High-Energy Neutrinos from Active Galactic Nuclei

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We calculate the spectrum and high-energy ν background flux from photomeson production in active galactic nuclei (AGN), using the recent UV and x-ray observations to define the photon fields and an accretion-disk shock-acceleration model for producing high-energy particles. Collectively, AGN produce the dominant isotropic ν background between 10^4 and 10^{10} GeV, detectable with current instruments. AGN ν's should produce a sphere of stellar disruption which may explain the "broad-line region" seen in AGN.

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Active galactic nuclei (AGN) have long been considered as potential sites for high-energy ν production[1] as they are the most powerful emitters of radiation in the known Universe. They are presumably fueled by the gravitational energy of matter infalling onto a supermassive black hole at the AGN center, though the mechanism responsible for the efficient conversion of gravitational to observed luminous energy is not yet known. One class of models assumes that the infalling matter forms an accretion shock at some distance from the black hole.[2] First-order Fermi acceleration of charged particles at this shock then converts a significant fraction of the total gravitational energy into highly relativistic particles which have a characteristic power-law spectrum.[3] A necessary consequence of this picture which we explore here is the production of high-energy ν's through the collisions of ultrarelativistic protons with the intense photon fields in AGN. Possible ν emission from the radio lobes in the radio-loud AGN has been considered elsewhere.[4] Here we investigate ν production primarily from the cores of radio-quiet AGN, which are a factor of 10 more numerous.[5]

A characteristic AGN spectrum has a number of notable features. Although roughly comparable amounts of power exist in each logarithmic energy interval, there is a pronounced "UV bump"[6] peaking at ~ 10 eV while at energies above ~ 200 eV, a power-law x-ray spectrum emerges.[7] The UV spectrum is consistent with thermal emission from an accretion disk,[8] where roughly $\sim 70\%$ of the luminosity comes from within 30 Schwarzschild radii ($R_S = 2GM/c^2$) of the AGN core. The x-ray emission is similar in luminosity to that of the UV bump but its rapid time variability indicates that the x rays are produced in a smaller region than the UV flux.[9] The x-ray spectrum can be explained as the end result of an electromagnetic cascade of secondaries from the proton energy-loss processes.[10] The lack of strong x-ray absorption features in AGN spectra[7] implies that the secondary x rays are produced in regions of low column density. This puts strict limits on the amount of target gas for pp interactions, and one finds that the very large photon density in the AGN core makes $p\gamma$ the dominant energy-loss mechanism.

At the lowest energies above the interaction threshold the dominant ν production channel is $\gamma p \rightarrow \Delta \rightarrow n\pi^+$.[11] The cross section for this reaction peaks at photon energies of $\epsilon' = 0.35 m_p c^2$ in the proton rest frame. In the observers frame $\epsilon E_p = 0.35$ with E_p in EeV and ϵ in eV. For UV-bump photons, with a mean energy of 40 eV, this translates into a characteristic proton energy of $E_c \sim 10^7$ GeV.

The optical depth to photomeson production for protons of energy E_p can be approximated by $\tau(E_p) \sim \epsilon n(\epsilon)\sigma_0 R$, where σ_0 at the Δ resonance peak[12] is $\approx 5\times 10^{-28}$ cm^2 and $n(\epsilon)$ is the differential number density of photons at this energy in cm^{-3}eV^{-1}. A crude estimate for $n(\epsilon)$ from the accretion disk can be found by assuming that all sources run at some constant efficiency. This is quantified in terms of the Eddington limit ($L_{\rm Edd} = 4\pi GMm_pc/\sigma_T$, where M is the mass of the black hole), the maximum steady-state luminosity that can be produced before radiation pressure disrupts the accretion flow. Fitting accretion-disk models to the UV spectrum[8] gives a typical luminosity of $(0.03\text{-}0.1)L_{\rm Edd}$ ergs s^{-1}, so here we assume that a luminosity of $\sim 0.05 L_{\rm Edd}$ is emitted isotropically within $R \sim 30 R_S$. Given the weak dependence of the characteristic accretion-disk temperature on black-hole mass ($T \propto M^{-1/4}$) and the very similar UV-bump shapes seen in the observational data, we can assume a luminosity-independent "generic" UV AGN spectrum. The AGN x-ray spectrum is also fairly universal, typically being an $\epsilon^{-1.7}$ power law above 2 keV,[7] with a cutoff around 1-2 MeV,[13] with the total x-ray luminosity being roughly the same as that in the UV bump, i.e., $L_x \approx L_{\rm UV} \approx 0.05 L_{\rm Edd}$. Normalizing so that $L \sim 4\pi R^2 c \int \epsilon n(\epsilon) d\epsilon = 0.1 L_{\rm Edd}$, where $R = 30R_S$, we obtain

$$n(\epsilon) \approx \frac{10^{14}}{L_{45}} \mathrm{cm}^{-3}\mathrm{eV}^{-1} \times \begin{cases} \epsilon, & \epsilon < 1\ \mathrm{eV}, \\ \epsilon^{-0.9}, & 1 < \epsilon < 40\ \mathrm{eV}, \\ 3.25\times 10^{-4}\epsilon^2 e^{-\epsilon/15}, & 40 < \epsilon < 192\ \mathrm{eV}, \\ 2.45\times 10^{-1}\epsilon^{-1.7}, & 192 < \epsilon < 10^6\ \mathrm{eV}, \end{cases} \tag{1}$$

where L_{45} is the total UV luminosity in units of 10^{45} $\mathrm{ergs\,s}^{-1}$. The $1/L$ scaling of $n(\epsilon)$ follows from our assumption of linear scaling of both R and L_{Edd} with M (i.e., with L).

First-order Fermi acceleration of protons in strong shocks produces a power-law proton energy spectrum $\propto E_p^{-2}$ up to a maximum energy $E_{\max}$. This maximum proton energy is determined by equating the $p\gamma$ lifetime $t_{p\gamma}(E_p) \approx (N_\gamma \sigma_{p\gamma} c\kappa)^{-1}$, where κ is the mean elasticity, with the proton acceleration time[2] $t_{\mathrm{acc}}(E_p) \approx 2.2\times 10^{-4} \times (R_{\mathrm{shock}}/R_S)(E_p/m_p)B^{-1}$. The shock radius R_{shock} is fixed at $\sim 10R_S$ by our assumption that the x-ray luminosity is $0.05L_{\mathrm{Edd}}$. The magnetic field B is taken to be 10^3 G, which assumes approximate equipartition with a typical AGN UV luminosity. With these parameters, we find an approximate fit

$$E_{\max} = 10^9\ \mathrm{GeV} \times \begin{cases} 3\times 10^{-3}, & L_{45} < 2.4\times 10^{-3}, \\ 0.25L_{45}^{0.73}, & 2.4\times 10^{-3} < L_{45} < 1, \\ 0.25L_{45}, & 1 < L_{45} < 100, \\ 25, & L_{45} > 100, \end{cases} \tag{2}$$

to our numerically generated curve. For all luminosities, the maximum proton energy is limited by $p\gamma$ interactions rather than by the scale size of the shock region.

The characteristic straight-line escape optical depth of high-energy nucleons to accretion-disk UV photons is ~ 150 at 40 eV. The optical depth is independent of the luminosity since $\tau(E_p) \propto n(\epsilon)R$ and $n(\epsilon) \propto 1/L$ while $R \propto L$. This implies that the secondary neutrons will not in general escape the shock volume, so that comparable amounts of power are generated via $n\gamma$ collisions. With roughly half of the energy loss going into π^0's and the other half into $\pi^\pm$'s, the luminosity for ν_μ ($\bar{\nu}_\mu$) is $\sim 0.2 \times L_{\mathrm{x}}$, and for ν_e ($\bar{\nu}_e$) is $\sim 0.1L_{\mathrm{x}}$. As the AGN photon spectrum drops exponentially between 40 and 200 eV, it is overwhelmingly the UV-bump photons which interact with the high-energy nucleons.

The mean pion energy is $\langle E_\pi \rangle \sim 0.2E_p$, while the mean ν energy is $\sim E_\pi/4 \sim 0.05E_p$.[14] Thus the ν spectrum from proton interactions with the UV bump extends from $E_c/20$ to $E_{\max}/20$, i.e., (5×10^5)–10^9 GeV with a spectral index of ~ 2, mirroring that of the proton spectrum. Above 10^9 GeV the cutoff in the proton spectrum leads to a cutoff in the ν spectrum. Below $E_c/20$ relativistic kinematics give rise to a flat ν energy distribution.[14] This flattening of the ν spectrum below the threshold energy is a critical point that has been neglected in previous studies.[15] This is shown in Fig. 1, where the ν spectra of NGC4151 and 3C273, the brightest radio-quiet and radio-loud AGN, respectively, are calculated using Monte Carlo techniques.

The diffuse ν flux can be found by integrating over the luminosity function (LF) for AGN. The most recent determinations of the x-ray LF come from the GINGA satellite.[16] Locally (i.e., at the present epoch) it is given by

$$\rho_0(L) = \begin{cases} n_1/L_1, & L_{\min} < L < L_1, \\ n_1/L_1(L/L_1)^{-2.6}, & L_1 < L < L_{\max}, \end{cases} \tag{3}$$

where $n_1 = 9.4\times 10^{-78}L_1/(10^{42}\ \mathrm{ergs\,s}^{-1})\ \mathrm{cm}^{-3}$, $L_{\min} = 3 \times 10^{38}\ \mathrm{ergs\,s}^{-1}$, $L_1 = 3\times 10^{42}\ \mathrm{ergs\,s}^{-1}$, and $L_{\max} = 10^{46}$ $\mathrm{ergs\,s}^{-1}$. These luminosities refer to the 2–10-keV x-ray flux, and so must be multiplied by a factor 10 to transform them into a total x-ray flux. The luminosity function at any epoch can be calculated by determining the

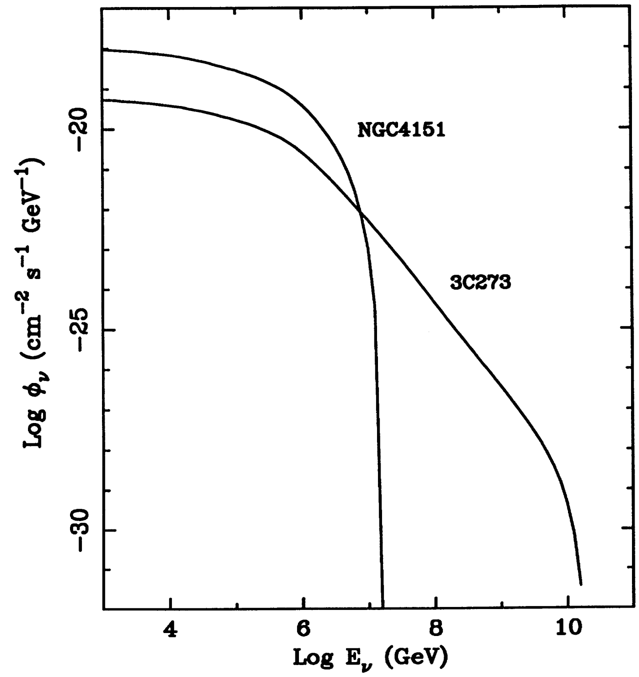

FIG. 1. The predicted ν_μ ($\bar{\nu}_\mu$) flux from NGC4151 with $L_{\mathrm{x}} = 3\times 10^{43}\ \mathrm{ergs\,s}^{-1}$ and a distance of 4.5×10^{25} cm (Ref. 25), and 3C273 with $L_{\mathrm{x}} = 10^{47}\ \mathrm{ergs\,s}^{-1}$ and a distance of 3×10^{27} cm (Ref. 25). The ν_e ($\bar{\nu}_e$) flux is half that of the ν_μ ($\bar{\nu}_\mu$) flux.

effects of evolution, and is well represented as a function of redshift z as

$$\rho(L,z)=\frac{g(z)}{f(z)}\rho_0\left[\frac{L}{f(z)}\right],\quad 0<z<z_{\max}, \tag{4}$$

where the luminosity and density evolution are given by the functions $f(z)=(1+z)^3$ and $g(z)=(1+z)^{2.6}$, respectively.[16] We calculate the diffuse ν background assuming an epoch of formation of AGN activity at $z=2.2$.[17] Figure 2 shows the results obtained assuming ~30% of the x-ray background is produced by AGN (Ref. 16) and assuming that all of the AGN x-ray flux is from the $p\gamma$ interaction and subsequent electromagnetic cascade.[10] The diffuse background from AGN can be seen above the atmospheric background in the range 10^4-10^{10} GeV. Note that a comparison with Fig. 1 implies that an angular resolution of ~3° is sufficient for detection of NGC4151 over the diffuse AGN background. Such a resolution is attainable in high-energy neutrino detectors.[18]

Event rates in the various ν detectors can be calculated from the spectrum. The Fly's Eye detector with its energy threshold of 10^8 GeV would expect to see ~0.02 downward event per year. This is consistent with the present nondetection of an extragalactic ν background from the Fly's Eye. The next-generation instrument, the HiRes Eye, could see ~0.7 downward event per year. Above the HiRes energy threshold of $\sim 10^8$ GeV, upward ν's are severely attenuated by absorption in the Earth.[19] At lower energies, covered by detectors[20] sensitive to both ν_μ and $\bar{\nu}_\mu$, the upward event rates at energies greater than 10^5 GeV are of order $10^2\ \mathrm{yr}^{-1}$ for IMB and MACRO, and 10^3 to $10^4\ \mathrm{yr}^{-1}$ for DUMAND II.

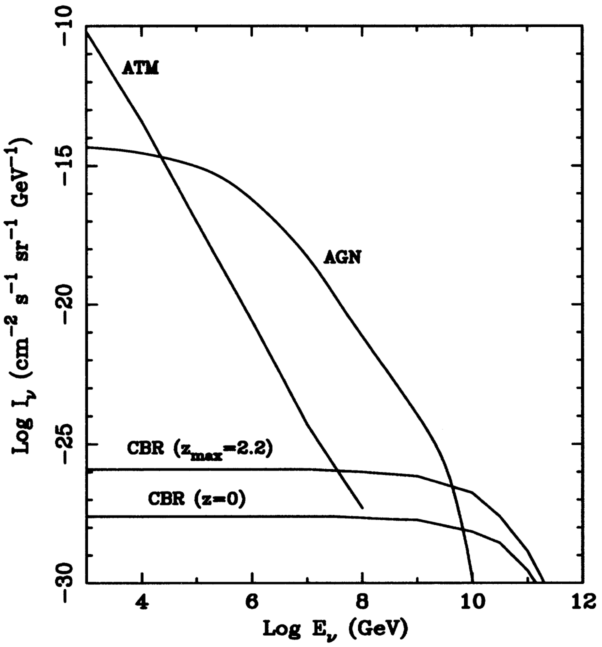

FIG. 2. The integrated high-energy ν_μ ($\bar{\nu}_\mu$) neutrino background from AGN. Also shown is the horizontal ν_μ ($\bar{\nu}_\mu$) flux from high-energy cosmic rays interacting with the Earth's atmosphere (Ref. 26) (ATM) and the background expected from photomeson production of the extragalactic high-energy cosmic rays with the cosmic background radiation (Ref. 27) (CBR).

AGN should be copious emitters of ν's, providing the largest contribution to the diffuse high-energy ν ($>10^4$ GeV) background. However, the high diffuse background masks the individual AGN ν flux. The diffuse background ν's should be observable in present-day and planned detectors, providing an observational test of AGN acceleration mechanisms. Coproduced high-energy γ rays are degraded into AGN x rays by electromagnetic cascading, owing to the large AGN photon densities.[10]

The galactic black-hole candidates (such as Cygnus X-1) may similarly produce high-energy ν's. Their much higher x-ray (and hence potential ν) fluxes at Earth may well provide a better possibility for detection of an individual point source over the AGN diffuse background. This possibility will be discussed in a later paper.

The high-energy ν luminosities predicted from AGN will have a profound effect on stars close to the center of the host galaxy, producing stellar winds, swelling the atmospheres and even causing their total disruption.[21] The column density of absorption for an $\sim 10^6$-GeV ν is $X = m_{\mathrm{H}}/\sigma_{\nu N} \sim 2\times 10^9\ \mathrm{g\,cm^{-2}}$, while the total column density for a solar-mass star $\langle\rho\rangle R \sim 10^{12}\ \mathrm{g\,cm^{-2}}$. Using a conservative disruption criterion that the ν energy deposited in the star be greater than its nuclear energy generation we find a sphere of stellar disruption at a radius of

$$R_{\mathrm{SSD}} \approx 30 L_{45}^{1/2}\left[\frac{M_*}{M_\odot}\right]^{-1.1} \text{ light days}, \tag{5}$$

where M_* and $M_\odot$ are the masses of the irradiated star and the Sun, respectively. This radius is the same as that inferred for the "broad-line region" (BLR) in AGN.[22] The existence of a BLR is an intrinsic characteristic of the AGN phenomena, the origin of which is poorly understood. Outflowing material from stellar disruption provides an environment similar to that in which the broad lines must arise.[23]

We note that $n\gamma$ and $\bar{p}\gamma$ interactions produce a significant flux of $\bar{\nu}_e$'s at 6.3 PeV, the Glashow resonance energy for the $\bar{\nu}_e e^- \rightarrow W^-$ process. An observation of an enhanced event rate at this energy indicates either that AGN are optically thick to neutrons (as indicated in this paper) or that there are antimatter AGN in the Universe.[24] We estimate that there would be ~10 throughgoing resonance events per year in IMB and MACRO and that DUMAND II would see ~300 throughgoing and ~10 contained events per year from

W^- resonance production.

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