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Young SNRs: a new family of High Energy γ-ray emitters

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Abstract. *Fermi* has recently detected young supernova remnants (SNRs) such as Tycho, Vela Jr, and RX J1713.7–3946, as well as Cas A. Multiwavelength studies of these amazing objects are presented, highlighting as a possible interpretation for the GeV-TeV γ-ray spectrum, the presence of a hadronic contribution, an indirect signature of cosmic-ray acceleration processes. Details on the environments where the SNRs are developing are also given and connections with the observed spectra are discussed.

Key words. SNRs – Molecular clouds – acceleration processes

1. Introduction

Among the brightest GeV γ-ray sources in the Galaxy detected by the *Fermi* Large Area Telescope (LAT) in the first three years of the mission are many middle-aged SNRs interacting with molecular clouds (MCs), such as W51C (Abdo et al. 2009), W44 (Abdo et al. 2010d), IC443 (Abdo et al. 2010e) , and W28 (Abdo et al. 2010b), to cite the brightest detected so far. These middle-aged SNRs constitute the dominant class of LAT-detected SNRs. The γ-ray luminosity L in the $1-10$ GeV band ranges from 1 to $10{\times}10^{35}$ erg s^{-1}, larger than young SNRs like Cas A or RX J1713.7+3946. The GeV γ-ray spectra typically show a spectral break at a few GeV, demonstrating the importance of LAT observations of these SNRs. Also, the synchrotron radio emission of the four SNRs can be characterized by a large flux density of $160-310$ Jy at 1 GHz with a flat spectral index of 0.3-0.4 (Green 2009). The large number of SNRs interacting with molecular clouds in the LAT-detected sources suggests that the observed γ-ray emission may be enhanced by interactions with the dense environment in the clouds. In these targets, it is expected that non-thermal bremsstrahlung radiation may be produced by relativistic electrons or that π^0s, produced in proton interactions with the targets, decay and produce the observed γ-ray spectrum. The inverse Compton (IC) scattering off the cosmic microwave background (CMB) and interstellar radiation fields, however, seems to be quite disfavored. *Fermi*-LAT has also discovered a new family of GeV-emitting SNRs: two historical and very young (Tycho and Cas A) and two young and TeV bright. These SNRs present very different evolutionary stages and much cleaner environments, and as such, are ideal laboratories

Send offprint requests to: F. Giordano where the acceleration processes can be studied.

2. The Historical SNRs

Kepler's SN (1604 AD), Tycho's SN (1572 AD), SN 1181 AD, SN 1054 AD that originated the well-known Crab Nebula, and the especially bright SN of 1006 AD all produced well known remnants of stellar explosions. All of them have been observed as supernovae (SNe) in our Galaxy over the last two millennia and recorded in East Asia (China, Japan, Korea), Europe, and the Arab dominions, as guest stars. Some of them have been observed in GeV γ-rays by the *Fermi* Gamma ray telescope since August 2008. Details of the *Fermi* observations of very young remnants are given and the GeV-TeV spectral energy distribution obtained joining *Fermi* data with the detections by ground-based telescopes are also discussed. The remnants of historical supernovae are generally well studied across the electromagnetic spectrum, making them excellent laboratories for studying high-energy phenomena associated with supernova shocks, and for testing our current understanding of diffusive shock acceleration theory. Apart from the Crab nebula which has recently demonstrated its uniqueness (Abdo et al. 2010c) (Abdo et al. 2011b) Tavani et al. (2011), the recent GeV-TeV detections of Tycho and Cas A demonstrate that their soft spectra may indicate that hadronic acceleration is taking place in these remnants, giving strong indications that SNRs are Galactic cosmic ray sources and accelerators.

2.1. Cas A

Cas A is thought to be the remnant of a Type IIb supernova that exploded around A.D. 1680. Cas A was the first SNR detected in the TeV γ-ray band Abdo et al. (2010a). Unlike the Tycho case, the emission mechanisms responsible for the TeV γ-rays is still a matter of debate, due to the much higher density in the surrounding medium. A clear detection of Cas A at a significance level of 12σ was made with the *Fermi* LAT using the γ-ray data between 2008 August 4 and 2009 September 4 Abdo et al. (2010a). The GeV γ-ray data are consistent with a point-like source, as expected from the angular size of the remnant (a radius of 2.5'), and also consistent with steady emission. The X-ray observations of synchrotron-emitting filaments measure the magnetic field at the forward shock; B = 0.3 mG is inferred from the observed width of the filaments (Parizot et al. 2006), which is consistent with the variability timescale of the synchrotron filaments (Uchiyama & Aharonian 2008). By combining the estimated magnetic field with the synchrotron spectrum in the radio bands, it was shown that the leptonic γ-ray emission model does not explain the LAT-detected emission. Instead, the GeV-TeV γ-ray emission can be ascribed mainly to the π^0-decay component. The total proton content at the current age of the remnant amounts to Wp $\approx 0.4\times 10^{50}$ erg for the shocked gas density of $n_H = 10$ cm^{-3} (Laming & Hwang 2003), which is estimated from the measured dynamics of the remnant. This would be the first case where one can estimate the number of CRs in SNRs with a reasonable accuracy. The spectral slope of the accelerated CR protons is assumed to be s = 2.3 from the radio spectral index, which seems compatible with the GeV-TeV spectrum. Both the CR content and spectrum are in reasonable agreement with the direct measurements of the CR flux and the CR anisotropy.

2.2. Tycho

Tycho's SNR is the remnant of a Type Ia explosion that took place in 1572, and is currently in transition from the ejecta-dominated phase to the Sedov-Taylor phase. Recent detection of TeV γ-rays from Tycho's SNR by the VERITAS Collaboration Acciari et al. (2011) has just been followed by the very recent 5σ detection of GeV γ-ray emission with the *Fermi* LAT Giordano et al. (2011). The LAT spectrum is characterized by a photon index $\Gamma = 2.3\pm0.2$ (stat) ±0.1 (sys), which smoothly connects with the VERITAS spectrum. Given the amplified magnetic field of 0.2 mG estimated for shock downstream Völk et al. (2005)

and the constraint on the ambient density (n_H < 0.3 cm^{-3}), the γ-ray spectrum of Tycho's SNR can be explained only by the π^0-decay emission. Compared with Cas A, the ambient density is smaller and the radio emission is much weaker, so that the leptonic scenario is much harder to reconcile than in the case of Cas A. The total CR proton content at the current age amounts to Wp $\approx(0.6-1.5) \times 10^{50}$ erg. The accelerated CR protons and electrons with number index s = 2.3 are inferred from the multi-wavelength fitting. Such a steep spectrum may be explained by the finite velocity of the scattering waves in the upstream shock region Morlino & Caprioli (2011). As in the case of Cas A, the LAT results obtained for Tycho's SNR strengthen the case for a SNR origin of the Galactic CRs.

3. Young and TeV Bright

3.1. RXJ1713–3496

SNR RX J1713.7–3946 (G347.3-0.5 in the Green's SNR list Green 2009) is among the best known TeV bright SNRs (H. E. S. S Collaboration: D. Berge et al. 2007). Moreover, it is also well known for its bright synchrotron X-ray emission that completely dominates the radiation output from the remnant (Ellison et al. 2010) and also matches well the TeV morphology. The energy spectrum of RX J1713.7–3946 measured with the *Fermi* LAT (Abdo et al. 2011a) shows a hard power law with photon index of Γ = 1.5 ± 0.1(stat)±0.1(sys), smoothly connecting with the steeper TeV spectrum. The hard power-law shape agrees with the expected IC spectrum (the leptonic model). Given the energy flux ratio of the observed synchrotron X-ray emission and the γ-ray emission, the leptonic model requires that the average magnetic field be about 10 μG (H. E. S. S Collaboration: D. Berge et al. 2007). If the leptonic scenario is playing the major role in accounting for the observed spectrum, the filamentary structures and variability in X-rays (Uchiyama et al. 2007) would be attributable to locally enhanced magnetic fields. Still in leptonic scenario, γ-ray spectrum provides a robust estimate of the total number of relativistic electrons, as We $\sim 1\times10^{48}$ erg, as well as an estimate of the proton content. Assuming a proton number index s = 2 (assumed to be same as the electron number index, the flux upper limit at 1 GeV corresponds to Wp < 0.3 $\times 10^{51}$ (with a density n_H = 0.1cm^{-3}) erg for d = 1 kpc (Abdo et al. 2011a), suggesting that even when the GeV luminosity is dominated by electrons scattering on photon seeds, the hadronic content is not negligible.

3.2. VelaJr

Very recently, *Fermi* has also detected the TeV-bright SuperNova Remnant RX J0852.0–4622 (also known as G266.2-1.2 or Vela Jr.) above 5GeV (Tanaka et al. 2011). Vela Jr SNR shows some similarities with RX J1713: it is one of the SNRs from which both nonthermal X-rays and TeV γ-rays are detected and it shows good circular overlap with a morphology with a diameter of about 2° and with rim brightening especially in the northern, northwestern, and western parts. The SNR was originally discovered in X-rays by ROSAT in the southeastern corner of the Vela SNR (Aschenbach 1998) and subsequently detected by ASCA (Slane et al. 2001). At TeV energies, the CANGAROO (Enomoto et al. 2006) and H.E.S.S. (Aharonian et al. 2007) collaborations reported the detection. Also for this case, the broadband spectrum of the nonthermal emission can be explained either by a leptonic scenario where the γ-rays are produced by inverse Compton scattering of high-energy electrons, or by a hadronic scenario where π^0 decays are responsible for the γ-rays (Aharonian et al. 2007). The very high energy threshold detection with *Fermi*, necessary to limit the low energy contamination from the bright and neighboring Vela pulsar, prevents us from disentangling the two scenarios, but slightly favors the hadronic interpretation. The measured photon index Γ = 1.85 ± 0.06 (stat) ± 0.2 (sys), and the flux integrated for the interval between 1 GeV and 300 GeV (extending at lower energy the fit) is 1.01±0.09 (stat) ± 0.36 (sys) $\times10^{-8}$ ph $cm^{-2}s^{-1}$. The injected proton spectrum is well described by a broken power law with a spectral break at 50 TeV and a total power budget of 5.2×10^{50} erg, for a density of $0.1\mathrm{cm}^{-3}$ and a magnetic field of few tens of μG. In the leptonic scenario, the data are fitted assuming a magnetic field of 12μG, a softer index of 2.15 and a break at 25 TeV. In this model, the energy available to the accelerated electrons is 1×10^{48}erg. Collecting more data, it will be possible to study the GeV emission from the remnant in the off-pulse window of Vela, lowering the energy threshold of the analysis.

4. Conclusions

After three years of data taking, the *Fermi* LAT is answering some of the fundamental questions regarding the SNR paradigm, including their acceleration processes, the morphology of the sites where the acceleration takes place, their efficiency and their spectral features, and they are confirming indirectly the effect of magnetic field amplification. We are also collecting the first clear evidence of sources where the hadronic scenario seems to be the dominant one and other where, despite an estimated proton energy of a $0.3\text{-}0.5\times10^{51}$ erg, the γ-ray emission comes mainly from electron IC mechanism. We expect in the next years to collect more SNR candidates, to lower the energy threshold to a few tens of MeV, to have a more suitable Galactic background description, and to better disentangle the hadronic emission from the leptonic energy loss for different SNRs in different evolution stages and environments, adding more crucial information to help solve the puzzle of cosmic rays.

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