Astroparticle Physics 72 (2016) 32–37

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

Neutrinos from extra-large Hadron Collider in the Milky Way

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ARTICLE INFO

Article history:
Received 4 June 2015
Revised 23 June 2015
Accepted 24 June 2015
Available online 30 June 2015

Keywords:
multi-messenger astronomy
cosmic ray physics
gamma-ray astronomy
neutrino astronomy

ABSTRACT

Neutrino telescope IceCube has recently discovered astrophysical neutrinos with energies in the TeV–PeV range. We use the data of Fermi γ-ray telescope to demonstrate that the neutrino signal has significant contribution from the Milky Way Galaxy. Matching the γ-ray and neutrino spectra we find that TeV–PeV Galactic cosmic rays form a powerlaw spectrum with the slope $p \simeq 2.45$. This spectral slope is consistent with the average cosmic ray spectrum in the disks of the Milky Way and Large Magellanic Cloud galaxies. It is also consistent with the theoretical model of cosmic ray injection by diffusive shock acceleration followed by escape through the Galactic magnetic field with Kolmogorov turbulence. The locally observed TeV–PeV cosmic ray proton spectrum is softer than the average Galactic cosmic ray spectrum. This could be readily explained by variability of injection of cosmic rays in the local interstellar medium over the past 10^7 year and discreetness of the cosmic ray source distribution.

1. Introduction

Our knowledge of the properties of cosmic rays produced by the star formation in the Milky Way Galaxy is both precise and largely incomplete. It is precise because the details of the cosmic ray spectrum and elemental composition are measured with high precision [45]. And it is incomplete because all the precision measurements refer to only single location within the Galaxy: the position of the Solar system. It is even not obvious what kind of information is contained in such single point measurements. Deflections of cosmic rays by turbulent component of Galactic magnetic field forces them into a random walk through the interstellar medium (ISM) [15]. As a result, cosmic rays arrive from random directions on the sky. It is clear that some information on the sources is encoded in the cosmic ray spectrum, mass composition and global anisotropy [45]. However, it is not clear how the spectral slope p and the break energies of the locally measured piecewise powerlaw cosmic ray spectrum $dN/dE \propto E^{-p}$ are related to the properties of source population(s) and their distribution in the Galaxy. The diffusion through the ISM and escape from the Galactic Disk modify the cosmic ray spectrum, in a model-dependent way. The locally measured properties of the spectrum are not necessarily representative for those of the global distribution of Galactic cosmic rays. Instead, they could be determined by the peculiarities of recent injection of particles in the local ISM [10,23,32,42,46–48,50,52].

An illustration of these uncertainties is found in the model of modification of the cosmic ray spectrum by the propagation effects encoded in an energy-dependent diffusion coefficient $D(E) \sim E^{\delta}$ [15]. The slope of the interstellar cosmic ray spectrum is determined by δ and by the slope p_s of the injection spectrum, $p = p_s + \delta$. The most commonly considered acceleration mechanism is diffusive shock acceleration (DSA) [14,35,36], which is expected to give a slope $p_s \simeq 2.0...2.2$. Comparison with the slope of the locally measured cosmic ray spectrum, $p \simeq 2.7$, points to a value of $\delta \simeq 0.5...0.7$. This is, however, in tension with the measurements of the ratio of abundances of primary and secondary nuclei which give $\delta \simeq 1/3$ [44] and with the measurements of anisotropy of the cosmic ray flux [17]. The value $\delta = 1/3$ is also favoured by theoretical models of cosmic ray diffusion through the ISM [15].

Recent data on cosmic ray positrons and antiprotons and also the slope and anisotropy properties of the cosmic ray nuclei spectra suggest that the TeV range cosmic ray spectrum has a strong contribution a supernova which exploded approximately two million years ago within several hundred parsec distance from the Sun [32,48]. The data on deposition of isotopes in the deep ocean crust provide information on the occurrence of such nearby supernova events [24] indicate that only one such nearby supernova event has occurred over last 14 million years [20,22]. The slope of the locally observed cosmic ray spectrum in the TeV range might be largely determined by this recent supernova event. The information on the "characteristic" slope of the Galactic cosmic ray spectrum is completely erased by this last supernova contribution.

Complementary information on the cosmic ray source and propagation parameters is provided by secondary γ-rays and neutrinos.

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http://dx.doi.org/10.1016/j.astropartphys.2015.06.004
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Contrary to the charged cosmic rays, neutral γ-rays and neutrinos go straight from their production sites to the Earth. γ-ray and neutrino signal from individual sources could provide information on the injection spectrum of cosmic rays, while diffuse γ-ray and neutrino emission from the ISM could provide the data on the propagation of cosmic rays in the Galaxy.

Analysis of the γ-ray signal from the Galactic Plane of the Milky Way Galaxy and from the disk of the Large Magellanic Cloud (LMC) Galaxy suggest that the average slope of the cosmic ray spectra produced by the star formation in these two galaxies is $p \simeq 2.45$, i.e. harder than that of the locally measured cosmic ray spectrum [21,40]. The slope of the neutral pion decay γ-ray spectrum produced by the interactions of cosmic rays with such hard slope is about $p_\gamma \simeq 2.4$.

This slope is close to that of the slope of the spectrum of the isotropic diffuse γ-ray background (IGRB)[2,18]. This suggests that significant part of the IGRB might originate from the cosmic ray interactions in the star forming galaxies [8,37,38] which are not individually resolved by the Fermi Large Area Telescope (LAT). The normalisation of neutrino and γ-ray flux in the GeV energy range is fixed by the known relation between the far infrared and γ-ray luminosity of galaxies, $L_\gamma \simeq 10^{-4} L_{FIR}$ [8], and by the known level of extragalactic far infrared background, $F_{FIR} \sim 10^{-5}$ erg/(cm^2 s sr) [29]. The most recent calculation of the γ-ray and neutrino flux from star forming galaxies which takes into account this relation along with the details of cosmological evolution of different types of galaxies [37,38] shows that they provide a significant contribution to the IGRB.

An independent verification of the result on the hard $p \simeq 2.45$ average cosmic ray spectrum resulting from the star formation in the Milky Way and other Galaxies could be obtained through the neutrino channel. The slope of the spectrum of neutrino emission from the Milky Way and other star forming galaxies is expected be about $p_\nu \simeq 2.4$, close to the slope of the γ-ray spectrum.

The IceCube collaboration has recently reported the detection of astrophysical neutrino signal in the energy range from 10 TeV to 2 PeV [3,5,6,30]. The signal forms a powerlaw spectrum $dN_\nu/dE \propto [E/100\ \mathrm{TeV}]^{-p_\nu}$, with $p_\nu = 2.46 \pm 0.12$ [6].

This slope and normalisation of the neutrino spectrum are obviously inconsistent with the possibility that the observed neutrino flux is produced by cosmic rays in the Milky Way and/or other star forming galaxies, if one assumes that the typical spectrum of the cosmic rays resulting from the star formation is about the locally observed cosmic ray spectrum slope, $p \simeq 2.7$, and it has a knee feature exactly at the same energy as the knee of the locally measured cosmic ray spectrum [31], an assumption was explicitly adopted in most of the previous calculations of the Galactic neutrino flux [16,39,43,49,51]. Different assumptions about the average Galactic cosmic ray slope result in the estimates of the Galactic contribution to the astrophysical neutrino flux which differ by orders of magnitude (see e.g. [1] for an example of calculation assuming $p = 2.58$). However, none of the assumptions about the slope and position of the knee of the Galactic cosmic ray spectrum relying on local measurements is justified.

The measured slope of the astrophysical neutrino spectrum is consistent with the neutral pion decay γ-ray spectrum of the Milky Way and LMC disks [21,40], as expected if the typical slope of the cosmic ray spectrum resulting from the star formation is $p \lesssim 2.5$ rather than $p \simeq 2.7$. Below we show that not only the slope, but also the normalisation of the neutrino flux is consistent with this hypothesis. We argue that this suggests the validity of a simple model in which the injection of cosmic rays with the spectrum with the slope suggested by the DSA, $p_{inj} \simeq 2...2.2$ is followed by the softening by $\delta = 1/3...1/2$ produced by the escape through the turbulent Galactic magnetic fields with Kolmogorov or Iroshnikov–Kraichnan turbulence spectrum. This simple model is valid for the spectrum of cosmic rays averaged over sufficiently large regions of galaxies. It is, however, not valid for the single point measurements of the cosmic ray spectrum, such as the measurements at the position of the Solar system in the Milky Way.

2. γ-ray and neutrino data analysis

Our analysis uses all publicly available Fermi/Large Area Telescope (LAT) data [12] collected over the period from August 2008 till June 2014. We have processed the data using the *Fermi Science Tools v9r32p5*[1]—a standard software package, provided by the Fermi collaboration to reduce the data, obtained by the Fermi/LAT. We have used the Pass 7 “reprocessed” event selection.

We have filtered the event lists using the *gtselect* tool with parameter `evclass=3`, which leaves the γ-ray events and rejects most of the cosmic ray background events. To produce the all-sky spectrum shown in Fig. 2, we have used the aperture photometry method[2], applied to the full sky. An estimate of the exposure in each energy bin was done using the *gtexposure* tool with the option `apcorr=no` (there is no need to correct the exposure for the point spread function for the full sky). To separate the diffuse emission from the point source contributions we subtract the flux in the circles of the radius 0.5° around point sources from the four-year Fermi catalogue [19]. This is sufficient for the analysis of the diffuse emission in the energy band above 10 GeV. In this energy band the point spread function of the LAT is smaller than ~0.3° [12].

We have verified that the aperture photometry approach gives the result which is consistent with the results obtained using the likelihood analysis. In particular, the spectrum of the $|b| > 20°$ part of the sky, calculated using the aperture photometry method is identical to that reported by the Fermi collaboration [18] over the entire energy range from 100 MeV up to 1 TeV.

To produce the Galactic latitude profiles for the neutrino data, we have binned the neutrino events reported by Aartsen et al. [5] in Galactic latitude and have estimated the IceCube exposure in each Galactic latitude bin. This was done via a Monte-Carlo simulation of the Galactic latitude distribution of neutrino events driven from an isotropic sky distribution, with account of the declination dependence of the IceCube effective area, derived from the information reported by Aartsen et al. [5]. Having estimated the exposure in each Galactic latitude bin, we have multiplied the model fluxes of the Galactic and isotropic components by the Galactic latitude dependent exposure to estimate the expected number of neutrino counts in each latitude bin.

3. γ-ray and neutrino all-sky spectrum

Fig. 1 shows the combined γ-ray and neutrino all-sky spectrum in a broad GeV–PeV energy range. The statistical errors of the γ-ray signal are small in all energy bins up to ~300 GeV. The uncertainty of the γ-ray flux measurement is dominated by the systematic errors [9]. The IceCube neutrino spectrum is derived from the analysis of [6]. The dark grey shaded band shows the 68% uncertainty of the flux and slope of the neutrino signal.

From Fig. 1 one could see that the neutrino spectrum lies at the high-energy extrapolation of the γ-ray spectrum of the entire sky. Thus, not only the slopes, but also the normalisation of the two spectra agree with each other. The uncertainty of the neutrino flux at 100 TeV is just by a factor of ≃2. Assuming a negligible uncertainty of the γ-ray flux at ≃30 GeV, one could find that a powerlaw fit to the combined γ-ray plus neutrino spectrum gives a very precise measurement of the slope of the powerlaw, $p_{\nu\gamma} = 2.37 \pm 0.05$, with an error $\Delta p_{\gamma\nu} = \log(2)/[2\log(100\ \mathrm{TeV}/100\ \mathrm{GeV})] \simeq 0.05$. This is due to a very large dynamic range of the energy on which the powerlaw is

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[1] http://fermi.gsfc.nasa.gov/ssc/data/analysis/

[2] http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/aperture_photometry.html