IL NUOVO CIMENTO **40 C** (2017) 134
DOI 10.1393/ncc/i2017-17134-2

Colloquia: SciNeGHE 2016

# High-energy and very-high-energy gamma-ray observations of the Milky Way

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received 3 June 2017

**Summary.** — Observations of the gamma-ray emission from the Milky Way have significantly improved in recent years thanks to the current space instruments such as *Fermi* LAT and AGILE, and to the ground-based telescopes at higher energies such as for example H.E.S.S., VERITAS, MAGIC, and HAWC. While these high-quality data are providing crucial information on Galactic sources, interstellar emissions, and high-energy particles, they are challenging our understanding. I will discuss the state of the art, recent results, and prospects for future instruments.

## 1. – The Milky Way in gamma rays

Present observatories at high and very high energies are offering an amazing and unprecedented view of the sky, discovering thousands of sources, and unveiling properties of the non-thermal emission in the Milky Way. The high-energy and the very-high-energy gamma-ray skies look very different. In fact, when we compare the beautiful all-sky maps from *Fermi* Large Area Telescope (LAT) at a few hundred MeV and at a few tens of GeV with the superb images of the very-high-energy sky seen for example by High Energy Stereoscopic System (H.E.S.S.) above 200 GeV, the Very Energetic Radiation Imaging Telescope Array System (VERITAS) at a few TeV, and the High-Altitude Water Cherenkov Observatory (HAWC) above 10 TeV, from lower to higher energy there is one major difference that catches our attention. At lower energies the emission appears to be mostly diffuse while at very high energies it appears to be more localized in sources. This is not only due to instrumental characteristics, such as for example a better point spread function at higher energies, but it is also intrinsic to the emission itself. In fact at lower energies most of the photons are diffuse because the emission is manly interstellar, while at higher energies this component decreases more rapidly than the emission from the sources allowing the sources to pop up. The effect is that at lower energies searching for faint sources strongly depends on interstellar models and it is very challenging, while at higher energies searching for interstellar emission is challenging, and it is possible only after subtraction of sources in very bright regions.

High- and very-high-energy gamma rays are generated by relativistic particles, cosmic rays (CRs), that collide with the gas, and interact with interstellar photons or magnetic fields. Gamma rays are produced by different mechanisms: by hadronic interactions of CRs with the gas via production of pions that decay originating photons; by leptonic mechanisms via inverse Compton scattering where CR electrons accelerate low-energy photons to gamma rays, and by synchrotron processes where CR electrons loose energies in the magnetic fields. In general, the intensity and the spectrum of gamma rays reflect the intensity and the spectrum of CRs. The main accelerators of CRs are believed to be supernova renmants (SNRs), which have to provide $10^{48}$ erg protons per year, and need to have a 10% efficiency in converting expansion energy into CRs.

## 2. – Gamma-ray sources as particle accelerators

While GeV/TeV photons from sources are undisputedly produced by accelerated particles, the origin of such high-energy particles, weather from the source itself or from their surroundings, is not yet understood. In general intensity and spectrum of gamma-ray sources directly reflect the intensity and spectrum of the CRs. SNRs are believed to be the major accelerators of CRs. Observations of x-rays and gamma rays from these objects reveal the presence of energetic particles, thus proving evidence of acceleration processes in their neighboring. Multi-wavelength spectra of SNRs undoubtedly show the presence of accelerated electrons. Recent observations of gamma-ray spectral features from several supernova shells interacting with dense interstellar medium, and the correlation of this emission with the gas column density indicate acceleration of protons ([1, 2]).

In the early 2016 the *Fermi* LAT Collaboration published the first SNR catalog [3], finding 36 candidates classified through spatial association with radio counterparts. This study has been performed accurately accounting for systematics given by the uncertain knowledge of the interstellar emission. Candidate SNRs were found to be within expectations if SNRs provide the majority of Galactic CRs. Indeed it is found that almost 10% of the energy is converted into CRs.

Observations at GeV energies with *Fermi* LAT and at TeV energies with H.E.S.S. and VERITAS show two classes of SNRs: 1) SNRs interacting with the interstellar medium, more numerous at GeV (*e.g.*, W51C and W44) that have been described as sources of protons. These are older SNRs, brighter at GeV energies due to high-density target, but show a clear break in their spectrum at few GeV, indicating that the acceleration process for older SNR is not efficient anymore. However the exact site of acceleration is not known yet (see a recent comprehensive review by [4]). Moreover it is not known how these sources could accelerate protons to high energies such as $10^{15}$–$10^{17}$ eV; 2) Young SNRs most luminous at TeV and less at GeV (*e.g.*, Tycho and Cas A) that could accelerate particles at such energies and are almost described with leptonic processes.

Massive star formations could also be sites of particle acceleration. Observations at GeV and TeV energies with *Fermi* LAT [5], Argo [6], and previously Milagro [7] of the Cygnus region have identified some extended emission with a harder spectrum with respect to surrounding regions. This suggests the presence of fresh accelerated CRs, and the emission could be correlated with many SNRs or stellar winds.

## 3. – The large-scale interstellar emission from keV to TeV energies

Most of the photons detected by *Fermi* LAT are diffuse, and almost half are of interstellar origin due to CRs interacting with the interstellar medium and photons from the interstellar radiation field. In order to study the sources this diffuse emission has to be removed, and hence it has to be modeled very well. On the other side, this interstellar emission is providing useful information about CRs, and hence it is one of the major scientific interests of gamma ray telescopes. However its modeling is very challenging. A promising way to extract information about CRs from the diffuse emission observed in gamma rays is to compare observations with CR propagation models.

The study of the diffuse emission in gamma rays started already in the early 70s with the Small Astronomy Satellite (SAS) and COS-B that observed the entire sky above 50 MeV. At lower energies (1–30 MeV), and from 1991 to 2000, the Imaging Compton Telescope (COMPTEL) seemed to observe some diffuse emission as well. This emission is believed to be a combination of purely interstellar and of unresolved sources. At higher energies, in the same period, the Energetic Gamma Ray Experiment Telescope (EGRET) showed truly diffuse emission in the whole sky with high significance, and the Milky Way appeared extremely bright, particularly toward the inner part of the Galaxy [8]. This interstellar emission has been attributed to and modeled as the sum of three distinct processes: inverse Compton scattering of CR electrons in the radiation field and cosmic microwave background; bremsstrahlung of CR electrons on the gas; and pion decay due to hadronic interaction of CRs with the gas [9]. Apart from the truly interstellar component, some of the emission is due to unresolved sources.

More recently, a detailed work [10] looked at the sky from 30 keV to 0.6 MeV with the spectrometer SPI on board of the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) after subtracting the sources. They showed that there is a diffuse emission left with its maximum at the Galactic center, which is associated to interstellar emission.

At energies below 100 MeV *Fermi* LAT maps show some sources but mostly diffuse emission, which is probably a mixture of truly interstellar and unresolved sources (*e.g.*, [11]). Here the *Fermi* LAT point spread function is very broad so that disantangle these components is very difficult. The emission at these energies is believed to be predominantly of leptonic origin. On the other side *Fermi* LAT maps above few GeV show that the emission is mostly of hadronic origin. In fact, here the pion-decay emission is at its maximum and it spatially correlates with the gas/dust maps. Using the GALPROP code([1]) for modeling the CR propagation in the Galaxy it is found [12] that the interstellar emission seen by *Fermi* LAT is reproduced quite well assuming that the CRs in the Galaxy are resembling the ones as locally measured (after accounting for solar modulation). However it is very difficult to select a CR propagation model that provides the best description of the whole sky [13]. This is likely due to the fact that some model parameters are degenerate while *Fermi* LAT uncertainties are relatively large. Excess in various regions of the sky are still persistent, such as in the outer Galaxy, in the inner Galaxy, and in some structures above and below the plane. The structures, called Fermi Bubbles, extend well above and below the Galactic center with hard spectral index with respect to the interstellar emission and sharp borders [14,15]. The spectrum and intensity do not vary within the bubbles, and the spectrum can be described either by hadronic or leptonic process [16]. Which acceleration mechanism produces these structures has

([1]) `www.galprop/stanford.edu`

been investigated by many authors (*e.g.*, [17]) but it is still unknown. Interesting is that at high energy these structures are visible also without interstellar model subtraction. Recently HAWC did not confirm the presence of the bubbles at very high energies [18]. Neither INTEGRAL/SPI has confirmed detection of such structures [19]. The interstellar emission has started to be observed even at very high energies with TeV telescopes, especially in the Galactic center region. Details in this region will be presented in the next section.

In summary the interstellar emission is a common feature in gamma rays already important at tens of keV, and extending to TeV energy ranges.

## 4. – The Galactic center region

This section presents recent observations and studies of the interstellar emission in the Galactic center region from keV to TeV energies. If we look at the sky from 30 KeV to 0.6 MeV with INTEGRAL/SPI after subtracting the sources, we see that there is some emission with its maximum toward the Galactic center. This has been explained as truly interstellar emission [19]. However model parameters, especially CR electrons, interstellar radiation field, and halo size are highly degenerate. Usual inverse Compton emission models are in agreement with data if the CR electron spectrum is increased by a factor of two with respect to the local measured one. Moreover, models with the interstellar radiation field in the inner Galaxy increased by a factor of ten and the halo size of the Galaxy of 10 kpc, *i.e.* larger than usually assumed, are preferred. In the COMPTEL energy range, *i.e.* 1–30 MeV, the observed diffuse emission in this region is higher than predicted by the present models, indicating the presence of unresolved sources. At higher energies with *Fermi* LAT extensive analyses of the diffuse gamma-ray emission reveal residuals in the inner Galaxy. Many independent accurate works have been published on the Galactic center attributing to dark matter the excess of diffuse emission over models (*e.g.*, [20]). However foreground and background modeling is critical in this region, so that contaminations from unresolved sources and uncertainties in the interstellar medium models are significant, yet leaving the question on the excess emission unsolved ([13, 21, 22] and reference therein). A recent analysis [23] confirmed a weak extended residual component peaked at the Galactic center, consistent with the expected dark matter profile, but no claim of the dark matter discovery was made due to uncertainties in the interstellar model and undetected sources. The inverse Compton component was found to be dominant and enhanced in this region. If this is due to CR or interstellar radiation field is still an open question. At higher energies H.E.S.S. recently completed the first survey of the Galactic plane above 200 GeV. Observations of the Galactic center ridge were updated [24] confirming the presence of a diffuse extended emission. A fraction of this emission is distributed like dense gas tracers confirming its CR hadronic and interstellar origin. The authors found the presence of diffuse emission with power-law spectrum to tens of TeV extending without a cutoff or a spectral break. This is produced by a CR profile peaked towards the Galactic center and compatible with a $1/r$ profile as the one expected from a stationary point source of CRs located at the Galactic center. This CR source should be in the inner 10 pc. The authors interpreted this diffuse emission as possibly associated to Sgr A* activity in the last $10^6$–$10^7$ years ago. At even higher energies also VERITAS [25] discovered a residual emission in the inner degrees around the Galactic center after subtracting the sources (Sgr A*, the supernova G09+01 and a new source). The contours of this emission overlaps with the ones seen by H.E.S.S.. The authors also confirmed no presence of cut off up to 20 TeV.

## 5. – Open questions

We have seen that from keV to TeV energies diffuse emission is a common feature, especially in the Galactic center region. This diffuse emission can be produced by undetected sources which are unresolved by the instruments, or it can be truly diffuse as produced by CRs interacting with the interstellar medium. In the latter case the diffuse emission provides important information on CRs. However model uncertainties still puzzle our description of the emission and our knowledge of CRs, their sources, and their mechanisms of acceleration.

Observations of the gamma-ray emission from the Milky Way have significantly improved in recent years thanks to the current space instruments. While high-quality data are providing crucial information on Galactic sources, interstellar emissions, and high-energy particles, they are still many open questions such as: What are all the Galactic sources producing CRs? How do CRs accelerate and propagate in the Galaxy? What is the origin of the diffuse emission in the Galactic center? What is the origin of the Fermi bubbles?

Continuous multi-wavelenght and multi-messenger observations compared with models, the advent of the Cherenkov Telescope Array, and possible missions at MeV such as e-ASTROGAM [26] and Amigo, will try to definitively answer these questions.

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The author acknowledges support via NASA Grant No. NNX16AF27G.

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