The Maximum Energy of Shock-Accelerated Cosmic Rays

REBECCA DIESING

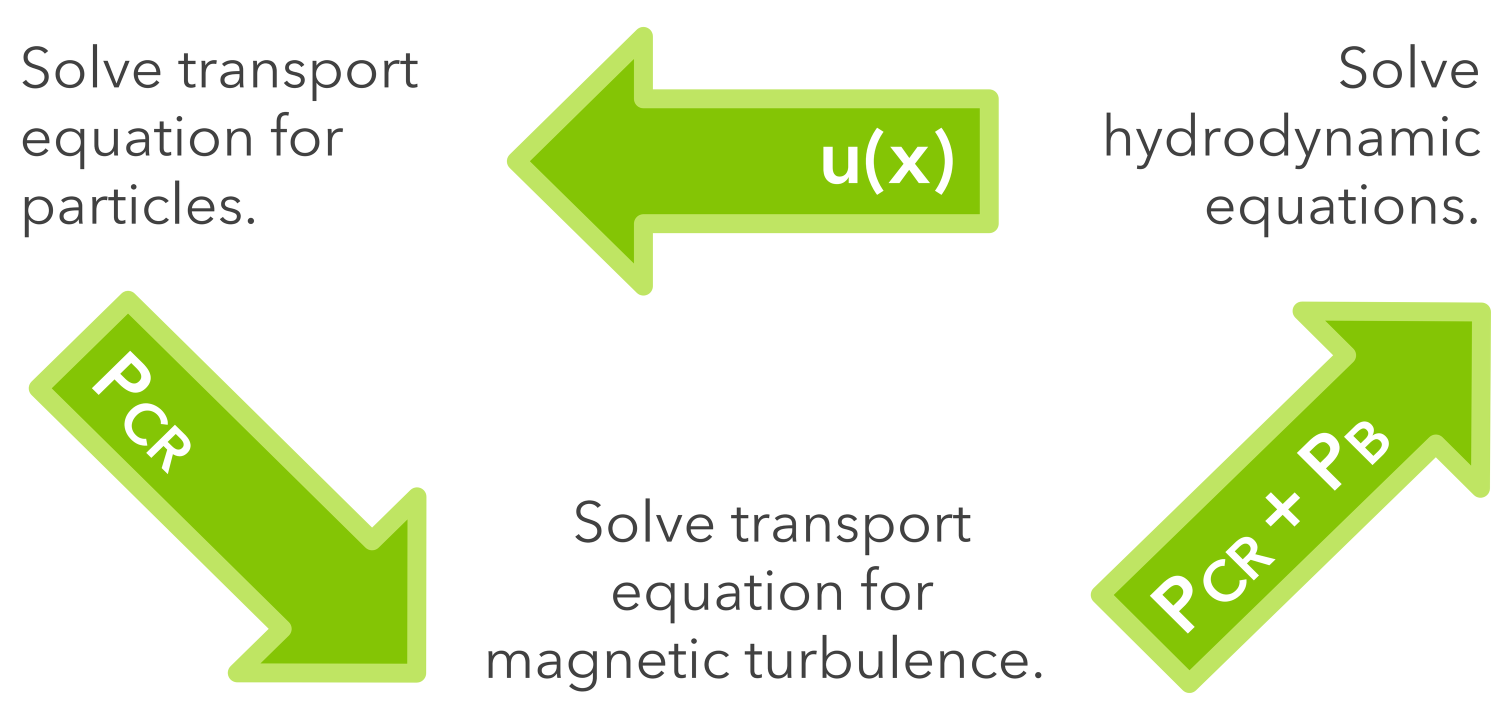
MOTIVATION

Identifying the accelerators of cosmic ray protons (CRs) with PeV energies (10^{15} eV) remains a theoretical and observational challenge. Supernova remnants (SNRs) represent strong candidates, as they provide sufficient energetics to reproduce the CR flux observed at Earth. However, it remains unclear whether they can accelerate particles to PeV energies, particularly after the very early stages of their evolution. This uncertainty has prompted searches for other source classes and necessitates comprehensive theoretical modeling of the maximum proton energy, E_{max}, accelerated by an arbitrary shock. While analytic estimates of E_{max} have been put forward [e.g., 1-8], they do not fully account for the interplay between particle acceleration, magnetic field amplification, and shock evolution.

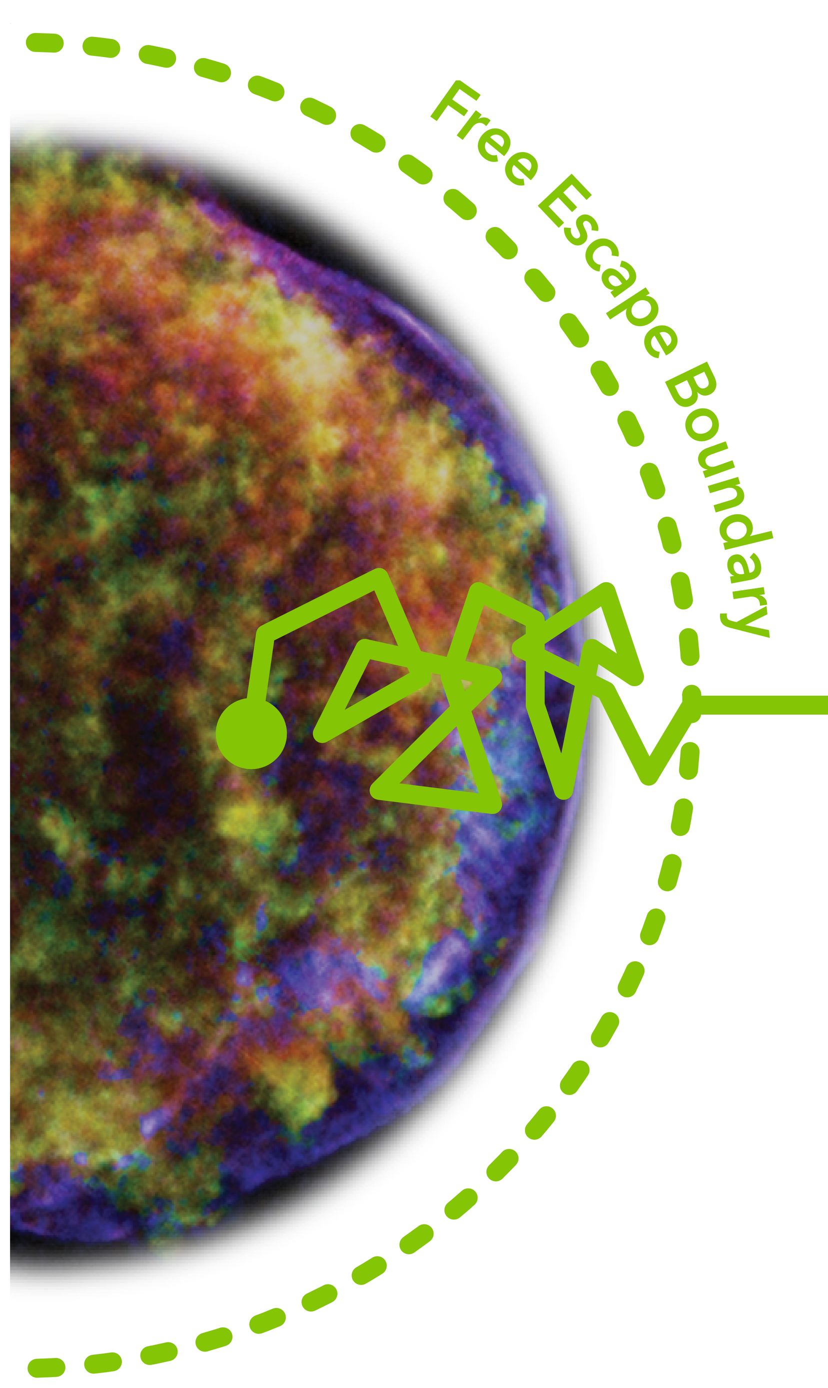
METHOD

MODELING PARTICLE SPECTRA

In the standard picture, SNRs accelerate CRs at their forward shocks via diffusive shock acceleration (DSA) [9-11]. We model this process in a range of simulated SNRs using a fast, multi-zone model of particle acceleration that self consistently accounts for magnetic field amplification and shock modification due to the presence of non-thermal particles [12-14].



ESTIMATING E_{MAX}



We estimate E_{max} by equating the diffusion length of particles with energy $E = E_{max}$ with the size of the acceleration region.

$$\frac{R_{\rm sh}}{10} \approx \frac{D(E_{\rm max}, B)}{v_{\rm sh}}$$

We estimate B by assuming saturation of the Bell instability [15]. To bracket uncertainty, we consider two scenarios:

A: Diffusing particles drive B-field amplification ($P_B(x) \sim P_{CR}(x)$).

B: Escaping particles drive B-field amplification ($P_B(x)$ is constant).

RESULTS

E_{MAX} EVOLUTION

To accelerate PeV particles, supernova remnants must be young, fast, and expanding into dense media. However, particles accelerated at early times can contribute to a higher E_{max} at later times.

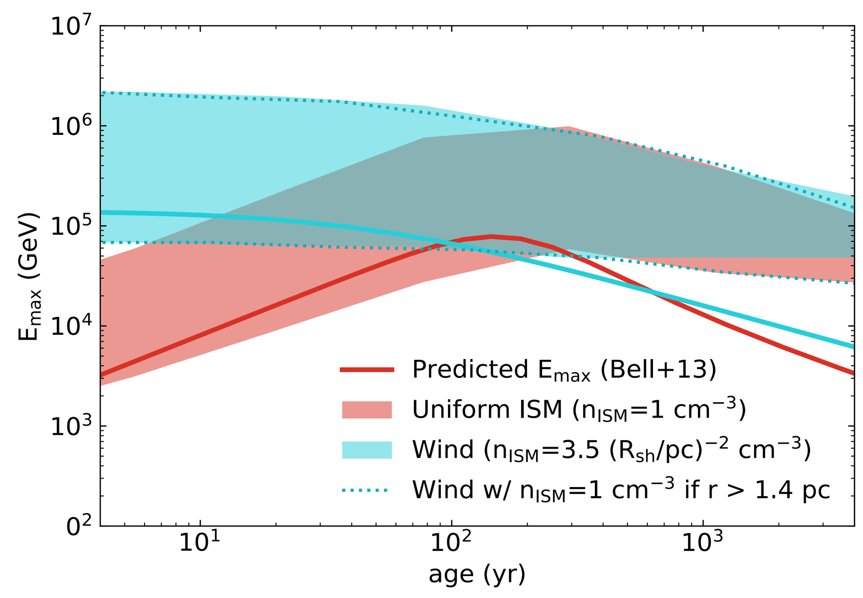


FIGURE 1. E_{max} versus time from a benchmark SNR ($E_{SN} = 10^{51}$ erg, Mej = 1M⊙), expanding into a uniform medium (red) and wind profile (blue). Band widths correspond to uncertainty in the nature of CR-driven amplification of the magnetic field. Solid lines give the single-zone prediction from [2], in good agreement with our results at early times.

EXPLORING PARAMETER SPACE

Roughly speaking, E_{max} goes as $n_{ISM}^{1/2} v_{sh}^2 R_{sh}$. However, even with high ambient densities (n_{ISM}) and shock velocities (v_{sh}) SNRs can only be PeVatrons if escaping particles drive magnetic field amplification.

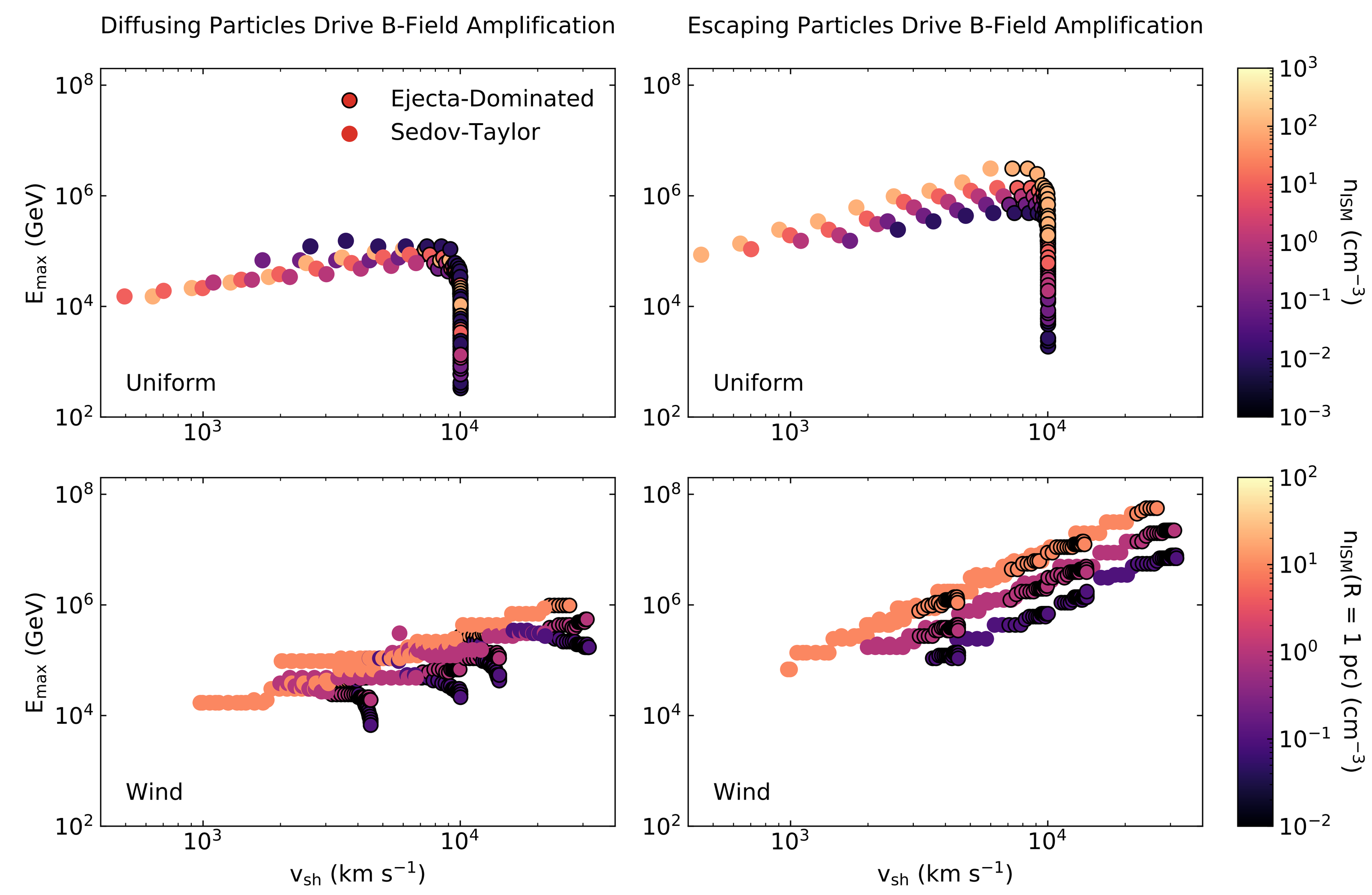
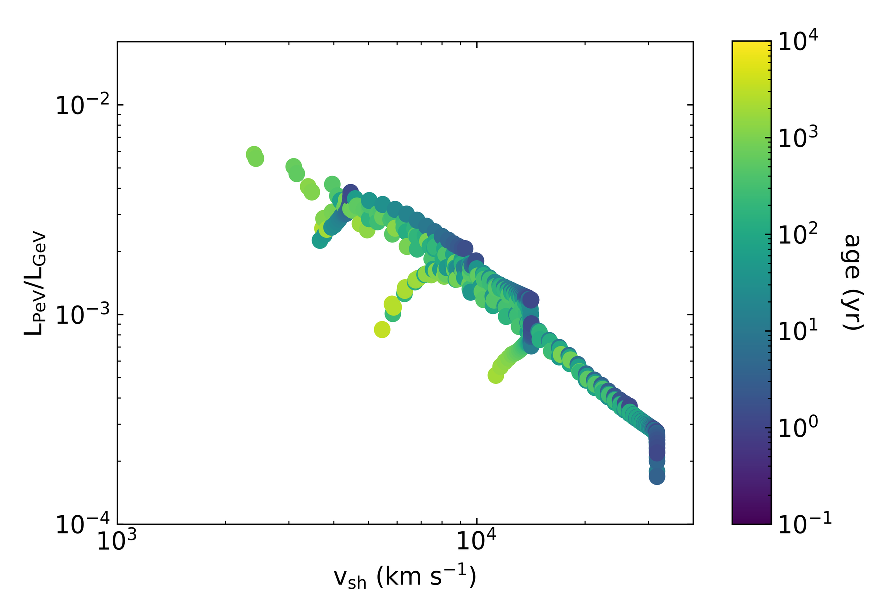


FIGURE 2. E_{max} as a function of v_{sh} for a variety of SNRs expanding into media of different ambient density normalizations (color scales), assuming diffusing particles drive magnetic field amplification (left column) or escaping particles drive magnetic field amplification (right column). The top row corresponds to expansion into uniform ambient media and, to be broadly consistent with an SNR from a Type Ia SN, only considers our benchmark scenario as in Figure 1. To capture the wider range of parameters associated with core-collapse SNe, the bottom row considers SNRs expanding into wind profiles with $E_{SN} \in [1, 10] \times 10^{51}$ erg and $M_{ej} \in [1, 5]$ M⊙.

OBSERVATIONAL CONSIDERATIONS

Faster shocks are more likely to be PeVatrons, but they also have steeper spectra [16]. This may affect PeVatron searches that select targets based on GeV γ-ray emission.

FIGURE 3. PeV to GeV luminosity ratio (L_{PeV}/L_{GeV}) as a function of v_{sh} for SNR PeVatron candidates (i.e., data points from Figure 2 with E_{max} > 10^6 GeV). Shock age is denoted with the color scale.



For additional information, see Diesing, ApJ (2023).

[1] Ptuskin, V. et al., ApJ (2010)
[2] Bell, A. R. et al., MNRAS (2013)
[3] Cardillo, M. et al., Astropart. Phys. (2015)
[4] Marcowith, A. et al., MNRAS (2018)
[5] Gabici, S. et al., IJMPD (2019)
[6] Cristofari, P. et al., Astropart. Phys. (2020)
[7] Cristofari, P. et al. A&A (2021)
[8] Brose, R. et al. (2022)
[9] Krymskii, G. F., Akad. Nauk SSSR Dokl. (1977)
[10] Bell, A. R., MNRAS (1978)
[11] Blandford R. D. & Ostriker J. P. , ApJL (1978)
[12] Amato, E. & Blasi, P., MNRAS (2006)
[13] Caprioli D. et al., Astropart. Phys. (2010)
[14] Caprioli, D. JCAP (2012)
[15] Bell, A. R. MNRAS (2004)
[16] Diesing, R. & Caprioli, D., ApJ (2021)

IAS INSTITUTE FOR ADVANCED STUDY
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK