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SNRs AS COSMIC ACCELERATORS

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Abstract

Supernova remnants are considered to be the main source of galactic cosmic rays up to the knee of the cosmic rays energy distribution. I review the increasing set of indications supporting this scenario together with the main open issues.

1 Introduction

The idea of a possible association between supernova remnants (SNRs) and cosmic rays (CRs) dates back to the 1930s, when it was first proposed that the observed flux of CRs can be due to a population of (extragalactic) supernova explosions 5). Indeed, the current scenario invokes an extragalactic origin only for very energetic CRs, i. e., particles with energies $> 10^{18}$ eV, given that their gyro-radii are larger than the thickness of the Milky Way. On the other hand, galactic SNRs are considered to be responsible for the acceleration of CRs up to 3 PeV (i. e., the "knee" in the CR spectrum), though it has been proposed that even energies of the order of 10^{18} eV can be achieved in our Galaxy 16).

The simplest argument supporting the association between CRs and SNRs is the energy argument 21), as summarized below. Different estimates of the energy density of CRs concur in providing a value $\epsilon \approx 1-2$ eV cm^{-3} (data from the Voyager and Pioneer spacecrafts indicate 44) $\epsilon = 1.8$ eV cm^{-3}). This value is much higher than that associated with starlight (~ 0.3 eV cm^{-3}), average magnetic field (~ 0.25 eV cm^{-3}), turbulence (~ 0.3 eV cm^{-3}), and thermal energy (~ 0.01 eV cm^{-3}), and this removes many galactic sources from the list of possible accelerators. Considering that the bulk of CR energy is carried by GeV particles with a galactic confinement times of about 1.5×10^7 yr 45), the power needed to sustain the observed CR flux is of $\sim 2 - 3 \times 10^{50}$ ergs per century. The characteristic energy released in a SN explosion is 10^{51} erg and the rate of SN explosions in the Milky Way is of about 2-3 events per century 35). Therefore SNRs can power the CRs in our Galaxy if they lose just $\sim 10\%$ of their energy in the acceleration process.

2 The acceleration mechanisms

The basic mechanism of particle acceleration is the Diffusive Shock Acceleration (DSA) and relies on the Fermi process 20) applied to SNR shock fronts, where the pre-shock and post-shock medium act as "moving mirrors", thus allowing first-order energy gains in v_{shock}/c for particles scattering back and forth the shock front. This scenario was introduced in a series of papers published in the late 1970s 4, 25, 9, 10, 13) and is described in details in several reviews 15). Interestingly, this process naturally produces a power law spectrum of particle energies $N(E)dE \propto E^{-s}dE$ with an index $s = (r+2)/(r-1)$, where r is the shock compression ratio. For a high Mach number shock, which is typical of a young SNR, $r = 4$, and then $s = 2$, which is very close to the exponent 2.7 observed for the differential energy spectrum of CRs, the small discrepancy possibly being associated with energy-dependent escape mechanisms.

The timescale of the acceleration process,t_{acc}, is also comparable with the age of the youngest observed SNRs. The value of t_{acc} can be estimated as 18) $t_{acc} = 3/(V_1 - V_2)\ (D_1/V_1 + D_2/V_2)$, where $V_{1,2}$ and $D_{1,2}$ are the upstream / downstream bulk velocities and diffusion coefficients. For a particle with energy E, the acceleration timescale is $\sim 150(E/(100\text{TeV})$ yr, for $B = 100\ \mu$G and $v_{shock} = 5000$ km/s (typical of a young SNR).

If SNRs lose a significant fraction of their energy to accelerate ultra-relativistic particles, the shock cannot be treated as adiabatic. The loss of energy "deposited" in the CRs and their non-linear back-reaction on the background plasma are predicted to increase the shock compression ratio above the Rankine-Hugoniot limit and decrease the post-shock temperature 17, 26, 14, 43). This effects is known as "shock modification". Another notable effect consists in the magnetic field amplification 11): cosmic rays streaming outward produce an electron return current. Electrons are then deflected by the magnetic field, thus originating a turbulent, amplified magnetic field.

3 Synchrotron emission: ultrarelativistic electrons

The direct proof that SNR shocks can accelerate particles up to ultrarelativistic regimes is the ubiquitous presence of synchrotron radio shells in all the galactic SNRs 22). This emission clearly traces the presence of GeV electrons. Moreover, the detection of synchrotron X-ray emission in SN 1006 24) and then in other young SNRs 34, 41) has proved that in these sources the electron energy can reach values of the order of 10 TeV. X-ray spatially resolved spectral analysis of the shape of the cutoff in the synchrotron emission of SN 1006 has revealed that the maximum energy that electrons can achieve in the acceleration process is limited by their radiative losses 29, 28). Similar results have been obtained by analyzing Tycho 30) and RX J1713.7-3946 37, 46). These results are promising, because suggest that hadrons, that do not suffer significant radiative losses, may be, in principle, accelerated up to higher energies.

The predicted effects of magnetic field amplification have also been observed in several cases. The thinness of the X-ray synchrotron filaments of young SNRs reveals that $B \sim 100 - 600\ \mu$G 42, 7, 8, 6, 31). Moreover, in RX J1713.73946 and in Cas A, some knotty X-ray synchrotron emitting regions varies on timescales of a few years, which may be indicative of very short synchrotron cooling times, corresponding to $B \sim 1$ mG 40, 32, 39).

Effects of shock modification have also been observed in SN 1006, where the post-shock density has been found to increase with the efficiency of particle acceleration, thus suggesting an efficient hadron acceleration 27).

4 Gamma-ray emission: leptonic vs. hadronic scenario

The current generation of TeV and GeV observatories has allowed us to reveal the γ-ray emission of a (rapidly growing) number of galactic SNRs. Gamma-ray emission can provide a striking signature of hadron acceleration, being associated with π^0 decay following proton-proton collision due to accelerated hadrons impacting the ambient medium (hadronic scenario). However, it can also be the result of IC scattering from the relativistic electrons on the CMB (and/or dust-emitted IR photons) and nonthermal bremsstrahlung (leptonic scenario). It is not easy to discriminate between these scenarios. For example, the γ-ray emission of RX J1713.7-3946 has been interpreted by different groups as leptonic 19, 33) or hadronic 12), though the Fermi LAT spectrum has almost ruled out the hadronic scenario 1).

Quite surprisingly, while it is difficult to ascertain the origin of the γ-ray emission of young, X-ray synchrotron emitting SNRs (e.g., Vela Jr. 36) or SN 1006 23)), older SNRs clearly revealed the presence of high energy hadrons, as for W44 3), W28 2), and IC 443 38). All these middle-aged SNRs interact with dense clouds and the hadronic emission probably originates from CRs leaving the acceleration source and interacting with the dense ambient medium.

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