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 astro-particle physics field. Gamma-ray observations at multi-TeV energies of Galactic sources have provided us 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, in the form of $dN/dE \propto E^{-2}$; however, PeV energies can hardly be achieved in these systems. The Hillas (or containment) criterium provides a zero-th order evaluation of the maximum attainable energy, by requiring that the particle Larmor radius is smaller than

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the source size. A young SNR, with a radius of $R \simeq 3$ pc and whose shock is moving at $v_s \simeq 3000$ Km/s in a typical magnetic field of $B \simeq 10$ μG, would produce protons with a maximum energy of $E_p \simeq 100$ 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 $E_\gamma \sim 30$ 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 $E_p \simeq 300$ 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 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 $E_\gamma = 10.7$ TeV. The diffuse emission spectrum is instead better described by an unbroken power, with no perceivable cut-off up to $E_\gamma \simeq 50$ TeV. The similar magnitude of the emissions and the close angular position make plausible the hypothesis 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 an 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 $E_\gamma = 10.7$ TeV, ii) the case of the same point-like source, where the intrinsic cut-off is located at $E_\gamma = 100$ 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 $E_\gamma = 600$ 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 $E_p \simeq 1$ PeV ($E_\gamma = 100$ TeV), two events per year might be detected in KM3NeT-ARCA. However, since most of the signal will be below $E_\nu \simeq 100$ 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.

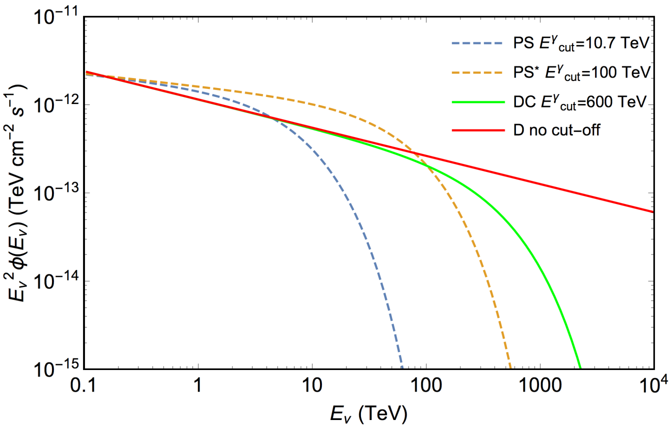

Figure 1.: Muon neutrino fluxes from the Galactic Center for different gamma-ray scenarios of the point-like source (PS) and the diffuse (D) emissions (see the text for details).

3. – Conclusions

The lack of observational evidences connecting the very-high energy protons that we observe on Earth 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 in shedding light on these unknowns.

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