The SNR W44: an ideal laboratory for Cosmic-Ray acceleration

M. Cardillo[1,2], A. Giuliani[3] and M. Tavani[1,2,4], for the AGILE collaboration.

[1] INAF/IAPS-Roma, Via del Fosso del Cavaliere 100, 00133, Roma, Italy
[2] Department of Physics, Univ. di Roma "Tor Vergata", via della Ricerca Scientifica 1, 00133, Roma, Italy
[3] INAF-IAFS Milano, via E.Bassini 15, 20133, Milano, Italy
[4] Consorzio Interuniversitario Fisica Spaziale (CIFS), Villa Gualino, V.la Settimio Severo 63, 00133, Torino, Italy

E-mail: mcardillo@roma2.infn.it

Abstract. W44 (G34.7-0.4) is one of the most studied Supernova Remnants (SNRs) because it is an ideal system to study Cosmic-Ray (CR) production, acceleration and propagation. In the last years, SNR study showed an increasingly complex scenario with a continuous rielaboration of theoretical models; moreover, until now, providing an experimental unambiguous proof of the CR origin has been elusive, despite many decades of attempts and controversial analysis. In this context the AGILE γ-ray satellite has an important role. During its five years of life it observed a great amount of different astrophysical sources, including SNRs. In case of W44 AGILE observed a spectrum extending to energies below $E = 200$ MeV that allows us to exclude leptonic emission as the main contribution to the γ-ray emission [36]. Moreover, refined AGILE data show that W44 spectrum could be the sum of two (or more) contributions from two different regions of the remnant where different processes influence CR acceleration and propagation. Future AGILE data will lead us to understand the intricate link between SNRs and CRs.

1. Introduction

Understanding Cosmic-Ray (CR) origin is one of the most important issues of high-energy astrophysics [11, 22, 25, 31, 34, 49]. In the last few decades, scientific community agrees that CRs with energies up to 10^{15} eV are produced by galactic sources, mostly by Supernova Remnant (SNR) generated shocks. This is mainly because, on one hand, the energy throwput, since about 10% of SN explosion energy can be converted into CR kinetic energy [23, 34] and on the other hand, the presence of high magnetic fields ($\sim 100\,\mu G$) and strong X-ray variations in the SNR environments.

The main mechanism for converting kinetic SN explosion energy into CRs is the energy dependent linear Diffusve Shock Acceleration (DSA) [20, 21, 24], that provides a simple power-law spectrum of accelerated CRs $N(E) \propto E^{-\gamma}$ with an index $\gamma = 2$. This spectrum is modified by diffusive propagation with a diffusion coefficient $D(E) \propto E^{\delta}$ and $\delta = 0.7$ because CR spectrum is well fitted by a power-law with an index $\alpha = 2.7 = \gamma + \delta$.

In order to test the SNR hypothesis there are two main issues to be considered: (1) finding the low-energy spectral signatures of the hadronic contribution in the γ-ray spectrum (CRs are
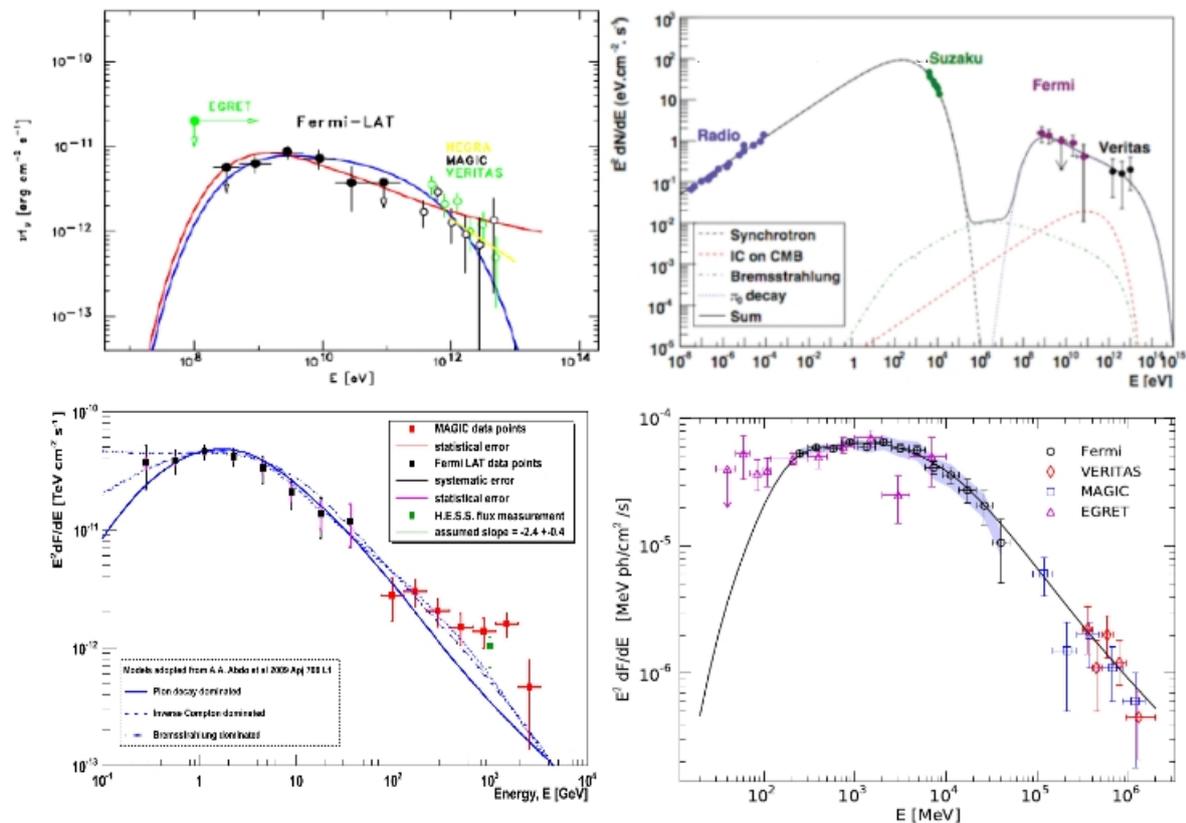
Figure 1: Spectra of four different SNRs where we highlight the lack of data at energies below 200 MeV (red solid line). **Upper left**: the youngest SNR known until now, Cas A, ∼300 years old [2]; **Upper right**: Tycho SNR, about 440 years old [35]; **Bottom left**: the SNR W51c, more 20.000 years old [14];**Bottom right**: the SNR IC443, ∼ 30.000 years old [4].

mainly protons),(2) observing SNR experimental spectra and understanding acceleration and propagation physical processes.

AGILE and Fermi-LAT γ-ray satellites, together with VHE instruments (HESS, VERITAS and MAGIC), provided a great amount of data from SNRs [1, 2, 4, 5, 3, 6, 7, 8, 9, 10, 12, 13, 14, 35, 37, 47] and in most cases, their spectra are well fitted by a hadronic model but we can not exclude yet the leptonic contribution (Bremsstrahlung and Inverse Compton scattering) as the main one in γ-ray emission. This is shown by experimental data below $E = 200$ MeV where hadronic and leptonic emission spectra have a well distinct behavior due to a steepening of the hadronic spectrum missing in the leptonic one (fig. 1).

Moreover all experimental SNR γ-ray emission data provide spectra steeper than those expected by a linear DSA theory especially for young SNRs (Tycho and Cas A). This feature represents a challenge even for a more detailed and realistic NLDSA theory [41] that seems to predict a concave high energy spectrum because of an highest energy hardening [15, 16].

In this context, the SNR W44 is a very interesting source. During its observations, AGILE for the first time found spectral points below $E = 200$ MeV that allowed us to exclude the leptonic emission as the main contribution to the γ-ray spectrum [36]. Moreover AGILE results confirm the steep spectral index found by Fermi-LAT; in [43] Malkov et al. try to explain this feature with the so called Alfvèn wave damping (see section 3) showing that the predicted model can well

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fit W44 spectrum. However, a more detailed analysis of W44 region with AGILE seems to show a more complicated scenario with the possibility that the spectrum is due to different contributions from different SNR regions. On the basis of this consideration and of spectral steepening of the other SNRs, we are studying a theoretical context that could explain W44 peculiar spectrum.

2. W44

2.1. General Issues

W44(G34.7-0.4) is one of the most studied SNRs. It is located in the Galactic disk at a distance of about 3 kpc from Earth, and it is a middle-aged SNR, 20.000 years old [29, 52]. Radio [28] and X-ray [51] data show the mixed-morphology of the remnant, centrally peaked in the X-ray band with a well defined radio shell. On the Southern side of W44 there is the pulsar PSR B1853+01 associated with the remnant [52]. The environment of W44 is very interesting because it has an high average density [44]; this is an important requirement to enhance the proton-proton interaction probability $t_{pp} = (c\sigma_{pp}n)^{-1} \simeq 10^8$ yrs $> t_{SNR} \sim 440$ yrs and so to detect hadronic emission from π^0 decay.

In the Northern part of the remnant there is a perfect correlation between Hα and [SII] emission [45]: [SII] traces hot-shocked gas in correspondence with the encounter between expanding shell and InterStellar Medium (ISM) density enhancement regions [33], indicating the presence of a radiative shock.

In the South-Eastern side of the remnant, instead, the presence of a molecular cloud complex and interaction between it and the SNR shell were confirmed by different analysis in the CO band [44, 45, 46, 53] and by maser OH emission [30, 38]. In the high-energy band Fermi-LAT measured a γ-ray spectrum for $E > 200$ MeV well fitted by a broken power-law hadronic distribution with a spectral index $\gamma = 3$ above the break energy E_{br} [3].

2.2. The AGILE results

The AGILE results give even more relevance to W44. The detected flux above 400 MeV is $F = (16.0 \pm 1.2) \times 10^{-8}$ ph cm^{-2} s^{-1}. Figure 2 shows that γ-ray emission detected by AGILE follows the quasi-elliptical pattern of the interior of the radio shell (green contours). There is a very good correlation with radio brightness enhancement on the North-West and South-East that are respectively in coincidence with [SII] emission and with the molecular cloud [36]. This correlation leads us to consider γ-ray emission due to CR proton acceleration by SNR shocks, confirming Fermi-LAT hypothesis.

The W44 spectrum measured by AGILE is even much more interesting (fig. 2b): comparing it with other SNR spectra in fig.1, it is evident that, for the first time, we have data at energies below 200 MeV and we can observe the low-energy steepening peculiar to hadronic γ-ray emission, being the fundamental proof of CR acceleration. A multiwavelength analysis taking into account radio data [28], TeV upper limits [3] and the previous medium density estimations, together with our data, allowed us to exclude all possible leptonic models, Bremsstrahlung or inverse Compton dominated. Assuming that synchrotron radio and γ-ray emissions are due to the same electron population, we can fit radio and TeV data only with density and magnetic field values not easy to explain in that environment [36]. The only model that can well fit γ-ray data is a hadronic power-law distribution with an index $\gamma = 3.0 \pm 0.1$ and a cut-off at $E_{cut} = 6 \pm 1$ GeV, fixing a density $n = 100$ cm^{-3} and a magnetic field $B = 70$ μG, in agreement with the values predicted by acceleration theoretical models and with radio and TeV data (fig.2c)[36].

2.3. Discussion

W44 confirms that SNRs accelerate galactic CR protons in correspondence with shocks; they interact with the nuclei of the surrounding environment producing π^0 that decay in γ-ray photons
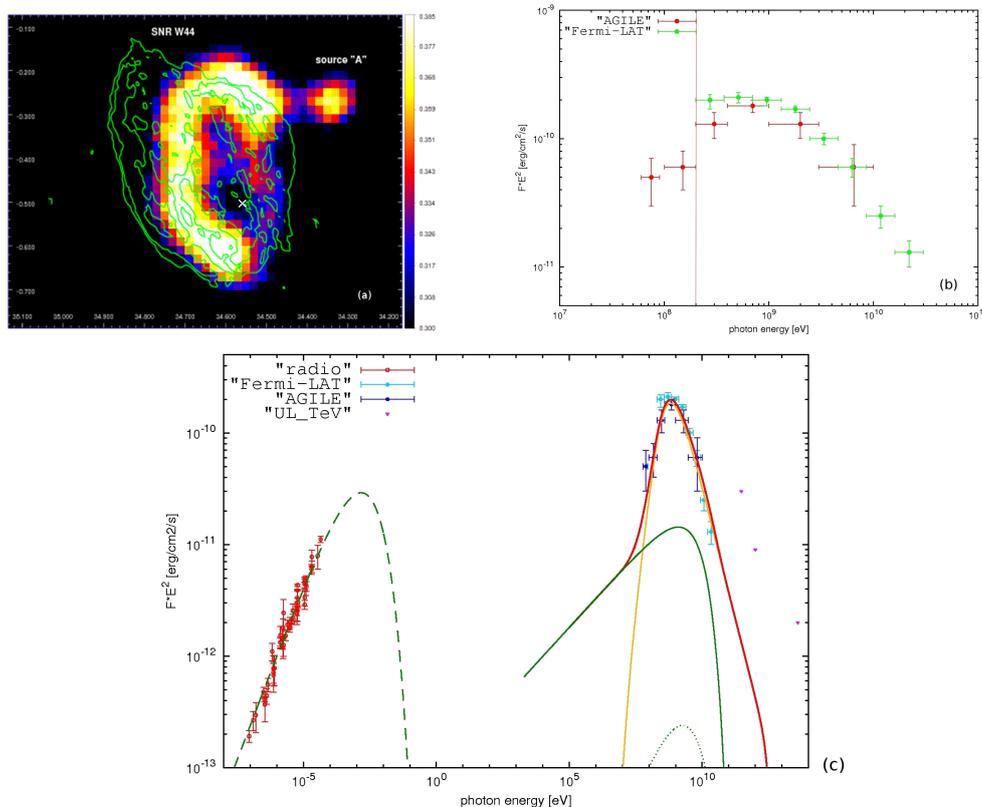
Figure 2: **(a)**: W44 region AGILE γ-ray intensity map (Galactic coordinates), in the energy range 400 MeV-3 GeV obtained by integrating all available data collected during the period July 2007 and April 2011. Green contours show the 324 MHz radio continuum flux density detected by the Very Large Array. The white cross indicates the position of the pulsar PSR B1803+01. Source A does not appear to be associated with W44. **(b)**: combined AGILE (red) and Fermi/LAT (green) spectral energy distribution (SED) for SNR W44. AGILE points are in the range 50 MeV-10 GeV and Fermi/LAT data span the energy range 0.2 - 30 GeV [3]. **(c)**: theoretical modeling of the broad-band spectrum of SNR W44 superimposed with radio data (in red color), γ-ray data of image (b) (in blue color) and TeV upper limits (magenta triangles). This is an hadronic model characterized by $B = 70$ μG and $n = 100$ cm^{-3}. The yellow curve shows the neutral pion emission from the accelerated proton distribution discussed in the text. The green curves show the electron contribution by synchrotron (dashed curve), Bremsstrahlung (solid curve), and IC (dotted curve) emissions. The red curve shows the total gamma-ray emission.[36]

[39]. However the spectral index found both in AGILE and Fermi-LAT spectra, $\gamma = 3.0$, is steeper than the one predicted by linear and non-linear DSA models like the index of all other SNR spectra (section 1) . We need to consider other physical mechanisms that can modify the predicted spectrum in order to explain experimental data. In [43] Fermi-LAT spectrum is explained by the so called Alfvén damping: when accelerated ions scatter with neutrals (e.g. in a Molecular Cloud), Alfvén wave propagation is prevented by their friction in a well determined frequency band [40], producing a less efficient acceleration and a consequent steepening of the spectrum of exactly one unit [43].

The AGILE data seem to confirm this possibility but a new deeper analysis could show an even more complex scenario. W44 could be divided in two different regions: the main one, in correspondence with high density ionized gas and molecular cloud, that contributes to γ-ray emission in the range 400 MeV-1 GeV and the SouthWestern one that emits in the range 1-3 GeV. They could give different contributions to W44 spectrum because of different environments and,

consequently, different physical mechanisms for CR acceleration and propagation.

We are considering this possibility, taking into account a different behavior of diffusion coefficient in the two regions [32] and the Alfvén damping correlated to the presence of the molecular cloud [43]: we will show our results in a forthcoming paper [27].

3. Conclusions

The SNR W44 AGILE data confirmed the importance of this object in the CR acceleration context. For the first time AGILE obtained spectral point below $E = 200$ MeV giving the final proof of CR acceleration by SNRs. Our data confirm a spectral index steeper than the one predicted by theoretical models as Fermi-LAT found; this is not the first case for SNRs and it highlights the importance of deeply understanding SNR environment and physical mechanisms related to acceleration and propagation. New AGILE data analysis seems to show a more complex structure of W44 that could result in a composite spectral contribution coming from different SNR regions and consequently two different physical mechanisms.

Further developments of this hypothesis will be explained in a forthcoming paper [27].

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