HIGH ENERGY NEUTRINOS FROM ACCELERATORS OF COSMIC RAY NUCLEI

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Ongoing experimental efforts to detect cosmic sources of high energy neutrinos are guided by the expectation that astrophysical accelerators of cosmic ray protons also generate high energy neutrinos through their interactions with ambient matter and/or photons. However the predicted neutrino flux is reduced if cosmic ray sources accelerate not only protons but also a significant number of heavier nuclei, as is indicated by recent air shower data. I consider two plausible extragalactic class of sources, active galactic nuclei and gamma-ray bursts, and demand consistency with the observed cosmic ray composition and energy spectrum at Earth after allowing for propagation through intergalactic radiation fields. This allows me to calculate the degree of photo-disintegration and pion production expected to occur in these sources, and hence the neutrino fluxes from them.

Keywords: Cosmic Rays; Nuclei; Neutrinos; Sources.

1. Introduction

It has long been recognised that high energy protons produced in cosmic ray accelerators may also generate an observable flux of cosmic high energy neutrinos, predominantly through pion production in collisions with the ambient gas/background radiation fields.[1] Neutrino telescopes such as AMANDA/IceCube,[2] ANTARES/KM3NeT,[3] RICE,[4] ANITA[5] and the Pierre Auger Observatory[6] have presented initial results and are approaching the level of sensitivity considered necessary to detect the first high-energy cosmic neutrinos.[7]

Candidate extragalactic sources include active galactic nuclei (AGN)[8] and gamma-ray bursts (GRBs).[9] If the cosmic ray sources accelerate heavy nuclei, the resulting high energy neutrino spectrum may be altered considerably from the all-proton picture which is usually assumed. Nuclei undergoing acceleration can interact with radiation fields in or near the cosmic ray engine, causing them to photo-disintegrate into their constituent nucleons which may then proceed to generate neutrinos through photo-pion interactions. Hence if most of the accelerated nuclei are broken up into nucleons before they can escape from their sources, the neutrino spectrum will not differ much from that predicted for proton accelerators. However if the radiation fields surrounding the sources are not sufficiently dense to fully disintegrate cosmic ray nuclei, fewer nucleons will be freed, leading to a reduced neutrino flux. In fact heavy nuclei can directly photo-produce pions on radiation fields but since the photo-pion production threshold is much higher than typical photo-disintegration thresholds, such interactions will be unimportant except at the very highest energies, well beyond the Galactic/extragalactic transition in the cosmic ray spectrum.

I here explore the impact of primary nuclei on the generation of high energy neutrinos in plausible extragalactic sources of cosmic rays. In the following I estimate the photo-nuclear interaction lengths for the suggested high-energy cosmic ray accelerators of AGN and GRBs. Using these results, I determine the subsequent neutrino fluxes expected to be produced from these sources during cosmic ray acceleration.

I will show that from AGN, nuclei with energies below $\sim 10^{19}$ eV can escape largely intact, while by $10^{19.5}$ eV most iron nuclei will suffer violently and only nucleons or light nuclei are expected to escape. In the case of GRBs, most energetic nuclei will undergo complete disintegration, with only nucleons being emitted as cosmic rays.

In Sec. 2 I motivate AGN and GRB to be good candidates as the source of extragalactic cosmic rays. In Sec. 3 and Sec. 4 I determine the interaction rates in both AGN and GRB sources. In Sec. 5 I obtain the subsequent neutrino fluxes from the cosmological distribution of both these source types. My conclusions are presented in Sec. 6.

2. Constraints on Cosmic Ray Sources

It is likely that the bulk of the cosmic radiation is created as a result of some general magneto-hydrodynamic process which channels kinetic or magnetic energy of cosmic plasmas into charged particles. The details of the acceleration process and the maximum attainable energy depend on the time scale over which particles are able to interact with the plasma. If the plasma disturbances persist for long periods, the maximum energy may be limited by the likelihood of escape from the region. If one includes the effect of the characteristic velocity, βc, of the magnetic scattering centres, the above argument leads to the so-called "Hillas criterion" for the maximum energy acquired by a charged particle moving in a medium with magnetic field B, $E_{\max} \sim 2\beta\, c\, Ze\, B\, r_{\rm L}$, where $r_{\rm L} \approx Z^{-1}(B/\mu{\rm G})^{-1}\,(E_{\rm CR}/10^{18}\ {\rm eV})$ kpc is the Larmor radius of cosmic rays with charge Ze.[10] The constraints this relationship places on the source size and magnetic field strength are shown below in Fig. 1.

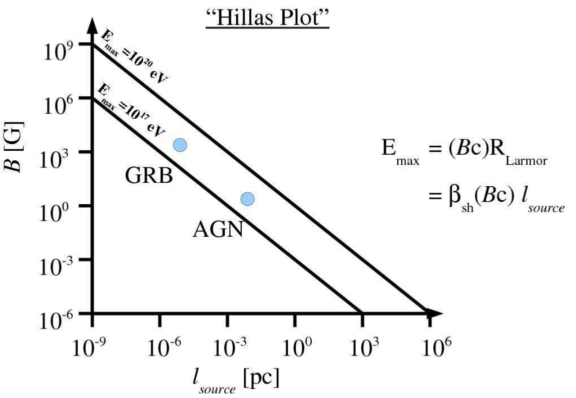

Fig. 1. A comparison of the source size and internal magnetic field strength for candidate ultra high energy cosmic ray sources.

In what follows, I consider the radiation fields associated with two classes of potential cosmic ray source and determine the particle's interaction rates, assuming that within these sources the trapping condition for efficient acceleration is fulfilled up to the highest energies.[11]

The dominant energy loss processes for ultra high energy nucleons/nuclei propagating through intergalactic space are pion production/photo-disintegration.[12] Details of how the relevant cross sections for all these processes are calculated here and the energy loss rates implemented in the simulation can be found in the main paper.[13]

3. Cosmic Ray Interactions in AGN

Among known non-thermal sources in the universe, radio–loud AGN are found to be some of the most energetic[14] and hence have long been considered the likely accelerators of ultra-high energy cosmic rays.[15]

The non-thermal emission of these powerful objects shows a triple-peak structure in the overall photon number density distribution shown in the left panel of Fig. 2. The first component (from radio to X-rays) being generally interpreted as due to synchrotron radiation from a population of non-thermal electrons, the second (UV) component as blackbody radiation originating from the accretion disk, and the third component (γ-rays) is explained as due to inverse Compton scattering of the same electron population on the various photon fields traversed by the jet.[16] The background radiation spectrum in AGN I adopt here is the Böttcher blazar flaring state model.[17] The two relevant components for these calculations are the synchotron radiation, peaking at $E_\gamma^{\rm peak} \sim 0.003$ eV, then falling as $dN_\gamma/dE_\gamma \propto E_\gamma^{-2.3}$, and a $20,000$ K blackbody radiation from the accretion disk. It is assumed that 10% of the Eddington luminosity is radiated as blackbody radiation and 1% as synchrotron radiation.[18]

The cosmic ray acceleration process is assumed to occur within a relativistic blob of plasma moving along the jet with Lorentz factor $\Gamma \sim 10^{1.5}$. The details of the determination of the interaction rates will only be sumarised in the following, for a more detailed account of their determination see the paper.[19]

The most relevant quantity in calculations determining the neutrino flux from $p\gamma$ interactions in the accelerator is ϵ_π, the fraction of the proton's energy it deposits as neutrino energy flux before leaving the source. For protons interacting with photons of energy $E_\gamma^{\rm peak}$ via the Δ-resonance, this fraction is found to be,

$$\epsilon_\pi \approx 553\left(\frac{10^{1.5}}{\Gamma}\right)^2\left(\frac{L_\gamma}{10^{45}\ {\rm erg/s}}\right)\left(\frac{3\ {\rm meV}}{E_\gamma^{\rm peak}}\right)\left(\frac{10^4\ {\rm s}}{\Delta t}\right). \tag{1}$$

In the right panel of Fig. 2, I show the expected photo-pion production and photo-disintegration interaction lengths for protons and nuclei.

One can also verify that photo-disintegration dominates over photo-pion production by nuclei at all energies, hence neutrino production through photo-nuclear interactions can be safely neglected.

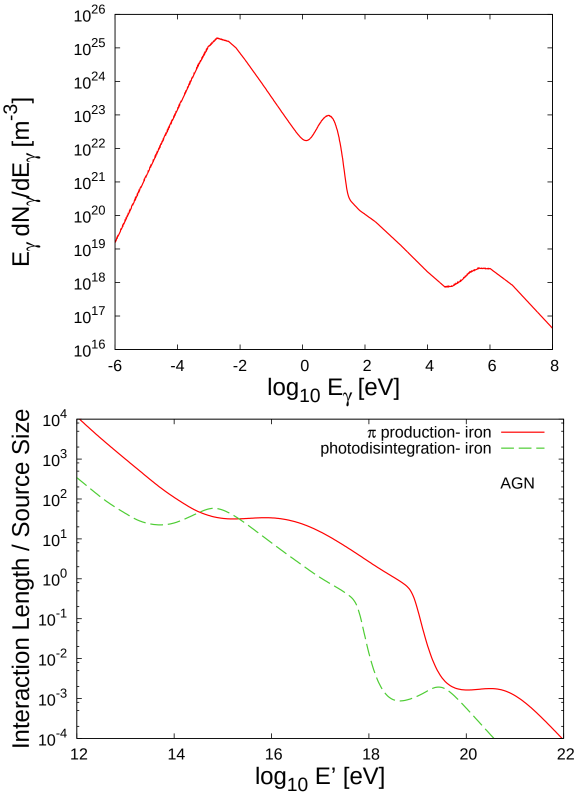

Fig. 2. (top) The photon energy spectrum of a flaring blazar in the observer's frame. (bottom)Comparison of the interaction lengths for photo-pion production by protons, photo-pion production by iron nuclei and photo-disintegration of iron nuclei, as a function of the proton/iron nucleus energy in the rest frame of the AGN plasma.

4. Cosmic Ray Interactions in GRB

GRBs are flashes of high energy radiation that can be brighter, during their brief existence, than any other source in the sky. If these sources are distant, the energy necessary to produce them is about 10^{51} erg of gamma rays, released in less than 1 second.

The most popular interpretation of the GRB-phenomenology is that the observable effects are due to the dissipation of the kinetic energy of a relativistic expanding plasma wind, a "fireball".[21] Although the primal cause of these events is not fully understood, it is generally believed to be associated with the core collapse of massive stars (in the case of long duration GRBs) and stellar collapse induced through accretion or a merger (short duration GRBs).[22]

The very short timescale observed in the light curves indicate an extreme compactness that implies a source which is initially opaque (because of $\gamma\gamma$ pair creation) to γ-rays. The radiation pressure on the optically thick source drives relativistic expansion, converting the internal energy into kinetic energy of the inflating shell. Baryonic pollution in this expanding flow can trap the radiation until most of the initial energy has gone into bulk motion with Lorentz factors of $\Gamma \sim 10^2 - 10^3$.[23] (In these calculations I set $\Gamma = 10^{2.5}$).

To describe the radiation fields associated with GRBs, I adopt a standard broken power-law spectrum, which is found to give good fits to the BATSE data,[24]as shown in the left panel of Fig.3.

In many ways the situation is similar to the blob of emitted plasma in the AGN model. However, in the fireball's *comoving* frame, a spherical shock expands relativistically in all directions (with Lorentz factor Γ), and thus a change in geometry to that of the AGN scenario is required.

For protons interacting with photons of energy $E_\gamma^{\rm break}$ through the Δ-resonance,

$$\epsilon_\pi = 0.2 \left(\frac{10^{2.5}}{\Gamma}\right)^4 \left(\frac{L_\gamma}{10^{51}\ \text{erg/s}}\right) \left(\frac{1\ \text{MeV}}{E_\gamma^{\rm break}}\right) \left(\frac{2\ \text{ms}}{\Delta t}\right) . \tag{2}$$

In the right panel of Fig. 3, I show the expected photo-pion production and photo-disintegration energy loss length for protons and nuclei.

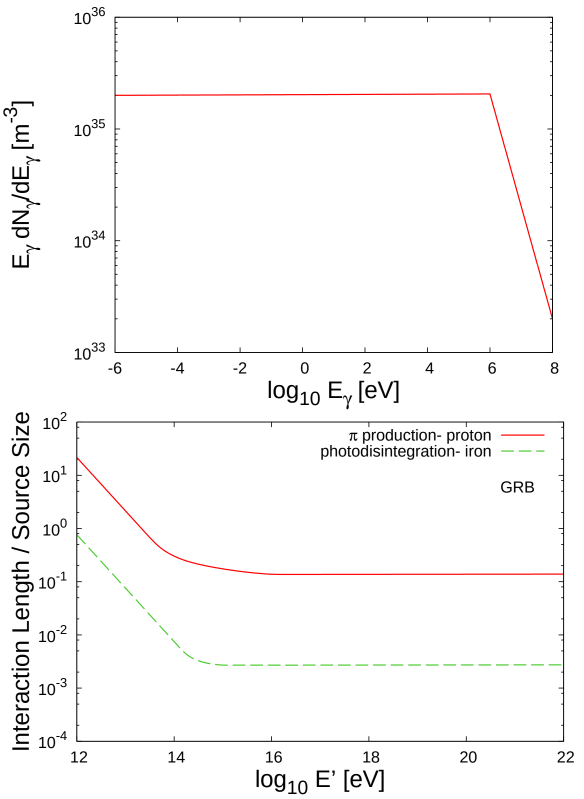

Fig. 3. (top) The photon energy spectrum of a GRB in the observer's frame. (bottom) Comparison of the interaction lengths for photo-pion production by protons, photo-pion production by iron nuclei and photo-disintegration of iron nuclei, as a function of the proton/iron nucleus energy in the rest frame of the GRB plasma.

5. The Cosmic Neutrino Flux from Extragalctic Sources

By performing a Monte Carlo simulation for cosmic ray protons and nuclei propagating through the sources considered, the neutrino flux produced in each of the candidate sources can now be calculated. The results shown in Fig. 4 are obtained assuming a cosmological distribution of sources which accelerate cosmic rays with a spectrum $\propto E^{-2.4}$. Using the emissivity of AGN, the corresponding peak neutrino flux is,

$$\Phi_\nu(E_\nu) = 2.3 \times 10^{-5} \left(1 - e^{-\epsilon_\pi/K_p}\right) \times E_\nu^{-2.4}\, \mathrm{GeV}^{-1}\, \mathrm{cm}^{-2}\, \mathrm{s}^{-1}\, \mathrm{sr}^{-1} \,, \quad (3)$$

where E_ν is in GeV and I have normalized to a cosmic ray production rate of:

$$\dot{\epsilon}_{\mathrm{CR}}^{[10^{18.7},\, 10^{22.0}]} = 2.2 \times 10^{44}\, \mathrm{erg\, Mpc^{-3} yr^{-1}} \,, \quad (4)$$

as indicated by Auger data. In the case of GRBs, because of the strong magnetic fields in the plasma, the neutrinos are created by parent protons with energies below 10^{18} eV. Following other calculations,[25] I assume in this case a break in the proton injection spectrum ($\propto E^{-2}$ below 10^{18} eV), so that the corresponding peak neutrino flux saturates the Waxman-Bahcall bound, yielding

$$\Phi_\nu(E_\nu) = 1.0 \times 10^{-8} \left(1 - e^{-\epsilon_\pi/K_p}\right) \times E_\nu^{-2}\, \mathrm{GeV}^{-1}\, \mathrm{cm}^{-2}\, \mathrm{s}^{-1}\, \mathrm{sr}^{-1} \,. \quad (5)$$

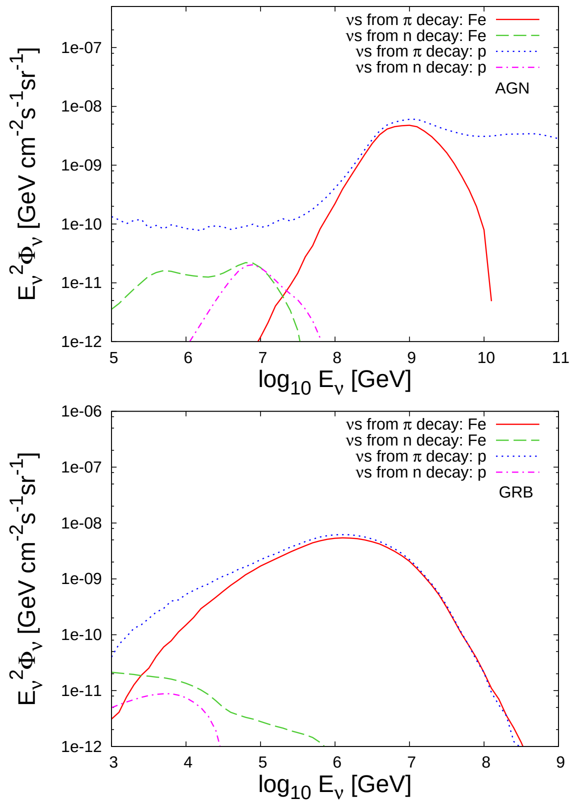

Fig. 4. The neutrino spectra produced by protons and iron nuclei being accelerated in AGN (top) and GRBs (bottom). The fluxes have been normalized following the Waxman-Bahcall prescription, namely assuming that all ultra-high energy particles observed on Earth are protons.

In closing, it must be stressed that the diffuse neutrino flux has an additional component originating in the energy losses of ultra-high energy cosmic rays *en route* to Earth. The main energy loss process here is photo-pion production with CMB photons, which causes the steepening of the cosmic ray spectrum beyond $10^{19.7}$ eV. The decay of charged pions produced in this process results in a diffuse flux of "cosmogenic" neutrinos,[26] which is comparable to the fluxes shown in Fig. 4. If there are heavy nuclei in ultra-high energy cosmic rays then they will preferentially lose energy through photo-disintegration rather than photo-pion production, so the cosmogenic neutrino flux will also be suppressed as has been discussed elsewhere.[27]

6. Conclusion

I have demonstrated here the role that heavy nuclei play in the generation of neutrinos in favoured candidate astrophysical sources of high energy cosmic rays. During acceleration the nuclei may be completely photo-disintegrated into their constituent nucleons and I find this indeed happens in GRBs, resulting in the outgoing cosmic rays being proton dominated. The neutrino flux is then left largely unchanged from previous estimates which had ignored the possibility of nuclei being accelerated as well as protons. In AGN the situation is in between, with nuclei being fully disintegrated only at the highest energies, so the neutrino flux is suppressed at lower energies.

The likely possibility of a substantial fraction of nuclei in ultra-high energy cosmic rays implies therefore a somewhat reduced expectation for the neutrino flux from their cosmic sources.

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