NEUTRINOS FROM ASTROPHYSICAL SOURCES*

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The detection of ultra high energy cosmic rays with $E > 10^{19}$ eV implies the existence of high energy neutrinos, originating from extragalactic sources. Neutrinos are suitable messenger particles, pointing back to the origin of cosmic rays when produced in local interactions. Extragalactic neutrino sources are among others gamma-ray bursts (GRBs) and active galactic nuclei (AGN), where protons are accelerated to high energies, collide and produce secondaries, which decay among others in neutrinos. Here, the focus will be on proton–proton interactions in AGN. First results for the target densities n_{H}, for FR-I galaxies will be presented.

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1. Introduction

The observations of non-thermal astrophysical processes in our Universe are influenced by magnetic fields, absorption, emission processes and the metric if the distances are large in comparison to the Hubble flow. Charged particles are deflected by magnetic fields and lose information about their origin.

At extreme energies compared to a given magnetic field strength, the deflection can be neglected, meaning that they point back to their origin. Nevertheless, high energy protons interact with photons from the cosmic ray background, leading to the fact that the sources of high energy protons are

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limited. An indirect way of observing cosmic rays is via their neutral interactions products at the source. Photons can be absorbed and re-emitted with lower energies by clouds, meaning that they cannot reproduce the exact mechanism of the processes in dense sources. The fact that different processes produce photons with the same energies leads to the situation that the photon flux is strongly model dependent.

The detection of neutrinos, on the other hand, is a huge challenge, since their cross sections are small, and the interactions rare. Although a huge amount of neutrinos cross the Earth, only a few interact with matter and can be detected.

Their low interaction cross section can, on the other hand, be used to observe the inner parts of sources like AGN and GRBs and help us to find information about the physical processes in these sources.

2. Extragalactic neutrino sources

Based on their observational properties, **GRBs** are intense flashes of γ-rays, in keV–MeV range, lasting from seconds up to minutes. Short bursts ($t < 2$s) are believed to result from the merging of two compact objects, like neutron stars. Long GRBs ($t > 2$s) are believed to be a collapse of the core of a massive star.

There are many models, trying to explain the mechanism of GRBs, but the widely accepted model is the fireball model [1]. Neutrino production is believed to take place in twin collimated outflows. If cosmic rays above the ankle originate from GRBs, they interact with ambient photon field, produce Δ^+ which decays in π^+. The pion itself decays in neutrinos. Different models for neutrino production in GRBs are explained in [2].

Neutrinos can also be produced in proton–proton interactions. The condition can be found in AGN, where particles are believed to be accelerated to the highest energies.

AGN are powerful objects in the Universe, producing high luminosities over a wide range. The current theory of an AGN is a supermassive black hole (SMBH) located in the center, accreting matter and producing the observed radiations. Since the accreting matter possesses angular momentum, it cannot directly fall into the SMBH, but circles on orbits, until it is swallowed by the SMBH. A fraction of the attracted matter is ejected and creates twin collimated plasma jets, strong radio sources if the host galaxy is elliptical, or weak radio sources if it is a gas-rich spiral. The production of the plasma jets are yet not known well, since observations cannot distinguish between the different theories. AGN are promising candidates from the production of high energy neutrinos, which are produced when high energy protons interact with matter and produce pions, which decay-among others-in neutrinos. We focus on proton–proton (p–p) interaction in AGN and concentrate on the muon neutrino flux calculation for FR-I galaxies. We assume the electrons lose all their energy to synchrotron radiation

$$L_e \approx L_{\mathrm{radio}} \,, \tag{2.1}$$

meaning that the radio luminosity is equal to the electron luminosity. In addition, we assume that protons and electrons are accelerated at the same site. That means, the proton luminosity can be determined by assuming a constant ratio $f_e = L_e/L_p$ between proton and radio luminosity. A detailed explanation of f_e can be found in [3]. Consequently, the proton luminosity can be estimated from radio observations of individual sources.

3. Modeling the neutrino fluxes for FR-I galaxies and the resulting target densities

High energy neutrinos are believed to be produced through inelastic proton–proton interactions, when high energy protons interact with ambient protons and produce pions which decay into neutrinos. The resulting neutrino flux at Earth is given by [4]

$$\begin{aligned} \phi^{\nu_\mu}(E_\nu) &= \epsilon_{\mathrm{osc}} \times c n_{\mathrm{H}} \int_0^1 \sigma_{\mathrm{inel}} \frac{dN_p}{dA\, dE_p}(E_\nu/x) F_\nu(x, E_\nu/x) \frac{dx}{x} \\ \text{with} \quad x &= E_\nu/E_p \,. \end{aligned} \tag{3.1}$$

Here, $\epsilon_{\mathrm{osc}} = 1/3$ considers the oscillation, n_{H} is the target density in cm^{-3}. The inelastic cross section, σ_{inel} and the muon distribution function $F_\nu(x, E_\nu/x)$ are explained in [4].

Further, $dN_p/(dA\, dE_p)$, the incident proton spectrum is given by

$$\frac{dN_p}{dA\, dE_p} = \frac{A_p}{E_p^p} \exp\left(-\frac{E_p}{E_0}\right) \left[\mathrm{cm}^{-2}\ \mathrm{TeV}^{-1}\right] . \tag{3.2}$$

Here, A_p is the normalization of the spectrum, E_0 is the cut-off energy and p is the spectral index, which will be set $p = 2$ in the following. The normalization is connected to the total proton energy W_p via

$$A_p = W_p \left(\int_{E_p} \left(\frac{\mathrm{TeV}}{E_p}\right)^p \exp\left(-\frac{E_p}{E_0}\right) E_p \, dE_p \right)^{-1} = W_p \tau \,. \tag{3.3}$$

The total proton energy of a single source is given by

$$W_p = t_{\mathrm{H}} L_{\mathrm{radio}} \frac{1}{f_e} \int\limits_0^z \frac{dz'}{(1+z')E(z')} \,. \tag{3.4}$$

The parameter t_{H} is the Hubble time and $E(z)$ [5] is given by

$$E(z) = \sqrt{\Omega_M (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda} \,. \tag{3.5}$$

The ratio f_e is

$$f_e = \frac{L_{\mathrm{radio}}}{L_p} = \frac{\int_{E_e} \frac{dN_e}{dE_e} E_e \, dE_e}{\int_{E_p} \frac{dN_p}{dE_p} E_p \, dE_p} \,. \tag{3.6}$$

Furthermore, assuming that the cosmic ray emission is isotropic, only the fraction $(4\pi d_{\mathrm{L}}(z)^2)^{-1}$ reaches the Earth, with $d_{\mathrm{L}}(z)$ representing the redshift dependent luminosity distance.

Considering the mentioned assumptions, the normalization is

$$A_p^{\mathrm{point}} = \frac{W_{\mathrm{radio}}}{4\pi d_{\mathrm{L}}(z)^2} \tau \frac{1}{f_e} \,. \tag{3.7}$$

3.1. Results

We calculated the target density n_{H} and the neutrino fluxes for FR-I galaxies, Table I and figure 1. The main contribution for the muon neutrino flux can come from proton–photon interactions in the disk or in the plasma jet [2]. Since the photon density is strongly model dependent, the neutrino production in proton–photon models is coupled with uncertainties. To reduce these uncertainties neutrinos from p–p interactions are considered, where detailed observations of the high energy part of CRs can be used to calculate the proton target density and the neutrino fluxes. Therefore, two assumptions are used (a) UHECRs originate from AGN and (b) that the protons are accelerated at shock fronts in the same way as electrons. Considering these assumptions, an upper limit to the target density n_{H}, which ranges between $\leq 20\,\mathrm{cm}^{-3}$ for 3C 028 and $\leq 1500\,\mathrm{cm}^{-3}$ for 3C 386 for $f_e = 0.1$ is calculated. Comparing our results with Kazanaz and Elliason [6], where a spherically symmetric accretion shock, accelerating a fraction of the inflowing plasma to the highest energies is assumed, the proton density is given by

$$n_{\mathrm{H}}(x) \approx 1.15 \times 10^9 \frac{\dot{m}}{M_9^2} x^{-3/2} \,\mathrm{cm}^{-3} \,. \tag{3.8}$$

Here, $\dot{m} = \dot{M}/(1\,M_\odot\,\mathrm{yr}^{-1})$ is the accretion rate, $M_9 = M/(10^9\,M_\odot)$ the black hole mass in units of 10^9 solar masses. The parameter $x = r/r_{\mathrm{S}}$, with the Schwarzschild radius r_S, gives the radial distance. Comparing equation (3.8) with our results implies that accelerated protons might originate from a maximum orbit $x \approx 3 \times 10^4$ for $\dot{m} = 0.1$, from $x \approx 5 \times 10^4$ for $\dot{m} = 0.2$ and from $x \approx 9 \times 10^4$ for $\dot{m} = 0.5$ and from a minimum orbit $x \approx 2000$ for $\dot{m} = 0.1$, from $x \approx 3000$ for $\dot{m} = 0.2$ and from $x \approx 6000$ for $\dot{m} = 0.5$.

TABLE I

The observed FR-I galaxies from [7]. Column 1 gives the names, column 2 the sine of right ascension, column 3 gives the sensitivity of IC40 from [8], column 4 the normalization and column 5 the target density for $f_e = 0.1$.

Name	sin(RA)	Sensitivity $\times 10^{-12}$ in $\mathrm{TeV\,cm^{-2}s^{-1}}$	Normalization in $\mathrm{TeV^{-1}\,cm^{-2}}$	$10\, n_{\mathrm{H}}/(f_e/0.1) <$ in $\mathrm{cm^{-3}}$
3C 028	0.24	3.34	287.16	230
3C 029	0.25	3.34	101.18	650
3C 031	0.29	3.54	48.93	1400
3C 066B	0.58	5.27	88.80	1400
3C 075	0.70	6.42	40.52	4200
3C 76.1	0.72	6.82	63.21	4200
3C 078	0.73	7.09	91.76	2800
3C 083.1	0.76	7.68	109.26	2800
3C 272.1	−0.11	9.46	9.76	10270
3C 386	−0.99	257.34	68.99	15520

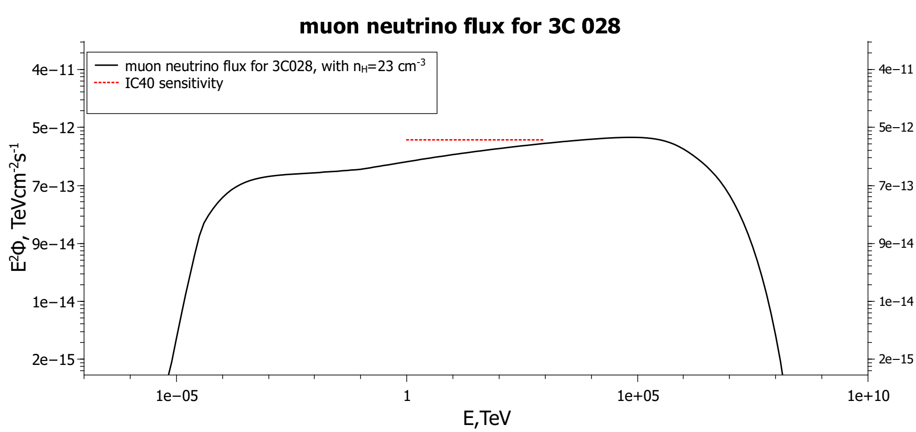

Fig. 1. Neutrino flux for the FR-I galaxy 3C028. The dashed (red) line is the IC40 sensitivity. The other sources have the same shape for the neutrino flux.

4. Conclusion

Neutrinos as messenger particles can yield information, charged particles and photons cannot. They are not deflected by magnetic fields and point back to their origin and they traverse huge amount of matter without any appreciable interaction, lighten the inner parts of objects like the Sun, supernovae, GRBs and AGN.

So far, the only known neutrino source outside our solar system is the SN1987A. The observations of neutrinos from different sources will help to answer the question about the physical processes in the sources. Therefore, huge detectors, like the IceCube Cherenkov detector have been built.

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