High Energy Cosmic Rays from Active Galactic Nuclei

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We suggest that at an energy of 10^{16} eV, and possibly even up to 10^{19} eV, a substantial fraction of the observed cosmic rays may originate in the central regions of active galactic nuclei.

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Cosmic rays with energies below about 10^{19} eV are usually thought to be of galactic origin, those below a rigidity (momentum/charge) of $\sim 10^{14}$ V being due to acceleration at supernova shocks. Between 10^{15} and 10^{16} eV, the "knee" in the cosmic-ray spectrum, the spectrum steepens from $\sim E^{-2.7}$ to $\sim E^{-3}$. At around 10^{19} eV the spectrum flattens, possibly due to an extragalactic component [1] of cosmic rays accelerated at shocks in jets of active galactic nuclei (AGN) [2–4]. Between 10^{15} and 10^{19} eV the origin is unknown, although it has been suggested to be due to reacceleration of the low-energy galactic population [5, 6]. In an important paper Stecker *et al.* [7] have shown recently that if particle acceleration occurs in the central regions of AGN then a diffuse flux of high energy neutrinos from unresolved AGN may be observable with proposed neutrino telescopes [8]. In this Letter we examine the consequences of this scenario for the production of high energy cosmic rays.

Following Stecker *et al.* [7], we adopt a model in which protons are accelerated by first-order Fermi acceleration at a shock in an accretion flow onto a supermassive black hole [9–15]. In this model, Kazanas and Ellison [10] found the black hole mass to be proportional to the luminosity and we can approximate their results by $M \simeq x_1[L_C/(10^{38}\,\mathrm{ergs\,s^{-1}})]M_\odot$, where $x_1 = R/r_S$ is the ratio of shock radius to Schwarzschild radius, and L_C is the luminosity in the infrared to hard x-ray continuum. We assume equipartition between the energy density in the magnetic field and radiation field at the shock, $B^2/8\pi = U_{\mathrm{rad}} \simeq L_C/\pi R^2 c$, to obtain the magnetic field and hence the gyroradius r_g at the shock. If we assume the diffusion coefficient to be a factor b larger than the Bohm diffusion coefficient, i.e., $D = b\frac{1}{3}r_g c$, then we obtain

$$D(E,R) \simeq 6.1 \times 10^{-21} b\, x_1^2 L_C^{\frac{1}{2}} E\ \mathrm{cm^2\,s^{-1}}$$

for the diffusion coefficient at the shock (radius $r = R$) where L_C is measured in $\mathrm{ergs\,s^{-1}}$ and E is in eV. For shock acceleration the acceleration rate is $dE/dt \simeq u_1^2 E/20D$ where u_1 is the upstream flow velocity (see, e.g., Ref. [16]). For freefall onto the black hole $u_1 = x_1^{-1/2}c$, and this leads to an acceleration rate

$$\frac{dE}{dt} \simeq 10^{-26} b^{-1} x_1 L_C^{\frac{1}{2}} U_{\mathrm{rad}}\ \mathrm{eV\,s^{-1}},$$

where U_{rad} is in $\mathrm{eV\,cm^{-3}}$.

We approximate the AGN continuum by a "UV bump" represented by a diluted blackbody spectrum with $T = 50\,000$ K, plus a power law with photon spectral index -1.7 extending from 10 eV to 1 MeV. We assume each component has equal energy density at the shock. This model spectrum is motivated by the possibility that the observed infrared may be UV radiation from the central region reprocessed at large radii [17]. Protons will suffer interactions with the radiation field and we use published cross sections for pion photoproduction [18, 19] and pair production [20] to treat these interactions by the Monte Carlo method (see Refs. [21] and [22] for more details). The maximum proton energy that can be achieved will occur when the acceleration rate equals the total energy loss rate for these processes. An approximate fit to our results is $E_{\max} \simeq E_0(x_1^2 L_C/b^2 L_0)^\alpha$, where $E_0 = 1.8 \times 10^{16}$ eV, $L_0 = 2 \times 10^{46}\,\mathrm{ergs\,s^{-1}}$, $\alpha = 0.18$ (for $x_1^2 L_C/b^2 L_0 < 1$) or 0.52 (for $x_1^2 L_C/b^2 L_0 > 1$).

As a result of interactions during and after acceleration, secondary particles will be produced. Assuming accelerated protons are trapped in the central region, the secondaries will include $e^\pm$ from pair production and from π-μ-e decay, ν's from π-μ-e decay, γ rays from π^0 decay, and neutrons.

The neutrons themselves are subject to pion photoproduction interactions. However, not being trapped magnetically some fraction will escape from the central region. We have calculated the optical depth for neutron-photon interactions in the radiation field for traversing the central region, τ_{in}, and for traveling radially out from $r = R$ to infinity, τ_{out}. We start by calculating the mean interaction length for a neutron of energy E at radius r moving radially outward,

$$x_{n\gamma}(E,r)^{-1} = \int_{\epsilon_{\min}}^{\infty} d\epsilon\, n(\epsilon) \times \int_{\mu_-}^{\mu_+} d(\cos\theta)\, \frac{1}{2}\sigma_{n\gamma}(s)(1-\beta\cos\theta),$$

where $n(\epsilon)$ is the photon number density per unit energy inside the central region, $\sigma_{n\gamma}$ is the cross section for pion photoproduction, $s \simeq 2\epsilon E(1-\beta\cos\theta)$, θ is the angle between the directions of the neutron and photon, μ_- is the minimum value of $\cos\theta$, and $\epsilon_{\min}$ and μ_+ are determined by the threshold for pion production. We assume that inside the central region ($r < R$) the radiation is isotropic and so $\mu_- = -1$, whereas outside the central region we assume photons can only come from the sphere of radius R, i.e., $\mu_- = (1-R^2/r^2)^{1/2}$. Optical depths calculated in this way are given in Ref. [22] and we use these results to estimate the probability of neutrons escaping from the central region. For the range of x_1 considered here we find that below $\sim 5\times 10^{16}$ eV neutrons traveling radially out from the shock will escape from the intense radiation field of the central region and below 10^{15} eV all neutrons will escape from the central region.

Having escaped from the intense radiation field of the central region, a relativistic neutron will decay on average after traveling a distance $r_0 \simeq 2.8\times 10^4(E/\text{eV})$ cm. The resulting proton will then diffuse in the magnetic field which is tied to the accreting plasma. The number density of particles in the accreting plasma falls off with radius as $n \propto r^{-3/2}$, while the temperature falls off as $T \propto r^{-1}$ based on model calculations [23]. Assuming the pressure in magnetic turbulence tracks the plasma pressure, then $D \propto r^{5/2}$. Hence, we obtain

$$D(E,r) \simeq 1.3\times 10^{61} b\, x_1^{-3} L_C^{-2} E\, r^{\frac{5}{2}}\ \text{cm}^2\,\text{s}^{-1},$$

where E is in eV and r in cm. Protons will be trapped in the accreting plasma for a time $t_{\text{esc}} \simeq r^2/2D$.

The time scale for pp collisions is given by $t_{pp} \simeq (n\sigma_{pp}c)^{-1}$, where $\sigma_{pp} \simeq 30$ mb is the pp inelastic cross section, and n is the number density of nuclei in the accreting matter obtained as described below. The total luminosity L_T of individual AGN is equal to the product of accretion rate, specific kinetic energy of accreting plasma at the shock, and the efficiency of conversion of kinetic energy of infalling matter to relativistic particles [10], $Q(x_1) \simeq 1 - 0.1x_1^{0.31}$. From this we obtain

$$n(r) \simeq 1.3\times 10^8 Q(x_1)^{-1} x_1^{\frac{1}{2}} L_C^{\frac{1}{2}} r^{-\frac{3}{2}}\ \text{cm}^{-3}$$

assuming $L_T \simeq 2L_C$.

Protons from neutron decay will also be subject to pair production and pion photoproduction collisions with photons. Although the radiation field is anisotropic, the protons' directions will be isotropized by the diffusion process. This means that the protons effectively see an isotropic field of energy density $U_{\text{rad}} = L_C/4\pi r^2 c$. We use the results of Monte Carlo simulations discussed earlier to estimate the attenuation time scale for proton-photon collisions $t_{p\gamma} = E/(dE/dt)_{p\gamma}$. The attenuation time scale is used rather than the interaction time scale because in pair production only a small fraction of the proton's energy is lost.

We approximate the probability of a proton from neutron decay surviving pp and $p\gamma$ collisions by

$$P_{\text{surv}} \simeq t_{\text{esc}}^{-1}/(t_{\text{esc}}^{-1} + t_{pp}^{-1} + t_{p\gamma}^{-1}),$$

where the time scales are worked out at radius $r = r_0$.

We show in Fig. 1(a) (solid lines) the spectrum of neutrons produced as a result of injecting one proton into the accelerator for the case where $b = 1$ (Bohm diffusion coefficient) and $x_1 = 30$ for various luminosities. We use the probability of neutrons escaping from the central region without undergoing $p\gamma$ collisions, together with the probability of protons from neutron decay surviving pp and $p\gamma$ collisions to obtain the spectrum of protons escaping from the enhanced density region of the accretion flow. We expect these protons will then readily escape from the host galaxy as extragalactic cosmic rays. We have added to Fig. 1(a) (dashed lines) the escaping cosmic ray spectrum per injected proton.

It is possible that the UV bump radiation may be produced at radii significantly outside the shock radius while only the power-law component is produced in a region coincident with the shock region (radius R). We have considered the effect of this scenario on the probability of neutrons from the central region escaping from the intense radiation field. We show in Fig. 1(b) results that

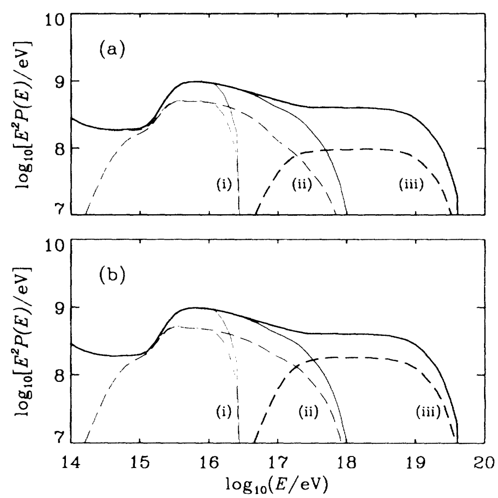

FIG. 1. Spectra of neutrons produced (solid curves) and cosmic-ray protons escaping from an AGN (dashed curves) per low energy proton injected into the accelerator. Results are multiplied by E^2, and are given for $L_X = 10^{42}$ (curves i), 10^{45} (curves ii), and 10^{48} erg s^{-1} (curves iii). In each case, $P(E)dE$ gives the number in the range E to $E + dE$ per injected proton. The reduction at high energies is due to interactions of neutrons with photons during escape from the central region, while the reduction at low energies is due to interactions of protons from neutron decay with protons in the accreting plasma. To obtain the matter densities, we have assumed spherical accretion; nonspherical accretion could give rise to more protons escaping from the AGN at lower energies. Part (a) applies to the case where the source region for both the power-law and blackbody components of the AGN continuum are coincident with the region inside the shock radius R. In part (b) we consider the effect on the escaping spectrum of the blackbody component being produced inside radius $10R$.

would apply if the UV bump photons were produced in a region of radius $10R$. As can be seen, the effect is to increase the spectrum of escaping cosmic rays at high energies. At 10^{17} eV, we would estimate the effect on the cosmic ray spectrum from AGN will be to increase it by about 40%.

We assume that secondary $e^{\pm}$ and γ rays will cascade in the radiation field and ultimately produce the observed AGN continuum. From our simulations, the energy going into $e^{\pm}$ and γ rays per injected proton is $W_{e\gamma} = 7$–10 GeV for $E_{\max} = 10^{15}$–10^{19} eV. We can then multiply the results in Fig. 1 by $L_C/W_{e\gamma}$ to get the spectrum of cosmic rays leaving individual AGN.

If we know the local luminosity function of AGN, i.e., the number density of AGN per unit of luminosity, how the luminosity function evolves with redshift z, and the differential luminosity of escaping protons, dL_{CR}/dE (eV s^{-1} eV^{-1}), then we can perform an integration over redshift and luminosity to obtain the cosmic-ray intensity from AGN. We follow Stecker *et al.* [7] and use the x-ray luminosity function. For our assumed AGN continuum spectrum, the 2–10 keV luminosity is related to L_C by $L_X \simeq 0.05 L_C$. For the Einstein–de Sitter model ($q_0 = 0.5$) we obtain

$$\frac{dI_{CR}}{dE} = \frac{1}{4\pi}\frac{c}{H_0}E^{-1}\int_0^{z_{\max}} dz\,\frac{g(z)}{f(z)}(1+z)^{-\frac{5}{2}}\int dL_X\,\rho_0\left(\frac{L_X}{f(z)}\right)\frac{dL_{CR}}{dE}\{(1+z)E, L_X\},$$

where $\rho_0(L_X)$ [cm^{-3} (erg s^{-1})$^{-1}$] is the local x-ray luminosity function of AGN, and f and g describe the evolution of luminosity and number density in comoving coordinate space. AGN data [24], after making a bolometric correction, appear consistent with $\log_{10} x_1$ having a flat distribution for $10 < x_1 < 100$ and we have included an integration over x_1 for this distribution. We use the parameters of models A–D of Morisawa *et al.* [25] to describe the luminosity function and its evolution. We have made a similar calculation of the neutrino intensity using the same AGN model [21], and our results are in excellent agreement above 10^{15} eV with those of Stecker *et al.* [7] provided their fluxes are reduced by a factor of $3^{2.6}$ to take account of an error in the luminosity function they used. Our results on the cosmic-ray spectrum are shown in Fig. 2 for $b = 1$ and $b = 10$ where they are compared with a recent survey of the observations [26]. To show the sensitivity of our result to the assumptions, we also plot results for an AGN continuum comprising a power law with differential index -2.0 extending from 10^{-3} eV to 1 MeV, plus a UV bump with $T = 26\,000$ K. The maximum proton energies for this case are lower, and this is because of interactions with infrared photons during acceleration.

It turns out that our result is rather insensitive to the way we estimate the magnetic field at the shock. If we had assumed the magnetic pressure at the shock to be equal to the ram pressure of accreting matter then we would have obtained only a slightly higher acceleration rate, a factor of ~ 3 higher for $x_1 = 10$ and ~ 6 higher for $x_1 = 100$. Perhaps the largest uncertainty in our calculations arises due to the uncertainty of about a factor of 2 in the value of L_C/L_X adopted. For example, if L_C/L_X were increased by a factor of 2 then the main effect on our results would be to increase the predicted cosmic-ray flux by approximately a factor of 2 at all energies. Bearing this in mind, for $b = 1$ (Bohm diffusion) and the infrared-deficient AGN continuum spectrum, it is not impossible for proton acceleration in AGN to account for all the observed cosmic-ray flux from 10^{16} to 10^{19} eV. With less optimistic conditions for acceleration to the highest energies, $b > 1$ or an AGN continuum spectrum in the central region extending to the infrared, the spectrum above the knee is steeper than that observed. Nevertheless, in the region of the knee one would still expect a substantial fraction of the observed cosmic rays to originate in AGN.

Note that our predictions shown in Fig. 2 have not

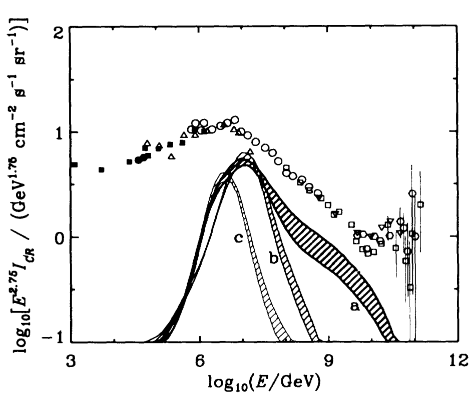

FIG. 2. Predicted cosmic-ray spectrum due to acceleration in AGN. The hatched bands give the range between the lowest and highest intensities obtained for the four models of the AGN luminosity function considered [25]. For an intergalactic diffusion coefficient $D > 3 \times 10^{34}$ cm^2 s^{-1} at 10^{16} eV cosmic rays from more than 500 AGN could have reached the Earth in the age of the Universe. Results are shown for the AGN continuum spectrum adopted (deficient in infrared at the shock) for a ratio of scattering mean free path to gyroradius of $b = 1$ (band a) and $b = 10$ (band b). Results for an alternative AGN continuum with enhanced infrared density at the shock and $b = 1$ are given (band c). Observations are from the survey by Stanev [26]. No normalization to cosmic-ray data has been made. Extragalactic cosmic rays are subject to galactic modulation, but for reasonable galactic wind parameters this is unimportant for rigidities above $\sim 10^{14}$ V [W.-H. Ip (private communication)].

been normalized in any way to the cosmic-ray data and are determined solely by the accretion-shock acceleration model used and by the observed x-ray luminosity function of AGN. We find it quite remarkable that the predicted contribution from AGN to the cosmic-ray spectrum is of the same order of magnitude as the observed intensity in the region of the knee and higher energies. As already mentioned, minor adjustments to the model, for example, by increasing the ratio of L_C to L_X by ~ 2 in the assumed AGN continuum, could be made to give even better agreement with the observations at 10^{16} eV.

We conclude that AGN may be an important source of cosmic rays in the region of the knee. The enhancement which appears to be present at the knee may be due to this extragalactic component. Although we have only considered the acceleration of protons in the AGN model, heavier nuclei will also be accelerated. However, no heavy nuclei will escape from the central region as they will be broken up in interactions with photons in the central region. Thus, any extragalactic component in the region of the knee will be 100% protons. If this model is correct, then one would expect to observe an enhancement in the relative abundance of protons in the cosmic rays at $\sim 10^{16}$ eV. At present the data in this energy range are indirect, being based on air shower data, and their interpretation is controversial. However, first indications from a recent study of the cosmic-ray composition using the MACRO detector at Gran Sasso [27] favor a light composition at energies up to several thousand TeV. Future experiments may well be able to measure the composition more directly.

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