In Search of a Source for the 320 EeV Fly's Eye Cosmic Ray

Jerome W. Elbert and Paul Sommers

High Energy Astrophysics Institute

Department of Physics, University of Utah

Salt Lake City, UT 84112, USA

ABSTRACT

The 320 EeV air shower detected by the Fly's Eye poses an important problem. Careful analysis of pathlength limitations for the possible particle types due to cosmic background radiation verifies that the particle very likely traveled less than 50 Mpc from its source. The best candidates for accelerating particles to such high energies are the very powerful radiogalaxies, however they are all more than 100 Mpc distant. Our search finds no likely source within 50 Mpc in the direction from which the particle arrived. This prompts consideration of less likely astrophysical sources, like M82, as well as non-standard mechanisms like cosmic string annihilation. It is also conceivable that the air shower was produced by some non-standard particle whose pathlength is unlimited because it does not interact with the cosmic background radiation. A less radical alternative is that relatively strong magnetic fields deflected the particle's path through a large angle, so it could have originated at a nearby radiogalaxy at an earlier time of strong activity.

Subject headings: acceleration of particles – cosmic rays – cosmic strings – galaxies: magnetic fields – elementary particles – galaxies: intergalactic medium

1 Introduction

Discovering the origins of the highest energy cosmic rays has been a goal in astroparticle physics for three decades since the first reported detection of a particle with energy greater than 100 EeV (10^{20} eV) (Linsley 1963). The Fly's Eye air shower with energy 320 ± 93 EeV should be a useful clue (Bird et al. 1994). This energy is substantially higher than that of any previously reported cosmic ray, and the issues concerning its origin are much more sharply focused. At such high energy, particles cannot propagate long distances through the cosmic background radiation. As will be discussed in detail in section 2, the pathlength is almost surely limited to less than 50 Mpc. The magnetic rigidity of such a particle, moreover, is large enough that it should be deflected little by the Galaxy's magnetic disk or by the smaller extragalactic fields which may exist between us and the source. In that case, the arrival direction of the air shower should point approximately toward its source, and the source should be a prominent astrophysical object within a distance of 50 Mpc.

There is, unfortuneately, no likely astrophysical source for such a high energy particle near its arrival direction and within 50 Mpc. Details of our search for a candidate source will be presented in section 3. Ordinary galaxies are not expected to accelerate particles to such high energy. Hillas (1984) analyzed the source requirements. Acceleration models generally require magnetic media moving with high relative velocity, and the models need a large value for the product of magnetic field strength times the characteristic size of the astrophysical system. Giant radiogalaxy hot spots most nearly meet the requirements. Rachen and Biermann (1993) have argued that some hot spots may indeed possess conditions which would produce such energetic particles by first-order Fermi acceleration. Acceleration at an accretion shock of a massive black hole in an active galactic nucleus is *not* a viable model because of the high photon densities there and the consequent rapid energy losses due to collisions with them (Stecker et al. 1991). It is conceivable, however, that an explosion in a galactic nucleus could cause a strong magnetic shock at a larger radius where photon densities are low enough to permit the acceleration. In shock acceleration scenarios, one might expect that there should also be accelerated electrons which would produce strong radio emissions. Our search in section 3 therefore emphasizes extragalactic radio sources near the arrival direction of the Fly's Eye air shower.

The arrival direction of the Fly's Eye air shower in 1950 celestial coordinates is ($\alpha = 85.2° \pm 0.5°$, $\delta = 48.0° \pm 6°$). The uncertainty in right ascension is small because the track-detector plane nearly contains the celestial poles (Bird et al. 1994). The directional uncertainty within that plane produces the larger uncertainty in declination. In galactic coordinates, the error box is centered on ($b = 9.6°$, $l = 163.4°$).

Since the arrival direction of the 320 EeV particle does not point to any obvious source within the distance limit, there may be some new physics or astrophysics to be learned from it. Some hypotheses to be considered in this paper are the following:

(1) Perhaps there are larger-than-expected magnetic fields outside the Galaxy. It is then possible that the particle's trajectory was bent through a large angle. It is important to note that its pathlength would then be much longer than that of photons with which we observe astrophysical sources. For example, the radiogalaxy Centaurus A is at a distance of about 3 Mpc (Hesser et al. 1984), but makes an angle of 136° with the arrival direction of the 320 EeV particle. For a trajectory of constant curvature, the particle would have a pathlength of 10 Mpc, which means it was produced more than 20 million years prior to the emission of the photons which constitute our current picture of Cen A. That time is longer than the decay time for strong radio galaxy activity (Schmidt 1966; van der Laan & Perola 1969). It is likely that Cen A was indeed extremely active in the past (Hey 1983). It has two sets of radio lobes (Clarke, Burns & Norman 1992), and the separation of the outer set is as great as in the strongest radiogalaxies like Cygnus A (Dreher, Carilli & Perley 1987). Cen A is not the only candidate source if such extragalactic magnetic trajectory bending is possible. Virgo A, whose direction makes an angle of 87° with the arrival direction of this particle and whose distance is 13-26 Mpc, also has a double-lobe structure on a much larger scale than that of the jet which is currently active (Kotanyi 1980).

(2) Less magnetic bending is needed if the particle originated at the starburst galaxy M82, whose direction differs only by 37° from the particle's arrival direction and which is only about 3.5 Mpc away. (The distance to M81, a member of a group of galaxies which includes M82, has been discussed recently by van den Bergh (1992), de Vaucouleurs (1993), and Madore, Freedman, and Lee (1993).) If the energy of this shower was actually near 230 EeV (near the experimental 1σ lower limit), then the shower's primary particle could

have been a nucleus of $Z \sim 18$ surviving from an iron nucleus accelerated to about 340 EeV at M82. The magnetic rigidity of a highly charged nucleus would be low enough that the deflection through 37° could be achieved by our Galaxy's magnetic disk. Also, the acceleration to superhigh energy is easier for a highly charged nucleus (like iron) than for a proton. Strong magnetic shocks may be associated with the intense starburst activity and superwind, and such shocks might accelerate nuclei to superhigh energies. The high density of expanding supernova shells in the starburst regions might also produce superhigh energy nuclei.

(3) Although there are no nearby likely sources near the direction of the detected air shower, there are some interesting objects near that direction at greater distances. One of these is the Seyfert galaxy MCG 8-11-11, also known as UGC 03374, which is at a distance of 62-124 Mpc (for Hubble constant in the range 50-100 km s^{-1} Mpc^{-1}). It has a strong luminosity of 7×10^{46} erg/s in low energy gamma rays. A comparable luminosity above 320 EeV would be more than enough to account for the Fly's Eye detection, despite the attenuation factor of 0.0028 associated with propagating 62 Mpc. This picture raises a question, however, as to why there should not be a large flux of particles from roughly the same direction at lower energy (10-50 EeV), where attenuation would be insignificant.

(4) One way to avoid that question is to conjecture that there is some type of particle which is immune to interactions with the cosmic background radiation, but which produces a normal air shower in the atmosphere. For example, perhaps neutrinos have a much higher interaction cross section than expected at such high energies. Or perhaps the shower was produced by some other non-standard neutral particle. Such conjectures can avoid the distance limits. It is then interesting to note that there is a remarkable quasar (3C147) within the nominal error box for the arrival direction of this shower. That source has a radio luminosity more than 2000 times greater than Cen A or Virgo A, and there is observational evidence for strong magnetic fields there. Even with no attenuation, however, its distance is so great that the luminosity required above 320 EeV probably exceeds the total luminosity of the quasar.

(5) The puzzle of the missing source can be resolved alternatively by supposing that the particle was not accelerated at any persistent astrophysical object, but originated instead from the annihilation of some topological defect like a cosmic string (Aharonian, Bhat-

tacharjee, & Schramm 1992). Such annihilations are expected to result in the production of GUT-mass particles ($mc^2 \approx 10^{24}\ eV$) which decay to superhigh energy hadrons. The superhigh energy flux reaching Earth might be dominated by neutrinos and gamma rays resulting from pion decays. The Fly's Eye measurement of the shower's longitudinal profile does not exclude a gamma ray as the primary particle. A cosmic string annihilation is a viable scenario.

We assume throughout this paper that the 320-EeV particle did not originate in the Galaxy. This is partly because it is not expected that conditions exist anywhere in the Galaxy for accelerating particles to such high energy, based on the arguments of Hillas (1984). In addition, the Fly's Eye composition and anisotropy studies have suggested that the highest energy cosmic rays do not originate in the Galaxy's disk (Bird et al. 1993a). Furthermore, the arrival direction of this shower does not point toward the Galactic center or any prominent galactic source of high energy radiation. It is more than 20° from either the Crab nebula or Geminga. The fact that its arrival direction is less than 10° from the Galactic plane might suggest a galactic origin. It should be noted, however, that 18% of the Fly's Eye's exposure is within 10° of the galactic plane, so the equatorial latitude of this shower could be an accident. Also, tracing backward the trajectory of a positively charged particle with this arrival direction through the Galaxy's regular magnetic field, it is observed to bend northward away from the Galactic plane rather than curving back toward any source at the plane. Acceleration in an extended halo of the Galaxy cannot be ruled out. In the Jokipii and Morfill (1985) model, however, particles do not reach 320 EeV per nucleon, and heavy nuclei photodisintegrate before reaching 320 EeV total energy. For these reasons, the source of the extraordinary Fly's Eye shower is assumed to be extragalactic.

2 Distance limits

2.1 Nucleons

At 320 EeV, a proton or neutron loses energy primarily through pion photoproduction:

$$p\gamma \Rightarrow p\pi^0 \qquad or \qquad p\gamma \Rightarrow n\pi^+ \tag{1}$$

$$n\gamma \Rightarrow n\pi^0 \qquad or \qquad n\gamma \Rightarrow p\pi^-. \tag{2}$$

The charge exchange reactions are approximately as common as those in which the nucleon isospin does not change. The mean free path is approximately 5 Mpc, and the emerging nucleon typically gets 80% of the incoming nucleon's energy. The 2.73° microwave photons constitute the main targets. The neutron decay mean free path (3 Mpc) is less than the collision mean free path, so a nucleon spends the majority of its time as a proton. At this energy, the energy loss rate due to $e^{\pm}$ pair production (Blumenthal 1970) is negligible compared to the pion photoproduction losses.

We have analyzed the effects of pion photoproduction on nucleon propagation using Monte Carlo programs which follow the history of a nucleon through successive interactions until its energy has been reduced below a threshold value. A brief account of the Monte Carlo method is given here. We begin by considering a nucleon of energy $E = \gamma mc^2$ moving through an isotropic intensity of photons of energy ε. Denoting by θ the angle a photon's direction makes with the nucleon's direction, the effective interaction cross section is

$$\sigma_{eff}(\varepsilon) = \frac{1}{4\pi}\int_0^{\pi} 2\pi sin\theta(1 - cos\theta)\sigma(\varepsilon')d\theta \equiv \frac{1}{2\gamma^2\varepsilon^2}\int_0^{2\gamma\varepsilon} \varepsilon'\sigma(\varepsilon')d\varepsilon', \tag{3}$$

where $\varepsilon' \equiv \gamma\varepsilon(1 - cos\theta)$ is the photon's energy in the nucleon's restframe, and $\sigma(\varepsilon')$ is the total interaction cross section for a γN interaction as a function of γ-ray energy ε'. In the 2.73°K blackbody radiation, the (inverse) mean free path is gotten by integrating over the photon energies:

$$\lambda^{-1} = \int_0^{\infty} \frac{dn}{d\varepsilon}\sigma_{eff}(\varepsilon)d\varepsilon = \frac{1}{2\pi^2\hbar^3c^3\gamma^2}\int_0^{\infty} \frac{1}{e^{\varepsilon/kT} - 1}\{\int_0^{2\gamma\varepsilon} \varepsilon'\sigma(\varepsilon')d\varepsilon'\}d\varepsilon. \tag{4}$$

For $\sigma(\varepsilon')$, we use the total cross section shown in Figure 2 of Hill & Schramm (1985). The mean free path λ defines an exponential pathlength distribution from which the Monte Carlo program samples an interaction step. The γ-ray energy ε' is sampled from the distribution implicit in the above integration. The center-of-momentum energy is thereby determined, and the nucleon's outgoing energy is determined once its direction in the center-of-momentum frame is chosen from an isotropic distribution (Hill & Schramm 1985).

A Monte Carlo simulation was used to evaluate the changes in a proton spectrum after propagation through various fixed distances ranging from 3 Mpc to 100 Mpc. Protons were sampled from a power law spectrum with a differential spectral index γ =2.5. The sampled energies ranged from 10 EeV to 10^4 EeV. Results are given in Figure 1a. The vertical axis gives the resulting *integral* spectrum multiplied by $E^{\gamma-1}$ and the vertical scale is arbitrarily normalized to unity for an unmodified spectrum. Separate curves are plotted for the different propagation distances. The effects on the spectrum are minimal below about 30 EeV, but become significant near 100 EeV. The attenuation is more severe for greater path lengths and the spectrum is reduced by a factor of about 0.005 for the integral flux above 320 EeV after a pathlength of 50 Mpc.

Of special interest here is the fraction of particles produced above 320 EeV which remain above that energy after various propagation distances. In Figure 2a the surviving fraction of the integral flux above 320 EeV is plotted as a function of propagation distance. The solid, dashed, and dotted lines represent results for $\gamma = 2.0$, 2.5, and 3.0, respectively. All curves show attenuation by more than or approximately 2 orders of magnitude for a propagation distance of 50 Mpc. The most penetrating spectrum is that with $\gamma = 2.0$. Compared with the other spectral indices, the mean proton energy at production is highest for $\gamma = 2.0$ and the mean free path is *shortest*, but the higher energy allows a larger number of interactions to occur before the proton energy falls below 320 Eev. The second factor (more interactions possible before dropping below 320 EeV) dominates, so that the "hardest" spectrum is the most penetrating. Roughly speaking, however, all three spectra are attenuated approximately exponentially, with attenuation lengths near 10 Mpc.

We can use figure 2a to derive a "2σ distance limit." In order to do this, we assume that the source of the 320 EeV shower has a production spectrum no flatter than a power law with differential spectral index 2. We also assume that magnetic deflection from the source direction is not greater than about 30° for protons of 10 EeV and above. All nucleons above 10 EeV from the source should then arrive within a $2\pi/3$ *sr* sky region centered on the galactic anticenter direction. It has been reported (Bird et al. 1993b) that the Fly's Eye detected 71 showers above 10 EeV from that region of the sky. Allowing for a 2σ downward fluctuation in the detected flux, the expected number above 10 EeV from the source cannot be greater than 90, and pion photoproduction attenuation is negligible at 10 EeV. Using an E^{-1} dependence for the integral flux gives 2.81 as the upper limit for the expected number of showers above 320 EeV from the source if there were no attenuation. We assume that the probability of detecting at least one shower above 320 EeV from the source was not less than 0.0454 (the 2σ probability level). Let F(D) be the integral flux reduction factor plotted in Figure 2a. Then $2.81 \times F(D) \geq 0.0454 \;\Rightarrow\; F(D) \geq 0.0162$. From Figure 2a, it is seen that this relation is satisfied only if D$\leq$47 Mpc. Therefore, 47 Mpc is a 2σ distance limit for nucleons. (This argument implicitly uses the fact that the Fly's Eye acceptance is almost independent of energy above 10 EeV.) For the source search of section 3, we round off this distance limit to 50 Mpc.

An example may clarify the reasoning which leads to this 2σ distance limit. Suppose the 320 EeV particle came from the Seyfert galaxy MCG 8-11-11. For a Hubble constant of 100 km s^{-1} Mpc^{-1}, its distance is 62 Mpc. The integral flux reduction factor at 62 Mpc (from Figure 2a) is $F(62) = 2.8 \times 10^{-3}$. We assume that the Fly's Eye was not extraordinarily lucky to detect that shower, i.e. the probability was at least as great as the 2σ probability 0.0454. In order to have a probability of at least 0.0454 for detecting a shower above 320 EeV after an integral flux reduction by 2.8×10^{-3}, the expected number of detected particles without attenuation would have to be at least 15.1 (i.e., 0.0454/0.0028). Then, under the assumption that its integral production spectrum is no flatter than E^{-1}, we find that the expected number is at least 483 above 10 EeV (where attenuation is negligible). This exceeds the experimental 2σ upper limit of 90 events from all sources in the $2\pi/3$ sr sky region which includes MCG 8-11-11. (In fact, it exceeds the number observed from *all* parts of the sky above 10 EeV.) In brief, MCG 8-11-11 is far enough away that detecting even a single shower from its attenuated flux above 320 EeV would imply (assuming an E^{-1} or softer integral source spectrum) a detectable flux above 10 EeV in excess of the observational upper limit. MCG 8-11-11 is therefore beyond the 2σ distance limit.

There is an alternative method for evaluating a distance limit which does not require any assumption about the source spectrum or any evaluation of what the observed flux would be in the absence of attenuation by pion photoproduction. Instead, it relies on an assumption that sources may occur anywhere and are located uniformly in space. Then we can ask for the probability that a particle with E$\geq$ 320 EeV traveled a path length D or greater before its detection. This amounts to asking, for the totality of particles above 320 EeV, "What is the fraction of the time spent at path lengths greater than D from the production sites?" The dependence on D of this probability is plotted in Figure 3a, where the different curves represent different spectral indices as in Fig. 2a. The probability that the source is beyond 50 Mpc is less than 0.007 in all three cases. The assumption of a spatially uniform distribution of possible sources may be appropriate for the model of topological defect annihilations. It is also an interesting approximation if superhigh energy particles can originate in normal galaxies or other common astrophysical entities. Like Figure 2a, Figure 3a shows an approximately exponential dependence on distance with attenuation length near 10 Mpc. The interpretation that we give to this result is that, without specific knowledge about the sites of superhigh energy particle production, the best guess is that the particle traversed a pathlength on the order of 10 Mpc.

2.2 Nuclei

Collisions of Universal Microwave Radiation (UMR) photons with high energy nuclei are important in the energy range near 320 EeV. The importance of these effects for the propagation of energetic nuclei was noted by Greisen (1966) and by Zatsepin and Kuz'min (1966). Stecker (1969) calculated characteristic lifetimes for ^{4}He and Fe nuclei in the UMR and found that the photodisintegration effects begin to produce significant limitations (mean lifetimes $\tau \ll 10^{10}$ yr) in the energy range 10 EeV (for He) to 100 EeV (for Fe).

Based on equation 4, we have performed simulations of the propagation of various energetic nuclei. In developing the Monte Carlo programs it was necessary, for incident nuclei of nuclear mass i and fragments of nuclear mass j, to find appropriate photo-spallation cross sections $\sigma_{ij}(\epsilon')$ for all ϵ' (nuclear rest frame gamma ray energies) of interest and for all $i \leq 56$ and all $j < i$. The simulations were done for nuclei with initial energies ranging from 10 to 10^4 EeV. For $\epsilon' \leq$150 MeV, these cross sections are available from Puget, Stecker, and Bredekamp (1976).

However, $\epsilon' >$150 MeV sometimes occurs in the present simulations. For example, a head-on collision of a UMR photon with a typical energy $\epsilon = 6 \times 10^{-4}$ eV gives $\epsilon' = 3.2$ GeV in the center of mass system of a 10^4 EeV ^{4}He nucleus. Consequently it was necessary to estimate higher energy cross sections than are available in Puget et al. (1976).

Several fitted approximations to photonuclear spallation cross sections have been done which extend into the GeV energy range. A number of approximations done for incident protons and gamma rays are modifications of the form given by Rudstam (1966). Although Rudstam fitted data for incident protons, Jonsson and Lindgren (1973, 1977) used a related 5 parameter formula for photo-spallation data. They pointed out similarities between three of their parameters and those of Rudstam, but they noted differences between the cases of incident gamma rays and incident protons. The most important difference was in the normalization of the cross sections. Jonsson and Lindgren (1973) approximated the total cross section factor by $\hat{\sigma} = 0.3A_t$ (mb) for photo-spallation, where A_t is the mass number of the target nucleus, while Rudstam gave $\hat{\sigma} = 50A_t^{2/3}$ (mb) for proton-induced spallation.

Silberberg and Tsao (1973a,b) give extensive and detailed fits to nuclear spallation data for incident protons. We have used this model with a renormalization factor given by the ratio of the above $\hat{\sigma}$ approximations for incident photons and protons. The factor is $0.006A_t^{1/3}$. The model parameters were taken from Tables 1-A to 1-D of Silberberg and Tsao (1973a), except that the formulas for peripheral reactions (Silberberg and Tsao 1973b) were used for photo-production of a single proton, or one to three neutrons, or a single proton and a number of neutrons (fewer than some specified number which depends on the target nucleus mass.) The resulting cross sections are in reasonable agreement with photospallation data for the production of ^{24}Na on nuclei with 10 A_t values ranging from 27 to 64 shown in Fig. 7 of Jonsson and Lindgren (1973). A comparison of the discontinuities at 150 MeV between the cross sections obtained by this method and those of Puget et al. (1976) show rms deviations of about a factor of 3. The cross sections described here were used only for $\epsilon' >$150 MeV and, considering the discrepancies noted above, are regarded only as estimates in the GeV energy range.

Equation 4 can be used to give the mean free path for nuclear spallation in a single radiation field. We have followed Puget et al. (1976) in including contributions from microwave, optical, and infrared radiation. The microwave radiation was evaluated for a 2.73 K black body. Following Puget et al. (1976), the intergalactic optical spectrum was estimated assuming a 5000 K black body, whose photon density is reduced by a factor of 1.2×10^{-15}. The infrared spectrum was taken from De Jager, Stecker, and Salamon (1994) who found $n(\epsilon) = 0.6 \pm 0.3 \times 10^{-3}\epsilon^{-2.6}(H_0/75$ km s^{-1} Mpc^{-1}) $cm^{-3}eV^{-1}$. The infrared spectrum is used for photon energies from 0.002 eV to 0.8 eV. Besides spallation, the nuclei lose energy by pair production. We have included the pair production loss rates given by Puget et al. (1976) in a continuous energy loss approximation in the Monte Carlo simulations.

For nuclei starting out with masses A=12 (C) and A=56 (Fe), results were obtained which are displayed in Figures 1-3 along with results for protons which were discussed in the previous section. For all the plots involving nuclei, the energies are the total energies per remaining nucleus, and fragments with $A < 3$ are ignored. Figures 1b (for C) and 1c (for Fe) show the fraction of the integral spectrum remaining after nuclei have traveled various distances. There are some similarities in shape between these curves and those from protons, but the differences are important. The flux reduction is more severe for nuclei than for protons. For energies above 200 EeV, both C and Fe are severely attenuated for distances above 10 Mpc. Below 100 EeV, the attenuation is more severe for C than for Fe, although for 3 and 10 Mpc C is more penetrating than Fe at 320 EeV. As energy increases for both the C and Fe curves at 10 Mpc there is a sharp fall followed by a rapid transition to a much flatter region. In these all-nuclei spectra, these flatter regions correspond to the emergence of the spectra of lower A, higher γ fragments which have weaker energy dependence of the nucleon loss rates than the initial nuclei.

In Fig. 2b (for C) and Fig. 2c (for Fe) the surviving fractions of the integral spectra above 320 EeV are shown for 3 spectral indices. If we approximate these curves by exponentials (not a very good approximation for Fe at $D < 3$ Mpc), the characteristic lengths are near 1.5 Mpc for C and on this order of magnitude for Fe. The distributions of path length probabilities (defined in the previous section) are shown in Fig. 3b (for C) and Fig. 3c (for Fe). The results are numerically similar to those of Figures 2b and 2c. Although only results for C and Fe are displayed here, all A values from 3 to 56 have been simulated in the Monte Carlo program and none have propagation characteristics which are much more favorable that the examples used here. The main conclusion of this section is that for path lengths greater than 10 Mpc heavy nuclei are not attractive candidates for the 320 EeV primary particle except in models in which it is acceptable to have severe attenuation between the point of production and Earth.

2.3 Gamma rays

The propagation of gamma rays through cosmic radiation fields has been studied in detail by others (Gould & Schreder 1967; Wdowczyk, Tkaczyk, & Wolfendale 1972; Halzen et al. 1990). The mean free path between collisions with microwave photons at this energy is 58 Mpc. More important is the radio photon spectrum. There is some uncertainty about the cosmic radio spectrum, but using the spectrum of Clark, Brown, and Alexander (1970), the mean free path for 320 EeV gamma rays is 7.4 Mpc. For radio and microwave photons together, the mean free path is 6.6 Mpc. It has been suggested that the leading electron produced in a $\gamma\gamma$ collision could deliver most of the original gamma ray's energy to a new gamma ray via inverse Compton scattering. If intergalactic magnetic field strengths exceed 10^{-11} G, however, then synchrotron losses will prevent this (Wdowczyk et al. 1972). We here assume that intergalactic fields are at least that strong. The survival probability for 320 EeV gamma rays to distance D in Mpc is then given by

$$P(>D) = exp(-D/6.6). \tag{5}$$

This survival probability becomes less than 1/1000 before reaching a distance of 50 Mpc.

2.4 Neutrinos

The dominant attenuation of 320 EeV neutrinos is due to interactions with the 1.9°K blackbody neutrinos (Yoshida 1994), but the mean time between interactions far exceeds the Hubble time. So neutrinos can come from arbitrarily distant sources. It is implausible that the Fly's Eye air shower was initiated by a neutrino, however, since the interaction probability for such a neutrino should be less than 10^{-5} while traversing the entire atmosphere. Moreover, the point of first interaction should be equally likely at all atmospheric depths, whereas this shower certainly started high in the atmosphere.

On the other hand, the interaction cross section for superhigh energy neutrinos is not experimentally confirmed. Expected cross sections are calculated with the Standard Model, and it is conceivable that new physics at high energies might enhance neutrino cross sections (e.g. Domokos & Nussinov 1987; Domokos & Kovesi-Domokos 1988). If the cross section were as large as hadronic cross sections, then such neutrinos would interact high in the atmosphere, producing air shower developments which could not be distinguished from other cosmic ray air showers on the basis of Fly's Eye data. Searches have been made for deeply penetrating particles in the Fly's Eye data without success (Baltrusaitis et al. 1985; Emerson 1992). Based on the standard cross section calculations, this has been interpreted as a weak limit on the intensity of neutrinos above 0.1 EeV. If the neutrino interaction cross section is large at all energies above 0.1 EeV, however, the Fly's Eye would not be able to distinguish the neutrino intensity from other cosmic rays. This non-standard hypothesis for a large neutrino interaction cross section at extremely high energies offers a speculative way to evade the distance limits which pertain to the other particle types.

3 The source search

An attempt has been made to identify plausible astronomical objects which could have produced the 320 EeV primary particle. As mentioned previously, we believe that the highest energy Fly's Eye showers originate outside the Galaxy. If we exclude the Galaxy, it is reasonable to assume that the source is a galaxy which differs from our Galaxy and similar nearby galaxies in having unusual luminosity in at least some part of the electromagnetic spectrum. The galaxies of interest should be strong radio sources if magnetic fields and large fluxes of energetic particles are present. In the previous section we showed that the ranges of nucleons, nuclei, and gamma rays are less than or on the order of 50 Mpc. Because the distances of interest are small relative to typical distances in radio galaxy catalogs, the number of potential sources is not large and a powerful galaxy in the volume of interest should not have been missed.

If we assume that extragalactic magnetic fields are small (less than about 10^{-9} G), then the primary particle would be deflected by less than about $10°$ from its original source direction. In this case the source direction is probably within $10°$ of the boundaries of a 2σ error box drawn around the shower's reconstructed arrival direction. This region is represented by the outer boundary in Fig. 4. We have searched for potential sources using a catalog of 459 powerful radio galaxies with measured redshifts (Burbidge and Crowne 1979). The galaxies included in this catalog were selected with a cut on radio luminosities ($L > 10^{41}$ ergs s^{-1}.) This cut is appropriate because, as stated by Burbidge and Crowne (1979), "Weak or normal radio galaxies have luminosities in the range $10^{37} - 10^{40}$ ergs

s^{-1}. By using the luminosity criterion given above, we have deliberately omitted from the catalog the large number of comparatively bright nearby galaxies which are weak sources similar to our own galaxy." In this paper, we also make a cut on the redshift parameter, z, which requires $z < 0.0125$ which corresponds, for a Hubble constant of 75 km s^{-1} Mpc^{-1}, to distances less than 50 Mpc. With the redshift cut, but without restricting the directions, 24 candidate galaxies remain, including such well-known galaxies as For A, M82, M84, M87 (Vir A), and Cen A. However, none of the candidate galaxies are within the outer boundary of Fig. 4.

A second search was done using the NASA/IPAC Extragalactic Database (NED) (G. Helou et al. 1991). The goal of this search was similar to that described in the previous paragraph, except that the search was limited to the region inside the outer boundary in Fig. 4. In order to make a cut on the radio luminosity using data taken at various frequencies, a criterion was defined which required the radio luminosity per decade of frequency to exceed 10^{40} ergs s^{-1}. This requires that the measured flux density, S, in Jansky, exceeds S_{min}:

$$S_{min} = \frac{2.3 \times 10^5}{\nu z^2}. \tag{6}$$

The frequency, ν, is given in Hz and z is the redshift parameter of the source. This cut separates sources of exceptional radio luminosity from ordinary sources. We can define a dimensionless luminosity parameter $R_L \equiv S/S_{min}$. (Where multiple radio measurements have been made on a source, the maximum value of R_L is used.) Some examples illustrate the range of the luminosity parameter. For galaxies which are not outstanding in radio emission, such as M31 and M81, the parameter is equal to 0.00002 and 0.002, respectively. The nearby starburst galaxy M82 has $R_L = 0.017$. The prominent radio sources Cen A and M87 give R_L values of 11. and 17., respectively, while 3C147 (discussed further below) gives 4×10^4. With a cut on z ($z < 0.0125$), but no R_L cut, the NED search yielded one galaxy within the outer boundary of Fig. 4. The galaxy is NGC 1569, or Arp 210. However, R_L is 0.0015 for this galaxy. Since the radio luminosity is so unremarkable, this galaxy is not regarded as a likely source.

A second NED search was done which was like the first except that the z limits were enlarged to $z < 0.0148$, which corresponds to a distance of 47 Mpc for the case in which $H_0 = 100$ km s^{-1} Mpc^{-1}. This search yielded an additional candidate, UGC 03351 (or

MCG 10-09-02). Its direction is nearly on the shower-detector plane for the 320 EeV event, but it is nearly 2σ north of the best fit direction. The direction is plotted in Fig. 4. It is a spiral galaxy, type Sab. The z value is near the limit of this search ($z = 0.0148$), and the radio luminosities at 1.4 and 4.85 GHz both give R_L near 0.2. The luminosity of this galaxy is very high in the infrared, with L_{IR} estimated to be 2×10^{11} times the solar luminosity. This galaxy is among a set of 31 identified OH megamasers (Henkel and Wilson 1990). Henkel and Wilson state that as a class, this sample of objects "probably consists of strongly interacting pairs of galaxies undergoing a starburst." Other than this, little information is available which would cause us to suspect that this galaxy is the source of the 320 EeV shower.

The direction of one prominent Seyfert galaxy, MCG 8-11-11, is close to the arrival direction of the 320 EeV shower (see Fig. 4.). It does not pass the cut $z < 0.0125$, since it has $z = 0.0205$. Its radio luminosity yields $R_L = 0.7$, nearly passing the criterion for selecting potential sources. Its X-ray and γ-ray luminosities greatly exceed its radio luminosity (Perotti et al. 1990) so that the observed total luminosity is not discouraging. In the X-ray spectral range from 20-100 keV its luminosity is 4.6×10^{44} ergs s^{-1}, while in the low energy gamma ray range from 0.09-3 MeV the measured luminosity is even higher (7×10^{46} ergs s^{-1}), according to Perotti et al (1981).

Such a large luminosity would allow this source to be considered as a potential source of the 320 EeV shower, in spite of the very significant attenuation that is expected at that distance. There is a serious problem with the scenario involving MCG 8-11-11, however, as described in the previous section. The problem is that a source spectrum at this distance which would have a reasonable chance of producing a 320 EeV shower at Earth would be expected to produce an essentially unattenuated flux of 10 EeV showers at Earth that would be too large to agree with Fly's Eye data. Because of this problem, MCG 8-11-11 is not considered to be a likely source of the 320 EeV shower unless the assumptions in the argument of the previous section are violated. For example, the lower energy ($\sim$10 EeV particles) might be efficiently trapped near the source somehow or the detected particle might somehow be immune to interactions with the cosmic background radiation.

The search described so far has targeted candidate production sites near the arrival direction of the detected air shower. If the extragalactic magnetic field is considerably larger than 10^{-9} G, however, and does not reverse its direction frequently along particle trajectories, the deflection angle of the primary particle can be large. To select potential sources of primary protons or nuclei in this case, we only require the sources to be powerful and nearby, with no cut on the source direction. With the redshift cut ($z < 0.0125$), there are 24 candidates remaining in the Burbidge-Crowne catalog referred to above. It is of interest to discriminate between the candidates on the basis of R_L. In Table 1, candidates are listed which have R_L exceeding unity or radio fluxes at 408 MHz exceeding 10 Jy. The values of R_L have been used to rank the candidates by radio luminosity at 408 MHz. The ranking gives M87, For A, and Cen A as the top 3 choices. These may be outstanding choices as source candidates in the "high" magnetic field model, but there is no clearly favored candidate since the arrival direction is not useful in discriminating between candidates in this case.

Object	Redshift Parameter, z	408 MHz flux Jy	R_L
M87	0.0043	510	17.
For A	0.0063	177	12.
Cen A	0.0016	2400	11.
NGC 4261	0.0073	37	3.5
NGC 5090	0.0110	10	2.1
NGC 4696	0.0093	7	1.1
M84	0.0031	12	0.21
M82	0.0009	12	0.017

Table 1: Nearby high flux radio galaxies

In the above cases, the primary particle was assumed to be deflected by the extragalactic magnetic field and limited in range. A more speculative proposal is that the primary particle was a currently unknown kind of neutral particle (or an already known neutral particle with unexpected high energy properties) which did not suffer energy losses in propagating intergalactic distances. In this case the source could be far away, but it should be powerful and it should be contained within the inner error box shown in Fig. 4. We can search for such a source in a sample of high radio luminosity sources. A "complete sample" of powerful radio sources with $\delta \geq 10°$ has been collected by Herbig and Readhead (1992). There are 173 of those sources, and the expected number in the solid angle of our 2σ error box is 0.24.

One of these sources falls within the inner error box in Fig. 4. It is 3C147. The position of 3C147 is plotted in the figure, where it can be seen that its position is actually within a 1σ error box. Its position might also be consistent with the remarkably high energy shower detected at Yakutsk (Efimov et al. 1991; Sommers 1993). The total radio luminosity of 3C147 is 7.9×10^{44} $erg\ s^{-1}$ (Herbig and Readhead, 1992). It's x-ray luminosity is approximately the same (Zamorani et al. 1981). There are 60 sources in the Herbig and Readhead catalog with radio luminosities as high as this value. Comparing the radio flux at 2.5 GHz, 28 of the 173 sources in that catalog are as bright as 3C147.

Previously we noted the requirements pointed out by Hillas (1984) for extremely high energy accelerators to have large magnetic fields extending over large distance scales. Such large scale fields, combined with large plasma densities, would produce very large Faraday rotations. In a search for extremely high Faraday rotations, Kato et al. (1987) measured the Faraday rotation measures of 100 extragalactic sources which were considered to be candidates for having very large rotation measures. They found a value of $-1,510 \pm 50$ rad m^{-2} for 3C147, putting it in the top four sources in their candidate sample. (The other 96 sources did not give clear evidence for rotation measures with magnitudes exceeding 500 $rad\ m^{-2}$). This result may add some plausibility to the hypothesis that 3C147 could be the source of the primary particle.

The searches described here have assumed that the 320 EeV particle was accelerated at or near a galaxy. If the source of the primary particle were a cosmic string, or some other non-galactic source, there is of course no catalog that can be searched. A cosmic string is intrinsically powerful, it could be nearby, and it could be in any direction.

4 Magnetic bending and nearby radiogalaxies

The source search described in the previous section finds no likely astrophysical source for a 320-EeV particle within the distance limits described in section 2 and near the arrival direction of that shower. One possibility is that the detected particle was a charged particle whose trajectory was bent through a large angle en route from the source. If the bending is due to extragalactic magnetic fields, this means that the line-of-sight distance to the source must be even shorter than the distance limits of section 2. It also means that the charged particle would have been produced long before those photons which are detected in contemporary studies of astrophysical sources. An additional 5 Mpc pathlength, for example, would mean that the acceleration occurred 15 million years prior to the state of the system as it is observed with photons. Although there are no strong radiogalaxy hot spots seen within 50 Mpc at the present time, the situation may have been very different 15 million years ago. The synchrotron lifetime of radio hot spot electrons can be less than the light travel time from the nucleus to a hot spot (Bridle & Perley 1984), less than a million years. Moreover, analyses of radiogalaxy populations indicate that stronger radiogalaxies have shorter lifetimes, with the strongest sources having lifetimes less than 10 million years (Schmidt 1966; van der Laan & Perola 1969). Multiple double-lobe structures in radiogalaxies have been interpreted as evidence for intermittent activity on such time scales (Leahy & Parma 1992). Candidate sources for the 320 EeV particle should therefore include such radiogalaxies even if the lobes do not presently have strong hot spots.

Cen A is a radiogalaxy which is only 3 Mpc (Hesser et al. 1984) or perhaps 5 Mpc (Burbidge & Burbidge 1959) away. It has two sets of double radio lobes. The size of the entire system is as large as that of strong radiogalaxies like Cygnus A. The widely separated radio lobes can be attributed to much greater activity in the past (Hey 1983). The line of sight to Cen A makes an angle of 136° with the arrival direction of the 320-EeV shower, so Cen A is a candidate source only if large magnetic deflection is plausible.

Virgo A (M87) is in the Virgo cluster, at a distance of 13-26 Mpc. It also has multiple lobe structure on large scales (Kotanyi 1980), which could be indicative of greater activity in the past. The line of sight to Virgo A makes an angle of 87° with the arrival direction of the 320-EeV air shower, so large magnetic deflection would be needed for it to be the source also.

Less powerful nearby radiogalaxies are M82 and M84. M82 is a starburst galaxy which is only about 3.5 Mpc away. It makes an angle of 37° with the 320-EeV particle's arrival direction. The possibility that the primary cosmic ray is a heavy nucleus accelerated at M82 is discussed later in this section.

To estimate the strength of magnetic fields required to make any of the nearby radiogalaxies a viable candidate, one can ask what uniform transverse field B_T (in μG) is needed to bend the trajectory of a particle of energy E (in EeV) and charge Z through ϕ degrees in the course of a pathlength D (in Mpc). The Lorentz force produces angular change according to

$$\phi = 5.3 \times 10^4 \; Z B_T D/E. \tag{7}$$

For example, suppose Z=1 and E=320. Then for ϕ to be a 90° bend over a path of D=10 Mpc requires $B_T = 0.05\ \mu G$. Scale sizes for regions of uniform field direction might not be greater than 1 Mpc, however. For a proton trajectory to bend through 90° in 1 Mpc requires $B > 0.5\mu G$. Similarly, $5\mu G$ would be needed over a region of 100 kpc dimension. Ptushkin (1991) estimated that extragalactic fields of 0.1 μG are likely, with directional coherence over distances of about 1 Mpc. That is slightly lower than what may be needed if the 320 EeV particle was a proton whose trajectory was bent from a nearby radiogalaxy.

The required extragalactic magnetic field strength can be reduced by 1/Z if the detected particle were a nucleus with charge Z. Because of photonuclear disintegration, that requires the source to be closer than if it were a proton. For example, an iron nucleus might lose half of its nucleons during a transit of 6 Mpc and arrive with Z=13. The required magnetic field strengths are then reduced by more than an order of magnitude.

Extragalactic fields are usually inferred observationally from Faraday rotation measure studies, which require a sufficiently high product of magnetic field (parallel to the line of sight) times electron density integrated over the thickness of the observed field region. Even relatively strong magnetic fields can go undetected because the electron density is not high and/or the integration distance is not long. Rotation measure studies have succeeded in detecting magnetic fields in regions of adequately high electron densities. For example, a field strength of $1.5\mu G$ has been inferred for a 10 Mpc region centered on the Virgo Cluster (Vallee 1990a). A $2\mu G$ field has been reported in the Coma cluster (Kim et al. 1990), and a field of 0.3-0.6 μG apparently exists between the Coma cluster and the Abell 1367 cluster over a distance of approximately 40 Mpc (Kim et al. 1989). The existence of fields of such magnitude elsewhere suggests that the magnetic fields needed to bend this particle's trajectory might be present.

It is conceivable that cosmic rays produced in the Virgo cluster drive a cluster wind, similar to the solar wind, which might extend to the Local Group and beyond. The magnetic field strength falls like 1/r in such a wind. The integrated magnetic field energy in a wind which extends to a radius of 20 Mpc and has a field strength of 0.1 μG at 20 Mpc is not greater than the field energy in the Virgo cluster's 1.5 μG field if it is uniform out to a radius of 5 Mpc (Vallee 1990a). Active galactic nuclei throughout the history of the Virgo cluster may have provided the energy for building up the observed field and for powering the hypothetical wind.

Disordered magnetic fields may exist as a result of past activity by galactic nuclei which are now dormant, even if there is no cluster wind. A portion of the prodigious energy released by an AGN is converted to magnetic fields at giant radio lobes. Fields of $\sim 100\ \mu G$ seem to envelope the lobes of Cyg A (Dreher et al. 1987), for example. Due to the high plasma conductivity, the dissipation time for such magnetic fields is long compared to the Hubble time (Parker 1979). Relic radio lobes, left from the early universe when quasars were common, may have a high population density within the Virgo Supercluster, including our own neighborhood. They may act as magnetic scattering centers.

Stringent upper limits exist for a uniform magnetic field of cosmological scale, but those limits do not preclude the existence of smaller scale fields capable of bending the trajectory of a 320 EeV particle. Those studies are based on Faraday rotation measures of distant quasars. Although a precise upper limit would require precise knowledge of the universal electron density, a universal magnetic field greater than $10^{-11}\ G$ is inconsistent with reasonable estimates for the electron density (Vallee 1990b). This result does not bear directly on the interpretation of the 320 EeV particle's origin, because it pertains only to a hypothetical field whose direction would be constant over the observable universe.

If this picture of the Fly's Eye particle originating at a nearby radiogalaxy is correct, it is possible that the cosmic ray spectrum above the ankle transition (Bird et al. 1993a) may be dominated by particles from the same source. If 320 EeV protons are magnetically deflected through large angles, then lower energy particles may be magnetically confined in a region containing the source as well as our Galaxy. The lower energy particles may diffuse out more slowly, steepening the spectrum from a source spectral index of 2 to a larger spectral index at detection, as is presumed to happen with Galactic sources and confinement below the spectrum's knee. It is interesting that the spectral index above the ankle transition has been measured to be 2.7 (Bird et al. 1993a).

The trajectory bending has so far been assumed to be accomplished by extragalactic magnetic fields. The possibility of large-angle bending by the Galaxy's fields should also be explored. For $B_T = 3\ \mu G$, Z=1, and E=320, equation 7 gives a deflection of 0.5° per kpc. The pathlength through the magnetic disk should not be greater than about 4 kpc, so the Galaxy's disk should not deflect such a proton more than about 2°. However, there is also the possibility of a galactic wind field (Johnson & Axford 1971; Jokipii & Morfill 1985) extending perhaps to a radius of 0.3 Mpc. Since the B-field of the wind falls as 1/r with radius, the differential form of equation 7¡ is needed:

$$d\phi = 5.3 \times 10^4\ (Z/E)B_T(r)dr. \tag{8}$$

Using $B_T = 3\mu G \times (.01Mpc/r)$ and integrating from r=.01 Mpc to r=.3 Mpc yields an angular deflection of $\phi = 17°$. That is still not enough to make the 320 EeV particle's direction point toward an interesting nearby radiogalaxy if it was a proton. Large angle bending in the Galaxy's wind is plausible, however, for atomic nuclei. In that case, the particle's path need not be much longer than the straight line photon paths, so changes in the source since its production should not be important.

One interesting possibility is that the Fly's Eye detected a nucleus which originated in M82 as an iron nucleus. Although M82 is only 3.5 Mpc away, this scenario seems unlikely unless the true energy of the particle was less than 320 EeV. Nuclei disintegrate too rapidly at energies above 300 EeV. The picture can work, however, if we assume that the energy of the detected particle was actually 230 EeV, which is within the 1σ error bar on its energy. As shown in Figure 5, a differential spectrum of starting iron nuclei develops a pile-up bump near 230 EeV after propagating 3.5 Mpc. The mean mass in the bump is $<A>=38$ and the mean charge is $<Z>=18$. We can therefore picture M82 as the source of an original iron nucleus with an energy of ~340 EeV which was detected at Earth as a Z~ 18 nucleus of energy ~230 EeV.

Even the magnetic disk of the Galaxy might then account for a 37-degree deflection of the 230 EeV nucleus with Z=18. For $\phi = 37°$, $B_T = 3\ \mu G$, and Z=18, equation 7 requires only a pathlength of $D = 0.0030\ Mpc = 3.0\ kpc$ through the Galaxy's magnetic disk. This is not unreasonable for this particle, in view of its equatorial arrival direction ($b = 10°$). The regular magnetic field of the Galaxy is known to be parallel to the galactic plane and point approximately toward $b = 90°$ (Rand & Kulkarni 1989). The position of M82 ($b = 41°$, $l = 141°$) could then be consistent with this particle's arrival direction ($b = 9.6°$, $l = 163°$) if it had that positive charge. The atmospheric depth of maximum of the air shower is also compatible with it being a mid-size nucleus.

Although M82 is not a strong radiogalaxy, it has been described as the archetypal starburst galaxy (Fitt and Alexander 1993) and as a prototype of superwind galaxies (Heckman et al. 1990). More than 40 discrete radio sources have been observed within the central 700 pc of M82 (T.W.B. Muxlow et al. 1994) most of which are supernova remnants which are probably only a few hundred years old. If older remnants are considered, the number must be very large. Atomic nuclei might be accelerated to superhigh energies through collisions with numerous expanding supernova remnants (Axford 1991). A bipolar magnetic field of perhaps 50 μG is oriented perpendicular to the galactic plane (H.-P. Reuter et al. 1992). In a magnetic field of that strength, the gyroradius of a 370 EeV iron nucleus would be only ~300 pc. There is also a kpc-scale bipolar wind which is emitted perpendicular to the galactic plane, originating in the starburst region (Bland and Tully 1988). As in the model of Jokipii and Morfill (1985), the termination shock of the galactic superwind provides a possible site for the acceleration of superhigh energy nuclei. Shock acceleration could be especially efficient where the superwind meets galactic winds from its neighbors, M81 and NGC 3077.

5 Discussion

There is no simple explanation for the 320 EeV cosmic ray detected by the Fly's Eye. The distance limits of section 2 imply that it originated within a radius of 50 Mpc. Very powerful radiogalaxies are the best candidate sources for such energetic particles, but these radiogalaxies are more than 100 Mpc away. We have suggested that some nearby radiogalaxies, such as Cen A or Virgo A, may have been much stronger in the past when this particle was produced. Because it did not follow a straight line trajectory (there are no close enough candidate sources near its arrival direction), it would have been produced long before the photons with which we study the nearby radiogalaxies. The viability of this hypothesis hinges on the existence of extragalactic magnetic fields which are capable of bending its trajectory. Because of the particle's high magnetic rigidity, relatively strong fields are needed. We have argued that such strong fields are not excluded observationally and may not be implausible.

The problem of magnetic bending is less severe if the detected particle was a highly charged nucleus. It is then possible that it was deflected significantly by the Galaxy's magnetic field. As a possible scenario, we have noted that the starburst galaxy M82 is only 37° from the particle's arrival direction, and positioned so that a positively charged particle from its direction would have been deflected toward the arrival direction of this particle. M82 is only about 3.5 Mpc away, so photodisintegration would not be expected to erode too much of its charge during transit, provided the energy at detection is somewhat less than the best experimental estimate. If this scenario is correct, detections of other superhigh energy nuclei can be expected to lie on a curve of directions determined by the position of M82 and the Galaxy's regular field and parametrized by magnetic rigidity.

An intriguing Seyfert galaxy MCG 8-11-11 lies very close to the arrival direction of the 320 EeV shower. It is a powerful source of low energy gamma rays. It apparently has ample luminosity to account for a detectable flux of superhigh energy particles (even allowing for severe attenuation by photopion production losses). A strong flux has not been detected, however, at somewhat lower energies where attenuation is not important.

A speculative idea is that the Fly's Eye detected a 320 EeV neutral particle which is immune to interactions with the cosmic background radiation. The quasar 3C147 becomes a candidate source in that case. Its position is consistent with the arrival direction of the air shower. 3C147 is a remarkable radio source with intense hot spots whose radio luminosity is more than 2000 times greater than either Cen A or Virgo A. Luminosity is still an issue for 3C147, however, due to its great distance. Its redshift is z=0.545, implying a luminosity distance (Weinberg 1972) of 2200 Mpc for Hubble constant $H_0 = 75$ km s^{-1} Mpc^{-1}. Dividing the 320 EeV energy by the Fly's Eye's exposure to 3C147 gives a time-averaged energy flux of 11 eV/cm^2·s. The implied luminosity at the source is then 10^{46} erg/s. This is a high luminosity, even for an active galaxy, and it certainly exceeds the radio and x-ray luminosities of 3C147. It is a challenge to explain such a high luminosity in secondary neutral particles of superhigh energy.

A radically different possibility is that the 320 EeV particle did not originate at any persistent astrophysical object which would be found in a catalog search. It need not have been accelerated at all. It could have been produced by the annihilation of a topological defect (Aharonian et al. 1992), e.g. a cosmic string. The absence of a close enough astrophysical source near the arrival direction of this high rigidity particle can be construed as evidence in favor of topological defect annihilations as the sources of superhigh energy particles. This explanation for the 320 EeV particle has been discussed by others (Sigl, Schramm, & Bhattacharjee 1994).

The decay of a topological defect is presumed to result in the production of X-particles with masses near the GUT energy scale of 10^{24} eV. Superhigh energy particles result from their decays. Gamma rays may be the dominant detectable particles at superhigh energies, since they are produced copiously by π^0 decays and also inverse Compton scattering by electrons and positrons which result from charged pion decays. The Fly's Eye air shower could have been initiated by a gamma ray. Above 100 EeV, the LPM effect (Landau & Pomeranchuk 1953; Migdal 1957; Mizumoto 1993) is expected to cause gamma ray air showers to develop anomalously deep in the atmosphere. The Fly's Eye shower was not anomalously deep. Its depth of maximum was typical for a hadronic shower. It might also be consistent, however, with a gamma ray which converted to an electron pair and initiated its electromagnetic cascade in the earth's magnetosphere before reaching the atmosphere (McBreen & Lambert 1981). Such a shower would behave as a superposition of lower-energy electromagnetic air showers. Cascading in the magnetosphere would be especially likely if this particular shower were a gamma ray, because it arrived transverse (at 85°) to the local geomagnetic field.

In summary, the 320 EeV Fly's Eye shower would seem to offer an excellent opportunity to identify a source of the highest energy cosmic rays. As shown in section 2, that cosmic ray almost surely originated within a distance of 50 Mpc. Because of its high magnetic rigidity, one might expect that its arrival direction should point approximately toward its source. Unfortunately, the arrival direction of this shower is not near the direction of any close enough astrophysical object known to us as a likely acceleration site for such energetic particles. Identifying the source of this particle constitutes an important challenge in astroparticle physics.

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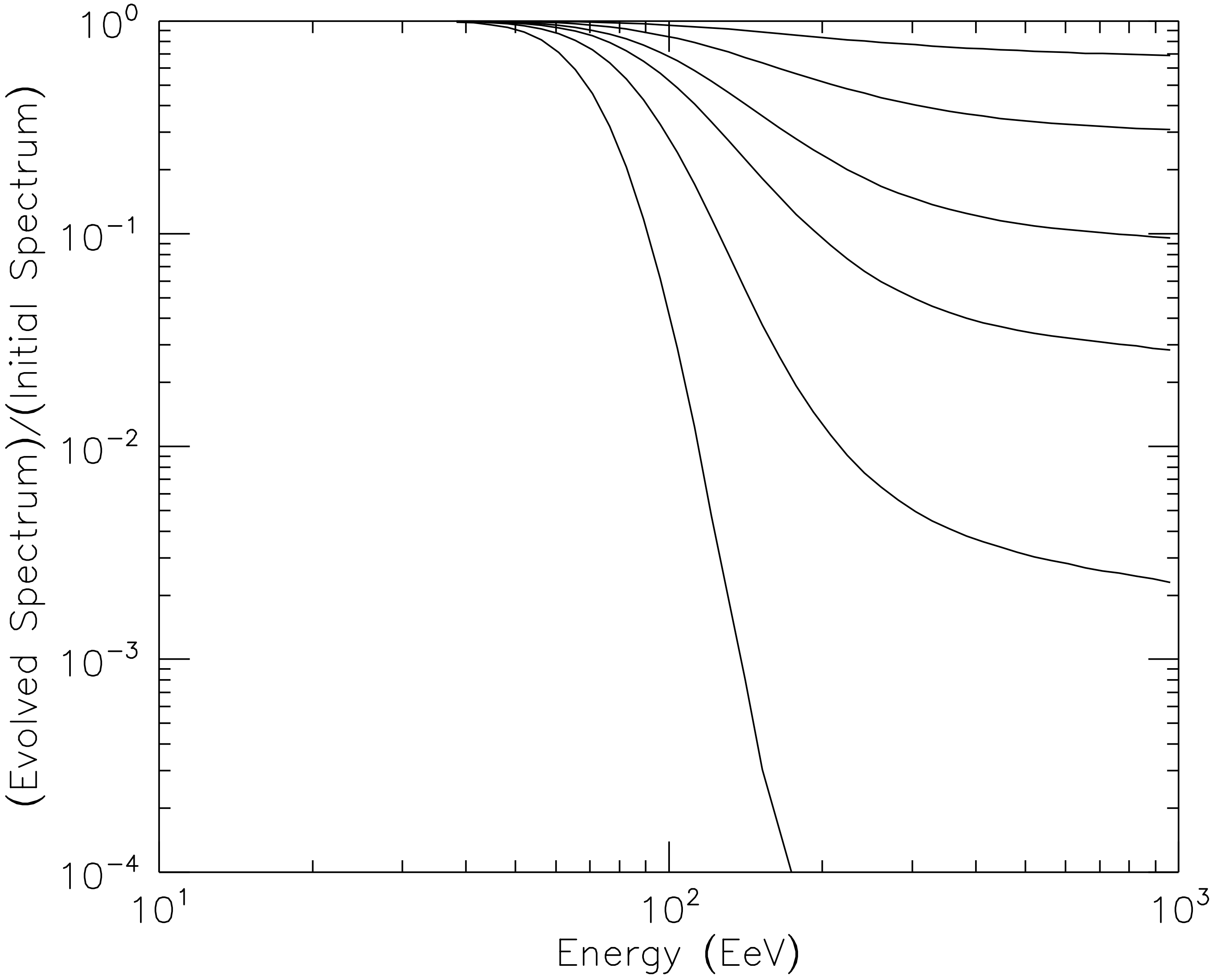
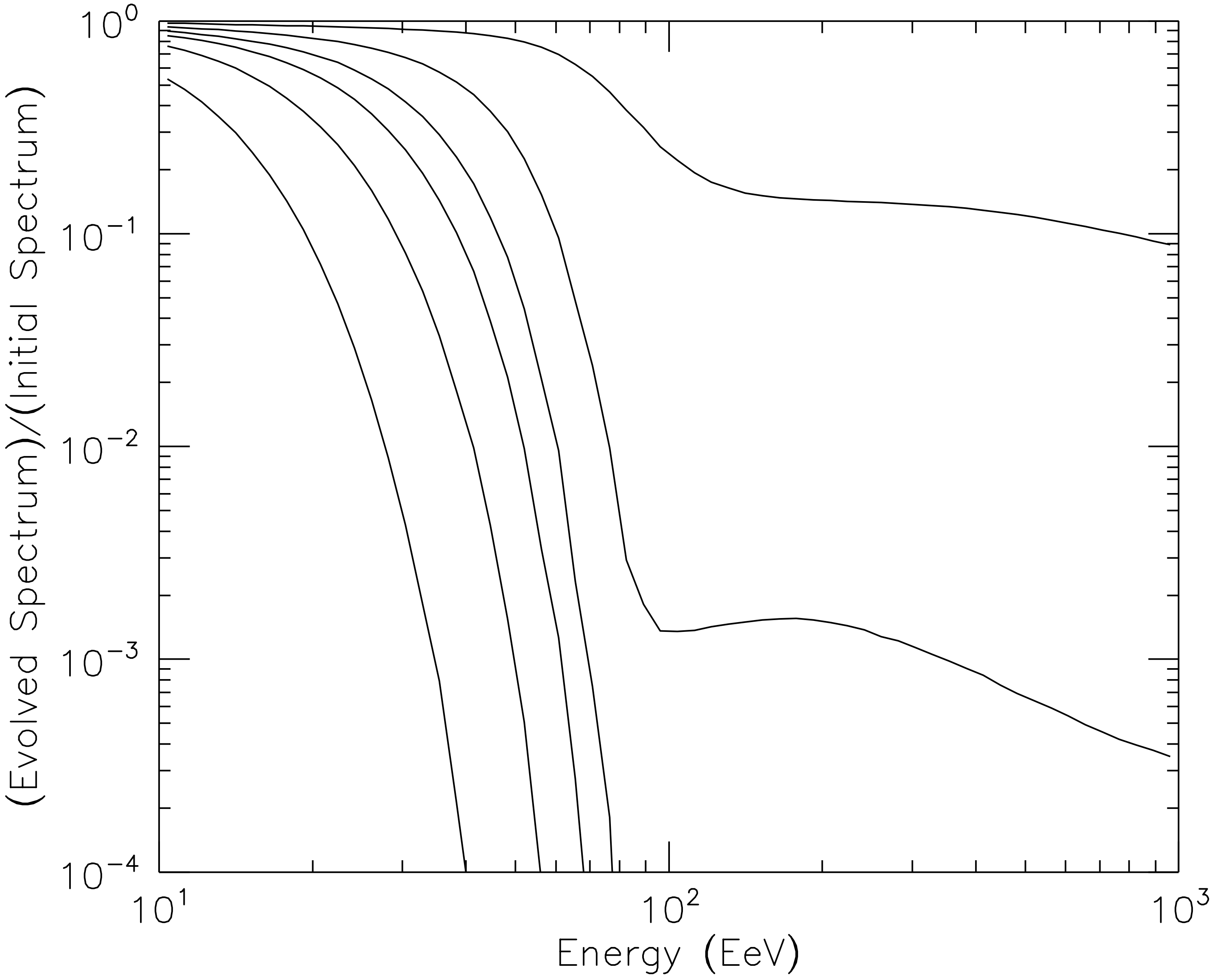
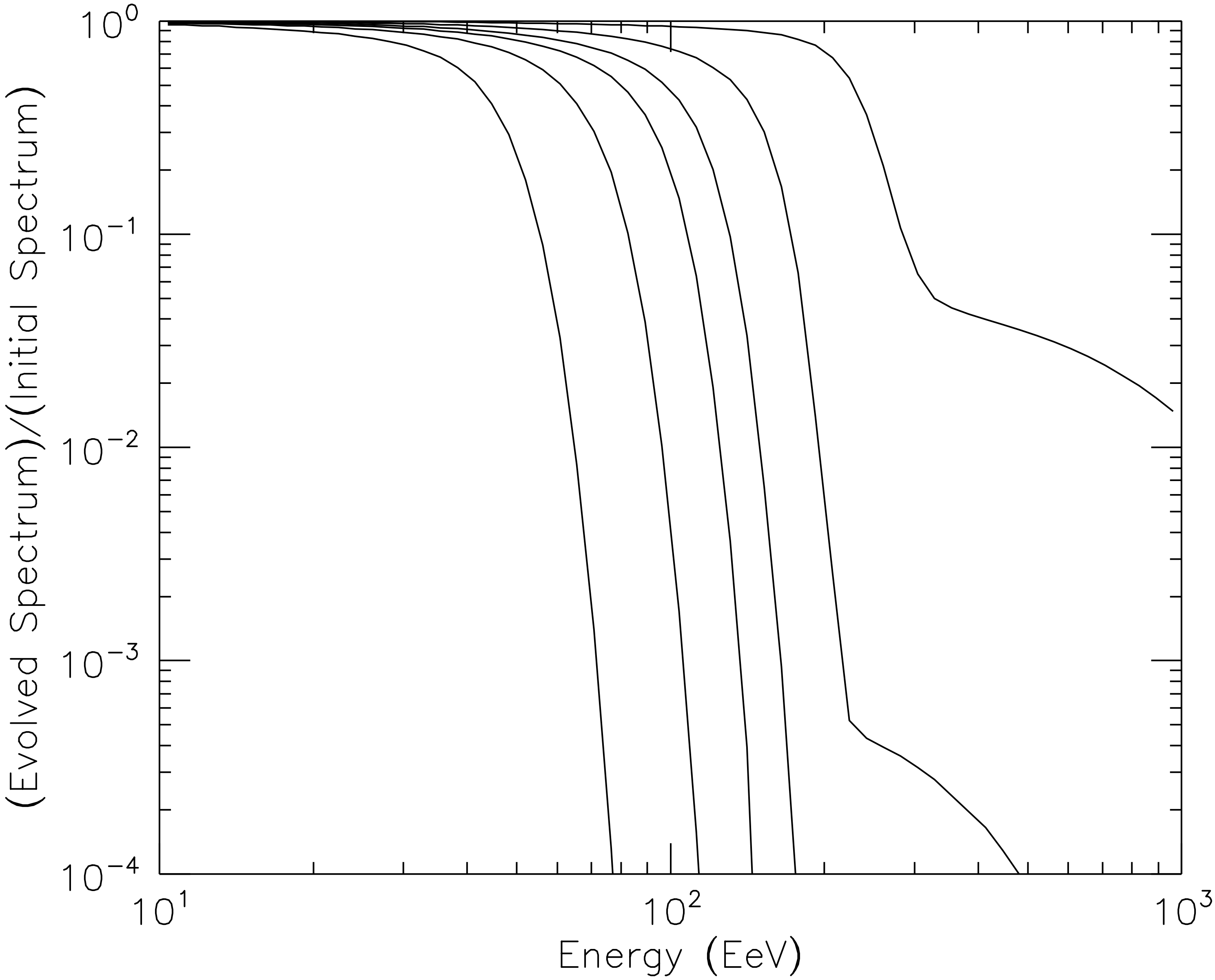


Figure 1: Integral flux reduction factors as a function of energy, after a spectrum with a differential spectral index of 2.5 has been propagated various distances. From top to bottom, the curves correspond to propagation distances 3 Mpc, 10 Mpc, 20 Mpc, 30 Mpc, 50 Mpc, and 100 Mpc. Results are given for the following initial particles: protons (1st plot), carbon nuclei (2nd plot), and iron nuclei (3rd plot).



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
(Evolved Spectrum)/(Initial Spectrum)
10^1
10^2
10^3
Energy (EeV)



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
(Evolved Spectrum)/(Initial Spectrum)
10^1
10^2
10^3
Energy (EeV)

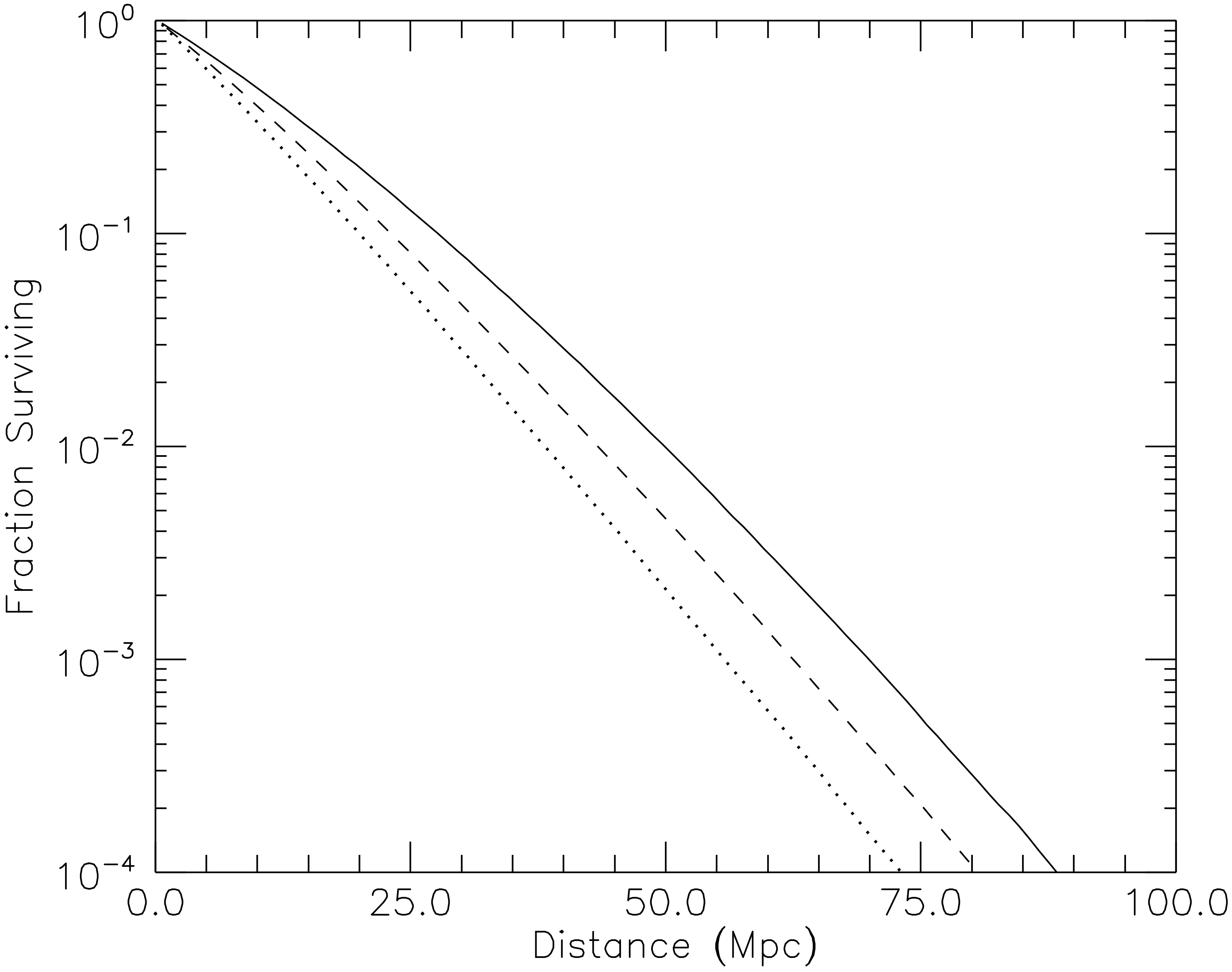
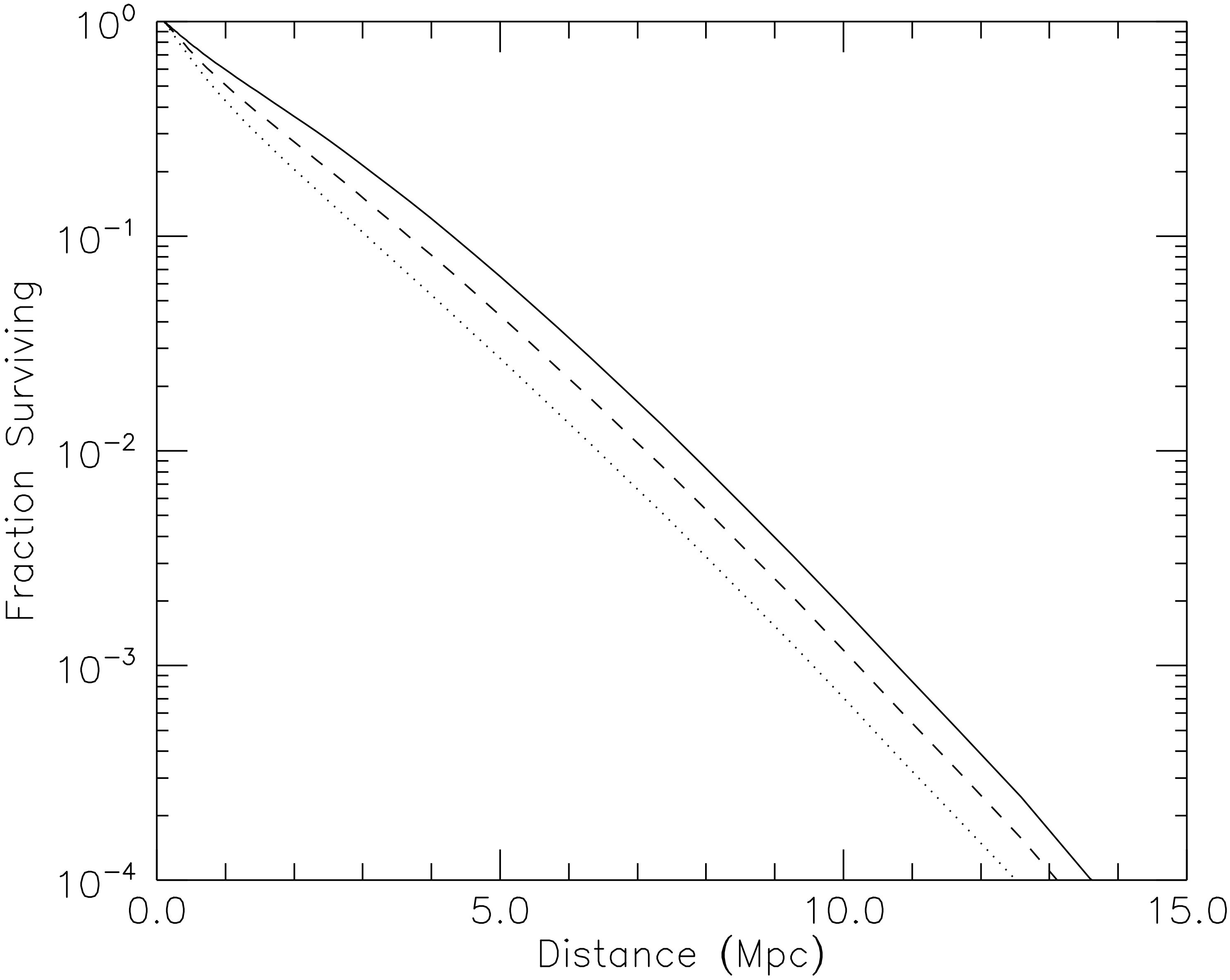
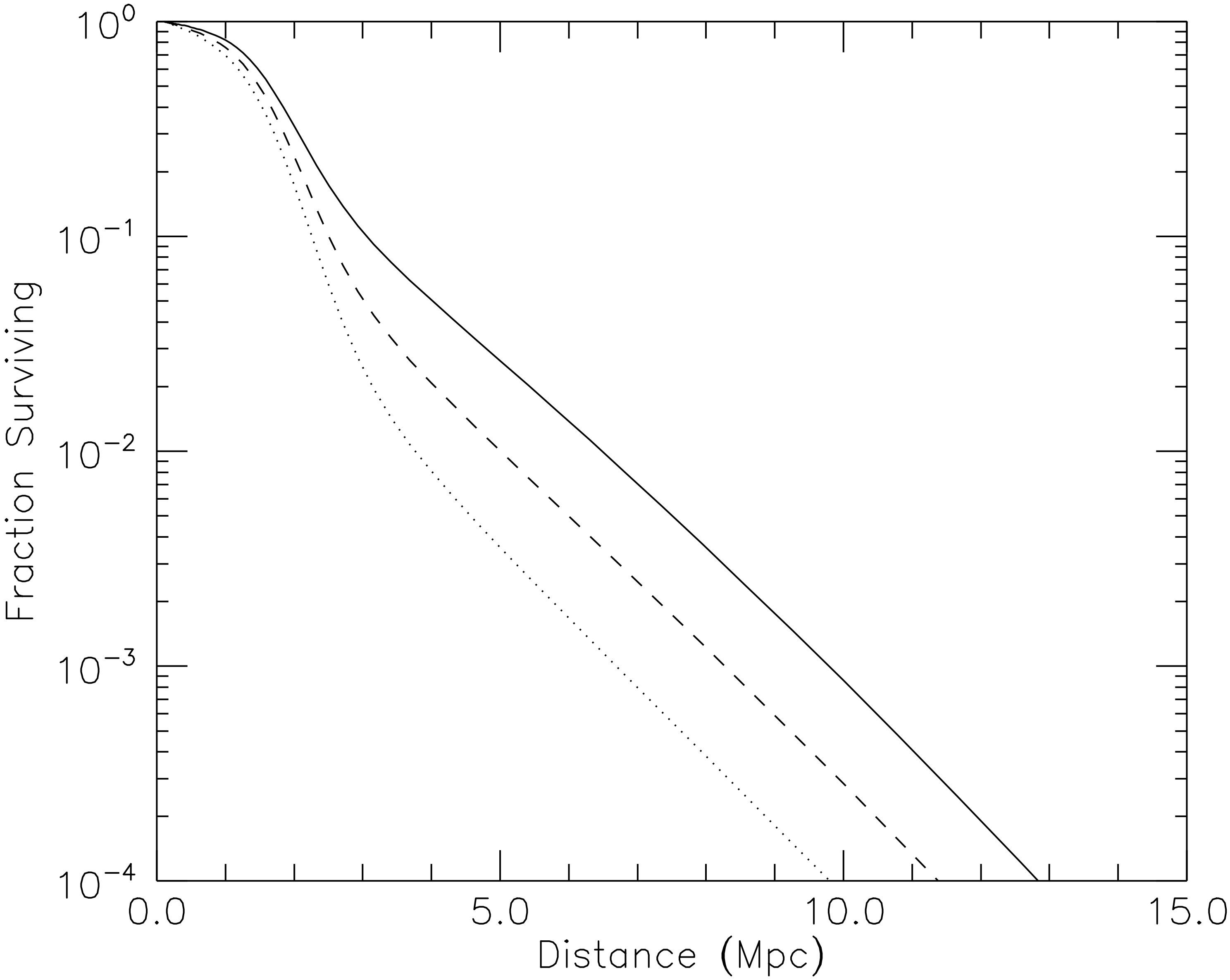


Figure 2: The dependence of the integral flux reduction factors on path length for cosmic rays with energies greater than 320 EeV. Spectra with differential spectral indices of 2., 2.5, and 3. are indicated by solid, dashed, and dotted curves, respectively. Results are given for protons (1st plot), carbon nuclei (2ndplot), and iron nuclei (3rd plot).



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Fraction Surviving
0.0
5.0
10.0
15.0
Distance (Mpc)


Fraction Surviving
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.0
5.0
10.0
15.0
Distance (Mpc)

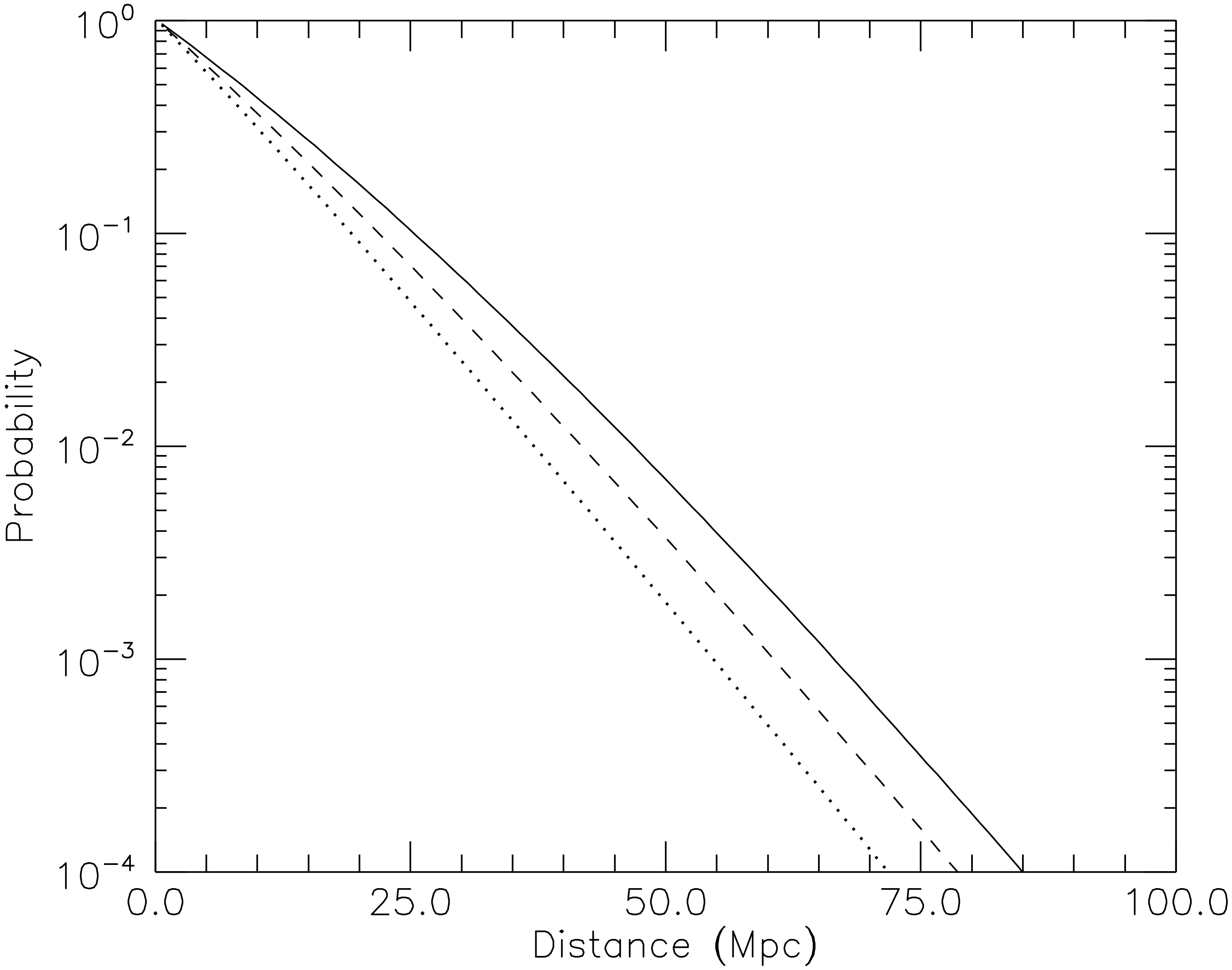
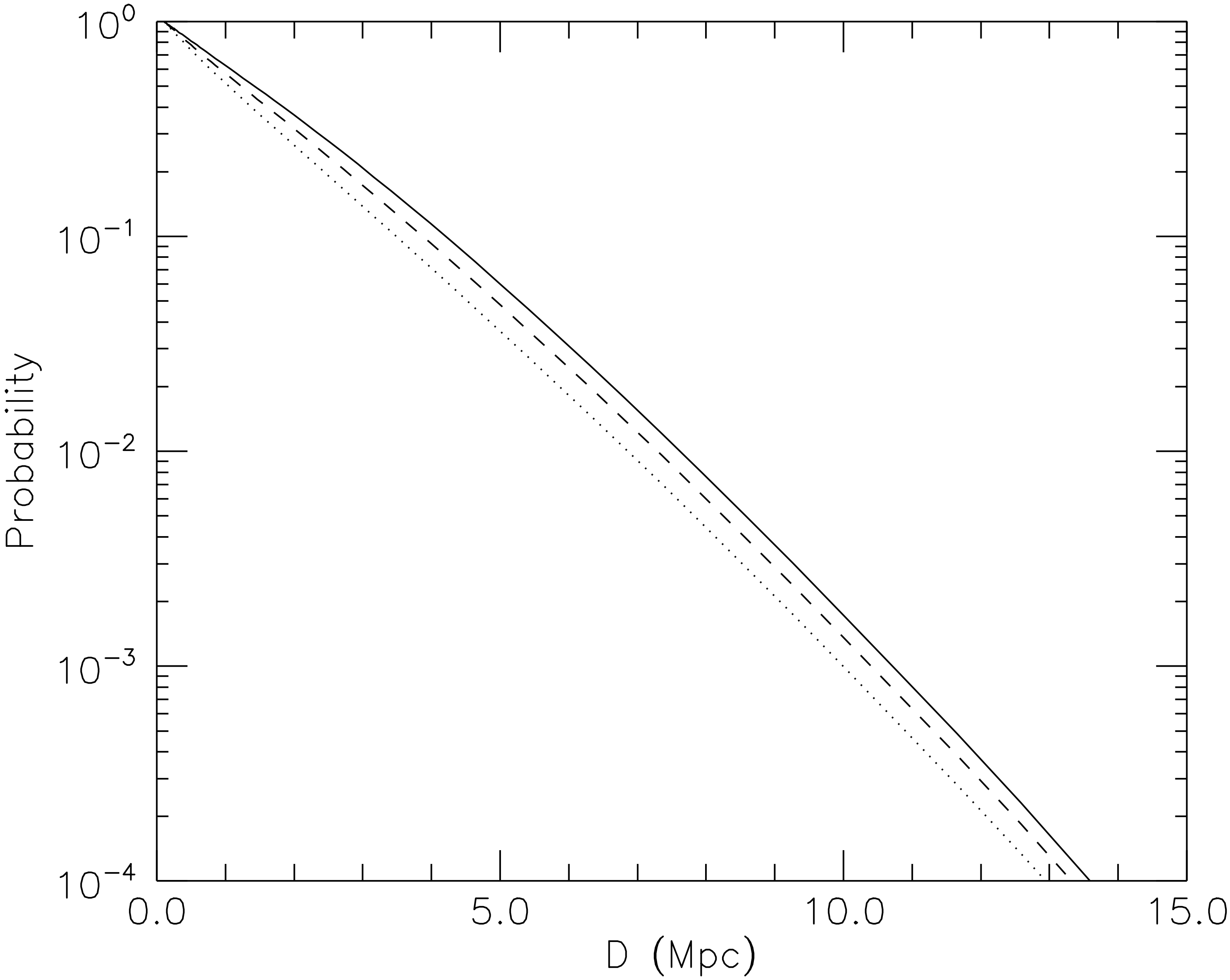
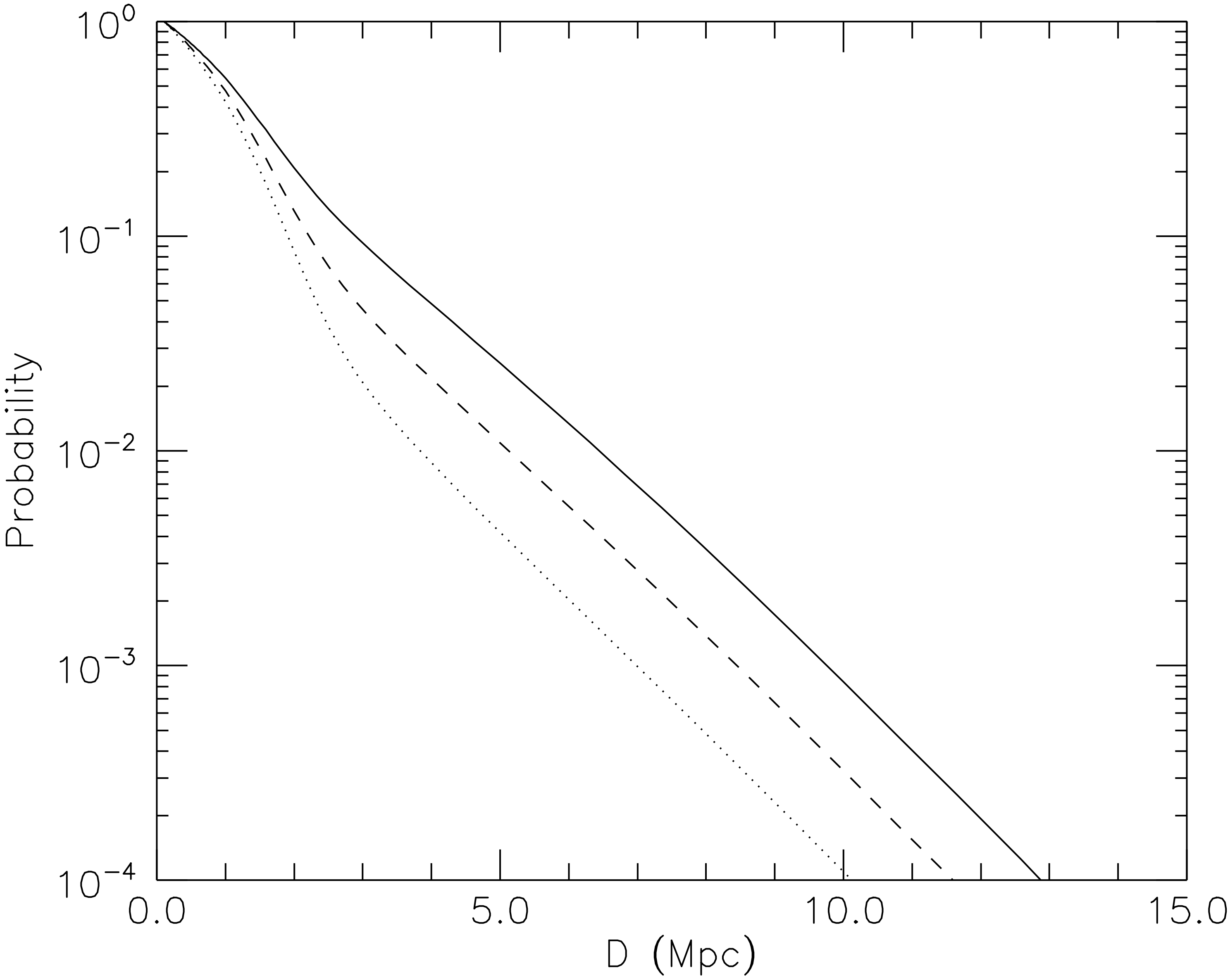


Figure 3: Probability of sources at various distances, considering only propagation effects (see discussion in text). Spectra with differential spectral indices of 2.,2.5, and 3. are indicated by solid, dashed, and dotted curves, respectively. Results are given for protons (1st plot), carbon nuclei (2nd plot), and iron nuclei (3rd plot).



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Probability
0.0
5.0
10.0
15.0
D (Mpc)



10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Probability
0.0
5.0
10.0
15.0
D (Mpc)

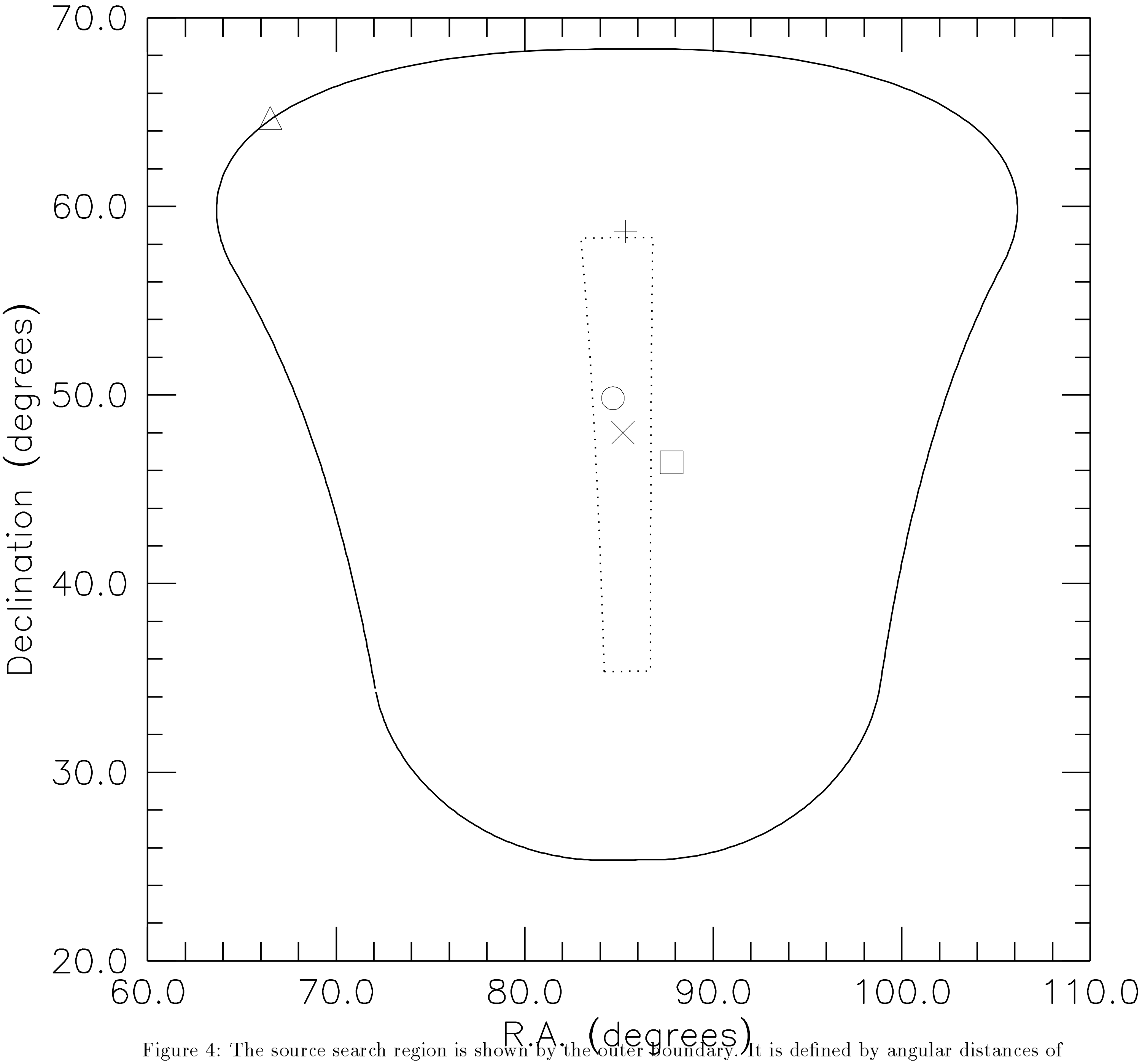


Figure 4: The source search region is shown by the outer boundary. It is defined by angular distances of 10° from the 2σ error box shown by the dotted lines. The best fit shower direction is shown by the cross. The circle and square represent the directions of 3C 147 and MCG 8-11-11, respectively. The triangle shows the direction of NGC 1569 (also known as Arp 210.) The + symbol is in the direction of UGC 03351, also known as MCG 10-09-02. See text for details.

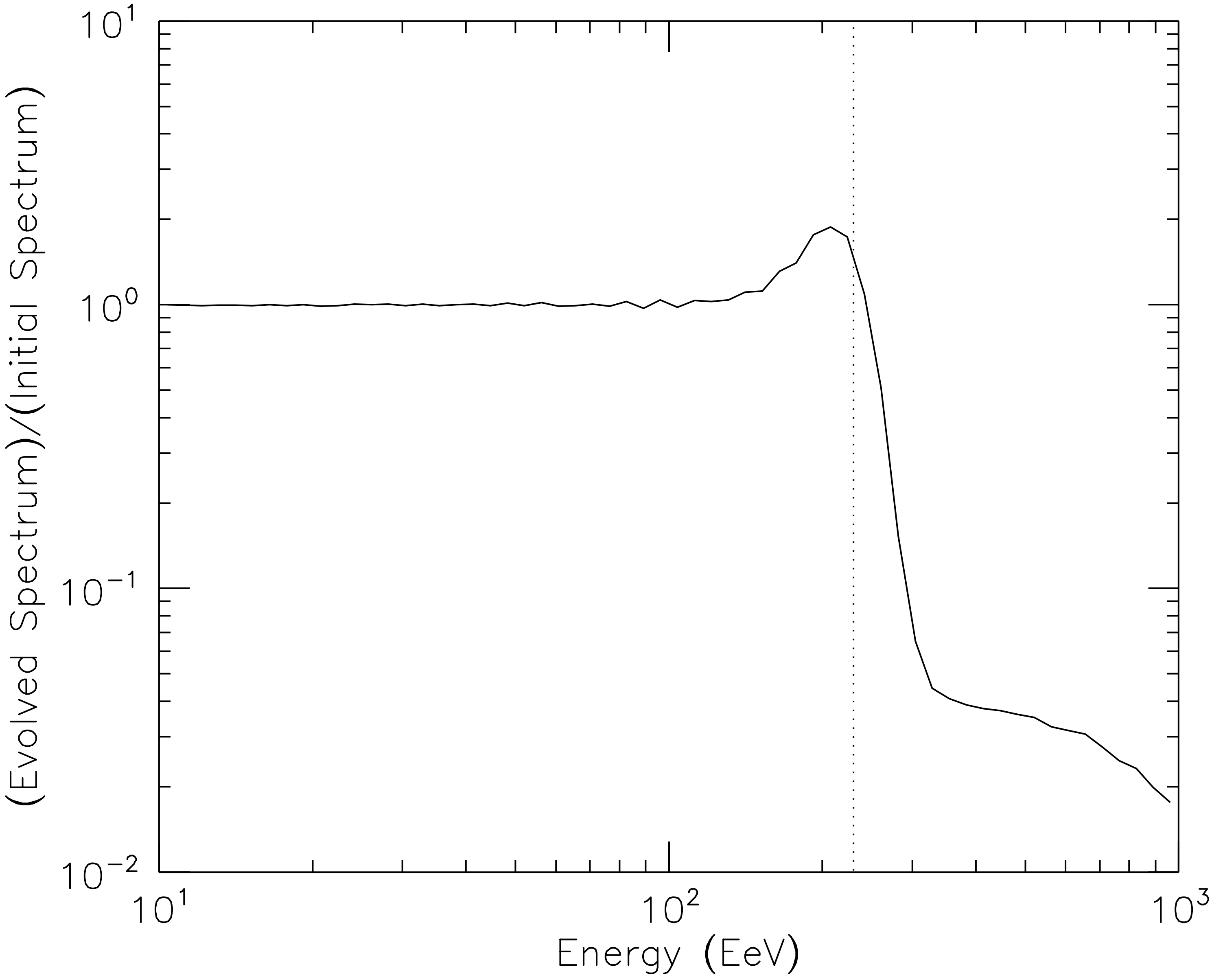


Figure 5: Ratio of surviving differential flux to source flux for primary iron nuclei as a function of the detected energy after a pathlength of 3.5 Mpc. The differential spectral index was chosen to be γ =2.5. A "pile-up" is observed near the shower energy (230 EeV, marked by a dotted line) proposed in a scenario involving acceleration of the cosmic ray near M82. (See text.)