Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B (Proc. Suppl.) 256–257 (2014) 89–93

NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

www.elsevier.com/locate/npbps

Evidence of hadronic interaction in Tycho Supernova Remnant using Fermi-LAT data

Caragiulo M.[a,b,c], Di Venere L.[a,b,d]

[a] Dipartimento di Fisica M. Merlin dell'Universitá e del Politecnico di Bari, I-70126 Bari, Italy
[b] Istituto Nazionale di Fisica Nucleare, Sezione di Bari, I-70126 Bari, Italy
[c] micaela.caragiulo@ba.infn.it
[d] leonardo.divenere@ba.infn.it

Abstract

The Fermi Large Area Telescope (LAT) has observed Tycho Supernova Remnant in the MeV-GeV energy range. The spectrum has been studied using the first three years of data and new data are being collected. We present a multi-wavelength model of the observed spectrum from radio to TeV energy range, based on the hypothesis of hadronic origin of γ-rays. As described by the Fermi acceleration theory, a single proton population was considered, modeled with a simple power-law in momentum. The photon emissivity is computed following Kamae et al (2006) [1]. The leptonic component is also taken into account according to Giordano et al. (2012) [2] prescriptions and it turns out to be negligible with respect to the hadronic one. The model returns a spectral index of 2.23($\pm$0.05) and an acceleration efficiency of 5% of the total kinetic energy expelled in Supernova explosion and it may provide a hint of the acceleration processes in SNRs up to energies close to the knee of cosmic ray spectrum. This work shows that experimental data can be easily explained with a simple model, representing a good test for the acceleration theory.

Keywords: cosmic rays, Supernova Remnant, Tycho, acceleration, hadronic interaction

1. Cosmic rays and Supernova Remnant

Since the first observation of cosmic rays (CRs) by Victor Hess approximately one hundred years ago, the study of their composition and origin has been one of the most challenging question. Observations of cosmic ray spectrum on the Earth showed that they are composed mostly of protons (more than 90%), with energy up to 10^{20} eV. The energy spectrum is described by a power-law with a spectral index which is constant on a very large energy scale. It is approximately equal to -2.7 for energies up to 10^{15} eV changing to -3 for energies between 10^{15} eV and 10^{19} eV and becoming again -2.7 for energies above this value. The shape of cosmic ray spectrum and the value of the spectral index is a combination both of the acceleration of cosmic rays and their propagation in the Galaxy.

The first change in the spectral index, called *knee*, is thought to represent the maximum energy at which galactic cosmic rays are accelerated, while the second change in spectral index, called *ankle*, can be explained adding an extragalactic component.

Supernova Remnants (SNRs) are candidates to be sources of accelerated cosmic rays. First-order Fermi acceleration mechanism predicts that the shock wave originating from Supernova explosion can accelerate particles up to energies close to the knee. The theory predicts a simple power-law spectrum in momentum for accelerated particles.

Due to the deflection of charged particles in the Galactic magnetic field, accelerated cosmic rays cannot be observed directly, but we can observe the photons (from radio to TeV energy range) produced through the interaction of accelerated particles with the environment of the SNR. The observed photon spectrum may give information about the spectrum of accelerated particles

http://dx.doi.org/10.1016/j.nuclphysbps.2014.10.010
0920-5632/

and their interactions in the SNR, providing a hint of the goodness of this hypothesis.

2. Tycho Supernova Remnant

Tycho's Supernova Remnant is one of the youngest remnant in the Galaxy, originating from a Type Ia in 1572 due to a thermonuclear explosion of a binary system. Its distance is not very well constrained. From HI absorption studies (Tian & Leahy 2011 [3]) it was estimated to be 2.5 to 3 kpc, while measurements of the shocked ejecta velocity (Hayato et al. 2010 [4]) report a value around 3 to 5 kpc. Tycho SNR shows a narrow width of the X-ray synchrotron rims, 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 μG (Cassam-Chenaï et al 2007 [5]).

Other important parameters useful for the development of a model of the gamma spectrum of this source are the ambient density and the explosion energy E_{51}, which are not precisely known but they strictly depend on the source distance. According to Giordano et al. (2012) [2], we assumed a distance of 3.5 kpc, corresponding to a density of 0.24 cm^{-3} and an explosion energy of $2 \cdot 10^{51}$erg.

3. Spectral Energy Distribution (SED) modeling

The interaction of accelerated cosmic rays with the SNR environment produces photons from radio to TeV energy range. The most important processes for photon production are: synchrotron emission from high energy electrons deflected in the SNR magnetic field, Inverse Compton scattering of the same electron population on local photons (Cosmic Microwave Background and infrared due to dust emission), bremsstrahlung radiation deriving from electron interaction with the gas surrounding the SNR and hadronic interaction between accelerated protons 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 gamma rays with Fermi-LAT telescope gives the chance to discriminate between leptonic and hadronic models.

Spectral Energy Distribution is evaluated through the folding of cross sections of the previous processes with the injection spectrum of accelerated particles and the free parameters in the model are determined through a fit to the data.

3.1. Particle spectra

According to Fermi acceleration theory, the density of particles accelerated by the shock is described by a simple power-law in momentum:

$$n(p) = k\left(\frac{p}{p_0}\right)^{-\gamma}. \tag{1}$$

The intensity of particles is obtained multiplying by the particle velocity and dividing by the solid angle:

$$J(p) = \frac{\beta c}{4\pi} n(p). \tag{2}$$

Since the cross sections of the processes in question are often expressed as a function on the kinetic energy of the particles, the intensity becomes:

$$\begin{aligned} J(E_k) &= J(p)\frac{dp}{dE_k} = \frac{1}{\beta} J(p(E_k)) \\ J(E_k) &\propto (E_k(E_k + 2m))^{-\gamma/2}, \end{aligned} \tag{3}$$

where m is the mass of the particle.

Figure 1 shows an example of the spectrum of the accelerated particles as a function of the particle kinetic energy. It can be noticed that the shape is almost the same as a simple power-law for energy above the mass of the particle m, while a natural break occurs in the spectrum at low energy.

According to these assumptions, both accelerated proton and electron spectra were modelled with a simple power-law in momentum. In order to account for energy losses, a super-exponential cut-off at high energy (around a few TeV) was added in the electron spectrum, as suggested by Blasi (2010) [6]:

$$\begin{aligned} J_e(E_k) &= A_e\left(\frac{p(E_k)}{p_0}\right)^{-\gamma_e} \exp(-(p(E_k)/p_{cut,e})^2) \\ J_p(E_k) &= A_p\left(\frac{p(E_k)}{p_0}\right)^{-\gamma_p}. \end{aligned} \tag{4}$$

In the following sections the processes through which the accelerated particles interact with the SNR environment are briefly described. The photon flux resulting from each process is evaluated folding the injection spectra of accelerated particles with the cross sections of the processes.

3.2. Synchrotron emission

Synchrotron emission occurs when a charged particle is deflected in a magnetic field. The spectrum of the emitted photons goes from radio to X-ray energy band,