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# Observations of supernova remnants and pulsar wind nebulae at gamma-ray energies

## *Observations de vestiges de supernovae et nébuleuses de pulsars en rayons gamma*

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A B S T R A C T

In the past few years, gamma-ray astronomy has entered a golden age thanks to two major breakthroughs: Cherenkov telescopes on the ground and the Large Area Telescope (LAT) onboard the *Fermi* satellite. The sample of supernova remnants (SNRs) detected at gamma-ray energies is now much larger: it goes from evolved supernova remnants interacting with molecular clouds up to young shell-type supernova remnants and historical supernova remnants. Studies of SNRs are of great interest, as these analyses are directly linked to the long standing issue of the origin of the Galactic cosmic rays. In this context, pulsar wind nebulae (PWNe) need also to be considered since they evolve in conjunction with SNRs. As a result, they frequently complicate interpretation of the gamma-ray emission seen from SNRs and they could also contribute directly to the local cosmic ray spectrum, particularly the leptonic component. This paper reviews the current results and thinking on SNRs and PWNe and their connection to cosmic ray production.


R É S U M É

Au cours des dernières années, l'astronomie gamma est entrée dans un âge d'or grâce à deux avancées majeures : les télescopes Tcherenkov au sol et le *Large Area Telescope* (LAT) à bord du satellite *Fermi*. L'échantillon des restes de supernova (SNR) détectés en rayons gamma de haute énergie est maintenant beaucoup plus vaste : il va des vestiges de supernovae évolués en interaction avec des nuages moléculaires jusqu'aux jeunes SNR en coquille et aux SNR historiques. Les études des SNR sont d'un grand intérêt, car ces analyses sont directement liées à la question de l'origine des rayons cosmiques galactiques. Dans ce contexte, les nébuleuses de pulsars (PWN) doivent également être prises en compte, car elles évoluent en conjonction avec les SNR. En conséquence, elles compliquent souvent l'interprétation de l'émission gamma en provenance des SNR et pourraient aussi contribuer directement au spectre local de rayons cosmiques, en particulier à sa composante leptonique. Cet article passe en revue les résultats et réflexions

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actuels concernant les SNR et les PWN, ainsi que leur connexion avec la production des rayons cosmiques.


## 1. Cosmic-ray acceleration at supernova remnant shocks

Supernova remnants (SNRs) have been considered as the sources of Galactic cosmic rays (CRs) since the 1930's. Support for this paradigm comes from observed CR abundances that match those of massive star forming regions, non-thermal emission from SNRs indicative of relativistic electron (and possibly proton) acceleration, and a theoretical mechanism that explains how particles gain relativistic energies in the strong shocks of SNRs by first order Fermi diffusive shock acceleration (DSA) [1]. The high efficiency of DSA has been demonstrated by non-linear models [2,3], though the mechanisms by which particles are injected and confined within the shock vicinity are still debated. It is also unclear how particle confinement and escape is regulated within SNRs, which is necessary for CRs to reach energies of a few times $10^{15}$ eV that are attributable to Galactic sources. Finally, it is important to study the diffusion parameters of accelerated particles as they leave the dense star forming regions where they are thought to arise, to understand the spectrum and isotropy of CRs that permeate the galaxy.

The recent development of gamma-ray observatories has led to sufficient sensitivity and spatial resolution to directly study SNRs as CR sources. Ground-based Cherenkov telescopes (e.g., *HESS, MAGIC, VERITAS*) and the *Fermi Gamma-ray Space Telescope* are able to spatially resolve SNRs at TeV and GeV energies, respectively. To date, dozens of SNRs have been detected varying in age, progenitor type, evolutionary stage and density of their surrounding environment. These observations show a diversity in the observed luminosities and spectra of SNRs that indicate a wide range of physical conditions that give rise to gamma rays. Either electrons or protons may dominate the radiation mechanism, and the large energy coverage of *Fermi* (from 0.03 to $>300$ GeV) is important in distinguishing between leptonic (inverse-Comtpon (IC) or bremsstrahlung) and hadronic ($\pi^0$ decay) processes. Observations of young SNRs (Section 2) help to establish the earliest periods of DSA and possible proton acceleration to very high energies. Studies of more numerous shell-type (Section 3) and middle-age SNRs (Section 4) provide tests of both the acceleration and propagation of CRs from their acceleration sites.

### *1.1. Diffusive shock acceleration theory*

In strong shocks, particles in either the preshock or postshock fluid have scattering centers such that they experience only approaching collisions. This allows energy gains of first-order as particles cross the shock front, with a spectrum that depends only on the shock compression ratio as explained in [1]. This formulation of DSA or first-order Fermi acceleration was proposed by several groups to explain radio-emitting electrons discovered in SNRs [4–7]. However, the GeV energies of radio synchrotron electrons are far less than needed to explain PeV energy CRs. More complex models have evolved to include heating of the upstream precursor, the pressure produced by accelerated particles, injection of electrons and protons, and different prescriptions for magnetic field amplification needed to confine the highest-energy particles e.g., [8]. Predictions of such models includes CR source spectra whose spectral indices are greater ("soft" spectra) or lower ("hard" spectra) than 2.0 and can have spectral curvature. For an in-depth review of advances in shock acceleration theory, see [1] in this volume.

### *1.2. Supernova remnant evolution*

Given the non-linearity of DSA, the evolution of SNRs has implications for when and at what efficiency CRs are produced. The key parameters governing the evolution of a supernova (SN) explosion are the initial energy, progenitor system, and surrounding interstellar medium (ISM), which are all tied together by the late-time evolution of massive stars. The progenitor system can be either a binary system (two objects orbiting one another) composed of a white dwarf and a companion star for Type Ia SNe, or a massive star ($M > 8\ M_\odot$) for type II SNe (also known as core-collapse SNe), or even massive stars that have lost their hydrogen-envelopes prior to explosion (Wolf–Rayet stars, $>25\ M_\odot$) for Type Ib/c SNe. The evolution of a SNR is then typically characterized by three phases: (1) an ejecta-dominated phase when the swept-up mass is much less than the ejected mass and does not slow shock expansion, (2) when the swept-up mass is much larger than the ejecta mass and the shock expansion is characterized by adiabatic expansion often called the Sedov–Taylor phase, (3) a radiative phase where recombining gas quickly cools the swept-up gas forming a dense shell [9]. Toward the end of this radiative phase, the dense shell of the SNR merges with and becomes indistinguishable from the ISM [10]. Simple evolutionary models with prescriptions for shock acceleration reproduce the expectation that $\sim 10\%$ the SN explosion kinetic energy is transferred to CRs, which is required if SNRs are the primary source of Galactic CRs [11]. Depending on the density profile of the surrounding gas, SNRs may transition between these phases at very different times [12]. The result of models that include evolution in complex density profiles indicate that young core-collapse SNRs will have decreasing hadronic gamma-ray emission, while Type Ia SNe are expected to increase their gamma-ray emission with time [13]. However, when the SNR shock evolves into a dense cloud or wind-blown bubble, the ambient density encountered by the shock rapidly increases, enhancing the target density for hadronic gamma rays while reducing shock velocities to no more than a few hundred $\text{km}\cdot\text{s}^{-1}$ [14]. It has been