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Gamma-ray observations of Supernova Remnants with *Fermi*-LAT data

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Summary. — After 8 years of data taking, the Large Area Telescope (LAT) onboard the *Fermi* satellite has shown an excellent capability to detect and observe Supernova Remnants (SNRs) from few hundred MeV up to few hundred GeV. It provides crucial information on physical processes happening at the source, involving both accelerated leptons and hadrons, in order to understand the mechanisms responsible for the acceleration of primary Cosmic Rays. We interpreted the multiwavelength Spectral Energy Distribution (SED) of a sample of different types of SNRs, which have been observed by the *Fermi*-LAT. We show how the environment in which the supernova shock is propagating affects the interpretation of its SED. We evaluated the spectral features of the accelerated particle spectra and estimated the acceleration efficiency, as well as the maximum energy of accelerated particles.

1. – Cosmic Rays and Supernova Remnants

According to the so-called *Supernova Remnant paradigm*, Cosmic Rays (CRs) with energy from about 1 GeV to about 10^8 GeV have a Galactic origin and Supernova Remnants (SNRs) are the most plausible candidates for acceleration sites. The acceleration mechanism, also known as *diffuse shock acceleration* (DSA), naturally predicts the accelerated particles distribution to be a power law $\propto E^{-q}$, whose spectral index in case of strong SNR shocks is $q = 2$.

Nevertheless, in the DSA theory, the required acceleration efficiency is not so small, so the dynamical reaction of the accelerated particles on the shock can be neglected and the CRs can no longer be treated as *test-particles*. They become an extra component into the hydrodynamical equations for the conservation of mass, momentum and energy. This *two-fluid* approach is also known as the Non-Linear DSA theory (NLDSA). The most important prediction of the NLDSA theory is the formation of a *precursor* due to the pressure in accelerated particles around the shocks. As a consequence, the resulting spectrum is steeper ($E^{-2.1}$–$E^{-2.4}$) than E^{-2} and it is compatible with the spectrum measured at Earth [1].

2. – Gamma-ray emission from Supernova Remnants

During the acceleration, CRs interact with the SNR environment producing photons from radio to TeV energy range. The most important processes for γ-ray production are:

- *synchrotron emission* due to high energy electrons deflected in the SNR magnetic field;
- *Inverse Compton (IC) scattering* of the same electron population on local photons from Cosmic Microwave Background and infrared radiation due to dust emission;
- *bremsstrahlung radiation* of high-energy electrons deflected in the Coulomb field generated by charged particles of the gas surrounding the remnant;
- *hadronic interaction* between accelerated particles and this gas.

The first of these processes can explain the radio to X-ray photon spectrum, while the other ones contribute to MeV-TeV observed emission. The detection of MeV-GeV γ-rays with the *Fermi*-LAT telescope gives the chance to discriminate between leptonic and hadronic models.

The Spectral Energy Distribution (SED) is evaluated through the folding of cross sections of the previous processes with the injection spectrum of accelerated particles. In particular, the injection spectrum was obtained using the CRAFT code to calculate a semi-analytic solution of NLDSA [2], while the cross section of γ-rays production in hadronic interaction using the Monte Carlo simulations with FLUKA code [3].

2˙1. *Tycho SNR*. – Tycho's Supernova Remnant is one of the youngest remnants in the Galaxy, originating from a Type Ia in 1572. Its distance is estimated to be 3.5 kpc, corresponding to a density of $0.24\,\text{cm}^{-3}$. Tycho SNR shows a narrow width of the X-ray synchrotron rims [4], probably due to fast cooling of the accelerated electrons behind the blast wave, that requires the magnetic field to be amplified by accelerated particles to approximately $200\,\mu$G.

The γ-ray spectrum of Tycho can be described by a hadronic model as shown in fig. 1 (left panel). The spectral index of proton spectrum obtained with the CRAFT code is around $\Gamma_p = 2.1$, which can be explained in the NLDSA theory. In comparison, the electron spectrum is scaled by a quantity K_{ep} (*electron-to-proton ratio*) $\sim 10^{-2}$ and then for energy above $E_{max} \simeq 11$ TeV there is a cut-off due to the synchrotron radiation losses.

2˙2. *RCW* 86 *SNR*. – RCW 86 is a supernova remnant resulting from a Type Ia explosion. It is located at a distance of 2.5 ± 0.5 kpc from the Milky Way. The ambient density around the SNR is inhomogeneous (on average $\sim 0.1\,\text{cm}^{-3}$) and the shock speed value, as the magnetic field, changes along the shell-like structure. RCW 86 has been recently detected as extended with *Fermi*-LAT [5].

Figure 1 (right panel) shows the leptonic model that describes properly the γ-ray spectrum of RCW 86. The spectral index of proton spectrum obtained with the CRAFT code is, again, around $\Gamma_p = 2.1$. In comparison, in this case, the electron spectrum is scaled by a quantity $K_{ep} \sim 10^{-1}$ and the cut-off is around $E_{max} \simeq 12$.

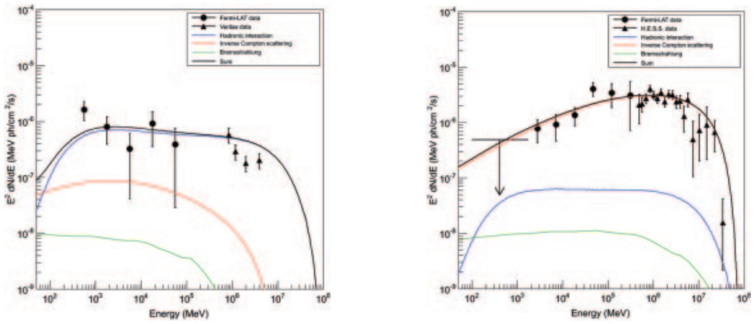

Fig. 1. – Spectral Energy Distribution of Tycho (left panel) and RCW 86 (right panel) as measured with the *Fermi*-LAT [5, 6], Veritas [7] and H.E.S.S. [8], respectively. The hadronic component is denoted by the blue line, the IC scattering by the red line, while the green one represents the bremsstrahlung emission. The black line is the sum of these three contributions.

3. – Conclusions

A model of the γ-ray emission from Tycho and RCW 86 sources has been developed to constrain parameters of the nearby medium and give new hints about the origin of such emission. The whole SNR modeling for Tycho supports a hadronic scenario, by contrast, for RCW 86 a leptonic scenario gives the best description of the SNR spectrum. Even though the two SNRs described have similar characteristics and the NLDSA thoery applies to both of them, the different environments in which the respective shocks are expanding, heavily influence the shape of the γ-ray spectrum, leading to different interpretations.

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