Fermi National Accelerator Laboratory

FERMILAB-Pub-95/282-A
August, 1995

Submitted to *The Astrophysical Journal Letters*

EXTRAGALACTIC MAGNETIC FIELD AND THE HIGHEST ENERGY COSMIC RAYS

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ABSTRACT

The strength and spectrum of the extragalactic magnetic field are still unknown. Its measurement would help answer the question of whether galactic fields are purely a primordial relic or were dynamically enhanced from a much smaller cosmological seed field. In this letter, we show that the composition, spectrum, and directional distribution of extragalactic ultrahigh energy cosmic rays with energies above $\simeq 10^{18}$ eV can probe the large scale component of the extragalactic magnetic field below the present observational upper limit of 10^{-9} Gauss. Cosmic ray detectors under construction or currently in the proposal stage should be able to test the existence of the extragalactic magnetic fields on scales of a few to tens of Mpc and strengths in the range $\simeq 10^{-10} - 10^{-9}$ Gauss.

Subject headings: cosmic rays — magnetic fields — gamma rays: theory

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

1 Introduction

Magnetic fields are universally present in astronomical bodies ranging from the Earth to the distant quasars, but it is still unknown if magnetic fields permeate the universe as a whole. Astrophysical magnetic fields may arise due to the existence of a primordial magnetic field that grows as galaxies form. The discovery of an extragalactic magnetic field on scales larger than virialized systems (i.e., larger than clusters of galaxies) would reveal the presence of a primordial field. The existence of such a primordial field would help understand the origin of astrophysical magnetic fields and may open a new window into processes ocurring in the early universe.

In this letter, we show that the study of ultra high energy cosmic rays (UHE CRs) with energies above $\simeq 10^{18}$ eV can probe primordial fields below the current upper bound. Our proposed method is complementary to traditional ones (e.g., Kronberg 1994) and more recent suggestions (e.g., Plaga 1995). At present, the most stringent constraint on large scale extragalactic fields comes from limits on the Faraday rotation of light coming to us from distant quasars. The upper bound on a widespread, all-pervading field is $\sim 10^{-9}$ Gauss (e.g., Kronberg 1994). There are weaker constraints derived from the synchrotron emission from nearby galaxy clusters (Kim et al. 1989) and the cosmic microwave background isotropy.

UHE CR nucleons from extragalactic sources are attenuated in energy while propagating through the cosmic microwave background (CMB). Above a few 10^{19} eV, nucleons produce pions on the CMB photons and the energy of the cosmic ray nucleons is degraded rapidly, which is known as the Greisen-Zatsepin-Kuz'min (GZK) effect (Greisen 1966; Zatsepin & Kuz'min 1966). Produced pions, on the other hand, decay into secondary leptons such as electrons, muons, and neutrinos, and photons. Since muons decay to electrons and neutrinos, the final secondary particles are photons, electrons, and neutrinos, among which photons are more readily detectable.

Very energetic secondary photons and electrons couple to form an electromagnetic (EM) cascade. The γ-rays produce electron pairs on the CMB and the universal radio background photons (see Lee & Sigl 1995, Lee 1995 and references therein for more detailed discussions). The resulting electrons (or positrons) in turn upscatter background photons via inverse Compton scattering (ICS), thus completing a cycle. It is through these two processes that an EM cascade develops in the intergalactic medium. As a result, if one propagates a purely protonic spectrum, one gets a processed nucleon spectrum with the GZK cutoff, and a secondary EM (photons and electrons) spectrum.

The extragalactic magnetic field (EGMF) influences the UHE CR flux mainly through their charged components, namely the primary hadrons and the secondary electrons. In the energy range under consideration the hadrons are deflected with negligible energy loss due to synchrotron radiation whereas the electrons are negligibly deflected before they lose most of their energy. In §2, we explore the effect of the electron energy loss due to the EGMF on the secondary EM cascade spectrum. We then discuss the deflection of the hadronic component in the EGMF, in §3. Finally in §4, we summarize our findings.

2 Extragalactic Magnetic Field and Ultrahigh Energy γ-Ray Flux

The EGMF plays a crucial role in the development of the EM cascade. In the presence of the magnetic field, electrons lose energy via synchrotron radiation loss, which is given by

$$\frac{dE}{dt} = -\frac{e^4 B^2}{24\pi^2 m_e^4} E^2 = -\frac{2}{3} r_0^2 B^2 \left(\frac{E}{m_e}\right)^2 , \tag{1}$$

where B is the strength of the large scale EGMF, r_0 is the classical electron radius, and m_e is the electron mass.

In fig. 1, we show the rates of ICS and synchrotron loss for electrons. Whereas the rate of ICS responsible for EM cascade development decreases with energy, the synchrotron loss rate increases with energy. Therefore, in a narrow energy range a transition occurs between a regime where ICS is dominant and electrons couple to photons efficiently and another where electrons are rapidly lost due to synchrotron loss and the cascade is suppressed. Below $\simeq 10^{20}$ eV (the threshold for pair production on the radio background), cascade development in the absence of an EGMF would give rise to a generic power law photon spectrum with index $\simeq -1.5$. The above mentioned transition in the secondary γ-ray spectrum will therefore occur between this generic cascade shape and a synchrotron loss dominated spectrum. As long as synchrotron quanta can be neglected the latter is given by the photons produced "directly" by source injection or from pion production by nucleons, before undergoing pair production in the low energy photon background.

In a magnetic field of strength B measured in G (Gauss) the synchrotron spectrum produced by an electron of energy E_e peaks at

$$E_{\rm syn} \simeq 6.8 \times 10^{13} \left(\frac{E_e}{10^{21}\,{\rm eV}}\right)^2 \left(\frac{B}{10^{-9}\,{\rm G}}\right) {\rm eV} , \tag{2}$$

and falls off exponentially at higher energies. In the following we assume that the observable EM flux is energetically dominated by γ-rays and electrons with energy $E \lesssim 10^{21}$ eV. Then, according to eq. [2], the contribution of synchrotron radiation to the γ-ray flux above 10^{18} eV can be safely neglected as long as $B \lesssim 10^{-6}$ G everywhere.

The energy where the transition in the γ-ray spectrum occurs is in general a function of the magnetic field strength and the background photon spectrum, but *not* a function of the source distance or the injection spectrum. If we consider only the CMB, the relation between the transition energy $E_{\rm tr}$ and the magnetic field strength is $E_{\rm tr} \propto B^{-1}$. In order to include the less well known diffuse extragalactic radio background into consideration we adopt its usual description by a power law with an overall amplitude and a lower frequency cutoff as parameters (Clark, Brown, & Alexander 1970) the latter one being the main source of uncertainty. Using a cutoff at 2 MHz as suggested by Clark et al. (1970) the above relation is modified to

$$E_{\rm tr} \simeq 10^{19} \left(\frac{B}{10^{-9}\,{\rm G}}\right)^{-1.3} {\rm eV} \quad (B \gtrsim 10^{-10}\,{\rm G}) . \tag{3}$$

For the same magnetic field a cutoff at lower frequencies would increase the rate of ICS of the then more abundant low frequency radio photons and thus the value for E_{tr} (see fig. 1). Assuming that the radio cutoff frequency lies somewhere in the range between 0.5 MHz and 3 MHz, for a given E_{tr} the EGMF strength B is uncertain within about a factor 5.

Therefore, for $B \gtrsim 10^{-10}$ G it is possible to approximately determine the EGMF strength by searching for a dip in the γ-ray flux below 10^{20} eV which would mark a transition between an ICS and a synchrotron loss dominated regime. For $B \lesssim 10^{-10}$ G, this transition occurs above the pair production threshold on the radio background where the γ-ray flux increasingly depends on several unknown factors such as the charged cosmic ray flux above the GZK cutoff. Thus, even though the γ-ray flux can be comparable to the nucleon flux above 10^{20} eV, a discussion of possible magnetic field signatures in its spectrum would presently be too speculative.

We developed a numerical code for the propagation of nucleons, photons, and electrons through the intergalactic medium which employs a transport equation formalism, the details of which can be found in Lee (1995). The observed UHE CR flux below 10^{20} eV (see, e.g., Bird et al. 1994; Yoshida et al. 1995) is reproduced quite well by a diffuse distribution of sources injecting protons with a spectrum $\propto E^{-2.3}$ up to some maximal energy considerably beyond the GZK cutoff (Yoshida & Teshima 1993; Sigl et al. 1995). For the calculations presented here we therefore adopted this proton injection spectrum with a maximal energy of 10^{22} eV (see figures). The EGMF enters the calculation via the synchrotron loss of electrons.

The transition between ICS and synchrotron loss domination can be easily seen in fig. 2, which shows the processed nucleon and photon spectra for a single source at a distance of 30 Mpc for a range of EGMF strengths. In general, one expects a distribution of cosmic ray sources rather than a single source at a fixed distance. In fig. 3, we show the diffuse spectrum from a continuous source distribution extending up to 1 Gpc. We assume a flat universe with zero cosmological constant and a Hubble constant of $H_0 = 75$ km sec^{-1}Mpc^{-1}, and a comoving source density scaling as $(1+z)^2$ in redshift z as in some "bright phase" models of CR sources (e.g., Yoshida & Teshima 1993; Hill & Schramm 1985 and references therein). The results are not very sensitive to these choices. In the diffuse case, the γ-ray to nucleon flux ratio tends to be smaller than for a single source, and the spectral features are not as pronounced, but still detectable for $B \gtrsim 10^{-10}$ G.

The "extragalactic magnetic field" in this analysis refers to the average component of the EGMF normal to the line of propagation. Primordial magnetic fields are expected to have very little structure on scales below $\sim$ few Mpc (Jedamzik, Katalinic, & Olinto 1995), but condensed structures such as galaxies and clusters of galaxies can "polute" the intergalactic medium with stronger magnetic fields on smaller scales. Fortunately, the effect of the EGMF on the γ-ray spectral shape discussed here is most sensitive to the average field on large scales. When the EM cascade goes through a strong field region, the electrons in the cascade lose energy rapidly and drop out of the UHE range. In contrast, the UHE nucleon and γ-ray fluxes are usually hardly affected directly by the radiation field of the intervening object (Stecker et al. 1991; Szabo & Protheroe 1994; Norman, Melrose, & Achterberg 1995). After escaping the object, the cascade redevelops and the cascade spectrum recovers quickly at only a slightly smaller amplitude. The influence of intervening objects decreases with increasing strength of the large scale field and becomes important only when the objects are very close to the observer (e.g., less than $\sim 5\,\mathrm{Mpc}$ away), or when their linear size is significant compared to the total propagation distance. We can derive conditions for the filling factors for such objects by requiring that they are much more sparsely populated along the line of sight to the source than the typical cascade regeneration length s_c (e.g., ~ 5 Mpc). For an average linear size $\bar{l}_{\rm iv}$ of the intervening objects their filling factor $f_{\rm iv}$ must satisfy

$$f_{\rm iv} \ll \frac{\bar{l}_{\rm iv}}{s_c}. \tag{4}$$

For field galaxies the above relation is $f_g \ll 10^{-3}$, and for clusters of galaxies $f_c \ll 0.1$. The actual filling factors for galaxies, $f_g \lesssim 10^{-7}$, and galaxy clusters, $f_c \lesssim 10^{-4}$ (Kolb & Turner 1992; Nichol, Briel, & Henry 1994) satisfy these constraints. Therefore, intervening objects do not modify the above discussion substantially. One interesting exception may be the effect of nearby large structures such as the Virgo Cluster. If Virgo has strong magnetic fields, e.g. of order 10^{-7} G on Mpc scales, the UHE γ-ray flux from background sources might be modified across Virgo's angular extension (see fig. 2).

The ability of future detectors to study EGMF features crucially depends on the γ-ray to nucleon flux ratio. For nearby strong sources, the secondary γ-ray flux could be measurable with instruments which are sensitive to ratios down to $\simeq 1\%$. This could be achieved by the proposed Pierre Auger Project (see e.g., Boratav et al. 1992), which would also allow an angular resolution of $\simeq 1°$. The case of a diffuse source distribution is more challenging; the γ-ray flux is typically smaller and the EGMF feature is less pronounced than for a single source at moderate distances (see figs. 2 & 3), but the dip in the γ spectrum may still be detectable. Thus, measuring the γ-ray flux between $\simeq 10^{18}\,\mathrm{eV}$ and $\simeq 10^{20}\,\mathrm{eV}$ has the potential to either detect or find strong evidence against an EGMF $\gtrsim 10^{-10}\,\mathrm{G}$.

3 Charged Cosmic Ray Deflection by Extragalactic Magnetic Fields

Here, we discuss the influence of the EGMF on the charged UHE CR flux from discrete sources. We restrict ourselves to the case of small deflection angles (for the opposite limit see, e.g. Wdowczyk & Wolfendale 1979; Berezinskii, Grigor'eva, & Dogel' 1989). In this case, the energy spectrum of charged UHE CRs from a given source is not significantly altered as compared to a straight-line propagation. However, if the sources are strong enough to cause an anisotropy in the UHE CR flux, the directional correlation of "hot spots" with possible sources will depend on the EGMF. The following discussion relates to this anisotropic component of the charged UHE CR flux.

As in §2, let us assume that the large scale EGMF can be characterized by a typical field strength B and a coherence length l_c. Furthermore, we assume for the moment that the source distance r is smaller than the energy attenuation length $\lambda = E(dE/dr)^{-1}$ for a charged cosmic ray of energy E which can then be treated as approximately constant throughout propagation. For nucleons, $\lambda \simeq 10$ Mpc above the GZK cutoff (at $E \simeq 6 \times 10^{19}\,\mathrm{eV}$), and $\lambda \simeq 1$ Gpc much below the GZK cutoff. A more sophisticated analysis would require a Monte Carlo simulation of both UHE CR propagation and deflection. However, since data on both UHE CR and the EGMF are so sparse to date, we feel that a qualitative discussion of the principle effects is more appropriate at the moment. We now consider two cases.

(i) The source distance is smaller than the coherence length, $r \lesssim l_c$. Then, in vectorial notation, the deflection angle α is given by

$$\alpha = -\frac{Ze}{E}\,\mathbf{r} \times \mathbf{B} = 5.3^\circ\, Z \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{r}{10\,\mathrm{Mpc}}\right) \left(\frac{B}{10^{-9}\,\mathrm{G}}\right) \left(\hat{\mathbf{r}} \times \hat{\mathbf{B}}\right)\,, \tag{5}$$

where $\mathbf{r}$ is the radius vector pointing to the source, Z is the charge of the UHE CR component, $\hat{\mathbf{r}} = \mathbf{r}/|\mathbf{r}|$, and $\hat{\mathbf{B}} = \mathbf{B}/|\mathbf{B}|$. Thus, a correlation between the UHE CR flux of charge Z and energy E and source counterparts, systematically shifted by an angle α, would indicate that $l_c \gtrsim r$ and for a known source distance r would allow to measure the combination $B(\hat{\mathbf{r}} \times \hat{\mathbf{B}})$. The characteristic E- and Z dependence of α would provide an additional test for the hypothesis that the deflection is caused by an EGMF.

(ii) The source distance is considerably larger than the coherence length, $r \gg l_c$. In this case the deflection angle undergoes a diffusion process during propagation and the source shape in the UHE CR flux will be smeared out over a typical angle

$$\alpha_{rms} \simeq \frac{2}{\pi}\frac{ZeB}{E}\left(r l_c\right)^{1/2} = 1.1^\circ\, Z \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{r}{10\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{l_c}{1\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{B}{10^{-9}\,\mathrm{G}}\right). \tag{6}$$

Therefore, if sources appear spread out in the UHE CR flux of charge Z and energy E by a typical angle α, this would indicate that $l_c \lesssim r$ and for a known source distance r would allow to measure the combination $B l_c^{1/2}$.

If the source distance is larger than the energy attenuation length, $r \gtrsim \lambda$, eqs. [5] and [6] tend to overestimate α. In fact, in the limit $r \gg \lambda$ the deflection angle α "saturates" as a function of r and for approximately energy independent λ, r has to be substituted by λ and $\lambda/2$ in eqs. [5] and [6], respectively.

Secondary γ-rays produced by the interactions of the charged UHE CRs are also expected to correlate with the sources. Due to their continuous production they will be smeared out over angles which are typically somewhat smaller than given in eqs. [5] and [6].

Sources which can act as suitable probes for the EGMF via the effects discussed above have to obey the following conditions apart from producing a detectable anisotropic UHE CR flux component: Their apparent angular size should be smaller than the deflection angle α. The same pertains to the apparent angular radius of a possible high magnetic field region around the source if it can cause deflections in excess of α. For example, a 10^{-6} G field over a scale $\gtrsim 100\,\mathrm{kpc}$ is possible in galaxy clusters (see, e.g., Kronberg 1994) and would completely bend around a $10^{20}\,\mathrm{eV}$ proton. However, as long as a detectable proton flux emerges from such an object and the above conditions are fulfilled, it could still be a suitable probe of the

EGMF. Finally, there should be no intervening high magnetic field regions between source and observer which could cause bending by more than α. For example, for $r \gtrsim l_c$, λ, this corresponds to the condition $l_{iv}B_{iv} \lesssim (\lambda l_c)^{1/2} B$ for linear scale l_{iv} and strength B_{iv} of the intervening field. This condition could well be satisfied along most lines of sight since known objects with high field regions like galaxies and galaxy clusters have a small filling factor $f \lesssim 10^{-5}$.

In light of these conditions we believe that some of the nearby galaxy clusters and powerful field radio galaxies could well be suitable EGMF probes since they are expected to contribute significantly to the UHE CR flux (Rachen, Stanev, & Biermann 1993). The accuracy to which the EGMF bending can be determined is limited by the (to date) unknown additional bending by the galactic magnetic field of strength B_g and scale height l_g. Thus, according to eq. [5], the sensitivity of deflection measurements of the EGMF is restricted to field parameters satisfying $Br \gtrsim 10^{-9}\,\mathrm{G\,Mpc}\,(B_g/\mu\mathrm{G})\,(l_g/300\,\mathrm{pc})$ where the fudge factors are the parameter values usually assumed for the galactic magnetic field.

4 Conclusions

We discussed how composition, spectrum, and directional distribution of UHE CR above $\simeq 10^{18}\,\mathrm{eV}$ can be used to gain information about the large scale (a few to tens of Mpc) EGMF. Spectral features in the γ-ray flux are sensitive to field strengths in the range $\simeq 10^{-10} - 10^{-9}\,\mathrm{G}$. In a similar range, correlations between an anisotropic charged UHE CR flux component and possible sources could provide independent information on the EGMF including its polarization. Both effects should yield consistent estimates for the EGMF strength. Strong discrete sources detected in UHE CRs by future instruments with an angular resolution of 1° or better and a sensitivity to γ-ray to nucleon flux ratios of 1% or smaller would provide the best conditions for detecting an EGMF in the range $\simeq 10^{-10} - 10^{-9}\,\mathrm{G}$. Since these conditions are not unreasonable, UHE CRs have the potential to provide important information on properties and origin of the EGMF.

Acknowledgments

This work was supported by the DoE, NSF and NASA at the University of Chicago, by the DoE and by NASA through grant NAG5-2788 at Fermilab, and by Alexander-von-Humboldt Foundation. S.L. acknowledges the support of the POSCO Scholarship Foundation in Korea.

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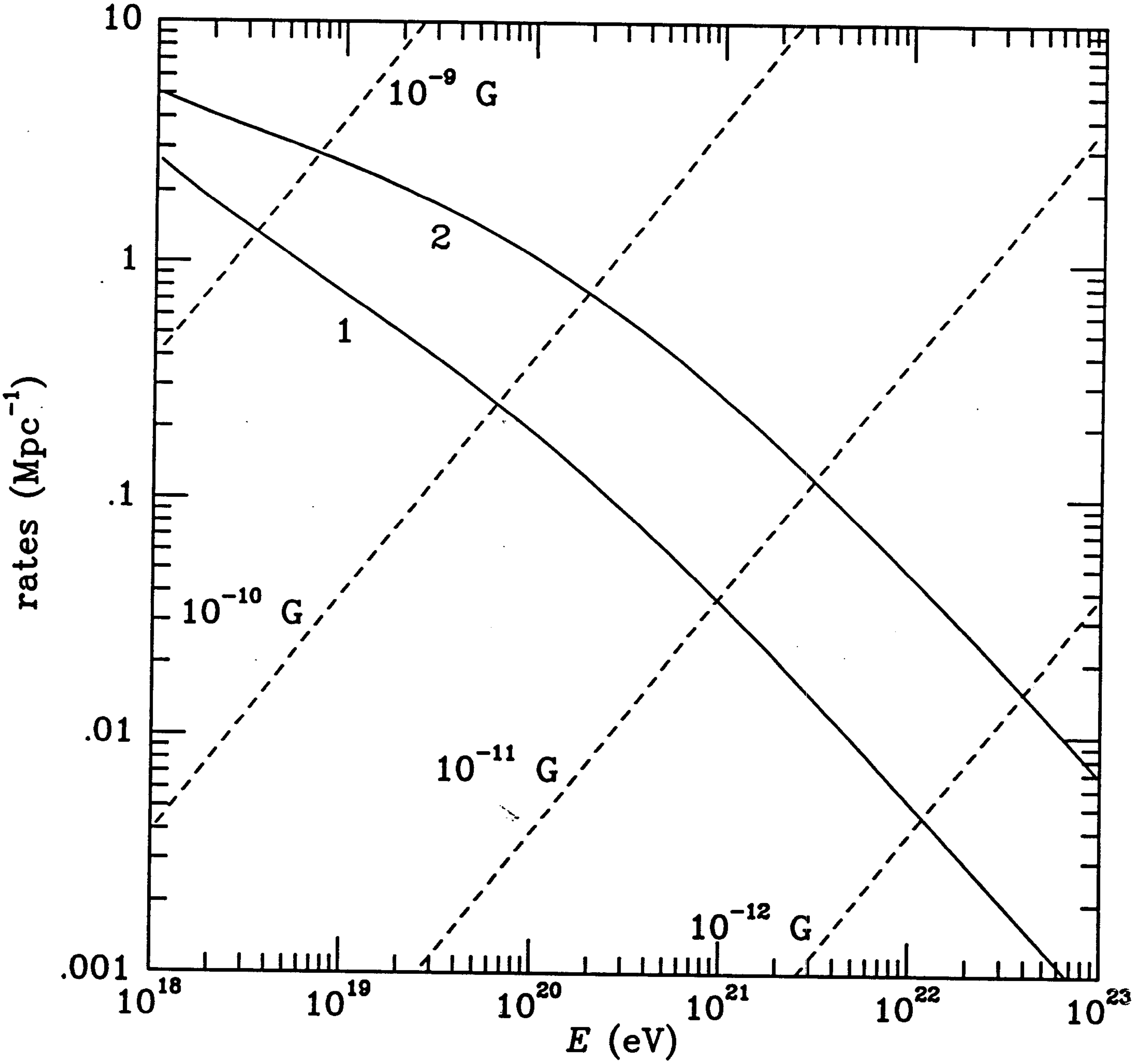
Figure Captions

Fig. 1: The rate of inverse Compton scattering (ICS; solid lines) and the fractional synchrotron loss rate (dashed lines) for different magnetic fields as functions of energy. 1 is for a frequency cutoff at 2 MHz in the diffuse radio background, and 2 is for 0.5 MHz, respectively.
Fig. 2: Cosmic ray nucleon spectrum (solid line) from a single source at a distance of 30 Mpc, and secondary γ-ray spectra for different magnetic fields. The short dashed lines are with no intervening objects, and the long dashed lines with dots are with a 5 Mpc sized object located at 12.5 Mpc from the observer. The magnetic field values are $B = 0, 10^{-10}, 3\times10^{-10}$, and 10^{-9} G, respectively from the top.
Fig. 3: Cosmic ray nucleon spectrum (solid line), and secondary γ-ray spectra (dashed lines) for a continuous source distribution up to 1Gpc distance whose comoving density scales as $(1+z)^2$. The sum of the nucleon and γ-ray flux is fitted to the combined data from the monocular Fly's Eye (Bird et al. 1994) and the AGASA experiment (Yoshida et al. 1995). Shown are 1σ error bars, and 84% confidence level upper limits. The magnetic field values are the same as in fig. 2.


rates (Mpc^{-1})
E (eV)
10
1
.1
.01
.001
10^{18}
10^{19}
10^{20}
10^{21}
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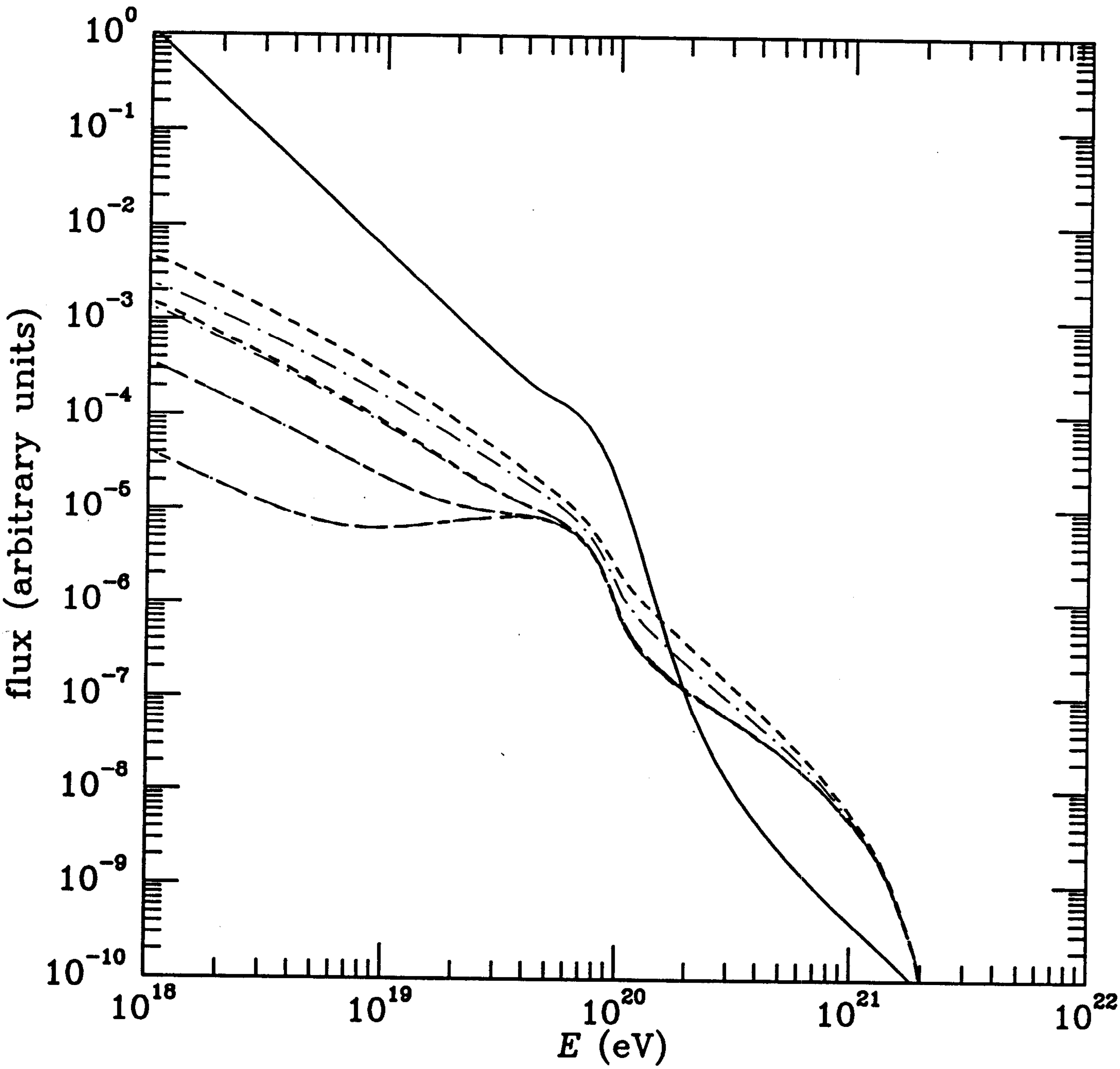
10^{23}
10^{-9} G
10^{-10} G
10^{-11} G
10^{-12} G
1
2

Fig. 1



flux (arbitrary units)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
E (eV)

Fig. 2

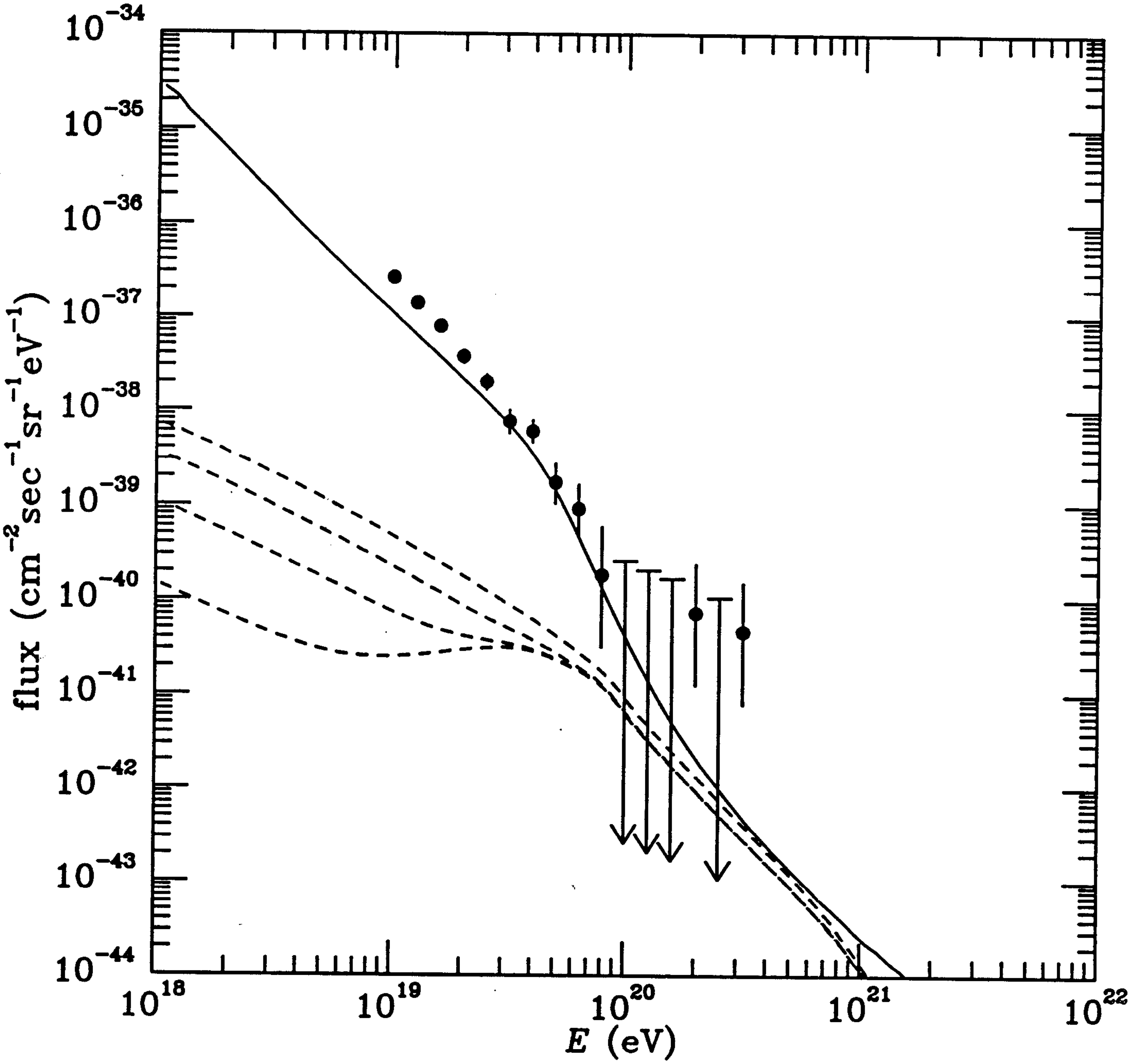

flux $(cm^{-2} sec^{-1} sr^{-1} eV^{-1})$
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
E (eV)

Fig. 3