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THE HUNT FOR THE SOURCES OF COSMIC RAYS

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Abstract. The identification of the sources of cosmic rays is a complex problem since it requires the understanding of several intricate problems: the acceleration, transport, and potential reacceleration on many astrophysical sites. Observations in the very-high-energy gamma-ray domain are now a powerful tool to directly study particle acceleration at numerous astrophysical sites. The next generation instruments (CTA, LHAASO, SWGO) will especially help to search for and study hadronic pevatrons, i.e., sources accelerating hadrons up to 10^{15} eV. These are of particular interest for the community since it is expected that the sources of Galactic cosmic rays can be pevatrons. In the search for pevatrons, the role played by supernova remnants (SNRs) and the shock waves subsequent to the explosion of a massive star are of particular interest since SNRs have long been thought to be the primary sources of Galactic CRs. Several recent results are now destabilizing the SNR paradigm, and understanding the microphysics, and especially the growth of instabilities leading to the amplification of magnetic field, is needed to clarify the role of SNRs.

Keywords: particle acceleration - supernova remnants - cosmic rays - turbulence

1 Introduction

The field of cosmic ray (CR) physics has been very active in the past years, with numerous remarkable results from satellite and on-ground instruments. It is not easy to summarize all these results briefly, but let us, for instance, mention recent direct measurements from the satellite DAMPE of protons up to 100 TeV (An et al. 2019), the detection of an extended emission of gamma rays around massive stars (Aharonian et al. 2019), or the discovery of more than a dozen of Galactic pevatrons (HESS Collaboration et al. 2016; Cao et al. 2021; Abdalla et al. 2021). The precision measurements from DAMPE of the protons spectrum and other nuclei illustrate our lack of understanding of the injection of CRs from sources and their propagation in the ISM. The detection of the $1/r$ profile of gamma rays around Cyg OB2 and Westerlund 1, expected in the case of a constant injection of particles, naturally revived the idea (Casse & Paul 1980; Cesarsky & Montmerle 1983) that massive stars could well be involved in the production of CRs. Finally, the detection of more than a dozen of Galactic pevatrons, i.e., accelerators of particles up to and above 10^{15} eV, that have been long hunted since the sources of Galactic CRs are expected to be pevatrons, seem to indicate that all gamma-ray bright pevatrons are not associated to any supernova remnant (SNR).

These results are all problematic in the context of the search for the origin of CRs, since they seem to disfavor SNRs, which have for long been thought to be the dominant sources of Galactic CRs (Blasi 2013; Gabici et al. 2019; Cristofari 2021).

The detection of gamma rays and of radiations in other wavelengths produced by non-thermal particles from numerous Galactic SNRs definitely attests that efficient particle acceleration is taking place at the shock waves. To improve our understanding of particle acceleration at non–relativistic collisionless shock waves, it is, therefore, crucial to understand the case of SNRs. In particular, one physical ingredient that is determinant for particle acceleration (as well as for transport) is the self-generated turbulence induced by CRs and the associated amplification of the magnetic field (Blasi 2019).

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2 Magnetic fields around SNR shocks waves

To specify the role played by SNRs in the origin of CRs, at least three fundamental questions must be answered:

1. What is the slope of the spectrum of particles accelerated?
2. What is the slope of the spectrum released in the interstellar medium (ISM), i.e., the cumulative spectrum including losses suffered by particles and accounting for the escaping of particles?
3. What is the maximum energy of particles accelerated? And especially, can SNR be pevatrons for a period of their evolution?

Interestingly, all these questions involved the magnetic field amplified at the shock.

Indeed, it has been shown that the streaming of CRs can excite instabilities (see, e.g., Marcowith et al. 2021, for a review) and lead to amplification of the magnetic field potentially several orders of magnitude above the typical ISM value. In the early stages of the evolution of the SNR, the dominant instability, because growing at the fastest rate, is expected to be the non–resonant instability, also often called the *Bell* instability (Bell 2004; Bell et al. 2013; Schure & Bell 2013). Moreover, in addition to the theoretical prediction, the measurements of X-ray filaments directly helped infer that the magnetic field at SNRs is substantially amplified with respect to the ambient average ISM field (Vink 2012).

The amplified magnetic field resulting from the growth of instabilities is expected to directly affect the possibility of reaching the PeV range (Schure & Bell 2014) leading to the idea that it is possible that only a few rare SNRs go to the PeV range for a short period of time (Zirakashvili & Ptuskin 2016; Cristofari et al. 2020). Moreover, the value of the magnetic field can affect the spectrum of accelerated particles, for instance, through the drift of scattering centers downstream of the SNR shock (Zirakashvili & Ptuskin 2008; Caprioli et al. 2020; Cristofari et al. 2022). Finally, the magnetic field plays a vital role in shaping the spectrum of particles released in the ISM. It can, for instance explain how the spectrum of electrons is substantially steeper than the one of protons, as the synchrotron losses suffered by electrons are $\propto B^2$ (Cristofari et al. 2021a,b). This problem is naturally connected to the question of the damping of the magnetic field downstream of SNR shocks.

In the coming years, understanding precisely how CR streaming leads to the amplification of the magnetic field is essential to clarify the role played by SNRs in the origin of CRs, and, more broadly, particle acceleration at non-relativistic collisionless shock waves.

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