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Gamma ray astronomy above 30 TeV and the IceCube results

Silvia Vernetto[1,a] and Paolo Lipari[2,b]

[1] *OATO-INAF and INFN Sezione di Torino, Torino, Italy.*
[2] *INFN, Sezione di Roma, Roma, Italy.*

Abstract. The study of the diffuse Galactic gamma ray emission is of fundamental importance to understand the properties of cosmic ray propagation in the Milky Way, and extending the measurements to $E \gtrsim 30$ TeV is of great interest. In the same energy range the IceCube detector has also recently observed a flux of astrophysical neutrinos, and it is important to test experimentally if the neutrino production is accompanied by a comparable emission of high energy photons. For $E \gtrsim 30$ TeV, the absorption effects due to e^+e^- pair production when the high energy photons interact with radiation fields present in space are not negligible and must be taken into account. Gamma rays, in good approximation, are completely absorbed if they have an extragalactic origin, but the absorption is significant also for Galactic photons. In this case the size and angular dependence of the absorption depends on the space distribution of the emission. In this work we estimate the absorption for different models of the space distribution of the gamma ray emission, and discuss the potential of future detectors.

1 Introduction

The observation of the diffuse Galactic gamma ray emission allows to study the space and energy distribution of cosmic rays (CR) in the Milky Way. This information is essential to determine the properties of Galactic CR propagation. The extension of the measurements of the diffuse emission to higher energy ($E_\gamma \approx 10$–10^3 TeV) is very important to shed light on this problem.

An additional motivation for the study of the diffuse emission at high energy comes from the recent results of the IceCube detector [1, 2] that has observed a signal of astrophysical neutrinos that emerges above the atmospheric foreground in the energy range $E_\nu \simeq 30$–2000 TeV. The IceCube signal is consistent with an isotropic flux, suggesting an extragalactic origin of the neutrinos, however it is also possible that a significant fraction of the events are generated in our Galaxy. At present, the low statistics and the large error boxes of most event directions prevent a definite conclusion.

The creation of high energy neutrinos in astrophysical sources is accompanied by a gamma ray emission with a similar spectral shape and intensity, since both neutrinos and gamma rays originate in the decay of pions produced in the hadronic interactions of relativistic protons and nuclei. The detection of an associate gamma ray flux could be of great importance for the identification of the neutrino sources.

[a] e-mail: vernetto@to.infn.it
[b] e-mail: paolo.lipari@roma1.infn.it

The new generation gamma ray telescopes, as LHAASO [3], HISCORE [4] and CTA [5], will have a much larger sensitivity at energies above 30 TeV with respect to the current instruments. Furthermore, the large field of view of the future air shower arrays, as LHAASO, will allow the measurement of diffuse fluxes, as those produced by cosmic ray interactions in the interstellar medium or originating by other processes inside our Galaxy. However, while neutrinos cross cosmological distances suffering a negligible absorption, gamma rays undergo pair production by interacting with the low energy radiation fields. The absorption is significant for photons travelling for intergalactic distances, making impossible to detect gamma rays of energy above 30 TeV unless the sources are very close to our Galaxy ($z < 0.01$). At these energy, however, the absorption is also not negligible for Galactic gamma rays, and modifies the spectrum with an absorption pattern that depends on the source spatial distribution.

In this paper we describe the effects of the absorption on a Galactic gamma ray flux, assuming different distributions of the sources, according to some models proposed in the literature on the possible origin of the IceCube neutrinos.

2 Attenuation of gamma rays

The gamma ray energy threshold for pair production is $E_\gamma^{th} = 0.52/[\epsilon(1 - cos\theta)]$ TeV where ϵ is the target photon energy in electronvolts. Since the maximum absorption occurs when $E_\gamma = 1.97\ E_\gamma^{th}$, the shape of the spectrum of the target photons produces well defined absorption features in the spectrum of gamma rays. To calculate the survival probability of gamma rays with a given energy, it necessary to know the number density, the spectrum and the angular distribution of the target photons in any point of the line connecting the source to the Sun.

The radiation field in our Galaxy is the sum of four components: two of extragalactic origin, permeating the Universe with a uniform and isotropic flux, and two originating in our Galaxy, highly anisotropic, with a larger flux from the direction of the Galactic center. The most intense extragalactic photon field is the Cosmic Microwave Background Radiation (CMBR), a pure blackbody radiation of temperature 2.725°K, that affects mostly gamma rays in the PeV range. The intensity of the CMBR is known with high accuracy, hence it is possible to evaluate precisely the relative absorption. A much weaker component is the Extragalactic Background Light (EBL), produced by the contribution of stars and dust of all galaxies during the history of the universe. The EBL absorption effects can be dramatic for gamma rays travelling in the extragalactic space, but are almost negligible in our Galaxy.

The most important Galactic component is the infrared light emitted by the dust heated by stars. The emission peaks around 0.01 eV and mostly affects gamma rays with energy of order 100 TeV. Since this is the energy most suitable to study the sources of neutrinos, an accurate evaluation of its intensity is necessary. The last component is the starlight, that peaks around 1 eV. The starlight mostly interacts with gamma rays of energy of order 1 TeV, but the absorption effect is almost negligible due to the small photon density. The flux of the radiation emitted by stars and dust have been measured locally, but a model is necessary to evaluate its spectrum and angular distribution in other locations in the Galaxy. Starting from a parametrization of the infrared radiation made by Misiriotis et al. [10] we developed a simplified Galactic emission model [7], whose results are in fair agreement with the available data, and with previous estimates [6]. Fig.1 shows the number density of photons for the four radiation components, according to the model. The infrared flux measured by COBE-FIRAS [8] and IRAS [9] are shown in the same figure. For the EBL spectrum, we used the parametrization by Franceschini et al. [11].

Our model allows the calculation of the absorption for any gamma ray trajectory in the Galaxy. As an example, the resulting gamma ray survival probability for three source positions in the Galactic

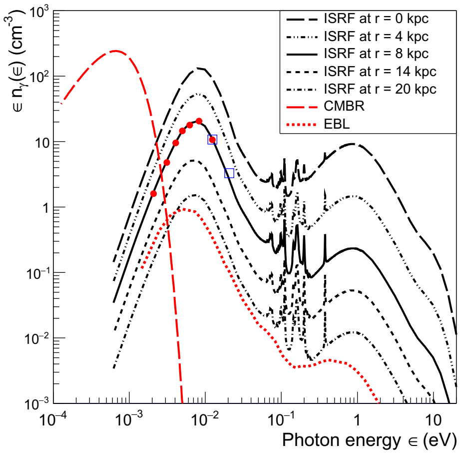

Figure 1. Photon number density (times energy) for the CMBR, the EBL and the Interstellar Radiation field (ISRF, i.e. the sum of star and dust emission). The ISRF is given for points on the Galactic plane at different distances from the Galactic center. Red dots (blue squares) indicate the COBE-FIRAS (IRAS) data.

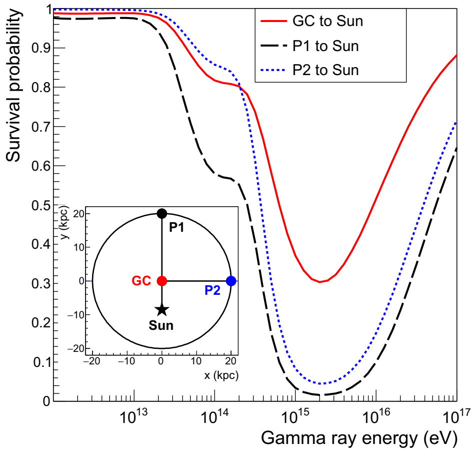

Figure 2. Survival probability of gamma rays for three different trajectories in the Galactic plane, as a function of the gamma ray energy. The inset shows a top view of the three sources positions in the Galaxy.

plane are shown in Fig.2. Up to ~20 TeV the flux attenuation is less than a few percent for every source position. Above ~20-30 TeV the absorption increases due to the interaction with the infrared radiation and reaches its maximum at ~150 TeV. Above ~200 TeV the CMBR becomes the major source of absorption, and practically only depends on the source distance. From these results one can conclude that the absorption is not a severe obstacle to measurements up to ~200-300 TeV, while at PeV energies the fluxes can be seriously affected when the source distance is larger than a few kiloparsecs.

3 Diffuse Galactic gamma ray flux

Cosmic rays confined in the Galaxy by magnetic fields generate gamma rays and neutrinos when they interact with the gas and radiation fields present in interstellar space. The gamma ray emission generates a diffuse Galactic flux that, in the region from 0.1 to 100 GeV, has been accurately measured over the entire sky by the FERMI telescope [12]. The dominant contribution to the diffuse flux is the production and decay of neutral pions in the interactions of protons and nuclei. Additional contributions are generated by Inverse Compton scattering and bremsstrahlung of CR electrons. The spectrum of the diffuse gamma rays measured by FERMI for $E_\gamma \gtrsim 10$ GeV has in good approximation a power law form with a spectral index of order $\alpha \simeq 2.65 \pm 0.05$ that reflects the shape of the spectra of CR protons and nuclei in interstellar space. The diffuse flux is is concentrated in a narrow region in Galactic latitude around the equator (approximately 50% of the emission is contained in the region $|b| \lesssim 5.6°$). The flux is also larger towards the Galactic center, with the flux from the direction of the center approximately four times larger than the flux from the anticenter.

Measurements of the diffuse Galactic gamma ray flux at TeV energies for some limited angular region of the Galactic disk have been obtained by the air shower arrays ARGO-YBJ [13] and Milagro [14, 15]. These measurements are consistent with a smooth extrapolation of the FERMI observations. No detection exist above 30 TeV, where the best upper limits have been obtained by the CASA-MIA air shower array in the energy rage 0.14–3 PeV [16]. The measurements and upper limits of the Galactic diffuse emission are shown in Fig. 3.

To extrapolate the FERMI observations to higher energy we have made the following assumptions: (i) π° decay is the dominant mechanism of the emission; and (ii) the spectral shapes of CR protons and nuclei in different points of the Galaxy are approximately equal to what is observed at the Earth. From these assumptions one can deduce that the energy and angular distribution of the diffuse Galactic flux calculated at the position of the Sun *neglecting absorption* factorize into an angle independent spectral shape, and an energy independent angular distribution (approximately equal to the one observed at $E_\gamma \simeq 10$ GeV). The predicted energy distribution of the emission reflects the spectral shape of the interacting CR and therefore follows the power law behaviour measured at $E_\gamma \simeq 10$ GeV, with a softening at 100 TeV due to the presence of the "knee" in CR spectra. The effects of the knee have been calculated numerically using a simple model of π° production in hadronic interactions and the model of the CR spectra given in [17].

To calculate the effects of gamma ray absorption one needs to estimate the space distribution of the Galactic diffuse emission rate. With the assumptions discussed above the emission rate has an energy independent form and is proportional to the product of the density of CR and of gas in the Galaxy: $q(\vec{r}) \propto n_{\rm ism}(\vec{x}) \times n_{\rm CR}(\vec{x})$. The form of this distribution can be estimated from the angular distribution of the diffuse flux when absorption is negligible. The main features of the diffuse flux angular distribution can be reasonably well reproduced with a simple axysimmetric, exponential form for the source density $q(r, z) \propto \exp(-r/r_0 - z/z_0)$ with r and z cylindrical coordinates. The parameters r_0 and z_0 can be estimated by fitting the observed angular distribution of the diffuse emission for $E_\gamma \simeq 10$ GeV with the result $r_0 \simeq 3.9$ kpc and $z_0 \simeq 0.27$ kpc.

It is now straightforward to compute the angular and energy distribution of the observable flux by summing the contributions of all points in the Galaxy, taking into account the absorption for each trajectory. The result is shown in Fig. 3, where the expected spectrum in the same galactic plane region explored by ARGO-YBJ is represented by a shaded band. The band width is determined by the uncertainties of the Fermi spectrum slope and normalization. It is interesting to note that at energies above 100 TeV the estimated spectrum is just below the CASA-MIA upper limits.

Future detectors have the potential to observe the extrapolation of the diffuse Galactic spectrum discussed above. Among the current projects, LHAASO has the highest sensitivity at ~100 TeV. A rough evaluation of its sensitivity to a diffuse flux can be obtained by multiplying the LHAASO point source sensitivity given in [18] by the factor $f_c = (\Omega_{PSF}\Omega_{GP})^{-1/2}$, where Ω_{PSF} is the solid angle of the observational window used for point sources and Ω_{GP} in the solid angle of the Galactic plane region to be studied. According to this calculation the minimum flux detectable at 5 sigma by LHAASO in one year at 100 TeV in the same region observed by ARGO-YBJ is F_{min} ~7×10^{-16} photons cm^{-2} s^{-1} TeV^{-1} sr^{-1}, a factor five smaller than the CASA-MIA upper limits at a median energy of 140 TeV, and below the expected flux produced by cosmic ray interactions in the same energy region.

4 The IceCube neutrinos and the Galactic gamma ray flux

The IceCube collaboration finds that the excess of neutrino events is consistent with an isotropic flux generated by the ensemble of all extragalactic sources. In this case the associated gamma ray emission is in good approximation entirely absorbed during propagation and is not observable. On

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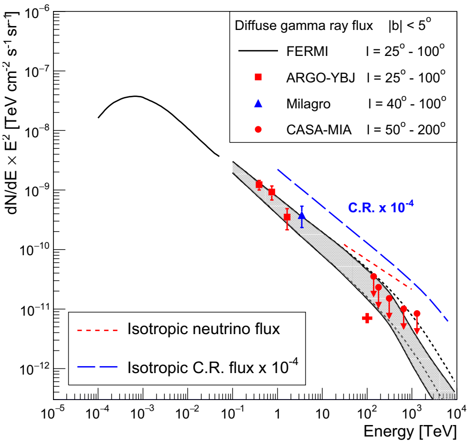

Figure 3. Galactic gamma ray diffuse flux measurements by different experiments. The shaded band shows the predicted flux in the energy range 100 GeV–1 PeV for the angular region of the ARGO-YBJ measurements. The dotted lines delimit the unabsorbed spectrum. The expected LHAASO sensitivity is indicated by a cross. The CR spectrum (rescaled by a factor 10^{-4}) and the isotropic neutrino flux are also shown.

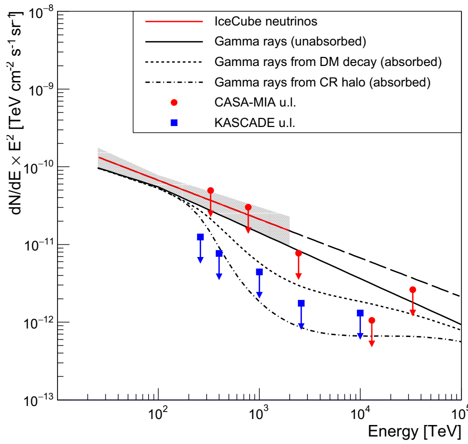

Figure 4. Effect of absorption on gamma rays emitted with a spatial distribution according to the DM model and the extended halo model. The shaded band indicates the IceCube neutrino spectrum with one sigma error. The arrows represent the 90% C.L. upper limits for the isotropic gamma ray flux measured by CASA-MIA and KASCADE.

the other hand several authors have discussed the possibility that all (or a not negligible fraction of) the astrophysical neutrinos are of Galactic origin. In this case the gamma rays associated to the neutrino emission are only partially absorbed and these Galactic models can be tested experimentally with gamma ray observations. In fact the existing limits of the diffuse gamma ray fluxes discussed above are already significant constraints. These studies require a detailed calculation of the absorption effects that can significantly reduce the observable gamma ray fluxes.

Two models that discuss an entirely Galactic origin for the IceCube neutrino signal are those of Esmaili and Serpico [19], and of Taylor, Gabici and Aharonian [20]. Esmaili and Serpico consider a model where the high energy neutrinos are generated in the decay of a very massive, unstable Dark Matter (DM) particle. In this case the space distribution of the emission corresponds to the mass density of the Galactic DM, and can be modeled with the (spherically symmetric) Navarro-Frenk-White [21] form $\rho_{DM}(r) = \rho_0/(r/r_c(1 + r/r_c)^2)$ with $r_c \simeq 20$ kpc. Taylor, Gabici and Aharonian hypothesize that neutrinos are produced by cosmic rays interacting in a large halo of gas extending at distances of order 100 kpc (in the following we will describe this halo as a simple Gaussian function $\rho(r) \propto \exp(-r^2/2r_0^2)$ with $r_0 = 57$ kpc, so that $\sqrt{\langle r^2 \rangle} = 100$ kpc). In both cases the associated gamma ray flux is not limited to the Galactic plane. Crossing regions with a lower infrared radiation, gamma rays of ~100 TeV suffer a smaller absorption than travelling inside the disk. On the other hand the average larger source distance increases the CMBR absorption in the PeV energy range.

Fig.4 shows the absorption effects (averaged over all solid angle) calculated for the two models discussed above. The unabsorbed gamma ray flux has been assumed equal to the lower limit of the neutrino spectrum. Note that in the case of the DM model the relation between the ν and γ emission depends of the branching ratios into different decay channels, and therefore on the assumed properties of the DM particle. The figure also shows the existing upper limits on the isotropic flux obtained by KASCADE [22] and CASA-MIA [23].

The KASCADE upper limits (only published on conference proceedings) are in tension with the DM model. It has to be noted however that both sets of upper limits has been obtained with observations from the northern hemisphere. Since the Sun has an offset of ~8 kpc from the Galactic center, a halo distribution will produce an anisotropic flux, higher from the direction of the Galactic center, that is not visible from the locations of KASCADE and CASA-MIA. Since the absorption too will be larger for gamma rays from the direction of the Galactic center, the anisotropy will be in some measure reduced. All these effects must be accurately taken into account to make a correct comparison between models and data.

Since the cosmic ray flux, the major background source for gamma ray observations, is about a factor 10^4 larger than the neutrino flux (see Fig.3), a background rejection better than 10^{-4} is necessary for future air shower arrays to detect the possible gamma ray flux associated to the IceCube neutrinos. Observation made from locations in both hemispheres will be advantageus, allowing the study of the global signal anisotropy, a fundamental ingredient to investigate the spatial distribution and the nature of the neutrino sources.

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