PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021 THE ASTROPARTICLE PHYSICS CONFERENCE Berlin | Germany
37th International Cosmic Ray Conference 12–23 July 2021

The low number of SNR pevatrons in the Galaxy

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The search for pevatrons (objects capable of accelerating partilces up to 10^{15} eV) has become one of the key targets of the high–energy gamma–ray community. These objects are of crucial importance in the context of the origin of cosmic rays (CRs), since the sources of Galactic CRs are expected to be pevatrons. Currently, the most famous candidates for the origin of Galactic CRs are supernova remnants (SNRs), the shocks expanding in the interstellar medium after the explosion of massive stars. But surprisingly, all detected SNRs have been shown to not be pevatrons, making the situation somewhat bewildering. A special attention is currently being devoted to the search of a SNR pevatron, and we discuss the possibility that only very rare SNRs might be pevatrons, and thus, the probability of detecting one remarkably reduced.

*37*th *International Cosmic Ray Conference (ICRC 2021)*
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

PoS(ICRC2021)151

1. Introduction

The supernova remnant (SNR) hypothesis for the origin of Galactic cosmic rays (CRs) is facing several issues. One of them, is the fact that all clearly detected SNR remnant shells seem to not be pevatrons, i.e., to not efficiently accelerate particle up to the PeV range, which is expected from the sources of Galactic CRs, in order to be able to account for the local CR spectrum up to the knee [see e.g., 1–5, for reviews on the topic]. This result, mainly comes from the observation of SNRs in the very–high–energy range ($\gtrsim 10^{12}$eV), that revealed very steep or exponentially suppressed spectra for all studied SNRs. This limited emission above a few tens of TeV for all well–studied SNR shells is seen as an indication that PeV particles are not accelerated [6].

2. The maximum energy at SNR shocks

The problem of the acceleration of particles up to the PeV range at SNR shock waves has been well identified. The Hillas criterion [7] explicits the idea that in order to be accelerated through a first–order Fermi mechanisms, particles be magnetically confined in the acceleration region. It is therefore possible to write a naive estimate of the maximum energy reached through DSA at SNRs:

$$E_{\rm max} \approx \left(\frac{r_{\rm sh}}{\rm pc}\right)\left(\frac{u_{\rm sh}}{1000\ {\rm km/s}}\right)\left(\frac{B}{\mu{\rm G}}\right)\ {\rm TeV} \tag{1}$$

with $u_{\rm sh}$ the SNR shock velocity, and B the magnetic field. Therefore, in order to attain the PeV range, for a typical SNRs of a few pc, expanding at a few 1000 km/s, we clearly see from Eq. (1) that values of at least $\gtrsim 10^2\mu$G are needed, i.e., two orders of magnitude above typical values of the ISM. Several mechanisms can potentially drive the amplification of the magnetic field at a strong shock waves. At SNRs, the dominant mechanism leading to the highest values of the magnetic field is expected to be *non–resonant*. This terminology refers to the fact that the perturbations in the magnetic field initially grow on scales that are typically much smaller than the CR Larmor radius $r_{\rm L}$.The level of saturation of the magnetic field due to the growth of the instabilities can be estimated by equating the wavenumber where the growth of the perturbation is the highest $k_{\rm max}$ to $r_{\rm L}^{-1}$. At saturation, the maximum energy is typically [8–10]:

$$E_{\rm max}(t) \approx \frac{r_{\rm sh}(t)}{10}\frac{\xi e\sqrt{4\pi\rho(t)}}{\Lambda c}u_{\rm sh}(t)^2 \tag{2}$$

where ξ is the efficiency of CR acceleration, e.g., the fraction of ram pressure converted into CRs at the shock, and $\Lambda = \ln(E_{\rm max}/mc^2)$. For SNRs from typical thermonuclear and CCSNe, the maximum energy of accelerated remains below < 1 PeV even in the first years of the evolution of the SNRs. From Eq. (2), we can however investigate under which conditions the maximum energy can reach the PeV range. Let us for instance consider a SNR shock wave from a CCSN expanding in a dense wind of its progenitor star of density $\rho(r) = \dot{M}/(4\pi u_{\rm w} r^2)$, where $\dot{M}$ and $u_{\rm w}$ are the mass–loss rate and velocity of the wind. Investigating the parameters needed to reach the PeV range at the transition between the free expansion phase and the Sedov–Taylor (adiabatic) phase of the evolution of the SNR, Eq. (2) implies that only a reduced portion of the parameter space can lead to SNR pevatrons. In Fig. 1, we illustrate the total explosion energy and mass–loss rate needed for an ejecta mass $M_{\rm ej} = 1\ {\rm M}_\odot$.

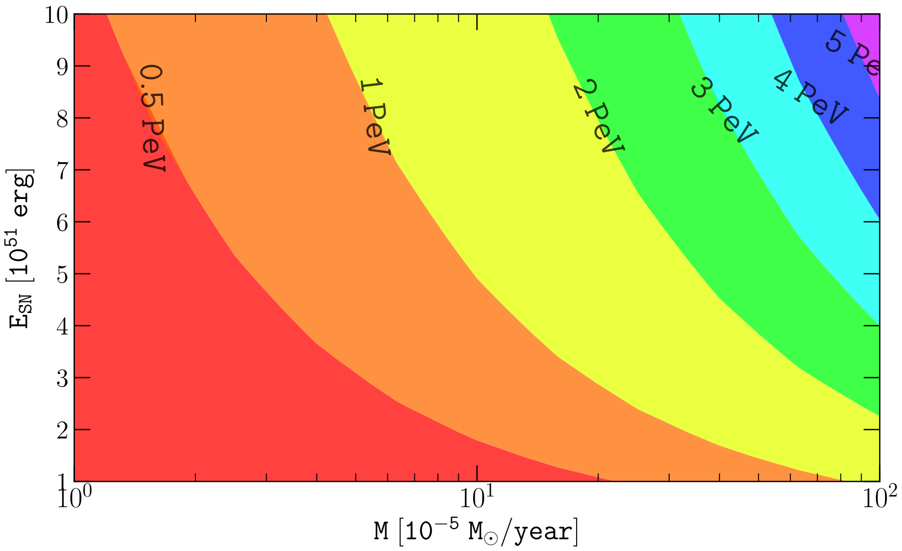

Figure 1: Maximum energy of accelerated particles at the transition between free expansion phase and Sedov Taylor phase, for a SNR shock from a core collapse supernova expanding in a wind profile. The mass of the ejecta is $M_{\rm ej} = 1\ \rm M_{\odot}$.

Since we are working under the assumption that SNRs are sources of Galactic CRs, this leads us to consider objects with high values of $E_{\rm SN}$ and $\dot{M}$. In the following, we thus consider objects for which $E_{\rm SN} = 10\ 10^{51}$ erg and $\dot{M} = 10\ \rm M_{\odot}/yr$, that we refer to as type $II*$ in the following, without any assumption on the actual type of SN to which it would correspond in the usual astronomical classification of SNe (IIb, IIn, etc.).

3. The proton spectrum from SNRs after propagation

We intend to estimate the CR protons produced by the type II* SNe defined above. We first compute the spectrum of protons injected in the ISM. This can be computed as two components: particles accelerated at the SNR and trapped inside the SNR until the end of the active life the SNR $N_{\rm acc}$, and particles accelerated at the shock and continuously escaping the SNR into the ISM $N_{\rm esc}$. The total sum $N_{\rm tot}$ of particles injected from these SNRs can thus be computed semi–analytically [see details in 11, 12]. For particles trapped inside the SNR, adiabatic losses are taken into account and contribute in shaping the spectrum released in the ISM. An important aspect of this calculation is that the normalization of injected spectrum scales with $\propto \xi$ (from the fact that a fraction of the ram pressure is converted into CRs), and that, $E_{\rm max}$ also scales with $\propto \xi$. This means that high values of $E_{\rm max}$ of the order of the PeV range, the requirement $\xi \gtrsim 5-10\%$ directly sets a constrain on the norm of the spectrum injected.

Once we have computed the spectrum injected by type II* SNRs, we calculate the spectrum after propagation, using a simple weighted slab model for CR transport [13]. In this approach, the thin Galactic disk of radius R = 15 kpc, and half thickness $h_{\rm d} << R$, in which SNRs are located and inject CRs. At the edge of cylindrical halo of height $H = \pm 4$ kpc, a free escape boundary is imposed. The transport of particles is thus described by a transport equation in cylindrical coordinates, discussed in detail in [14]. Adiabatic and ionization losses in the think disk are taken into account. A key ingredient of this description is the diffusion coefficient D. The diffusion coefficient is assumed to have the functional form proposed in **(author?)** [15] adjusted using available AMS-02 measurements [16]. The spectrum of CR protons from type II* SNRs can thus be obtained after propagation.

In this approach, the injection of particles of momentum p in the thin disk is $q(p) = N_{\rm tot}(p)\nu_{\rm SN}/(\pi R^2)$, where $\nu_{\rm SN}$ is the SN rate. This means that the normalization of the injection from SNRs depends at least (provided that all other quantities are known) on the CR efficiency ξ and on $\nu_{\rm SN}$. And since the maximum energy $E_{\rm max}$ depends on ξ, in order to reach the PeV range, we fix $\xi = 0.1$ for our type SNR prototype. We are thus only left with $\nu_{\rm SN}$ to adjust the normalization of the CR spectrum. The results of the calculation for remnants from type II* SNe are shown in Fig. 2. For these very energetic events, the PeV range can be reached, and thus the proton spectrum around the knee can be accounted for. However, in order to not overproduce the CR proton level from the 100 GeV range to the 100 TeV range, we need to have a rate of these events remarkably reduced of at most ~ 2 % of the typical Galactic SN rate. In other words, the level of CR spectrum imposes a direct limit on the rate of Galactic SNR pevatrons.

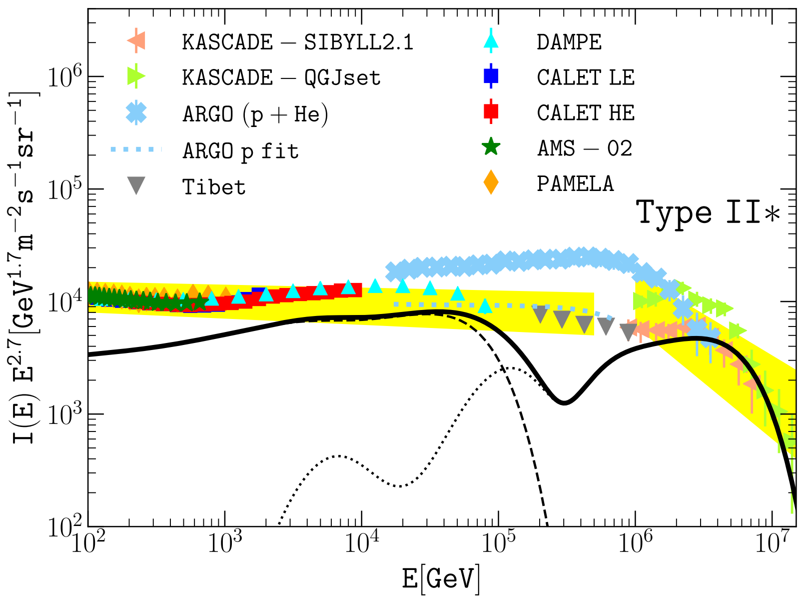

Figure 2: Galactic CR protons from type II* SNRs. Contributions from cumulative accelerated particles $N_{\rm acc}$ (dashed), escaping particles $N_{\rm esc}$ (dotted) and their sum $N_{\rm tot}$(solid) are shown. $\alpha = 4$, $\nu_{\rm SN,Ia} = 1/100\ {\rm yr}^{-1}$ and $\xi_{\rm SN} = 0.11$ ($\xi = 0.10$). Local data from various experiments are shown: AMS-02 [17], PAMELA [18], CALET LE and HE [19], DAMPE [20], ARGO–YBJ [21], ARGO fit for protons [22], Tibet [23] and KASCADE [24]. The yellow areas correspond to the typical level of measured protons. The CR efficiency is fixed $\xi = 0.1$ and the SN rate is adjusted in order to not overproduce the CR data. $\nu_{\rm SN,II*} = 2\text{‰} \times 2/100\ {\rm yr}^{-1}$.

4. Conclusions

This novel calculation on the CR protons from very energetic SNe comes reinforce previous works [25, 26]. It illustrates that if magnetic field amplification is governed by the growth of non–resonant streaming instabilities [27], thus only SNRs from very rare SNe should be able to reach the PeV range, and it allows to set a quantitative value on this rate using the normalization of the CR local spectrum of the order of a $\sim$ few % of the Galactic SN rate. If the typical active pevatron phase duration is of the order of the century, this means that it would be probable that no SNR pevatron is currently active in the Galaxy, thereby significantly reducing the chances of detecting a SNR pevatron with future instruments [28, 29], even with the possibility of observing very young ($\sim$ month) nearby extraGalactic SNRs [30]. Of course this result is an additional illustration of the tensions met by the SNR paradigm in the origin of Galactic CRs. Along with recent results on the detection of VHE gamma rays from stellar clusters [31, 32], this comes as a reminder that several astrophysical objects could be very significant sources of the CR spectrum [33].

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