Fluxes of diffuse gamma rays and neutrinos from cosmic-ray interactions with circumgalactic gas

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Abstract

The Milky Way is surrounded by a gravitationally bound gas corona extending up to the Galaxy’s virial radius. Interactions of cosmic-ray particles with this gas give rise to energetic secondary gamma rays and neutrinos. We present a quantitative analysis of the neutrino and gamma-ray fluxes from the corona of the Milky Way together with a combined contribution of coronae of other galaxies. The high-energy neutrino flux is insufficient to explain the IceCube results, while the contribution to the FERMI-LAT diffuse gamma-ray flux is not negligible.

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I. INTRODUCTION

The origin of recently discovered high-energy astrophysical neutrinos [1–4] is not obvious. The flux of the neutrinos is quite large: they were observed already in two-year IceCube data. The global distribution of arrival directions of the events is consistent with isotropy, as expected for their extragalactic origin, but the observed spectrum is a bit soft for powerful extragalactic sources. Moreover, if the neutrinos are born in $\pi^{\pm}$-meson decays, which is the most natural astrophysical scenario, the accompanying flux of gamma rays from $\pi^{0}$ decays overshoots the observed isotropic diffuse photon flux measured by FERMI LAT [5] below 820 GeV unless a significant part of the neutrinos are of the Galactic origin. This is because of electromagnetic cascades [6, 7] which transfer the energy of gamma rays from multi-TeV to sub-TeV bands by means of efficient $e^{+}e^{-}$-pair production on the background radiation and subsequent inverse Compton scattering. To overcome these troubles, models with several components of the neutrino flux of completely different origin, e.g. from cosmic-ray interactions with the interstellar matter and from distant blazars, are discussed. In these explanations, two very different classes of sources give roughly equal contributions to the observed neutrino flux by coincidence. Another option is to consider optically thick sources which emit neutrinos but totally absorb photons.

An interesting proposal to explain the IceCube observation has been put forward in Ref. [8], where the interactions of cosmic-ray protons escaping the Galaxy with the circumgalactic gas result in the required diffuse neutrino flux. Note that a similar mechanism has been proposed in Ref. [9] to contribute a significant amount to the diffuse gamma-ray background at energies $\sim$GeV. The energy fluxes carried by diffuse GeV photons and IceCube sub-PeV neutrinos are of the same order, and one may hope that they might have a common origin.

In this paper, we calculate the corresponding neutrino and gamma-ray fluxes, account for propagation of photons and compare the resulting fluxes at the Earth with the observational data obtained by IceCube and FERMI-LAT. We demonstrate that the flux of secondary neutrinos from cosmic-ray interactions with the circumgalactic gas is insufficient to explain IceCube astrophysical neutrino events, if realistic density of cosmic rays escaping the Galaxy, normalized to the present-day cosmic-ray spectrum in the disk, is assumed. At the same time, secondary photons from the same interactions contribute substantially to the diffuse
gamma-ray background at FERMI-LAT energies.

The rest of the paper is organized as follows. In Sec. II, we briefly discuss observational data about the Milky-Way circumgalactic gas and fix the gas density profile to be used in our calculations. In Sec. III, we determine the density and the spectrum of cosmic rays escaping from the Galaxy and describe their interactions with the gas. Section IV addresses the contribution of similar processes taking place in other galaxies throughout the Universe. The results of our calculations are formulated and discussed in Sec. V.

II. THE MILKY WAY’S CORONA

Recent observations suggest that our Galaxy is surrounded by a huge (extending to \( \sim 250 \) kpc from the Galactic center) halo of gas which we call here the Milky Way’s corona in order to clearly distinguish it from the halo of stars whose size is approximately ten times smaller. Cosmic rays escaping from the Galaxy interact with this gas; these interactions have been considered as the source of (a part of) the cosmic diffuse gamma-ray background \[9\]. Order-of-magnitude estimates in Ref. \[8\] suggested that the very same interactions may produce a significant part of the high-energy neutrino flux observed by IceCube. The aim of the present paper is to calculate the corresponding neutrino and gamma-ray fluxes in a more precise way.

There are two classes of observational results pointing to the existence of the Milky-Way gaseous corona:

- OVII and OVIII absorption X-ray lines observed at zero redshift in the spectra of extragalactic sources and corresponding emission lines observed in the blank-sky spectrum, see e.g. Refs. \[10\]–\[12\];
- evidence for the ram-pressure stripping of MW satellite galaxies, see e.g. Refs. \[13\]–\[16\].

X-ray spectroscopic observations are more precise statistically but have large systematic uncertainties because the oxygen is only a tracer of much more abundant hydrogen and other gases. Derivation of the total gas density from these results depends crucially on the assumptions about the metallicity \( Z \) of the circumgalactic gas and of the fraction \( f \) of the particular observed oxygen ion. The most precise studies \[12\] assume \( f = 0.5 \) and \( Z = 0.3Z_\odot \), where \( Z_\odot \) is the solar metallicity. These values are quite arbitrary; moreover, they are assumed
to be constant all the way up to the virial radius, while qualitative arguments suggest that $Z$ should decrease with the galactocentric distance $r$. In addition, recent simulations and ultraviolet OVI observations suggest that the hot gas is accompanied by a similar amount of cold and/or warm component, so that X-ray observations may underestimate the total amount of matter by a factor of two. Therefore, both the normalization and the radial dependence of the gas density inferred from the X-ray spectroscopy remain largely uncertain. Contrary, estimates of the gas density from ram-pressure stripping of MW satellites are considerably less precise, but at the same time less model-dependent.

In Ref. [19], the two classes of observations are combined to constrain the density and metallicity of the corona gas simultaneously. There, the best-fit gas density profile and the 68% confidence-level region of its parameters were determined in the frameworks of the commonly used “beta profile” for the electron density,

$$n_e(r) = n_0 \left(1 + \left(r/r_c\right)^2\right)^{-3\beta/2}, \quad (1)$$

where $r$ is the distance to the Galactic center and $n_0$, $r_c$ and $\beta$ are parameters. The value of $r_c \lesssim 5$ kpc can hardly be constrained presently but does not affect the density in the outer Galaxy (we use $r_c = 3$ kpc in our numerical calculations). At large distances $r$, the profile reduces to a simple power-law falloff, $n_e \approx n_0 r_c^{3\beta} r^{-3\beta}$. As it is stated in Ref. [19], however, these observational constraints are related to $r \gtrsim 45$ kpc, while the gas profile at smaller radial distances is poorly constrained. Given the lack of observational constraints for the inner region of the corona (which, however, is still outside the stellar halo!), we invoke the results of computer simulations to describe the gas density profile there. To be specific, we note that the simulated profile of Ref. [9] is well approximated, at $r \lesssim 45$ kpc, by the same Eq. (1) with

$$\beta = 0.843, \quad n_0 = 0.738 \text{ cm}^{-3}. \quad (2)$$

In our calculations, we use, for the gas density profile, the maximum of two beta profiles, Eq. (1), one giving the fit to the simulated profile of Ref. [9], with parameters (2), and another with

$$\beta = 0.195, \quad n_0 = 0.00153 \text{ cm}^{-3}, \quad (3)$$

determined as the best-fit profile in Ref. [19]. Following Ref. [13], we assume that the gas density is cut at $R_{\text{max}} = 250$ kpc. The resulting $n_e(r)$ is presented in Fig. One can see that, indeed, the change between the two regimes takes place at $r \sim 45$ kpc.
FIG. 1. The circumgalactic gas density profile. Dashed: approximation of the simulated profile of Ref. [9] valid at $r \lesssim 45$ kpc. Dotted: the best-fit profile of Ref. [19] valid at $r \gtrsim 45$ kpc. Full line: the profile used in this work.

III. COSMIC RAYS AND THEIR INTERACTIONS

Much less is known about the cosmic-ray densities and spectra in the Galactic corona. As described in detail in Ref. [9], this region contains all cosmic-ray particles of relevant energies which escaped from the Galactic disk throughout the Milky-Way lifetime. The propagation of particles is determined by the diffusion coefficient $D$ which depends in turn on the particle energy and location. The cosmic-ray escape from the disk is non-spherical [20, 21], but for purposes of the present work we assume spherical symmetry; the contribution of the very same physical processes in the strongly asymmetric inner part, including the Galactic disk, have been studied elsewhere [22, 24].

We will further consider the proton component of cosmic rays. Within the approximation
of spherical symmetry, the diffusion equation for protons in the corona reads as
\[
\frac{\partial j}{\partial t}(E, r) = D(E, r) \Delta j - c \sigma_{pp}(E) n_{cr}(r) j(E, r) + Q(E, r, t),
\]
where \( E \) is the cosmic-ray energy, \( r \) is distance from Milky Way center, \( j = dn_{\text{CR}}/dE \) is the cosmic-ray spectral density, \( D \) is the diffusion coefficient (we disregard its dependence on \( r \) and assume the Kolmogorov turbulence regime \( D(E) = D_0(E/\text{GeV})^{1/3} \)), \( t \) is time, \( \Delta \) denotes the radial part of the three-dimensional Laplace operator, \( \sigma_{pp} \) is p-p interaction cross section, \( c \) is the speed of light and \( Q \) is the source term. We solve Eq. (4) numerically to obtain the cosmic-ray concentration and spectrum for two marginal values of the diffusion coefficient, \( D_0 = 1.2 \times 10^{29} \text{ cm}^2/\text{s} \) and \( D_0 = 4 \times 10^{30} \text{ cm}^2/\text{s} \), used in Ref. [9]. We assume the time-dependent source term, constant within \( r \leq r_Q = 5 \text{ kpc} \) and zero at \( r > r_Q \), having power-law energy dependence with exponential cut-off. For the source evolution, we use the same expression as in Ref. [9], so
\[
Q(E, r, t) \propto E^{-\alpha} \exp \left( -\frac{E}{E_{\text{max}}} \right) \Theta(r_Q - r) \times \left\{ \begin{array}{ll}
1 + t/(1 \text{ Gyr}) & \text{if } t \leq 2 \text{ Gyr}, \\
3 & \text{if } 2 \text{ Gyr} < t \leq 6 \text{ Gyr}, \\
3 - 0.5(t - 6 \text{ Gyr}) & \text{if } 6 \text{ Gyr} < t \leq 10 \text{ Gyr},
\end{array} \right.
\]
where \( \Theta \) is the step function.

The normalization of the source term is chosen in such a way that the cosmic-ray flux at the solar location, \( r \approx 8.5 \text{ kpc} \), does not exceed the observed one at all energies. We choose \( \alpha = 2.4 \) and \( E_{\text{max}} = 10^{17} \text{ eV} \) as our working model because this saturates the observed spectrum (which is softer by 1/3 because of the Kolmogorov diffusion).

We comment briefly on other options in Sec. [V]

Figures 2, 3 present the resulting cosmic-ray density in the corona obtained from the solution of Eq. (4). These numerical results are in a good agreement with general expectations. The cosmic-ray density in the corona should fall off like \( 1/r^A \), where \( 1 \leq A \leq 2 \) (the value \( A = 2 \) corresponds to the free escape with \( D = \infty \) while \( A = 1 \) corresponds to a constant \( D \)). The spectrum of cosmic rays is harder, compared to the injected one, with the difference of power-law spectral indices of 1/3, assuming the Kolmogorov turbulence.

To calculate the fluxes of photons and neutrino we use the open-source numerical code [25] for solving transport equations in one dimension. The code [25] has been extended to
FIG. 2. The radial dependence of the cosmic-ray density, \( n(r) \), in the Galactic corona, obtained as a solution to the diffusion equation, Eq. (4), for two values of the diffusion coefficient \( D_0 \) and for proton energy \( E = 0.1 \) PeV.

include \( pp \) interactions as follows: The inelastic cross sections \( \sigma_{\text{inel}} \) of CR nuclei on gas were calculated with QGSJET-II-04. For the spectrum of secondary photons and neutrinos produced in \( pp \) interactions, differential cross sections tabulated from QGSJET-II-04 were used.

The Milky-Way corona contribution is direction-dependent because of the non-central position of the Sun in the Galaxy. We calculate the flux from each direction by solving the transport equation for propagation along the corresponding straight line with the source term proportional to \( n_g(r)n_p(r) \),

\[
Q_i(E_i, r) = n_g(r) \int dE_p n_p(E_p, r) \frac{d\sigma_{pp}}{dE_i}(E_p), \ i = \nu, \gamma.
\]

We include the \( e^+e^- \) pair production term to the transport equation to take into account that \( \gamma \)-rays with \( E \gtrsim 100 \) TeV are subjected to attenuation on CMB photons. Note that their interaction with infra-red background is negligible on the scales of hundreds of kpc.
FIG. 3. The energy spectrum of the cosmic-ray density, $n(E)$, in the Galactic corona, obtained as a solution to the diffusion equation, Eq. (4), at various galactocentric distances $r$. The diffusion coefficient $D_0 = 1.2 \times 10^{29}$ cm$^2$/s.

IV. CONTRIBUTION OF OTHER GALAXIES

It has been pointed out in Ref. [9] that the contribution of coronae of other galaxies to the diffuse gamma-ray background is comparable to that of our own Galaxy. Here we assume that properties of galactic coronae throughout the Universe are similar and estimate their contribution to the observed gamma-ray and neutrino fluxes. The total amount of cosmic rays in coronae is determined by the evolution of galaxies. Indeed, circumgalactic gas structures similar to the Milky Way have been recently found in other galaxies, see e.g. Refs. [28, 29]. Assuming that all cosmic rays, which had been produced in a galaxy and subsequently escaped from it, are now contained within its virial radius (this is true [9] for the Milky Way) and that the cosmic rays are accelerated in some stellar processes, related e.g. to supernova explosions, one concludes that the amount of cosmic rays is proportional
to the total stellar mass in a galaxy. Note that the amount of cosmic rays in a disk is often
assumed to be proportional to the star formation rate which is the time derivative of the
total mass. This is because cosmic-ray particles do not stay in a disk for long.

Therefore, to calculate the photon, \( \gamma \), and neutrino, \( \nu \), fluxes from coronae of remote
galaxies, we solve the transport equations with the source term proportional to the total
stellar mass density \( \rho^*(z) \) at the redshift \( z \),

\[
Q_i(E_i, z) \propto \rho^*(z) \frac{d\sigma_{pp}}{dE_i}(E_p), \quad i = \nu, \gamma,
\]

and include extra term for \( \gamma \) interactions with extragalactic background light (EBL) into
the transport equation. For the EBL, we employ the baseline model of Ref. [30].

We use the redshift-dependent total stellar mass function of galaxies \( \rho^*(z) \) given in
Ref. [31] to parametrise the relative normalization of injected cosmic-ray fluxes as a function
of redshift. All of the contributions are summed up (for photons, with the account of ab-
sorption) and, knowing the total stellar mass of the Milky Way (see e.g. Ref. [32]), we relate
the overall normalization of the extragalactic contribution to the flux from the Milky-Way
corona as follows.

To obtain the relative extragalactic contribution, we use the fact that the \( pp \) cross section
\( \sigma \) and the average number \( \kappa \) of neutrinos produced in a single \( pp \) interaction moderately
depend on the cosmic-ray proton energy \( E_p \) for sufficiently high \( E_p \gtrsim \) TeV. For this reason,
the secondary neutrino spectrum roughly follows the cosmic-ray proton spectrum for which
we assumed the power-law dependence. Therefore, we omit the energy dependence in the
following equations.

Since the amount of cosmic rays in a galactic corona scales with the total stellar mass of
the galaxy \( M^* \), one may write, for the cosmic-ray density,

\[
n_{\text{CR}}(r) = \frac{M^*}{M^*_{\text{MW}}} \bar{n}_{\text{CR}}(r),
\]

where the function \( \bar{n}_{\text{CR}}(r) \) is universal. The Milky-Way contribution to the neutrino flux
from the Galactic anticenter direction is then

\[
j_{\text{MW}} = \frac{c}{4\pi} \kappa \sigma \int_{R_{\odot}}^{R_{\text{max}}} \bar{n}_{\text{CR}} n_g \, dr \equiv \frac{c}{4\pi} \kappa \sigma M^*_{\text{MW}} I_{\text{MW}},
\]

where \( R_{\odot} = 8.5 \) kpc is the distance from the Sun to the Galactic center and \( R_{\text{max}} = 250 \) kpc
is the corona radius.
The extragalactic contribution is given by the integral over the volume of the Universe,

\[
\dot{j}_{\text{EG}} = \frac{c}{4\pi} \kappa \sigma \int dV \frac{1}{4\pi d^2(1+z)} \frac{\rho^*}{M_{\text{MW}}^*} \int_0^{R_{\text{max}}} \bar{n}_{\text{CR}} n_g 4\pi r^2 dr,
\]

where \(\rho^*\) is the total stellar mass comoving density, \(d\) is the comoving distance and the \((1+z)\) denominator takes into account redshifting of the time interval. We denote

\[
I_z \equiv \int dV \frac{1}{4\pi d^2} \rho^*
\]

and

\[
I_V = \int_0^{R_{\text{max}}} \bar{n}_{\text{CR}} n_g r^2 dr
\]

to obtain

\[
\xi \equiv \frac{\dot{j}_{\text{MW}}}{\dot{j}_{\text{EG}}} = \frac{M_{\text{MW}}^* I_{\text{MW}}}{4\pi c I_z I_V}.
\]

One should take into account the redshift difference between the observed and emitted energies, \(E' = (1+z)E\), to obtain, for a power-law spectrum, \(dN/dE \propto E^{-\alpha}\),

\[
I_z = \frac{1}{H_0} \int_0^{z_{\text{max}}} \frac{\rho^*(z)(1+z)^{-\alpha}}{\sqrt{(1+z)^3\Omega_M + \Omega_\Lambda}} dz,
\]

where \(H_0\) is the Hubble constant, \(\Omega_M\) and \(\Omega_\Lambda\) are cosmological matter and vacuum energy densities, respectively.

The total stellar mass density \(\rho^*(z)\) may be determined from the total stellar mass function,

\[
\Phi(M^*, z) = \frac{dN}{dV d\lg M^*},
\]

as

\[
\rho^* = \frac{1}{\ln 10} \int \Phi dM^*,
\]

and the function \(\Phi\) we use is presented in Ref. [31] (Model 3). The value of the total stellar mass in the Milky Way, \(M_{\text{MW}}^* = (6.43 \pm 0.63) \times 10^{10} M_\odot\), is taken from Ref. [32]. The value of \(\xi\) depends on the assumed spectral index \(\alpha\) but in all realistic cases \(\xi < 1\). This calculation neglects the absorption and the cut-off of the proton spectrum and therefore is valid for neutrino fluxes far away from the cut-off region; the propagation effects for photons are taken into account numerically as it is described above.
V. RESULTS AND DISCUSSION

Results of the calculation are presented in Fig. 4, where, for our baseline scenario (cosmic-ray injection spectrum with $\alpha = 2.4$ and $E_{\text{max}} = 10^{17}$ eV) we show the spectra of secondary gamma rays and neutrinos from cosmic-ray interactions with the circumgalactic gas. One can see that this contribution to the IceCube astrophysical neutrino flux is almost negligible and does not exceed 1%. At the same time, these interactions provide a sizeable contribution

FIG. 4. Diffuse neutrino (blue lines) and gamma-ray (red lines) spectra predicted by the model described in the text ($\alpha = 2.4$, $E_{\text{max}} = 10^{17}$ eV, $D_0 = 1.2 \times 10^{20}$ cm$^2$/s). The Milky-Way corona contribution is shown by dashed lines, the total flux from coronae of all galaxies, including the Milky Way, is shown by solid lines. The isotropic part of gamma-ray flux is shown by the black dotted line. The blue error bars: IceCube astrophysical neutrino flux [33]. The red error bars: FERMI-LAT extragalactic gamma background flux [5] (the upper flux level is shown allowed by galactic foreground model uncertainty). Crosses: total cosmic-ray flux measured by KASCADE and KASCADE-Grande [34].
Due to the non-central position of the Sun in the Galaxy, this contribution is not isotropic but follows a dipole-like pattern with respect to the Galactic center, see Fig. 5.

One may compare the expected neutrino flux from cosmic-ray interactions in the corona with a similar contribution from the Galactic disk. For the conventional assumptions about the cosmic-ray spectrum in the Galaxy, which correspond to our $\alpha = 2.4$ injection spectrum, the disk contribution was estimated in Ref. [23] to be about $(4-8)\%$ of the IceCube neutrino flux, significantly exceeding the corona contribution. Note that the Milky-Way disk contribution to the neutrino flux should exhibit a clear Galactic-plane anisotropy in the arrival directions, very different from the dipole anisotropy from the corona. While there exist some claims of the Galactic-plane excess [24], inclusion of the muon track events in the analysis makes them insignificant [35].

One may attempt to discuss possible variations in the model which might enlarge the neutrino flux. The largest uncertainty in our calculations is related to the cosmic-ray con-
centration and spectrum in the corona. Let us discuss the effect of its possible variations.

(i) Variations in the diffusion coefficient. The coefficient $D$ depends strongly on the value of the magnetic field in the outer halo, which is poorly constrained. The solution to the diffusion equation with fixed source normalization depends on $D$, as it is obvious from Fig. 2. However, since we choose the normalization of the source term $Q(E,r,t)$ to touch the observed cosmic-ray spectrum, the variations in $D$ by an order of magnitude do not change the result qualitatively, see Fig. 6.

In our calculations, we have normalized the cosmic-ray density in the corona in such a way that the observed cosmic-ray spectrum at the Earth location is never exceeded. The diffusion in the Galactic disk is likely slower than in the corona, and additional amount of cosmic rays confined in the disk contribute to the observed spectrum. Account of this effect would further reduce the normalization of the cosmic-ray density in the corona, and hence the diffuse gamma-ray and neutrino fluxes we discuss here.
(ii) Variations in the cosmic-ray spectral shape. The spectrum of IceCube astrophysical neutrinos looks harder than the one we obtained in our simulations with $\alpha = 2.4$. Examination of Fig. 4 suggests that taking a harder spectrum of the original cosmic rays might result in a considerably larger neutrino flux. Note that $\alpha = 2$ is predicted by the usual second-order Fermi acceleration, and some recent studies, see e.g. Ref. [36], suggest that the soft, $\alpha \approx 2.7$, cosmic-ray spectrum observed at the Earth is attributed to the effect of a nearby soft source. However, in the frameworks of our approach, hardening of the injection spectrum results in the suppression of its normalization, required in order not to overshoot the observable cosmic-ray spectrum at high energies. Figure 7 presents our results for the injected cosmic-ray spectrum with $\alpha = 2.0$ and $E_{\text{max}} = 10^{16}$ eV. Even in this extreme case, the neutrino flux cannot contribute to the IceCube flux significantly. Note that the disk contribution enhances under these assumptions [24].

(iii) Variations in the cosmic-ray injection history. A very important assumption for our
calculations is the choice of the time dependence of the source term \((5)\) in the cosmic-ray diffusion equation. If cosmic rays are accelerated, e.g., in supernova shocks, then the source term should be proportional to the time-dependent star formation rate in the Galaxy, which motivates the time dependence used in Eq. \((5)\). This leads to a temporal, factor of \(\sim 3\), enhancement in the injected spectrum, which does not affect our conclusions qualitatively.

However, other sources of cosmic-ray protons might work at various stages of the Milky-Way history. Temporary activity of the Galactic Center could, in principle, result in an additional contribution of energetic protons which, by now, may find themselves already in the corona. Both the shape and the normalization of their spectrum are hardly constrained by the present-day spectrum observed at the Earth. The interactions of these particles with the circumgalactic gas may lead to a considerable enhancement of secondary neutrino and gamma-ray fluxes at high energies. In this case, diffuse gamma rays would provide an important constraint on the model \([37, 38]\). We will address this interesting possibility in a forthcoming work \([39]\).

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