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Very-high-energy gamma rays and neutrinos: The search for PeVatrons

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Summary. — Since its discovery more than one hundred years ago, the origin of the cosmic-ray flux measured on Earth is still unknown: in order to explain the energy region below the knee, supernova remnants are usually addressed, even though no clear indication of PeV energies has been observed so far in such a kind of sources. However, recently, the Galactic Center region has been detected as a multi-TeV gamma-ray emitter: in the case of hadronic origin of the radiation, this would imply the existence of PeV primary protons. Hence, this detection triggers the search for a PeVatron at the center of our Galaxy. In order to identify the origin of the emission, a multi-messenger strategy appears suitable: in fact, in the hadronic scenario, neutrinos would constitute a natural counterpart of the electromagnetic emission. The fundamental role of neutrinos in disentangling the origin of the observed gamma rays is here discussed.

1. – Introduction

The cosmic-ray (CR) flux measured on Earth extends over more than thirty orders of magnitude, with energies ranging between 10^8 eV up to 10^{20} eV. The region below 10^{15} eV (PeV) is believed to be mainly contributed by Galactic sources [1]. Nowadays, many Galactic source classes have been detected at very-high energies, including supernova remnants (SNRs) and pulsar wind nebulae. The search for the sites where Galactic PeV CRs are accelerated, the so-called PeVatrons, represents one of the main open problems of the astroparticle physics field. Gamma-ray observations at multi-TeV energies of Galactic sources have provided us with the strongest evidence for the existence of efficient acceleration mechanisms: among these, diffusive shock acceleration [2] is expected to be operating at SNR shocks. This process naturally produces a hard proton spectrum,

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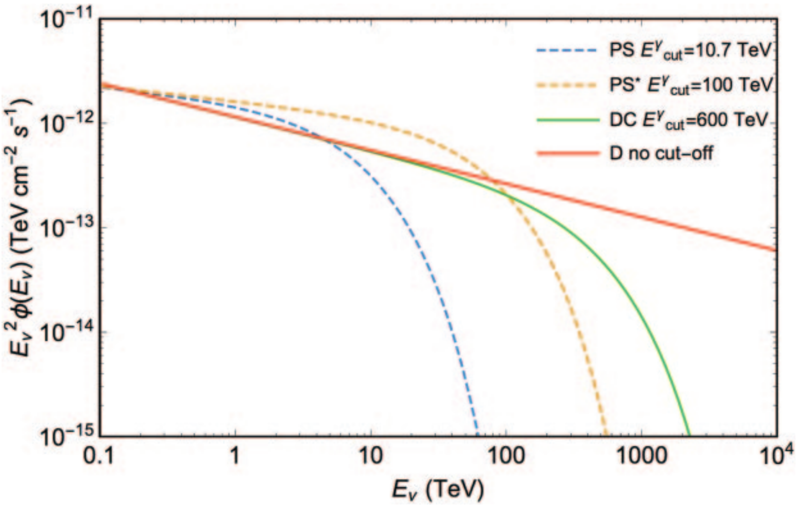

Fig. 1. – Muon neutrino (and antineutrino) fluxes from the Galactic Center for different gamma-ray scenarios of the point-like source (PS) and the diffuse (D) emissions (see the text for details).

in the form of $\mathrm{d}N/\mathrm{d}E \propto E^{-2}$; however, PeV energies can hardly be achieved in these systems. The Hillas (or containment) criterium provides a zeroth order evaluation of the maximum attainable energy, by requiring that the particle Larmor radius is smaller than the source size. A young SNR, with a radius of $R \simeq 3\,\mathrm{pc}$ and whose shock is moving at $v_s \simeq 3000\,\mathrm{km/s}$ in a typical magnetic field of $B \simeq 10\,\mu\mathrm{G}$, would produce protons with a maximum energy of $E_p \simeq 100\,\mathrm{TeV}$. Magnetic field amplification by a factor of 10 is required in order to achieve PeV energies. Up to now, gamma-ray observations of young SNRs, as RX J1713.7-3946 and Vela Jr, indicated photons with a maximum energy of $E_\gamma \sim 30\,\mathrm{TeV}$. In the hypothesis of a hadronic origin of the radiation, where gamma rays are produced in the decay of neutral pions from the collision between accelerated protons and the circumstellar matter, protons of $E_p \simeq 300\,\mathrm{TeV}$ would be responsible for the observed photons. Thus, a clear evidence for PeV energies is still missing.

Recent observations of the Galactic Center region from H.E.S.S. [3] point towards the presence of a PeVatron in the center of our Galaxy, where a supermassive black hole (several millions of solar masses) is located. This central source is surrounded by a complex system of molecular clouds, called Central Molecular Zone, which would offer a dense proton target to accelerated protons for proton-proton (pp) interaction. In the same pp interaction producing gamma rays, also charged pions are expected to be produced, which then decay into neutrinos: multi-TeV neutrinos are hence expected from the Galactic Center region in the hadronic hypothesis, as discussed in the next section. The multi-messenger strategy is therefore well suited for the identification of CR proton acceleration sites: neutrinos indeed are a unique probe of hadronic acceleration processes acting at the source. Recently, the first evidence for PeV cosmic neutrinos [4] has opened the era to neutrino astronomy, though no sources have been yet identified in angular correlation with any of the neutrino events. The comprehension of the origin of such a signal is of primary interest, as it might be connected to the PeVatron scientific case, and it is among the goals of the incoming cubic-kilometer-scale neutrino telescope, KM3NeT.

2. – The Galactic Center in the multi-messenger era

The latest H.E.S.S. observations of the Galactic Center [3] have revealed the presence of a central source with an angular size of $R = 0.15°$, surrounded by a diffuse component extending up to $R = 0.45°$. The spectrum of photons coming from the central source is described by a power-law with a cut-off at an energy of $E_\gamma = 10.7\,\text{TeV}$. The diffuse emission spectrum is instead better described by an unbroken power, with no perceivable cut-off up to $E_\gamma \simeq 50\,\text{TeV}$. The similar magnitude of the emissions and the close angular position suggest that the two emission components are related among each other. However, the absence of a cut-off in the diffuse spectrum is puzzling. A possible explanation has been presented in [5], where a non-standard radiation field in the infrared (IR) spectral band is supposed to be present in the close vicinity of the central source, being responsible for the observed cut-off, which would then be an effect of the absorption of gamma rays due to $\gamma\gamma \to e^+e^-$ interaction. However, neutrinos would not be affected by such absorption. A realistic evaluation of the number of neutrinos expected in an instrumented volume of a cubic kilometer is also presented, considering muon neutrinos only, as in astronomical searches, given that it will be possible to attain an angular resolution of $\sim 0.1°$ in the muon event sample. Neutrino fluxes are estimated following [6], assuming that the observed radiation has a 100% hadronic origin. Different scenarios are exploited for neutrino predictions, as shown in fig. 1: i) the case of the point-like central source emission, with an intrinsic cut-off at $E_\gamma = 10.7\,\text{TeV}$, ii) the case of the same point-like source, where the intrinsic cut-off is located at $E_\gamma = 100\,\text{TeV}$ due to the non-standard IR radiation field, iii) the case of the diffuse emission with no cut-off, as detected by H.E.S.S., and iv) the case of a diffuse emission with a high-energy cut-off at $E_\gamma = 600\,\text{TeV}$ (not yet in the reach of current Imaging Atmospheric Cherenkov Telescopes). In the best case, that of the point-like source where the acceleration cut-off seen through neutrinos is located at $E_p \simeq 1\,\text{PeV}$ ($E_\gamma = 100\,\text{TeV}$), two events per year might be detected in KM3NeT-ARCA. However, since most of the signal will be below $E_\nu \simeq 100\,\text{TeV}$, where the atmospheric muon background is still a limiting factor, a data-taking period of the order of ten years is required for a significant detection.

3. – Conclusions

The lack of observational evidences connecting CRs and cosmic sources is a crucial issue that needs to be addressed. The multi-messenger paradigm might be fundamental in this respect: neutrinos are in fact very significant, as they are able to clearly probe the hadronic origin of the radiation observed from astronomical sources. The next generation of cubic kilometer neutrino telescopes will contribute to shed light on these unknowns.

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