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A DECADE OF AGILE

Gamma-ray astronomy as a milestone in the cosmic ray origin issue

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Abstract
During the last years, high-energy astrophysics has not been considered at the same level as other scientific disciplines. In doing so, there is a very high risk neglecting the γ-ray energy band that has a strong importance to solve some still open issues. This paper is focused, in particular, on the galactic cosmic ray origin issue, and it shows how only a coexistence of low-energy (MeV–GeV) and high-energy (GeV–TeV) γ-ray instruments can allow us to solve this century-old issue.

Keywords Cosmic rays · Gamma-ray astronomy · CTA · e-ASTROGAM · AGILE

1 Introduction

Despite the amount of high-energy data available so far, cosmic ray (CR) origin is still an open issue. Supernova remnants (SNRs) are thought to be primary sources of galactic CRs and it is plenty of theories and models developed to explain γ-ray data coming from these sources in the context of CR acceleration (see Amato 2014 for the most recent review). For a long time, we had only indirect evidences of CR acceleration from SNRs coming from X-ray (Vink 2012) and optical wavelengths (Morlino et al. 2012). However, to have a strong confirmation that galactic CRs are accelerated in SNR shocks (but the same is valid also for alternative sources), we need direct evidences that only γ -ray photons can provide: first, photons are not deviated during their propagation, allowing a more easy reconstruction of the arrival direction, and, moreover, they keep the same spectral behavior of their parents hadronic particles, with $E_\gamma \sim 10\% E_\mathrm{p}$.

These proves can be provided both at low ($E < 200$ MeV) and high ($E > 100$ GeV) γ-ray energies. CR proton electromagnetic emission has a typical feature, called *pion bump*, due to decaying π^0 rest mass; only the related low-energy decay visible at $E < 200$ MeV can allow to distinguish CR accelerated hadron γ-ray emission from the letponic one. CR particle spectrum, instead, shows that likely Galactic component reaches energies up to about 3×10^{15} eV [see discussions in Cardillo et al. (2015)]; consequently, we should detect γ-ray spectrum up to $E = 100$ TeV. Only very young SNRs ($t_\mathrm{age} \sim 10^2$ years, high shock velocity) can be detected up to these energies but, in spite of the large number of young SNRs detected in the γ-ray band, none of these seems to reach $E = 100$ TeV (see Fig. 1).

However, in the last few years, an important step forward has been taken thanks to some middle-aged SNRs interacting with high-density molecular clouds (MCs). These sources are very luminous in the γ-ray band and they can be detected below the critical threshold $E < 200$ MeV (Giuliani et al. 2011; Ackermann et al. 2013; Cardillo et al. 2014; Jougler and Funk 2016). Because of their high age ($t_\mathrm{age} > 10^4$ years), they have very low shock velocity, that is why it is unlikely that freshly accelerated particles could be present in correspondence of shock interaction with surrounding medium. The hypothesis of pre-existing CR re-acceleration was introduced to explain hadronic γ-ray emission coming from these sources (Uchiyama et al. 2010; Lee et al. 2015; Cardillo et al. 2016).

At the light of these considerations, new hypothesis are added to the SNR paradigm, like Superbubble multiple shocks (Binns et al. 2008; Ackermann et al. 2011) or young star wind shocks (Aharonian et al. 2019), and the more recent Galactic Center γ-ray emission (Abramowski 2016),

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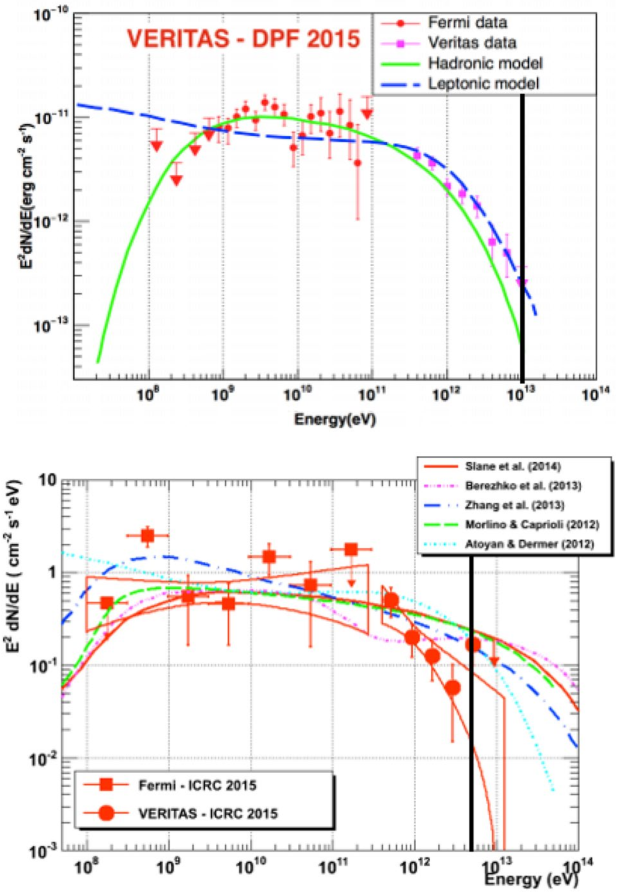

Fig. 1 Top: VERITAS and Fermi-LAT data points for Tycho with models from Park (2015). Bottom: VERITAS and Fermi-LAT data points for Cas A with models from Ghiotto (2015). The black line indicates $E = 100$ TeV

even if with large statistical errors, seems to provide the first pevatron evidence. Nevertheless, direct evidence is still missing. For this reason, future γ-ray instruments focused on the two extremes of γ-ray energy band are fundamental. On one hand at higher energies, we will have the Cherenkov telescope array (CTA) (CTA 2017); on the other hand, at lower energies, we risk to have no instruments focused on the γ-ray energy band between [1 MeV to 10 GeV], after the recent rejection of the enhanced-ASTROGAM mission (e-ASTROGAM) De Angelis et al. (2017, 2018) by ESA, in the context of M5 call.

2 AGILE: the breakthrough and open issues

After a variety of hypothesis and theoretical models, the launch of the Astro Rivelatore Gamma ad Immagini LEggero (AGILE) satellite (Tavani 2009) in 2007 and of the Fermi-Large Area Telescope (Fermi-LAT) satellite (Atwood 2009) in 2008 enhanced the chances to finally solve the CR origin issue. High-energy Cherenkov Telescope [High-Energy Stereoscopic System (HESS)] (Hinton 2004), Major Atmospheric Gamma-ray Imaging Cherenkov Telescope (MAGIC) (Ferenc 2005), and Very Energetic Radiation Imaging Telescope Array system (VERITAS) (Krennrich 2004)], indeed, could not detect any galactic Pevatron; consequently, high-energy astronomy needed to focus on the search of Galactic CR acceleration evidence at lower γ-ray energies. However, because of the low sensitivity below $E \sim 200$ MeV of the two satellites, scientific community had to wait a very luminous and near source for a breakthrough in CR paradigm.

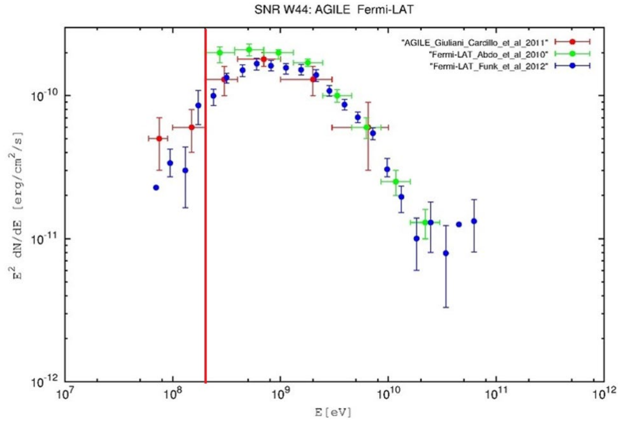

Fig. 2 AGILE (Giuliani et al. 2011) and Fermi-LAT old and new (Abdo et al. 2010; Ackermann et al. 2013) W44 γ-ray spectrum. The red line indicated $E = 200$ MeV (color figure online)

This breakthrough was in 2011, when AGILE detected, for the first time, γ-ray emission at $E < 200$ MeV in the SNR W44 (Giuliani et al. 2011; Cardillo et al. 2014), a middle-aged (> 20,000 years) SNR very bright in radio (Castelletti et al. 2007) and γ-ray bands, interacting with an MC at its South-East side. This SNR was already detected by Fermi-LAT but only down to about 400 MeV (Abdo et al. 2010). The spectrum detected by AGILE shows the low-energy decay due to the *pion bump*, giving the first evidence of CR presence at the shock between an SNR and the surrounding medium. In 2013, Fermi-LAT confirmed AGILE results and found evidence of hadronic γ-ray emission also in another middle-aged SNR, IC443 (Ackermann et al. 2013). AGILE and Fermi-LAT (old and new) data points are shown in Fig. 2, where a red vertical line shows the critical threshold energy. The breakthrough provided by AGILE observations, the improvement of Fermi-LAT analysis, and the very good correlation between their results is invaluable.

2.1 Acceleration or re-acceleration?

After the discovery by AGILE, the first attempts to fit γ-ray data are all based on hadronic Fermi first-order mechanism of acceleration described by the Diffusive Shock Acceleration (DSA) theory (see Amato 2014 for a recent review). In Giuliani et al. (2011), the model was based on a simple power law with a low-energy cut-off and a very steep high-energy spectral index, $\alpha \sim 3$. In both Ackermann et al. (2013) and Cardillo et al. (2014) (see Fig. 3, top panel), instead, the best fit was a broken power-law distribution with a low-energy index (below $E \sim 20$ GeV) steeper than 2 and a high-energy one steeper than 3. Even if these models give a good data fit, however, there are some more issues to consider. A broken power-law distribution with such a steep spectral index, as well as a low-energy cut-off, are hardly explained by DSA theory. Moreover, W44 (as like as IC443) is a middle-aged SNR with a low shock velocity ($v_{\mathrm{sh}} \sim 100$ km/s); since the acceleration efficiency, ξ_{CR}, is proportional to v_{sh}^2 (Amato 2014), we cannot expect an efficient acceleration.

Thus, the possibility of a re-acceleration of pre-existing galactic cosmic rays was analyzed (Uchiyama et al. 2010; Lee et al. 2015). The first re-acceleration models of W44 γ-ray emission, however, still presented some features that are not easy to explain in a DSA context, such as broken power-law distributions and low-energy cut-off. A model more consistent with theoretical predictions was developed in Cardillo et al. (2016) taking into account re-acceleration and compression [following the 'crushed cloud' model of Blandford and Cowie (1982)] of pre-existing Galactic CRs, with a simple power-law model with an index $\alpha \sim 2.3$ and an high-energy cut-off at $E \sim 10$ due to the necessity of a energization time shorter than loss time (see Fig. 3, bottom panel).

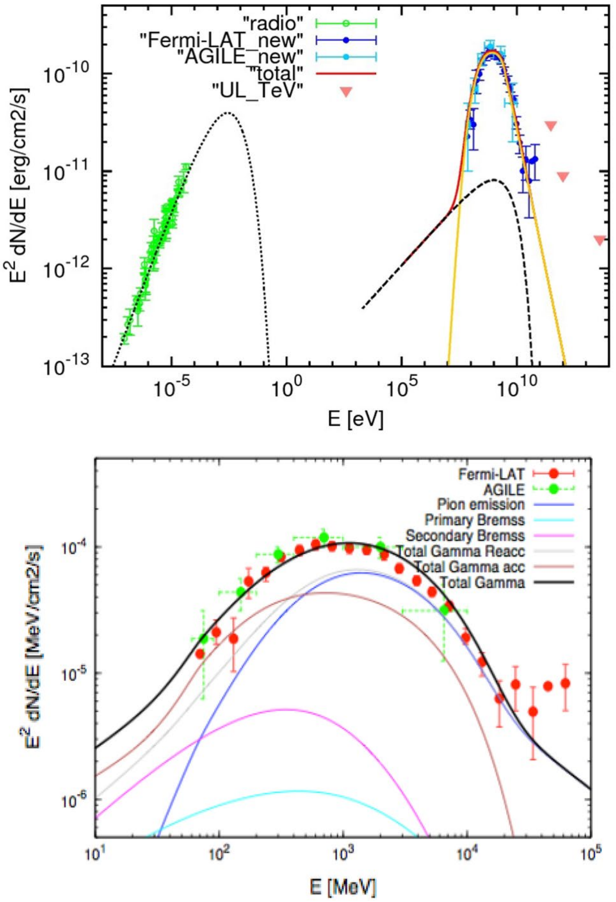

Fig. 3 Top: acceleration model for γ-ray spectrum of the SNR W44 (Cardillo et al. 2014). Bottom: emission model for the SNR W44 γ-ray spectrum obtained with contributions from primary and secondary particles and from both re-acceleration and acceleration mechanisms (Cardillo et al. 2016). Data points are the same of Fig. 2

An obvious conclusion is that, despite the presence of γ-ray emission from neutral pion decay in SNR shocks, there is no evidence of the presence of freshly accelerated particles in the SNR shocks.

3 The importance of gamma-ray astronomy

This overview aimed at stressing a very important but well-known issue. New instrumentations allow us to analyze "from inside" several years of theories and predictions, confirming some of these but, often, opening new and different questions, making new discoveries or finding unexpected physical behaviors from astrophysical sources. The CR and SNR issue, and more generally the Galactic CR origin issue, is just an example but one of the clearest. Despite the great amount of GeV and TeV data collected in the last 20 years, we are still looking for a confirmation about CR acceleration (not only re-acceleration) by SNRs or any kinds of sources. For this reason, in the next future, we need more sensitive instruments at the lowest and highest γ-ray bands.

3.1 High-energy: CTA

CTA (2017) will give start to the next generation of ground-based γ-ray instruments and will be an open observatory for the wide astrophysics community. Its energetic range will be very large, [10 GeV to 100 TeV], thanks to its design providing two arrays: a southern hemisphere array, which covers the full energy range with large, medium, and small size telescopes (LST, MST, SST), and a northern hemisphere array, consisting only of LST and MST, focused on the lower energy part of TeV spectrum.

From Fig. 4, top panel, we can see that the very good sensitivity of CTA at $E >$ TeV is at least one order of magnitude better than the one of the previous IACT instruments. This feature is fundamental to enhance the number of SNRs detected at the highest energies and the chance to detect the first SNR Pevatron or to discovery Galactic CR sources others than SNRs.

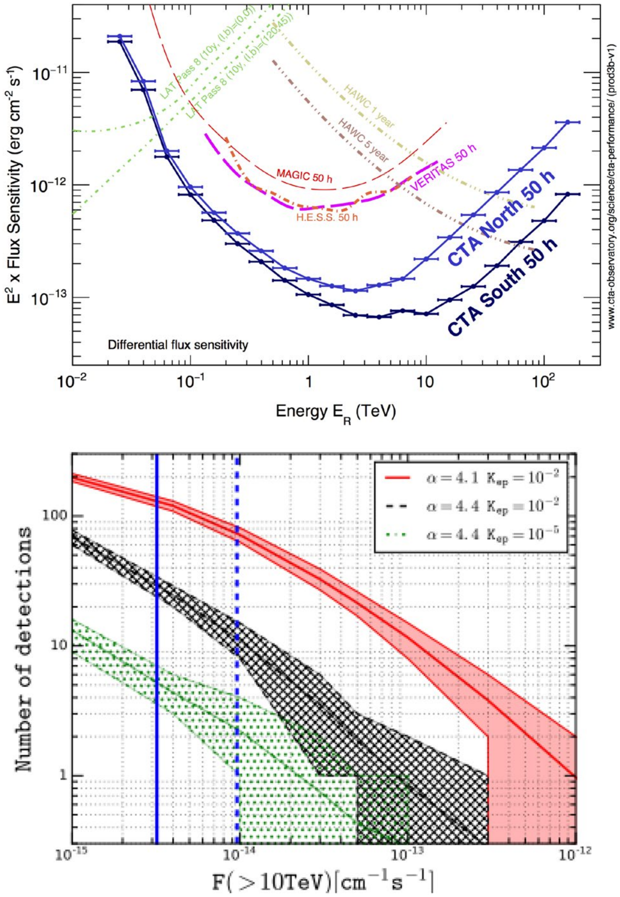

Fig. 4 Top: different differential flux sensitivities curve for CTA. Bottom: SNRs in the entire Galaxy with integral γ-ray flux above $F(>1$ TeV) and standard deviation. Figures from CTA (2017)

In the context of CR origin, an improvement in angular resolution at higher energies such as the one in CTA telescope (< 0.05° at 1 TeV, see Fig. 4, bottom panel) can be resolutive. Indeed, the accurate location of TeV emitting regions will allow us to establish their correlation with other wavelength emissions and to constraint radiation mechanisms in different zones of the same source.

However, there is the possibility that CTA by itself will not be sufficient to solve the centuries-old issue of CR origin. Indeed, according to some theoretical models (e.g., Cardillo et al. 2015), even if SNRs were effectively Galactic CR accelerators, hadronic CRs would reach PeV energies only in the first hundred years of the SNR life. Consequently, we have a very low chance to detect Pevatron emission from these sources. This tricky issue shows the importance to cover the MeV–GeV γ-ray band to confirm the presence of freshly accelerated CRs in correspondence of the SNR shocks, detecting young-fast SNR shocks at $E < 200$ MeV.

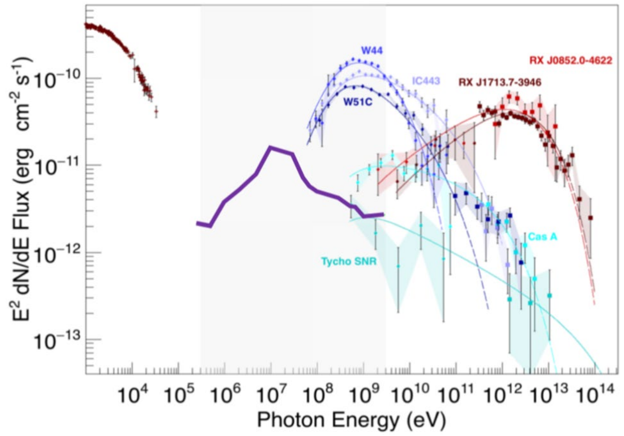

Fig. 5 e-ASTROGAM sensitivity for 1-year exposure (thick purple line) compared to typical γ-ray energy spectra for several SNRs; young SNRs (< 1000 years) in green. High-energy data ($E > 100$ MeV) from Funk (2016); low-energy data from Tanaka et al. (2008). Figure from Funk (2016)

3.2 Low-energy: e-ASTROGAM-like missions

At the light of the low-energy γ-ray band importance, it is worrying that ESA had rejected the e-ASTROGAM mission in the context of M5 call. e-ASTROGAM (De Angelis et al. 2018) is a breakthrough Observatory based on advanced space-proven detector technology (e.g., silicon trackers) and focused on the photon energy range [0.3 MeV and 3 GeV].

The improve technology of e-ASTROGAM detector could make available a very good sensitivity below $E = 200$ MeV. From Fig. 5, we can see that the its sensitivity curve is well below all the most important SNR γ-ray spectra. We could enhance, then, the number of SNRs detected in the critical energy range as well as the chances to detect younger remnants where efficient CR acceleration is the dominant mechanism.

e-ASTROGAM could give a very strong contribution also in the multi-wavelength characterization of sources. Like CTA, it has a very good angular resolution but at lower energies (< 1.5° at $E < 100$ MeV), that allows, for instance, to find important correlation or anti-correlation with CTA TeV emission or in general with other wave-band emissions, implying more constraints for several physical parameters.

4 Conclusions

Detection in several electromagnetic bands had contribute to understand the CR origin, but direct evidence of their acceleration by SNRs (or by any other sources) can be obtained only in the γ-ray band.

AGILE brought one of the most important breakthroughs in the CR science thanks to the first low-energy γ-ray

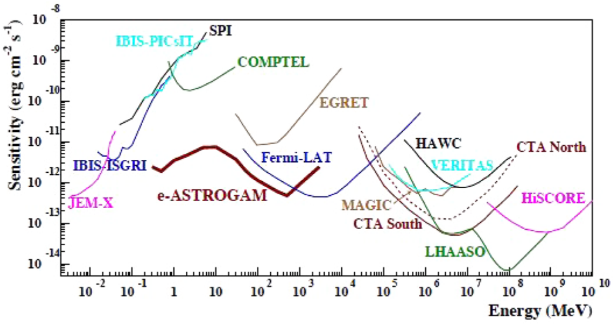

Fig. 6 Point source continuum sensitivity of different X- and γ-ray instruments. INTEGRAL/JEM-X, IBIS, and SPI for Tobs = 1 Ms; COMPTEL and EGRET Tobs ~ 9 years; Fermi/LAT high latitude source over 10 years; MAGIC, VERITAS, and CTA for Tobs = 50 h; HAWC obs = 5 years; LHAASO obs = 1 year; HiSCORE obs = 1000 h; and e-ASTROGAM for 1 year at high latitude. Figure from De Angelis et al. (2018)

detection in a SNR, W44, opening a new window and stressing new interesting questions. Indeed, W44, like the others SNRs detected in the same range subsequently, IC443 and W51c, is a middle-aged SNR with a very low shock velocity (v_{sh} ~ 100 km/s). Such as slow shock cannot accelerate high-energy particles with a high efficiency; there is a high probability, indeed, that γ-ray emission from these sources is due to hadronic CRs from re-acceleration of pre-existing Galactic CRs.

Then, despite the great amount of data, we still have no effective evidence of the presence of freshly accelerated particles at SNR shocks. To solve the CR origin issue, we need to study the whole γ-ray energy band from the very low-energy ($E > 1$ MeV) to the highest ones (E of about 100 TeV). For the highest energies, we will shortly have CTA that with its high sensitivity and good angular resolution will allow us to enhance the chance of detecting Pevatron emission from SNRs (or other sources). For the lowest energies, instead, the e-ASTROGAM observatory was proposed in the ESA M5 call with the aim of detecting more SNRs and, consequently, to enhance the chance of finding typical *pion bump* feature from the youngest ones, giving the final evidence of freshly accelerated CR presence in correspondence of their shocks. Observing Fig. 6, it is clear the great improvement that e-ASTROGAM and CTA could give in the two different γ-ray bands with respect to the previous missions.

But unfortunately, we will have no instrument focused on the critical energy band below $E \sim 200$ MeV, since the mission e-ASTROGAM was rejected by ESA in M5 call. If there were no other similar missions proposed in the near future, a very large and important γ-ray band would continue to be uncovered and any chance to prove CR acceleration by SNRs or by any other source would be very remote.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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