Probing cosmic ray acceleration through molecular clouds in the vicinity of supernova remnants with H.E.S.S.

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The detection of cosmic-ray acceleration within supernova remnants (SNR) using γ-ray experiments requires a significant amount of target matter to produce γ-rays. Dense molecular clouds in the vicinity of SN blast waves could be a probe of proton acceleration. Several very high energy (VHE) γ-ray excesses detected towards known associations between SNRs and molecular clouds are reported. A hadronic scenario could explain part or the overall of these sources.

1 Introduction

It is commonly believed that supernova remnants (SNRs), or more precisely the strong shocks associated with them, are the main particle accelerators in the Galaxy up to 10^{15} eV. Recently, VHE (E >100 GeV) γ-ray emission has been detected from several shell-type SNRs with H.E.S.S. (High Energy Stereoscopic System [4]), which confirms that these objects accelerate particles up to at least 100 TeV [1]. The observed γ-ray emission in a narrow energy band is not sufficient to disentangle the contributions from inverse Compton scattering by accelerated electrons, or neutral pion decay ($\pi^0 \rightarrow \gamma\gamma$) after hadronic interactions of accelerated protons. However, hadronic interactions require a significant amount of target matter to produce a detectable γ-ray flux. The observation of dense molecular clouds in the vicinity of supernova blast waves could thus be a probe of proton acceleration by supernova remnants [2]. The additional presence of OH masers (1720 MHz) indicates physical associations as these masers occur in shocked molecular clouds [3].

The H.E.S.S. experiment has covered several associations. A γ-ray emission have been detected towards some of them. The detection of these emissions is reported and the interpretation of these γ-rays as the product of CR interactions within these clouds is discussed.

2 VHE γ-ray detections towards molecular clouds and SNRs associations

2.1 The W28 field

W 28 (G6.4-0.1) is a middle age mixed-morphology SNR, distant between 1.8 and 3.3 kpc. This remnant is interacting with molecular clouds along its north and northeastern boundaries. The physical associations is traced by a high concentration of OH masers and high density shocked gas [5].

The H.E.S.S. telescopes observed this region between 2004 and 2006 [6]. Fig. 1 *left* is the resulting VHE γ-ray excess map. Two sources have been detected with a statistical significance

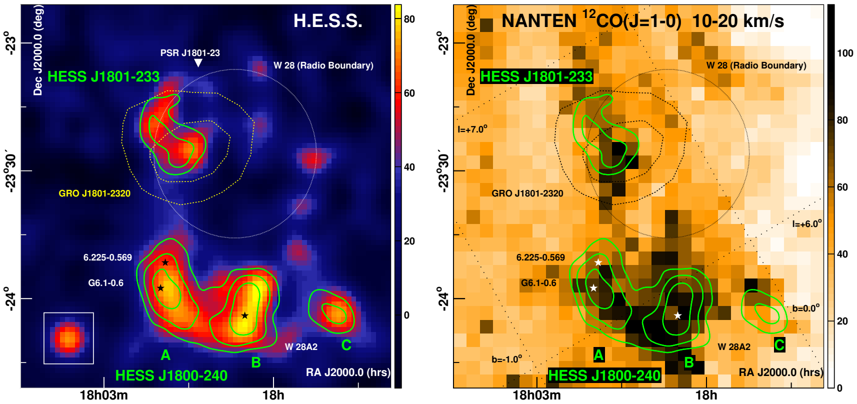

Figure 1: *Left:* H.E.S.S. γ-ray excess map, with 4σ to 6σ significance contours overlaid. Several objects detected at other wavelengths are indicated: SNR W 28 boundaries (thin-dashed circle), HII regions (black stars), PSR J1801-23 (white triangle), GRO J1801-2320 (dashed yellow lines - 68% and 95% position confidence levels). The inset show the H.E.S.S. point spread function. *Right:* NANTEN ^{12}CO(J=1→0) velocity integrated map (10 to 20 km s^{-1}) with the same significance contours overlaid.

larger than 8σ, at the northeastern and southern boundary of the remnant, HESS J1801-233 and HESS J1801-240. The latter can be further divided into three components, A, B and C.

NANTEN observations in the ^{12}CO(J=1→0) line show the presence of dense molecular clouds coincident with both excesses. These clouds are visible in the 0 to 10 km s^{-1} range or in the 10 to 20 km s^{-1} range (fig. 1 *right*), both corresponding to a distance compatible with the SNR W 28. Assuming extremal distances for the SNR, a hadronic scenario for the γ-ray emissions implies a CR density enhancement in unit of local CR density ranging between 10 and 30 for both sources. Such CR density enhancement is expected in the neighborhood of a CR accelerator and is compatible with an acceleration and diffusion from the nearby SNR W 28.

An analysis of EGRET data (CGRO observation cycles 1 to 6) has been performed and reveals a point-like E>100 MeV source GRO J1801-2320. The position of this source (visible on fig. 1 *left*) matches well the position of HESS J1801-233. However, an association with HESS J1801-240 cannot be ruled out. This coincidence with an EGRET source argues for a hadronic scenario for which a spectral continuity to lower energy is expected. Further details on alternative scenarios can be found in [6].

2.2 HESS J1745-303 and the SNR G359.1-0.5

The VHE γ-ray source HESS J1745-303 was discovered in the H.E.S.S. galactic plane survey [7]. Additional observations have been performed and the increased exposure allows a more detailed study [8]. Figure 2 *left* is the resulting γ-ray excess map. The morphology appears more complex than previously reported. The energy spectrum of the excess is well described by a power law with a photon index of $2.71\pm0.11_{\mathrm{stat}}\pm0.2_{\mathrm{sys}}$ and an integrated flux over 1 TeV equivalent to 5% of the Crab nebula flux above the same energy. The source remains unidentified. There is no obvious counterparts at other wavelenghts, except a unidentified EGRET source, 3EG J1744-301, coincident with the VHE γ-ray source. Several scenarios which could explain a fraction of this source have been studied. Further details can be found in [8].

The northern fraction of the H.E.S.S. source is coincident with the edge of the shell-type SNR G359.1-0.5. This remnant is interacting with a ring of matter surrounding its shell, as revealed by OH masers [9]. Two of these masers are coincident with the northern fraction of HESS J1745-303. ^{12}CO(J=1→0) observations by the Cerro Tololo Inter-American Observatory (Chile) [10] reveal that a fraction of the matter ring is coincident with the region A (fig. 2 *right*). This concentration amounts for 5×10^4 M$_\odot$ with a density of 5×10^3 cm^{-3}. Assuming that the

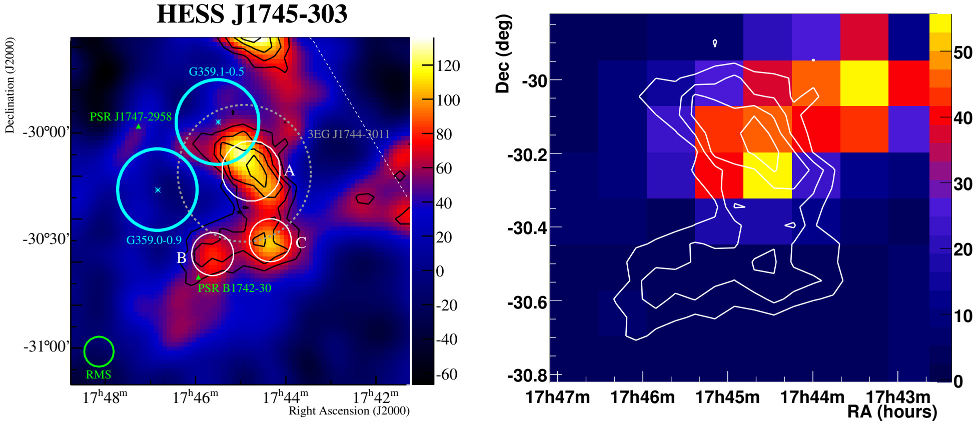

Figure 2: Left: H.E.S.S. excess map of HESS J1745-303 with 4σ to 7σ statistical significance contours overlaid in black. The dashed circle is the 95% error circle for the location of 3EG J1744-3011. The Galactic plane is marked with a dotted line. Right: Velocity-integrated map (-100 to -60 $\mathrm{km\,s^{-1}}$) of ^{12}CO emission showing the molecular cloud coincident with the shell of G359.1-0.5, with overlaid HESS 4σ to 7σ significance contours.

region A is produced by CRs accelerated by the SNR interacting into the cloud, the γ-ray flux implies a conversion efficiency of the mechanical explosion energy into CRs around 30%. A hadronic scenario is also supported by the coincidence with the EGRET source.

2.3 HESS J1714-385 and the SNR CTB 37A

The VHE γ-ray source HESS J1714-385 has been discovered recently by H.E.S.S. [11]. It is located in the region of the SNR RX J1713.7-3946, close to HESS J1713-381 (fig. 3 *left*). The source is extended ($\sigma\sim 4'$) and is coincident with the supernova remnant G348.5+0.1 (also called CTB 37A). Its energy spectrum is well described by a power law with a photon index of $2.30\pm0.13_{\mathrm{stat}}\pm0.2_{\mathrm{sys}}$ and an integrated flux over 1 TeV equivalent to 3% of the Crab nebula flux above the same energy. HESS J1714-385 lies between the 68% and 95% confidence level of an EGRET source 3EG J1714-3857. The H.E.S.S. spectrum is compatible with an extrapolation of the EGRET spectrum. Although such compatibility is expected by chance, this good agreement makes the new H.E.S.S. source a good counterpart candidate for the EGRET source amongst the three VHE γ-ray sources possibly associated with.

The SNR CTB 37A is physically associated with dense molecular clouds detected by ^{12}CO observations [12]. The detection of OH masers indicates that the forward shock is passing through the clouds. Figure 3 *right* shows the matter distribution overlaid on the γ-ray excess map. These clouds are mostly contained within the H.E.S.S. source extension and could be the origin of the γ-ray emission. In a hadronic scenario, the conversion efficiency of the mechanical explosion energy into CRs would range between 4% and 30%. This estimate appears in good agreement with theoretical expectations.

Recent X-rays observations by XMM-Newton and Chandra show a complex region with several emission of various nature. A non-thermal emission is seen coincident with the remnant. This source could be a pulsar wind nebula associated with CTB 37A and could be the origin of the γ-ray emission. Further details can be found in [11].

3 Summary

The γ-ray emission detected toward these three associations can be interpreted as the π^0 decay after interactions of CRs accelerated by the remnant into molecular clouds. The CR energies

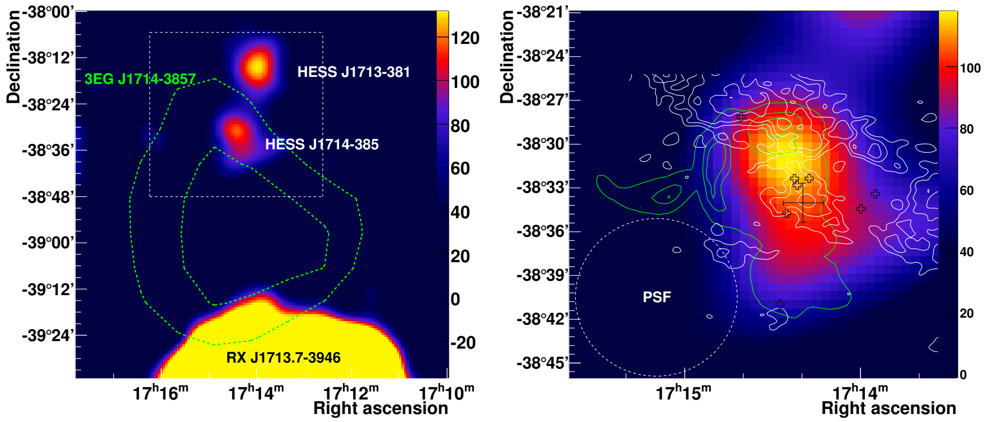

Figure 3: *Left:* H.E.S.S. excess map of the region of the SNR complex CTB 37. The 68% and 95% position confidence levels of 3EG J1714-3857 position are overlaid in green. *Right:* Expanded view toward HESS J1714-385. The 0.1, 0.9 & 1.4 Jy/beam radio contours at 843 MHz are overlaid in green and CO emission (-68 to -60 $\mathrm{km\,s^{-1}}$) at 17, 25, 33, 41 and 49 K $\mathrm{km\,s^{-1}}$in white. OH masers are marked with small black open crosses. The best fit position for HESS J1714-385 is reported with a large black cross. The white dashed circle illustrates the 68% containment radius of the H.E.S.S. smoothed PSF.

implied are compatible with theoretical expectations. These discoveries are completed by the detection by MAGIC of a VHE γ-ray emission toward IC 443 [13], also known to be interacting with a dense molecular cloud. All these observations suggests that shell-type SNRs are effective CR accelerators. Further studies of associations with H.E.S.S. and soon H.E.S.S. II and GLAST seems promising.

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References

1. Aharonian F.A. et al. (H.E.S.S. Collaboration) 2007, ApJ, 661, 236A
2. Aharonian F.A., Drury L.O'C. & Völk H.J. 1994, A&A, 285, 645A
3. Elitzur M. 1976, ApJ, 203, 124
4. Aharonian F.A. et al. (H.E.S.S. Collaboration) 2006, A&A, 457, 899A
5. Frail D.A., Goss W.M. & Slysh V.I. 1994, ApJ, 431L, 35V
6. Aharonian F.A. et al. (H.E.S.S. Collaboration) 2008, A&A, 481, 401A
7. Aharonian F.A. et al. (H.E.S.S. Collaboration) 2006, ApJ, 636, 777A
8. Aharonian F.A. et al. (H.E.S.S. Collaboration) 2008, A&A, 483, 509A
9. Yusef-Zadeh F., Uchida K.I. & Roberts D. 1995, Science, 270, 1801Y
10. Bitran M., Alvarez H., Bronfman L., May J., & Thaddeus P. 1997, A&AS, 125, 99
11. Aharonian F.A. et al. (H.E.S.S. Collaboration) 2008, submitted to A&A (arXiv:0803.0702)
12. Reynoso E.M. & Mangum J.G. 2000, ApJ, 545, 874
13. Albert J. et al. 2007, ApJ, 664L, 87A