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Probing cosmic ray acceleration through molecular clouds in the vicinity of supernova remnants

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Very high energy γ-ray emission has been recently detected by H.E.S.S. from the direction of associations between supernova remnants and molecular clouds. In such associations dense molecular clouds may reveal accelerated cosmic rays in the vicinity of supernova remnant forward shocks. Hadronic interactions could explain part or all of the observed γ-ray fluxes. The discovery of a new VHE γ-ray source, HESS J1923+141, coincident with the supernova remnant W51C, is reported. Amongst possible associations for this source is a shocked molecular cloud.

1 Introduction

Up to hundreds of PeV, the very high energy (VHE) cosmic-ray (CR) spectrum is likely to be of Galactic origin. Since the H.E.S.S. telescope has started its observations in 2003, various shell-type SNRs have been detected. The VHE gamma-ray spectra of several of them extend to energies beyond 50 TeV, confirming that these objects indeed accelerate particles up to more than 100 TeV. The H.E.S.S. effective threshold, a few hundred GeV, is too high to probe whether these gamma rays originate from inverse Compton scattering of VHE electrons off CMB and infrared photons or from the decay of π^0 produced in hadronic showers initiated by VHE protons interacting with interstellar matter. Such interactions require a significant amount of target matter to produce a detectable γ-ray flux. Dense molecular clouds in the vicinity of SNRs could thus be such a target [1]. The presence of 1720 MHz OH masers ensures physical associations as these masers occur in shocked molecular clouds [2]. The H.E.S.S. experiment has recently detected a γ-ray emission towards several associations: W28, G359.1-0.5, CTB 37A and very recently W51C, whose detection is reported in this paper. The interpretation of these γ rays as the product of CR interactions within these molecular clouds is discussed.

2 The W28 SNR, G359.1-0.5 and CTB 37A: three association candidates

The SNRs W28, G359.1-0.5 and CTB 37A are three candidate of SNRs associated with molecular clouds. Several OH masers at 1720 MHz have been detected towards these remnants and

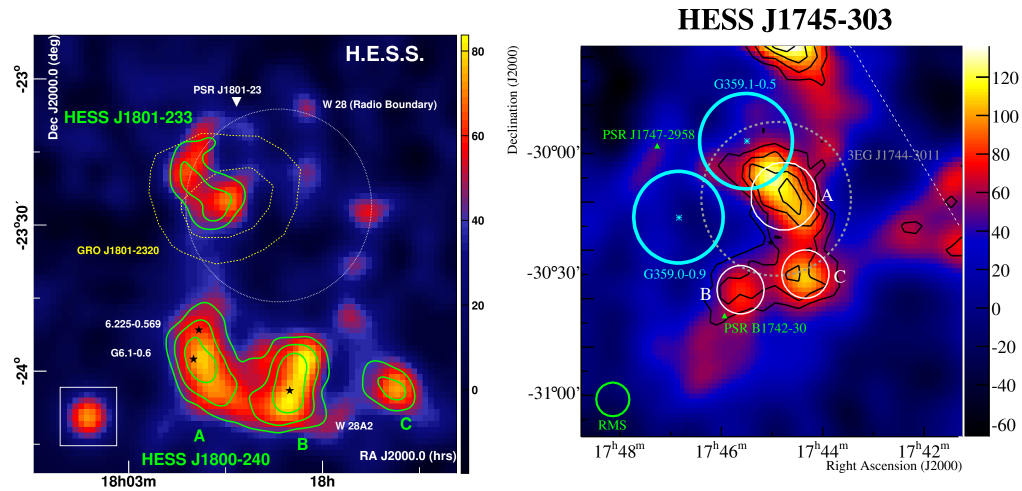

Figure 1: *Left:* H.E.S.S. γ-ray excess map Gaussian smoothed (σ=4.2′), with 4σ to 6σ significance contours overlaid. Several objects are indicated: SNR W 28 radio boundaries (thin-dashed circle), HII regions (black stars), PSR J1801-23 (white triangle), GRO J1801-2320 (dashed yellow lines - 68% and 95% position confidence levels). The inset shows the H.E.S.S. point spread function.*Right:* H.E.S.S. excess map Gaussian smoothed (σ=0.07°) of HESS J1745-303 with 4σ to 7σ statistical significance contours overlaid in black. The dashed circle is the 95% error circle for the location of 3EG J1744-3011. The Galactic plane is marked with a dotted line.

confirmed the physical associations of the SNR blast waves with dense molecular clouds. They have been observed by H.E.S.S. between 2004 and 2007.

Figure 1 *left* is the resulting VHE γ-ray excess map of the W28 field. Two sources have been detected [3] each with a statistical significance larger than 8σ: at the northeastern boundary of the remnant, HESS J1801-233, and to the South, HESS J1801-240 (possibly divided into three components, A, B and C). The W 28 SNR is interacting along its northern and northeastern boundaries with molecular clouds visible within NANTEN observations in the ^{12}CO(J=1$\rightarrow$0) line. A hadronic origin of the γ-ray emission implies a CR density enhancement of a factor 10 to 30 with respect to the local CR density; an enhancement indeed expected in the neighborhood of a CR accelerator such as W28.

Figure 1 *right* shows the VHE γ-ray source HESS J1745-303 [4]. The northern part of the H.E.S.S. source, A region, is coincident with the edge of the SNR G359.1-0.5. Observations performed in the ^{12}CO(J=1$\rightarrow$0) line [5] reveal that a fraction of a shocked ring of matter is coincident with the A region. A hadronic origin of the A region γ-ray flux infers a conversion efficiency of the mechanical explosion energy into CRs around 30%, assuming the extrapolation of the spectrum down to GeV energies. In the view of the uncertainties on this estimate, mainly the extrapolation of the spectrum down to GeV energies and the cloud mass estimation, it is in good agreement with theoretical expectations.

Finally, the discovery of the VHE γ-ray source HESS J1714-385 [6], coincident with the SNR CTB 37A, has been reported by H.E.S.S. in 2008. Figure 2 *left* shows the matter distribution superimposed with the γ-ray excess map. These molecular clouds are mostly contained within the H.E.S.S. source extension. In a hadronic scenario, the conversion efficiency of the mechanical energy of the explosion into CRs ranges between 4% and 30%, also in good agreement with theoretical expectations. However, recent X-rays observations by XMM-Newton and Chandra show a non-thermal emission coincident with the remnant. Its spectrum suggests a pulsar wind nebula (PWN) nature and it could be an alternative counterpart candidate for the γ-ray emission.

For all these VHE gamma-ray sources, a hadronic origin is also supported by the coincidence with EGRET sources. A spectral continuity to lower energy is expected in the case of a

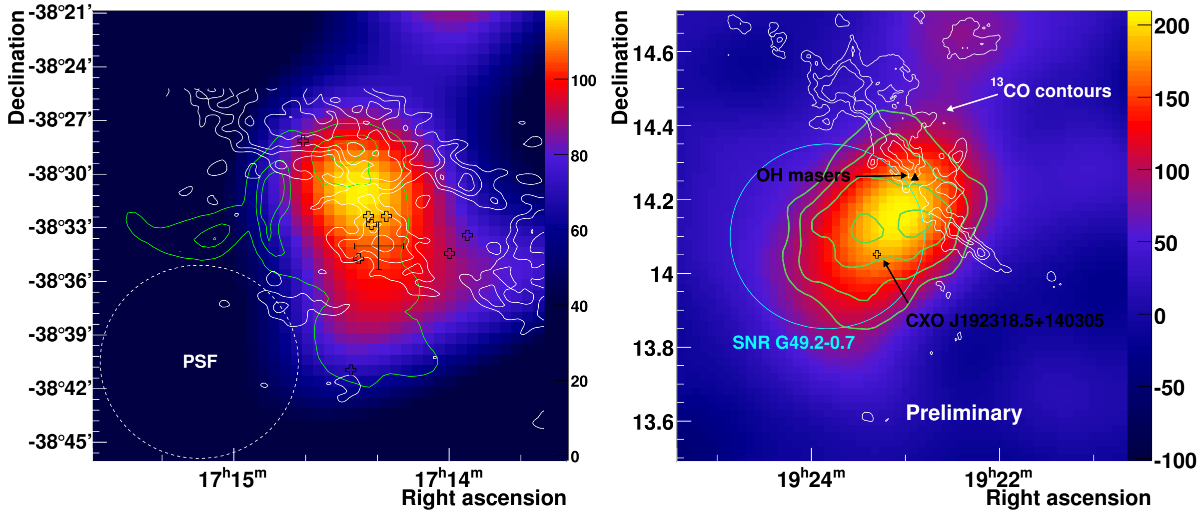

Figure 2: *Left:* HESS J1714-385 excess map, Gaussian smoothed (σ=2.9′). The 0.1, 0.9 & 1.4 Jy/beam radio contours at 843 MHz are overlaid in green and CO emission (-68 to -60 km s^{-1}) at 17, 25, 33, 41 and 49 K km s^{-1}in white. OH masers are marked with black open crosses and the best fit position for HESS J1714-385 with a large black cross. *Right:* HESS J1923+141 VHE γ-ray excess map, Gaussian smoothed (σ=7.6′). The green contours indicate the 3 σ to 6 σ significance level of the excess. The white contours show the measurement of the CO line at 30, 65 and 100 K km s^{-1}, integrated around the maser velocity between 60 km s^{-1} and 80 km s^{-1}.

hadronic origin. The H.E.S.S. spectra are compatible with extrapolations of the EGRET spectra. Although such compatibility is expected by chance [7], these H.E.S.S. sources are interesting counterpart candidates for the EGRET sources.

3 A new VHE γ-ray source: HESS J1923+141

3.1 H.E.S.S. observations

The W51 radio complex has been covered in 2007. A VHE γ-ray hotspot was visible in these observations and triggered dedicated observations performed in June 2008. After quality selection and dead-time correction, a total of ∼17 hours of observations are available within 2 degrees offset from the centre of the W51 field. These data have been analyzed using a combined Model-Hillas analysis [10]. The energy threshold for this analysis is 420 GeV. Figure 2 *right* shows the resulting excess map. An excess of VHE γ-ray is detected in the W51 region with a statistical significance of 6.7σ using an oversampling radius of 0.22°. Accounting for a number of trials updated from the HESS Galactic plane survey [11] to the current survey, this new source, HESS J1923+141, has a statistical significance post-trials of 4.4σ. The source is clearly extended compared to the H.E.S.S. PSF, and the exact morphology is still under study. The integrated flux over 1 TeV is equivalent to ∼3% of the flux from the Crab Nebula above the same energy.

3.2 The multiwavelength view

W51 is an extended radio complex composed of two HII regions W51A and W51B, embedded in a giant molecular cloud [12] hosting several star forming regions. The SNR W51C (also called G49.2-0.7) appears as a partial shell in radio continuum. It is interacting with the giant molecular cloud as evidenced by two 1720 MHz OH masers [13] and shocked material [14–15]. Fig. 2 *right* show the matter distribution revealed by the ^{13}CO line of this region. This region has been also observed with several detectors in X rays which revealed a complex region in the keV energy range. A candidate PWN, CXO J192318.5+140505, is detected coincident with the SNR W 51C [16].

3.3 Discussion on HESS J1923+141 origin

Amongst the possible counterparts, the presence of a shocked molecular cloud allows a hadronic origin. Assuming that 10% of the cloud is involved in the γ-ray production, a CR density 30 times higher than the local average value is required to produce the VHE γ-ray emission above 1 TeV. The presence of a PWN candidate provides a competitive leptonic scenario. The pulsar spin-down luminosity is estimated to be around $L_{\rm SD} = 4.5 \times 10^{36}$ erg s^{-1}, assuming a distance to the PWN of 6 kpc, identical to that of the SNR [14–17]. Using this distance, the γ-ray luminosity between 1 and 10 TeV is lower than 0.1% of the pulsar spin-down luminosity and could be explained by IC emission from relativistic electrons accelerated within the PWN. A third scenario is provided by the presence of star forming region. VHE gamma-rays have been already detected toward star forming regions by H.E.S.S. [18]. Stellar clusters could thus participate to the γ-ray emission. However, the γ-ray map does not reflect the star forming region distribution within the cloud. A VHE γ-ray emission through these scenarios cannot be excluded. More detailed spectral and morphological studies are under progress to understand the origin of this new VHE γ-ray source.

4 Summary

The γ-ray emission detected toward the SNRs of W28, G359.1-0.5 and CTB 37A, can be interpreted as originating from π^0 decay after interactions of CRs from the remnant with molecular clouds. The CR energy required is compatible with theoretical expectations. Recent observations with HESS of the W51 region led to the discovery of a new VHE γ-ray source, which could be also associated with a shocked molecular cloud. All these observations suggest that shell-type SNRs are effective hadron CR accelerators. Further studies of associations with H.E.S.S. and then FERMI and H.E.S.S. II will certainly help understanding the mechanism at the origin of the Galactic CRs.

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