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# AGILE observations of Middle-aged supernova remnants

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**Abstract.** The gamma-ray imager on-board the AGILE satellite detected several middle-aged Supernova Remnants. Unlike young SNRs, these objects are bright also for energies greater than some tens of MeV. Here we present an overview of the AGILE observations of middle-aged SNRs in the "low energy" band (50-400 MeV) and the spectral and morphological studies performed for some of them (IC443, W28, W44. W51C). These data, combined with the results from instruments operating at higher energy (Fermi, HESS, MAGIC, Veritas) can constrain the theoretical models for the gamma ray production in SNRs.

**Key words.** gamma rays: observations - Supernova Remnants: individual: W44, W28, IC443, W51C

## 1. introduction

AGILE (Astrorivelatore Gamma a Immagini LEggero,) is an Italian Space Agency (ASI) mission aunched on April 23rd 2007. The Gamma Ray Imaging Detector (GRID) on-board AGILE is sensitive in the 50 MeV-30 GeV energy range. After more than 25000 revolutions in its low-Earth orbit AGILE covered the whole sky, with extended exposure on the Galactic plane. In these proceeding are presented the results achieved from the observations of supernova remnants.

## 2. SNR W44

The AGILE/GRID instrument detected gamma ray emission from SNR W44 in the energy range 50 MeV - 10 GeV with a significance of 15.8 sigma, as an extended source with a morphology well correlated with the radio shell (Giuliani et al. 2011). This energy band is complementary with respect to the band 0.2-30 GeV already investigated by the Fermi/LAT instrument for the same SNR (Abdo et al. 2010). The spectrum obtained combining the AGILE/GRID and Fermi/LAT data shows with unprecedented precision that the gamma-ray emission from W44 is described by a broad peak around 1 GeV (see figure 2). Such an accurate spectrum allows to precisely deduce the spectral parameters of the parent particle population (energy of the sp. break, spectral index below and above the break), which are not compatible with the electron population seen by radio continuum observations (Castelletti et al. 2007).

On the other hand an hadronic scenario can adequately explain this feature in the gamma-ray spectrum. The spatial distribution shows that the gamma-ray emission originates in the shell of the SNR. The large dimensions of W44 combined with the good imaging capabilities

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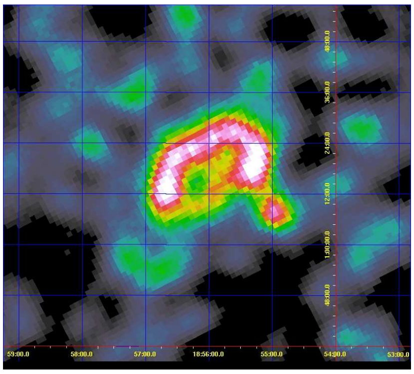

**Fig. 1.** SNR W44 as seen by AGILE for energies greater than 400 MeV

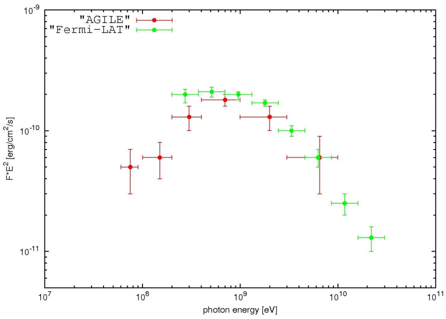


**Fig. 2.** Combined AGILE (red) and Fermi/LAT (green) spectral energy distribution (SED) for SNR W44. AGILE points are in the range 50 MeV - 10 GeV divided in six energy intervals. Fermi/LAT data span the energy range 0,2 - 30GeV (from Abdo et al, 2010).

of AGILE for E>400 MeV allow us to detect spectral variations along the SNR shell. The energy-resolved spatial distribution shows that the bulk of the emission in the 0.4-1 GeV band is generated in the northern part of the shell while most of the emission in the 1-3 GeV energy band come from the southern part of the shell (see figure 3). These observations are in agreement with several theoretical models which predict that, at any given time, protons are monochromatically injected in the ISM, with an energy depending on the magnetic field at that time (see, for example, Gabici et al. 2009). This allows us to deduce the energy of the protons currently emitted by the different part of the SNR, which is crucial for understanding the overall acceleration mechanism in SNRs.

## 3. SNR W28

W28 is a mixed morphology SNR with an age of more than 35 000 years located at a distance of about 1.9 kpc. A system of massive molecular clouds is associated to the SNR as revealed by the CO (J = 0 → 1) observation carried by the NANTEN telescope (Fukui 2008). Two main peaks in the molecular hydrogen distribution can be seen at R.A., dec = 270.4, -23.4 (cloud N) and at R.A., dec = 270.2, -24.1 (cloud S, see fig. 4)

The molecular clouds distribution correlates nicely with the gamma rays observations

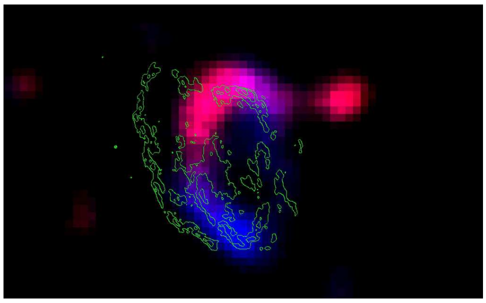

**Fig. 3.** AGILE intensity map for the W44 region in the energy range 400MeV-1GeV (Red) and 1-3 GeV (blue). Green contours show the radio continuum flux density at 1,4 GHz as observed by the VLA (Castelletti et al, 2

in both the TeV energy band (Aharonian et al. 2008) and in the E > 400 MeV energy band observed by AGILE. However the ratio between the TeV and the multi-MeV emission is significantly different for the cloud N and the cloud S. In figure 5 the gamma-ray spectra for the two clouds are shown.

The interpretative scenario proposed in Giuliani et al. (2010) assumes that the N cloud is closer to the CR acceleration site than the S cloud. If protons diffuse in the interstellar medium with a diffusion coefficient given by $D(E) = D_0 \; E^{0.5}$ the resulting proton energy spectrum is suppressed below a threshold energy $E_t \sim R^4 t^{-2}$ where R is the distance from

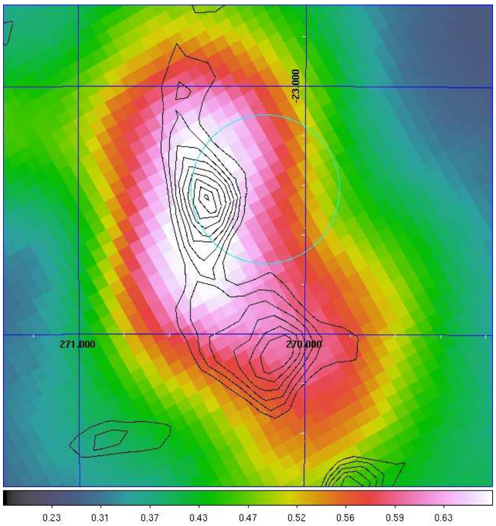


**Fig. 4.** AGILE counts map for the W28. The blue circles indicate the location of the supernova remnant W28, the black contours show the CO intensity emission

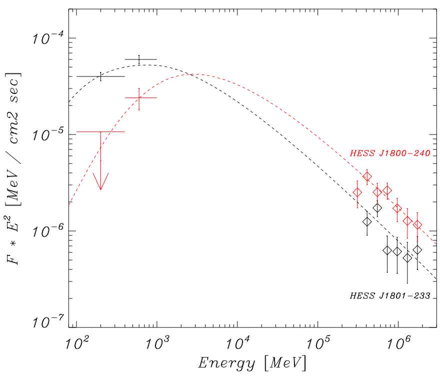


**Fig. 5.** Combined AGILE and HESS gamma-ray photon spectra for cloud N (black) and cloud S (red). The curves represent the gamma-ray spectra estimated (accordling to the model presented in the text) for the two clouds.

the acceleration site and $t$ the age of the SNR. Figure 5 shows the gamma-rays spectra produced by protons (through neutral pion decay) interacting with the cloud N and S assuming respectively R = 9 and 4 pc.

This scenario can explain also the morphology of the gamma-rays emission seen at different energies ranges (see figure 6). Assuming that CR are accelerated in a spherical region (indicated by the blue circle) we evaluated the tridimensional distribution of cosmic rays N(r,E,t) around the SNR as a function of the particle energy and SNR age solving the diffusion equation :

$$\frac{dN(r,E,t)}{dt} = D(E)\,\nabla^2 N + \frac{\partial}{\partial E}\,[b(E)N] + Q(E)$$

where b(E) represents the energy losses, and assuming that the cosmic rays were injected impulsively with a spectrum $Q(E) \sim E^{-2.2}$. Black countours shows the distribution of targets (molecular hydrogen) as derived by the observations of the NANTEN telescope.

The sky maps in the upper row of figure 6 refer to the gamma ray emission for energies greater than 400 MeV, 3 GeV and 400 GeV expected for an age of 40000 yrs. We assumed that gamma ray emission is produced by p-p collision between accelerated protons and the nuclei of the molecular hydrogen. In the lower row, the maps produced by the AGILE, Fermi and HESS observations of SNR W28 are shown.

## 4. SNR W51C

AGILE detects SNR W51C with a significance of 8.3 sigma and a flux above 400 MeV of 8.9 $\pm 1.3\ 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ The gamma ray shape is similar to the radio shell seen in radio continuum at 330 Mhz .

## 5. SNR IC 443

IC 443 is a SNR lying at a distance of about 1.5 kpc in the Galactic anticenter direction. In radio, optical and X-rays a shell structure is clearly visible, where the interaction of the SNR and the ISM creates a shock. A system of molecular clouds is also associated to the SNR, and an evidence of interaction is given by the observations of an high value of the ratio CO (J=2-1)/(J=1-0) (Seta et al. 1998). A TeV source has been detected by MAGIC

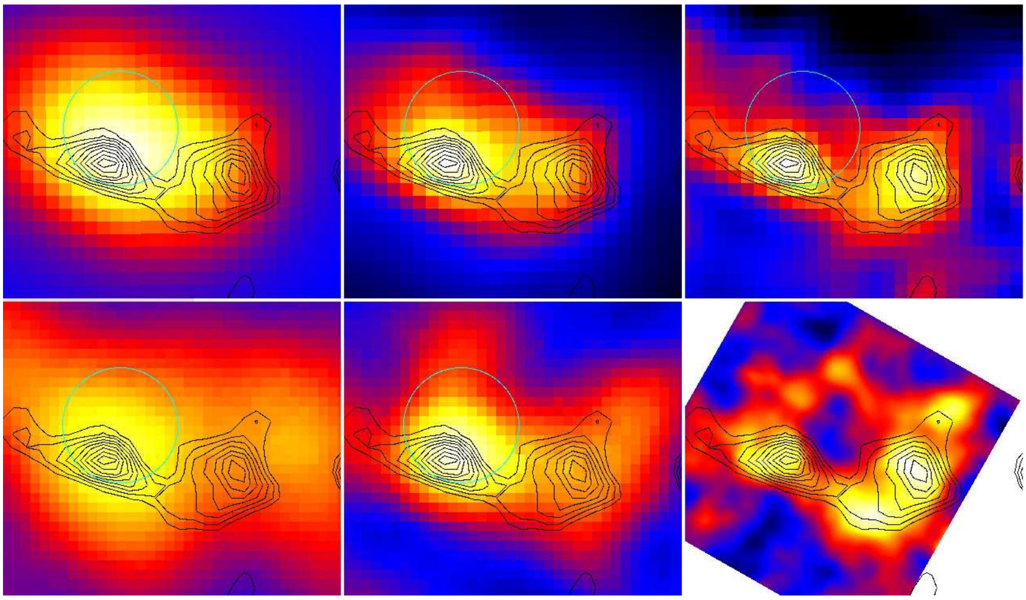

**Fig. 6.** *Upper row*: Predicted gamma-rays emission for energies greater than 400 MeV (left column), 3 GeV (center column) and 400 GeV (right column) for SNR W28. *Lower row*: Maps produced from the AGILE, Fermi and HESS observations of SNR W28.

**Table 1.** Middle-aged Supernova Remnants seen by AGILE. Luminosity is given for E > 100 MeV.

| SNR | Age (*years*) | Distance (*kpc*) | Luminosity (*erg/s*) |
|---|---|---|---|
| W28 | > 35000 | 1.9 | $3.3 10^{34}$ |
| IC 443 | 30000 | 1.5 | $2.4 10^{34}$ |
| W44 | 20000 | 2.8 | $6.5 10^{34}$ |
| W51C | 20000 | 6.0(?) | $7.3 10^{34}$ |

(Albert et al. 2007) and VERITAS (Acciari et al. 2009).

Thanks to the good angular resolution of the TeV telescopes it was possible to locate the source in a small error box coincident with the most massive cloud. AGILE observed a gamma-ray source, obtaining an error box which is not compatible with the MAGIC and VERITAS error boxes (Tavani et al. 2010). The different position of the source in the TeV and gamma energy ranges implies a difference in the the CR spectrum in the two emitting places or in the targets distributions. A possible interpretation can be given assuming a different distance of the emitting clouds which can lead to a different spectrum of the accelerated protons seen by the near/far clouds (Aharonian et al. 2006; Torres et al. 2008).

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