PROCEEDINGS OF SCIENCE

Particle escape from supernova remnants: a multi-messenger view

Silvia Celli[a,*]

[a] *Sapienza University and INFN-Sezione di Roma,*
Piazzale Aldo Moro 2, 00185, Roma, Italy

E-mail: silvia.celli@roma1.infn.it

The escape of accelerated particles represents a fundamental piece of information in the context of the supernova remnant (SNR) paradigm for the origin of Galactic cosmic rays (CRs) to interpret both the observed CR spectrum and the radiative signatures emerging from these sources. The particle release process from SNR shocks is energy dependent, such that high-energy particles are expected to leave the shock region before low-energy ones, the absolute temporal scale depending on the diffusion coefficient in the region surrounding the shock. This fact might result into broken power law spectra of hadronic gamma rays, similar to those observed from several middle-aged SNRs. The presence of dense gas targets, such as interstellar clouds, nearby the accelerators might provide evidence for the escaping flux of particles through the production of gamma rays and neutrinos at hadronic collisions. Exploring such scenarios is extremely timely given that recent wide field-of-view survey instruments have revealed an unexpectedly large population of Galactic gamma-ray sources at ultra-high-energies (UHE, E >100 TeV) with no counterpart.

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[*] Speaker

1. Introduction

Considerable experimental advancements in recent years have led to the emergence of UHE gamma-ray astronomy, most notably due to ground-based particle detectors such as LHAASO. Gamma rays and neutrinos with energies above 100 TeV are of particular interest to investigate the origin of CRs in the *knee* energy region, as the production of these energetic particles is necessarily due to primaries with PeV energies. Although direct and conclusive evidence of SNRs as hadronic PeVatrons is still lacking in UHE gamma-ray observations, SNRs remain candidate PeV accelerators, as they might be producing particles at PeV energies in short time intervals, namely during their early evolution. Currently, the majority of UHE gamma-ray emitters are unidentified (UNID) [1], i.e. the cause of their emission is not known or ambiguous. Additionally, a number of UHE emitters are unassociated or *dark* in origin, referring to the lack of known counterparts, of noticeable interest as their emission might arise from the illumination by nearby accelerators (e.g. SNRs) of in dense targets through a particle beam colliding in there. To explore the possibility that the dark systems are passive targets of SNRs, it is necessary to investigate physical associations between the known population of SNRs and molecular clouds, consisting of both spatial and spectral correlation. The methods and results of such investigation are presented in the following sections, while a more extended description of the work can be found in [2].

2. Methods

Spatial association among SNRs and clouds can be studied via the catalogued positions of both populations, which are provided as 3D information for Galactic objects. Specifically, for SNRs both the Green's catalogue [3] and the SNRcat [4] are used to obtain the corresponding properties (location, age, distance and physical size). For Galactic molecular clouds, the Rice et al. catalogue [5] is here adopted, providing size and 3D position of CO over-densities in the plane of our Galaxy. On the other hand, a spectral connection among two class members can be established based on a physical model describing impulsive acceleration in SNRs, transport to the cloud location, and hadronic collisions in nearby target clouds [6]. The present description of particle acceleration in remnants of type II and type Ia SNe mainly differs in the onset of the Sedov stage at $t_{\rm Sed}$: fixing the energetics and upstream density, taken uniform in both cases, the Sedov time is shorter for thermonuclear explosions because of the reduced ejecta mass. The behavior of particle escape can be described by a power-law dependence of the escape time $t_{\rm esc}$ with respect to the particle momentum p

$$t_{\rm esc} = t_{\rm Sed} \left(\frac{p}{p_M} \right)^{1/\beta}$$

where the parameter β embeds information about the evolution of the magnetic turbulence and its confinement properties. In this work, we set $\beta = 2.5$ and $p_M = 3$ PeV/c, corresponding to the maximum energy reached at the Sedov time, as required to achieve the CR knee. The diffusive transport of particles through the interstellar medium is parameterised through a Kraichnan-like diffusion coefficient, possibly suppressed with respect to its average Galactic value due to CR-induced turbulence and self-confinement in the vicinity of Galactic accelerators. Inelastic hadronic collisions are treated as due to proton-proton interactions only, according to the parametrization by

[7] for the production of secondary particles. In the following, only gamma-ray emissivity from clouds is discussed, while the neutrino component is left for a dedicated analysis.

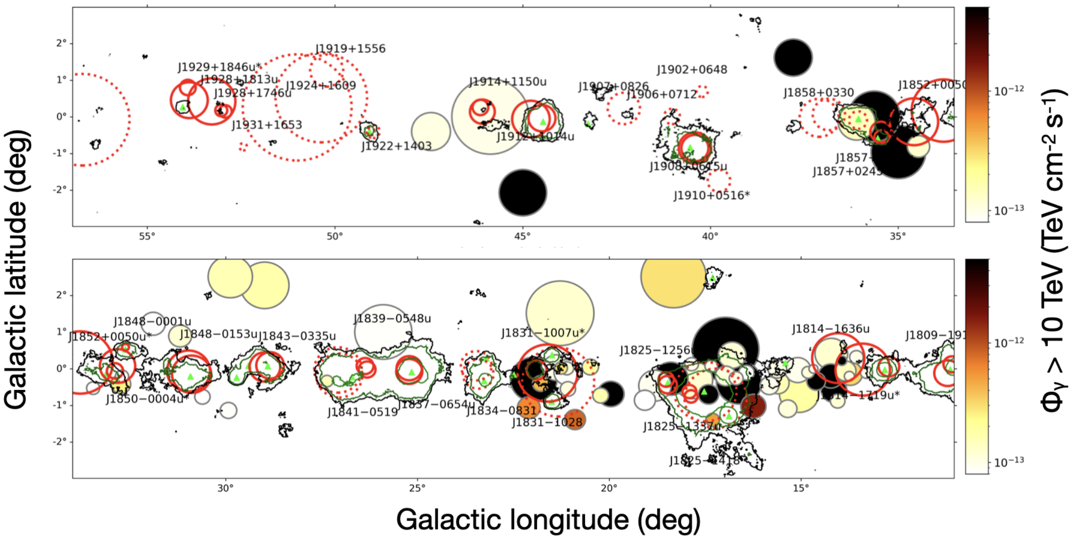

Figure 1: The predicted integral gamma-ray flux above 10 TeV from molecular clouds of the catalog in [5], due to illumination by type Ia nearby SNRs. Significance contours (green and black) from the HGPS [8] are reported together with name and locations of 1LHAASO sources [1] (red circles), with solid red circles indicating UHE sources (with high-significance emission reaching beyond ∼ 100 TeV). Figure from [2].

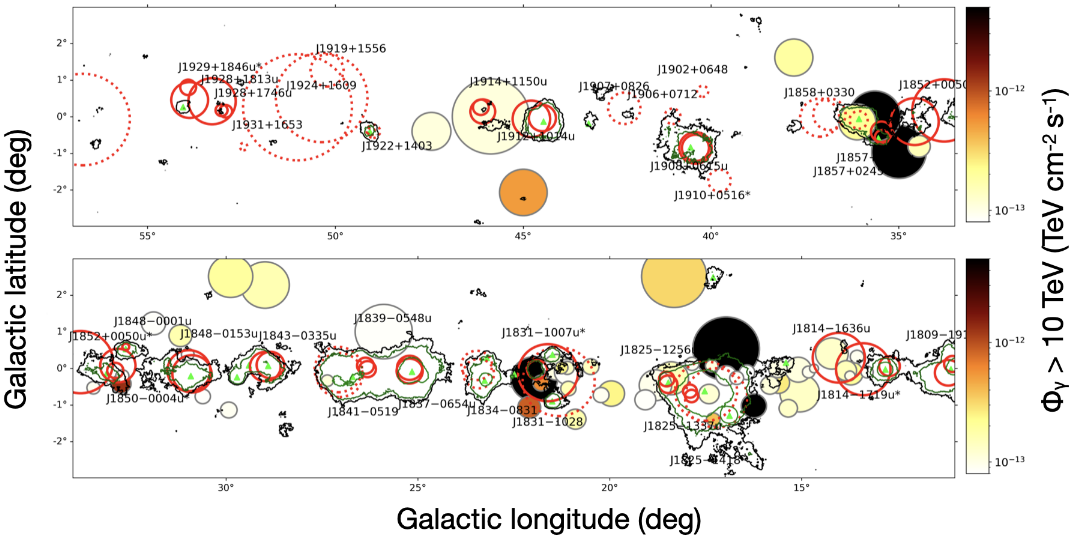

Figure 2: Same as Fig. 1 assuming type II origin scenario. Figure from [2].

SNRs are coupled to clouds based on their coordinates and distance: the latter are provided either with an unambiguous distance or a preferred distance estimate (near or far), which is adopted for this study. Where a distance estimate for an SNR is available, this is required to be consistent with the distance of the cloud (within errors); otherwise each SNR is assumed to be located at the same distance from Earth as the respective cloud, for the purposes of the present model. Each pair

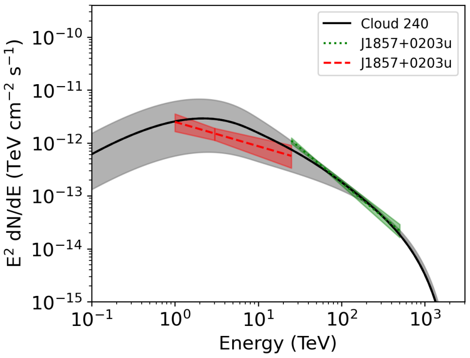

Figure 3: Gamma-ray flux from 1LHAASO J1858+0330 as measured by WCDA (red line) and KM2A (green line), compared to the predicted emission by cloud 240 as illuminated by SNR G036.6-0.7 (solid line). The grey band represents the model uncertainty related to the absolute value of diffusion coefficient in the interstellar medium and the level of magnetic turbulence inside the cloud [2].

must have a physical separation no larger than 100 pc to be taken into account. As such, the resulting gamma-ray flux from the CR escaping their SNRs and impacting nearby clouds in shown in Figs. 1 and 2, obtained respectively for a type Ia SN progenitor scenario and type II, in the standard 10% assumption of energy conversion between shock ram pressure and CRs.

3. Comparison of the first LHAASO source catalog

The situation shown in Figs. 1 and 2 is relatively complex, because of the high density of molecular clouds and gamma-ray sources overlapping along the line-of-sight, complicating the identification of counterpart objects. To identify regions that require more detailed studies, we searched for illuminated clouds that are coincident with 1LHAASO sources along the line-of-sight (also shown in Figs. 1 and 2 as red empty circles), particularly among UNID systems where the total emission may be contributed to by an illuminated cloud scenario. We consider a cloud to be coincident with a 1LHAASO source if the angular separation between their best-fit positions is less than the sum of their radii (implicitly assuming spherical symmetry): a conservative estimation is used for the 1LHAASO source size, namely their 39% containment radius. A coincidence is evaluated assuming the most positive scenario where the cloud and the LHAASO source are at the same distance from Earth, given that the distance to LHAASO sources cannot be determined solely from the gamma-ray emission. [2] reports a full list of SNR-illuminating clouds and spatially overlapping LHAASO sources: among these, an interesting case study is constituted by LHAASO J1857+0203u, as it results spatially coincident with cloud 140 and its spatial region moreover contains the UNID H.E.S.S. source J1858+020. As shown in Fig. 3, the level of predicted gamma-ray flux from the escaping CRs by SNR G036.6-0.7 provides a reasonable explanation to the observed LHAASO emission in the broad energy range covered by its two instruments WCDA and KM2A, making the scenario of cloud illumination plausible also in terms of spectral shape. Other interesting cases are discussed more in details in [2].

References

[1] Z. Cao et al. [LHAASO Collaboration], *The First LHAASO Catalog of Gamma-Ray Sources*, ApJSS 271 (2024) 25;

[2] A. W. Mitchell & S. Celli, *Exploring the supernova remnant contribution to the first LHAASO source catalog via passively illuminated interstellar clouds*, JHEAp 44 (2024) 340-355;

[3] D. A. Green, *A revised catalogue of 294 Galactic supernova remnants*, Journal of Astrophysics and Astronomy 40 (2019) 36;

[4] G. Ferrand & S. Safi-Harb, *A census of high-energy observations of Galactic supernova remnants*, Advances in Space Research 49 (2012) 1313-1319;

[5] T. S. Rice et al., *A Uniform Catalog of Molecular Clouds in the Milky Way*, ApJ 822 (2016) 52;

[6] A. W. Mitchell et al., *Using interstellar clouds to search for Galactic PeVatrons: gamma-ray signatures from supernova remnants*, MNRAS 503 (2021) 3;

[7] S. R. Kelner et al., *Energy spectra of gamma rays, electrons, and neutrinos produced at proton-proton interactions in the very high energy regime*, PRD 74 (2006) 034018;

[8] H. Abdalla et al. [H.E.S.S. Collaboration], *The H.E.S.S. Galactic plane survey*, A&A 612 (2018) A1.