THE LOW NUMBER OF GALACTIC SUPERNOVA REMNANT PEVATRONS*

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Although supernova remnants remain the main suspects as sources of galactic cosmic rays up to the knee, the supernova paradigm still has many loose ends. The weakest point in this construction is the possibility that individual supernova remnants can accelerate particles to the rigidity of the knee, 10^6 GV. This scenario heavily relies upon the possibility to excite current-driven non-resonant hybrid modes, while the shock is still at the beginning of the Sedov phase. These modes can enhance the rate of particle scattering thereby leading to potentially very-high maximum energies. Here, we calculate the spectrum of particles released into the interstellar medium from the remnants of different types of supernovae. We find that only the remnants of very powerful, rare core-collapse supernova explosions can accelerate light elements such as hydrogen and helium nuclei to the knee rigidity, and that the local spectrum of cosmic rays directly constrains the rate of such events if they are also the source of PeV cosmic rays. This would imply that the possibility to detect SNR pevatrons with future gamma-ray observatories is drastically limited.

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1. Introduction

In the search for the origin of galactic cosmic rays (CRs), supernova remnants (SNRs) have been extensively discussed as probable dominant contributors. From the former works discussing this hypothesis [1–4] to recent reviews [5–10], several arguments supporting, or challenging the SNR paradigm have been discussed. One point of concern is the capability of SNR shocks to accelerate particles (protons) up to the knee of the local CR spectrum ($\sim 3\times 10^{15}$ eV $=3$ PeV). In order to efficiently accelerate particles up to the PeV range, the magnetic field at SNR shocks must be

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substantially amplified with respect to the typical values found in the interstellar medium (ISM). Such amplification of the magnetic field has been observationally confirmed [11] and is theoretically expected. At young SNR shocks, the dominant mechanism expected to be driving the amplification is due to the non-resonant streaming of accelerated CRs escaping the shocks, a mechanism often referred to as the *Bell* streaming instability [12, 13]. We present the results of a calculation of the proton spectrum expected from typical SNRs, after propagation in the Galaxy [14].

2. Protons from supernova remnants

We compute the total proton spectrum from typical supernova remnants released in the ISM [15]. Propagation of CR protons in the Galaxy is accounted for relying on a one-dimensional *weighted slab* model, where protons from SNRs are injected in the thin Galactic disk and propagate in a cylindrical halo [16, 17]. In the context of the non-resonant streaming instability, the maximum energy of accelerated particles is found to be, for typical SNRs, below the PeV range [18, 19]. In order to reach the PeV at SNRs from core-collapse SNe, high mass-loss rates and total explosion energy and, loss ejecta mass are required. A CR efficiency, ξ_{CR}, for particle acceleration of 5–10% is required since $E_{\max} \propto \xi_{\mathrm{CR}}$. Moreover, the normalization of the total number of protons from SNRs released in the ISM Scales as Norm $\propto \xi_{\mathrm{CR}}\nu_{\mathrm{SN}}$, where ν_{SN} is the rate of the SN considered. This means that, in order to reach the PeV range with usual very energetic remnants from core-collapse SNe, all parameters are fixed (including ξ_{CR}), and in order not to overproduce the CR proton spectrum, the rate of these objects ν_{SN} must be reduced and must be at most $\sim 5\%$ of the total SN rate (typically ~ 2–3/century), thus of the order of 1 every 1000 years, with a typical duration of a few centuries.

3. Results

Our calculation, performed under reasonable assumptions for the propagation of CRs in the Galaxy and in the current consensual framework of particle acceleration at SNR shock, indicates that the number of SNR pevatrons is expected to be limited, typically a few percent ~ 1–5% of the typical SN rate in the Galaxy, corresponding to unusual very energetic events. This could explain the non-detection of an SNR pevatron with current and next generation instruments, even in the SNR paradigm. We conclude by listing several aspects that could potentially affect our result:

1. the size of the Galactic halo in which CRs propagate could be significantly greater than the 4–5 kpc used in this work [20, 21];

2. one or several of the parameters used to describe particle acceleration (*e.g.*, efficiency, slope [22]) and the SNR dynamics (*e.g.*, mass-loss rate) strongly depend on time;

3. another mechanism governing magnetic field amplification is at play;

4. the diffusion coefficient differs from the one inferred from recent measurements [23].

Finally, other astrophysical sources, such as massive stars [24, 25], superbubbles [26, 27], and supernovae [28, 29] have recently regained interest. In addition to specifying the role played by SNRs in the production of galactic CRs, the contribution of these other sources should also be taken into account in attempts to interpret the local CR spectrum.

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