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Modeling cosmic rays escaping from RXJ1713.7−3946 - Is it a really a PeVatron?

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RXJ1713.7−3946 is one of the most prominent supernova remnants (SNRs) at high energies, with clearly rim-brightened emission from X-ray to TeV gamma-ray energies. Its relatively young age (1.6 kyr) also makes it a perfect example to search for evidence of escaping cosmic rays up to PeV energies. However, the level of gamma-ray emission that might trace escaping cosmic rays depends heavily on the presence of ISM gas clouds around the SNR, the physics of cosmic-ray escape from SNR shocks, and the transport properties of the escaping cosmic rays. We apply here a newly developed 3D model of escaping cosmic rays from RXJ1713−3946 coupled to the measured molecular and atomic gas at arc-minute scales, to assess the gamma-ray emission at several places around the SNR and its detectability by future gamma-ray facilities such as the Cherenkov Telescope Array (CTA).

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1. Introduction

The existence of particle acceleration in the Milky Way has been established for many decades via observations of cosmic rays (CRs) up to the *knee* feature in the PeV energy regime (e.g. [11, 29]). Additionally, the detection of localised and diffuse Galactic gamma-ray emission reaching ~0.1 PeV in energy and beyond has provided clues as to the nature of multi-PeV particle accelerators (i.e. PeVatrons) in our galaxy [2, 4–6, 9, 9, 10, 12, 14, 15]. Supernova remnants (SNRs) have for decades believed to be the major sources of Galactic cosmic-rays (e.g. [27]). However their role as PeVatrons is still debated with discussion centering on the ability of SNR shocks to accelerate partices to PeV energies (e.g. [13, 30]). Besides the expectation that supermassive black holes provide PeV particle acceleration (e.g. [1, 6]), additional or alternative PeVatrons are being put forward with several > 50 TeV and PeV gamma-ray sources now linked to pulsar wind nebulae (PWN), pointing to their ability to accelerate PeV electrons [9]. There is also renewed interest in massive stellar clusters as PeVatrons, given their intense winds operating over long time scales > 10^5 yr [8].

2. Cosmic Rays Escaping SNRs - Looking for PeVatrons

However, there still remains a clear way forward to finally test the notion of SNRs as PeVatrons. In this work, we made use of the idea first put forward by [7] and later by [23] which considers the time- and energy-dependent escape of cosmic rays (CRs) from impulsive accelerators such as SNRs. After acceleration from the SNR shock, CRs escape and are assumed to propagate diffusively through the interstellar medium (ISM) [25]. The energy-dependent diffusion coefficient $D \sim E^{\delta}$ for δ in the range 0.3 to 0.7 means that the highest energy CRs propagate the farthest distances from the SNR in a given time. Our focus here is on CR hadrons (hereafter labeled as CRs) for which radiative losses from CR and ISM proton collisions only become noticeable in ISM clouds with high number density $n >> 100\,\mathrm{cm}^{-3}$. After diffusing some distance from the SNR shock, the escaped CRs may collide with ISM protons 10's of pc away from the SNR to produce extended gamma-ray emission spatially co-locating with local ISM clouds or clumps. The model has been applied to explain the GeV to TeV emission detected around several mature (> 10^4 yr) SNRs (e.g. [24, 28, 35]). Most recently [33] applied this model in a systematic study of catalogued SNR and ISM cloud combinations to search for PeVatrons via their >100 TeV emission detectable with future TeV facilities like the Cherenkov Telescope Array (CTA) [18].

3. Application to RXJ1713.7–3946

Our SNR of interest is the young (1600 yr) TeV-bright shell-type SNR RXJ1713.7−3946 (hereafter, RXJ1713). RXJ1713, at ~1 kpc distance [34], is one of the best-studied SNRs at gamma-ray energies with the latest results from H.E.S.S. resolving the TeV gamma-ray emission down to several arc-minutes and pushing the energy spectrum beyond 30 TeV in energy [3]. H.E.S.S. was also able to show that the TeV emission spatially extended beyond the synchrotron X-ray shell, providing the first evidence for particles beyond the shock front. Whether or not these particles represent those truly escaping from the shock, or those travelling upstream in what is known as the shock precursor remains to be seen, due to the present sensitivity limits of H.E.S.S. The first

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application of the escaping CR model to RXJ1713 was by [16]. They utilised a 3D data cube of ISM gas from the LAB HI and Nanten CO surveys, with a combined angular resolution of 0.6° and assumed the gas spanned the full heliocentric distance from 50 pc to 30 kpc. Here, we adapt the escaping CR mode to account for CRs escaping the expanding SNR shock (as also done by [35]) and utilise the molecular ^{12}CO(1–0) gas data cube from the more sensitive Nanten2 CO survey [21] with 3′ resolution (FWHM), plus the SGPS HI data [32] at very similar resolution. The molecular gas is expected to dominate the ISM in the large dense clouds although the atomic gas is a significant component at the SNR location [26]. Some key aspects of the escaping CR model are shown below with full details given in [20].

We evaluate the 3D CR density f (cm^{-3}GeV^{-1} units) at radius R' for CRs after they have escaped the SNR ($t > t_{\rm esc}(E)$) via the following:

$$f(E, R', t') \approx \frac{f_0}{\pi^{3/2} R_d^3} \exp\left[-\frac{(\alpha-1)t'}{\tau_{pp}} - \frac{R'^2}{R_d^2}\right] \quad (t > t_{\rm esc}(E)) , \tag{1}$$

where $t' = t - t_{esc}(E)$ for the SNR escape time $t_{\rm esc}(E)$, α is the power law index of the injected CR spectrum, and the diffusion radius R_d is given by:

$$R_d(E, t') = 2\sqrt{D(E)t' \frac{\exp(t'\delta/\tau_{pp}) - 1}{t'\delta/\tau_{pp}}} \tag{2}$$

Here, δ is the diffusion coefficient index as given above and $\tau_{\rm pp}$ is the cooling time for CR-ISM collisions. The normalisation f_0 of the CR density accounts for the release of CRs from an expanding SNR shell of radius $R_{\rm SNR}$:

$$f_0 = \frac{\sqrt{\pi} R_d^3}{\left(\sqrt{\pi} R_d^2 + 2\sqrt{\pi} R_{\rm SNR}^2\right) R_d + 4 R_{\rm SNR} R_d^2} . \tag{3}$$

The escape time is related to Sedov time $t_{\rm Sedov}$ (onset of the Sedov phase of the SNR) via $t_{\rm esc} = t_{\rm Sedov}(p/p_M)^{-1/\beta}$ which is a function of CR momentum p. The SNR radius $R_{\rm SNR}$ is estimated using Eq. 8 of [36]. The maximum CR momentum is set to p_M = 1 PeV/c thus assuming the SNR can act as a PeVatron. The Sedov time for an SNR depends on its total energy $E_{\rm SN}$, ejecta mass $M_{\rm ej}$ and density n_0 of the surrounding ISM the SNR expands into. For core-collapse SNRs like RXJ1713, $t_{\rm Sedov}$ could vary between a few 100 yrs to > 1000 yr (e.g. see Eq. 7 of [38]). Thus for a young SNR like RXJ1713, $t_{\rm Sedov}$ will have a significant effect on the level of escaping CRs, and in fact the SNR could still be in the initial free-expansion phase (e.g. [39]). Assuming $n_0 = 0.5\,{\rm cm}^{-3}$, $E_{\rm SN} = 3 \times 10^{51}$ erg and $M_{\rm ej} = 5{\rm M}_\odot$ we arrive at $t_{\rm Sedov} \sim 650$ yr and $R_{\rm SNR} = 8.6$ pc (to match the observed SNR X-ray outer shock at 1 kpc). Similarly, the β parameter (often assumed to be 2.5) varying with the magnetic field turbulence evolution will also play an important role [17]. Following [22] we parametrise the diffusion coefficient as:

$$D(E) = \chi D_0 \left(\frac{E/{\rm GeV}}{B/3\mu{\rm G}}\right)^{\delta} \tag{4}$$

where the suppression factor χ characterises the level of turbulence within the ISM, D_0 is the reference diffusion coefficient $D_0 = 3 \times 10^{27}$ cm^2/s at E = 1 GeV, and B is the magnetic field.

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Fig. 1 shows the Nanten2 ^{12}CO(1–0) images integrated in several kinematic velocity ranges encompassing the 1 kpc distance of RXJ1713. Four molecular features (labeled NW, SW, SE, NE) are identified around RXJ1713 that all have broad ($\Delta V > 20$ km/s) CO spectra. The NW, NE and SE features have peak CO emission $V_{\rm peak} \sim -10$ to –5 km/s, perfectly overlapping the kinematic systemic velocity of RXJ1713 (~ -7.5 km/s). The SW feature peaks in the slightly different $V_{\rm lsr}$ range -15 to -10 km/s and thus might lie behind RXJ1713. We note the supershell SG 347.3–0.5–21 situated at 2.5 to 3 kpc distance [31, 34] creates a prominent CO void that becomes quite apparent in the –30 to 0 km/s image. The NW position is the star formation region RCW 120 formally placed at 1.3 kpc distance and may originate from a cloud-cloud collision scenario [37]. Given the broadness of the all four features reflecting local gas motions, and the fact they lie towards the near side the Sagittarius arm (RXJ1713 is in fact placed at front edge of this arm [34]) suggests they could be within a few 100 pc distance of RXJ1713 and thus potential targets for escaping CRs.

In applying the escaping CR model to RXJ1713, we will therefore set up the ISM gas as a 3D region of physical length $L < 300$ (pc) discretised along the line of sight to create an array of voxels (3D pixels) as the target ISM. Similarly, we will investigate the predicted CR densities and gamma-ray emission under a variety of parameters (e.g. changing L, $M_{\rm ej}$, χ). Initial results will be presented at the conference and in the final version of this proceedings.

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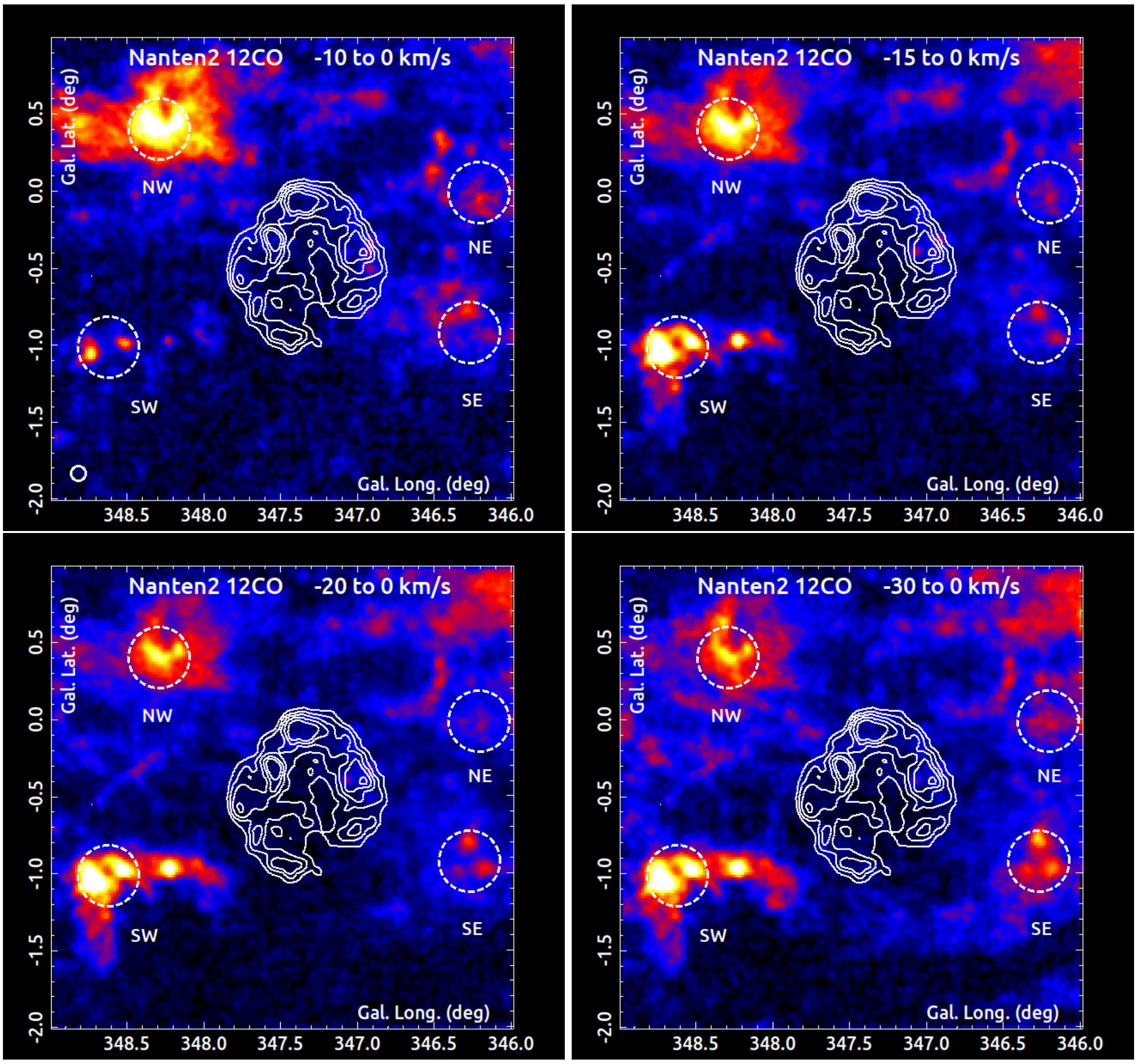

Figure 1: Nanten2 ^{12}CO(1–0) images (K km/s units, max level at 99%) integrated over the indicated range of kinematic velocity $V_{\rm lsr}$. H.E.S.S. > 2 TeV significance contours (10, 15, 20, 25, 30σ) from RXJ1713.7−3946 [3] are shown as white lines. White dashed circles indicate regions (radius 0.2°) selected for examination by our escaping CR model (see text). The Nanten2 ^{12}CO(1–0) resolution (3′ FWHM) is the solid white circle at the bottom left of the -10 to 0 km/s image.

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