direction of the TeV emission's center of gravity. The CO emission is spatially averaged for each band and integrated over the cloud's velocity range. These values (usually called $\langle W(CO) \rangle$) are converted into average H_2 column density using the conversion coefficient by [12]. We consider here the total average gradient of each distribution by defining the contrast as the ratio between the maximum and minimum values of the density and the characteristic scale as the distance needed for the density to decrease by a factor two. These numbers are given for each sources in Table 2.

Results

Half of the cases seems to have a configuration compatible with the simulations of [6]. Only one case is rejected (HESSJ 1420-607) due to the geometric configuration incompatible with the reverse shock hypothesis. The major conclusion of this study is that the asymmetric reverse shock is a credible hypothesis if we consider the ISM distribution around most of the middle-age PWN VHE candidates. However it remains difficult to get a strong conclusion on this study, firstly because of the distance near-far ambiguity and secondly because of the effect of projection in the line of sight.

Conclusion

We established a list of potential PWNe candidates in the H.E.S.S. data and calculated an energetic criterion for each of them, taking into account the pulsar spindown power evolution over time together with average synchrotron losses. This study allowed to build the first VHE catalogue of middle-age PWN candidates consisting of 9 sources. Many of these candidates show an asymmetric shape around the putative associated pulsar. By probing the ISM through CO data, we showed that for many of them, the hypothesis of an aymmetric reverse shock is not to exclude, given the ISM density distribution.

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Name HESS	Pulsar PSR	Age (yrs)	Dist (kpc)	$\dot{E}$ 10^{36} (erg/s)	$L_{\gamma_{mes}}(\theta)$ 10^{35} (erg/s)(deg)	$L_{\gamma_{theo}}$ 10^{35} (erg/s)	ϵ (%)	RX	A
J1303-631	J1301-6305	11 000	6.6	1.7	1.80(0.32)	6.78	27.00	x	Y
J1420-607	J1420-6048	13 000	5.6	10	0.61(0.16)	61.37	1.01	rx	Y
J1616-508	J1617-5055	8 100	6.5	18	1.59(0.4)	5.04	3.16	–	Y
J1702-420	J1702-4128	55 000	5.2	0.34	0.57(0.35)	10.8	5.30	–	Y
J1718-385	J1718-3825	89 500	4.2	1.3	0.14(0.18)	62.75	0.22	–	Y
J1804-216	J1803-2137	15 800	3.9	2.2	0.70(0.49)	16.79	4.20	x	Y
J1809-193	J1809-1917	51 000	3.7	1.8	0.33(0.5)	54.78	0.59	x	Y
J1825-137	J1823-13	21 000	3.9	2.8	1.96(0.8)	31.74	6.10	x	Y
J1912+101	J1913+1011	170 000	4.48	2.9	0.87(0.5)	199.2	0.43	–	Y
J1632-478	J1632-4818	19 800	7	0.05	2.67(0.36)	0.42	534	–	–
J1745-303	B1742-30	546 000	2.1	0.008	0.12(0.4)	0.32	32.77	–	–

Table 1: This table shows the complete selected sources list, with the corresponding pulsars characteristics, the measured (with the associated radius of intergation) and predicted γ-ray luminosity in the [200 GeV - 10 TeV] energy band and the γ-ray efficiency. The detection of a radio (r) or X-ray(x) nebula around the pulsar and an asymmetric shape of the VHE nebula (A) are also indicated.

Source name HESS	Cloud name MC	M_{CO} 10^3 (M_{sol})	density mol cm^{-3}	D_{Cl} kpc	Offset % R_{SNR}	H 10^{19} cm	Cont pc	D	G	Gr	RC
J1303-631	304.1+0.3	62	18	6.2	19.2	4	2	Y	Y	Y	Y
J1420-607	314+0.0	225	75	3.5/8	14	—	–	Y	N	N	N
J1616-508	332.7-0.6	222	164	3.9	10	12.2	2	Y	Y	Y	Y
J1718-385	348.8-0.4	11	16	4	20	—	–	Y	?	?	?
	348.8-0.5	13	40	3.5	20	—	–	Y	?	?	?
J1804-216	8.3+0.25	71	129	3	23	11.2	1.3	Y	Y	?	?
	8.7-0.6	132	107	4	23	—	–	N	–	–	–
J1809-193	11.1+0.12	80	67	3.7	25	13	2	Y	Y	Y	Y
J1825-137	18.15-0.32	80 000	150	4	20	4.2	3.6	Y	Y	Y	Y
	18.32-0.75	16 000	200	4	20	4.2	3.6	Y	Y	Y	Y

Table 2: Summary of the asymmetric PWNe candidates observed by H.E.S.S. for which we have detected one or several molecular clouds with distance compatible with the associated pulsar. The name, mass, density and approximate distance of the clouds are summarized. The offset between the pulsar and center of gravity of the source in percentage of the SNR radius, the contrast and the scale of the gradient of matter are calculated. Finally the distance (D), geometric configuration (G) and gradient (Gr) compatibility are compared with the simulations of [6](Y:compatible, N:not compatible).The final conclusion of the study is given in the last column (RC : reverse shock) (Y:compatible with the RC hypothesis, N:not compatible with the RC hypothesis).