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Are Extragalactic Gamma Ray Bursts The Source Of The Highest Energy Cosmic Rays?

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ABSTRACT

Recent observations with the large air shower arrays of ultra high energy cosmic rays (UHECR) and recent measurements/estimates of the redshifts of gamma ray bursts (GRBs) seem to rule out extragalactic GRBs as the source of the cosmic rays that are observed near Earth, including those with the highest energies.

Subject headings: cosmic rays; gamma rays bursts

1. INTRODUCTION

The origin of high energy cosmic rays (CR), which were first discovered by V. Hess in 1912, is still a complete mystery (e.g., Berezinskii et al. 1990; Gaiser 1990, and references therein). Their almost single power-law spectrum, $dn/dE \sim E^{-\alpha}$, that changes slightly at the so called " knee" around $10^{15.5}$ eV and at the so called " ankle" around $10^{18.5}$ eV, seem to suggest a single origin of CR at all energies (Ginzburg 1957; Burbidge 1962; Longair 1981). However, it is generally believed (e.g, Morrison 1957; Ginzburg and Syrovatskii 1964; Berezinskii et al. 1990; Gaiser 1990, and references therein) that CR with energy below the knee are accelerated in Galactic supernova remnants (SNR), those with energy above the knee may be either Galactic or extragalactic in origin, and those with energy above the ankle, that are not confined by Galactic magnetic fields, are extragalactic because of their nearly isotropic sky distribution (e.g., Takeda et al. 1998; Yoshida and Dai 1997).

If the CR accelerators are Galactic, they must replenish for the escape of CR from the Galaxy in order to sustain the observed Galactic CR intensity. Their total luminosity in CR must therefore satisfy,

$$L_{MW}[CR] = \int \tau^{-1}(Edn/dE)dEdV, \qquad (1)$$

where $\tau(E)$ is the mean residence time of CR with energy E in the Galaxy. It can be estimated from the mean column density, $X = \int \rho dx$, of gas in the interstellar medium (ISM) that Galactic CR with energy E have traversed. From the secondary to primary abundance ratios of Galactic CR it was inferred that (Swordy et al. 1990) $X = \bar{\rho} c\tau \approx 6.9(E/20ZGeV)^{-0.6}\ g\ cm^{-2}$, where $\bar{\rho}$ is the mean density of interstellar gas along their path. The mean energy density of CR and the total mass of gas in the Milky Way (MW), that have been inferred from the diffuse Galactic γ-ray, X-ray and radio emissions are, $\epsilon = \int E(dn/dE)dE \sim 1\ eV\ cm^{-3}$ and $M_{gas} = \int \rho dV \sim \bar{\rho}V \sim 4.8 \times 10^9 M_\odot$, respectively. Hence, simple integration yields (e.g., Drury et al. 1989)

$$L_{MW}[CR] \sim cM_{gas} \int \frac{Edn/dE}{X} dE \sim 1.5 \times 10^{41}\ erg\ s^{-1}. \qquad (2)$$

The only known Galactic sources which can supply the bulk of the Galactic CR luminosity are supernova explosions (SNe) (e.g., Ginzburg and Syrovatskii 1964; Völk 1997) and perhaps Galactic gamma ray bursts (GGRBs) (Dar et al. 1992; Dar et al. 1998), but not extragalactic GRBs. For completeness and for later use, we shall first rederive this result and than proceed to show that recent data from the large air shower arrays (e.g., Hayashida et al. 1996; Yoshida and Dai 1998, and references therein) on ultra high energy cosmic rays (UHECR) and the recent redshift measurements/estimates of some GRBs and host galaxies of GRBs (Metzger et al. 1997; Kulkarni et al. 1998; Bloom et al. 1998; Djorgovski et al. 1998; Fruchter et al. 1998a, 1998b) seem to rule out extragalactic GRBs as the source of the UHECR.

2. ARE SUPERNOVA REMNANTS THE MAIN COSMIC RAY SOURCE ?

Approximately, $E_K \sim 10^{51}\ erg$ is released by SNe as nonrelativistic kinetic energy of ejecta at a rate (Woosley and Weaver 1986), $R_{MW}[SNe] \sim 2.5 \times 10^{-2} y^{-1}$. If a fraction $\eta \sim 20\%$ of this energy is converted into CR energy by collisionless shocks in the supernova remnants (SNR), then the total SNe luminosity in CR is,

$$L_{MW}[CR] \approx 1.5 \left(\frac{\eta}{0.2}\right) \left(\frac{R_{MW}[SNe]}{0.025y^{-1}}\right) \left(\frac{E_K[SNe]}{10^{51} erg}\right) \times 10^{41}\ erg\ s^{-1}, \qquad (3)$$

as required by eq.2. Supernova remnants are also natural sites for Fermi acceleration of cosmic rays by collisionless magnetic shocks and the SNR environment seems also to explain the chemical composition of CR at low energies (see, e.g., Ramaty et al. 1998 and references therein) where it is well measured. Moreover the non thermal X-ray emission from SNR 1006 observed by ASCA (Koyama et al. 1995) and by ROSAT (Willingale et al. 1996), the GeV

γ-ray emission from several nearby SNRs observed by EGRET (Esposito et al. 1996), and the recent detection of SNR 1006 in TeV γ-rays by the CANGAROO telescope (Tanimori et al. 1998), were all interpreted as supportive evidence for the assumption that SNRs are the source of the bulk of CR. However, the TeV γ rays from SNRs can be explained by inverse Compton scattering of microwave background photons by multi-TeV electrons whose synchrotron emission explains their hard lineless X-ray radiation. Furthermore, the mean lifetime of strong shocks in SNRs limits the acceleration of CR nuclei in SNRs to energies less than $\sim Z \times 0.1 PeV$ (e.g., Lagage and Cesarsky 1983) and cannot explain the origin of CR with much higher energies. In fact, the most nearby SNRs in the northern hemisphere have not been detected in TeV γ-rays (Buckley et al. 1998). Moreover, the scale height of the Galactic distribution of SNRs (~ 4.8 kpc) differs significantly from that required (≥ 20 kpc) to explain the observed Galactic emission of high energy ($> 100 MeV$) γ-rays by cosmic ray interactions in the Galactic ISM (Strong and Moskalenko 1998). Furthermore, the diffusive propagation of CR from the observed/inferred distribution of Galactic SNRs yields anisotropies that at an energy of about 100 TeV are in excess of the observed value by more than an order of magnitude (Ptuskin et al. 1997). All these suggest that, perhaps, SNRs are not the main source of Galacic CR ?

3. COSMIC RAYS FROM GGRBs

Gamma ray bursts (GRBs) have also been proposed as CR sources (Dar et al. 1992, Waxman 1995, Vietri 1995, Milgrom and Usov 1995; 1996; Dar et al. 1998, Dar 1998, Dar and Plaga 1998). But, if GRBs emit similar energies in CR and in γ-rays (Waxman 1995, Vietri 1995, Milgrom and Usov 1996), i.e., if $\Delta E_{CR} \sim \Delta E_\gamma$, then Galactic GRBs cannot produce the bulk of the CR . This is because the total CR luminosity due to Galactic GRBs is only,

$$L_{MW}[CR] \sim R_{MW} \frac{4\pi}{\Delta\Omega} E_\gamma \frac{\Delta\Omega}{4\pi} = 3 \left(\frac{R_G}{10^{-8}\ y^{-1}}\right) \left(\frac{E_{isot}}{10^{52}\ erg}\right) \times 10^{36}\ erg\ s^{-1}, \tag{4}$$

independent of the solid angle $\Delta\Omega$ which the gamma ray emission is beamed into. The "isotropic" energy emission in eq.4 is defined as $E_{isot} \equiv 4\pi(\Delta E_\gamma/\Delta\Omega)$ and R_{MW} is the rate of observable GGRBs (those GRBs in the Milky Way galaxy that emit γ-rays in our direction). Wijers et al. (1997) pointed out that if the origin of GRBs is related to the birth of neutron stars and black holes, then the GRB rate is proportional to the star formation rate. In fact, the recent spectral observations of CGRBs afterglows strongly suggest that GRBs are produced in star burst regions. Wijers et al. (1997) used the new distance scale of CGRBs, which follows from the measured/estimated redshifts of CGRB afterglows and their host galaxies, and the assumption that the CGRB rate follows the star formation rate, to show that the current GRB rate per galaxy is $< 2 \times 10^{-8}\ y^{-1}$. This value is two orders of magnitude smaller than that was thought before. We have reestimated the current GGRB rate (GRBs in a Milky Way) from new measurements (Steidel et al. 1998 and references therein) of the star formation rate as function of redshift z, as shown in Fig.1, using $R[CGRB] \simeq 10^3\ y^{-1}$ for the rate of observable CGRBs (Fishman and Meegan 1995). The present $(z = 0)$ rate of observable GGRBs is given approximately by

$$R_{MW}[GRB] \simeq \frac{R[CGRB] L_{MW} R_{SFR}(z=0)}{\rho_L \int (1+z)^{-1} R_{SFR}(z)(dVc/dz)dz}, \quad (5)$$

where $L_{MW} \sim 2.3 \times 10^{10} L_\odot$ is the stellar luminosity of the Milky Way and $\rho_L \simeq 1.8h \times 10^8 L_\odot\ Mpc^{-3}$ is the luminosity density in the local universe (Loveday et al. 1992). For a critical universe, with $\Omega_M = 1$ and $\Lambda = 0$, one has $dV_c = 16\pi(c/H)^3(1 + z - \sqrt{1+z})^2(1+z)^{-7/2}dz$, and the volume average of the observed star formation rate (Fig.1) yields a mean rate which is about 15 time larger than that in the local Universe, $\bar{R}_{SFR} = \int (R_{SFR}/(1+z)(dV_c/dz)dz/V_c \sim 15 R_{SFR}(z=0)$ (the factor 1/(1+z) in the volume integral is the cosmological time dilation factor). Consequently, with $\int (1+z)^{-1}(dVc/dz)dz = (16\pi/15)(c/H)^3$ and $h \sim 0.5$, eq.5 yields $R_{MW}[GGRB] \sim 2 \times 10^{-8}\ y^{-1}$, which is similar to the value obtained by Wijers et al. (1997). (The dependence on h, where $H = 100h\ km\ s^{-1}\ Mpc^{-1}$ is the Hubble constant, cancels out in eq. 5. The value $h = 0.5$ was chosen for the consistency with Fig. 1). The result is not much different (but somewhat smaller) for other standard cosmological models, such as $\Omega_M \sim 0.3$ and $\Omega_\Lambda \sim 0.7$ or, $\Omega_M \sim 0.2$ and $\Omega_\Lambda \sim 0$. Thus, we conclude from eqs. 4-5 that GGRBs with integrated CR luminosities similar to their integrated γ-ray luminosities, cannot explain the Galactic CR luminosity.

4. COSMIC RAYS FROM CGRBs

It was suggested independently by Waxman (1995), by Vietri (1995) and by Milgrom and Usov (1995) that, perhaps, most of the CR luminosity of GRBs is in UHECR, and then, isotropically emitting extragalactic GRBs, with similar integrated CR and γ-ray luminosities, may be the source of the UHECR and, perhaps, the source of CR with energy down to the knee (Usov and Milgrom 1996). However, the mean attenuation length (lifetime) of CR with energies above about $10^{20} eV$, the so called "GZK cutoff" energy in the intensity of UHECR that was predicted independently by Greisen (1996) and by Zatsepin and Kuz'min (1996) for extragalactic cosmic rays due to their interaction with the cosmic background photons, is (e.g., Lee 1987) $D < 15\ Mpc$ ($\tau < 5 \times 10^7\ y$), as can be seen from Fig. 2. Cascade protons with an initial particle spectrum $dn/dE \sim E^{-\beta}$, increse their mean distance (life time) from where protons can reach near Earth with final energy E, but they do not change the observed spectral index above the (red shifted) threshold energy for "inverse" photoproduction because of Feynman scaling. The enhancement factor is given approximately by $k = 1/(1- < x >^{\beta-1})^2 \simeq 2 \pm 0.4$, where $< x >\rightarrow 0.5$ is the mean fraction of the initial momentum retained by protons in inverse photoproduction, which is energy independent because of Feynman scaling, and $\beta \simeq 2.7 \pm 0.2$ is the observed particle spectral index of the UHECR above the CR ankle. A uniform distribution of galaxies (CGRB sites) around the Milky Way, with a number density n per unit volume, produces CR energy flux (energy per unit area, per sr, per unit time),

$$S \approx R_G \Delta E_{CR} \frac{1}{4\pi} \int \frac{4\pi r^2 n e^{-r/kD}}{4\pi r^2} dr = \frac{n R_G \Delta E_{CR} k D}{4\pi}. \tag{6}$$

Cosmic expansion and evolution can be neglected for cosmological distances $kD \ll c/H$. If the UHECR are trapped locally by (unknown) strong extragalactic magnetic fields that surround our Milky Way galaxy, then D in eq.6 must be replaced by $c\tau(E)$, where $\tau(E)$ is the lifetime of UHECR with energy E in the trap due to attenuation by radiation fields and/or escape by diffusion in the magnetic fields. The measured luminosity density in the local Universe is (Loveday 1992), $\rho_L \simeq 1.8h \times 10^8 L_\odot\ Mpc^{-3}$. If $R_G < 10^{-8}\ y^{-1}$ per $L_* \simeq 10^{10} L_\odot$ galaxy and if the kinetic energy release in UHECR per GRB is, $\Delta E_{CR} = 5\epsilon \times 10^{50}\ erg$, where ϵ is the mean energy of UHECR in $10^{20} eV$ units (Waxman 1995, Vietri 1995, Milgrom and Usov 1996), then eq. 6 yields an energy flux of UHECR,

$$S \simeq 6 \left(\frac{n}{1.8h \times 10^{-2} Mpc^{-3}}\right) \left(\frac{R_G}{10^{-8} y^{-1}}\right) \left(\frac{\Delta E_{CR}}{10^{51} erg}\right) \left(\frac{kD}{30 Mpc}\right)\ eV\ m^{-2} s^{-1} sr^{-1}. \tag{7}$$

The CR above the ankle have an approximate power-law spectrum (Takeda et al. 1998), $dn/dE \approx E^{-\beta}$, with $\beta \simeq 2.7 \pm 0.$. Even if the bulk of the GRB energy is carried by CR with energy above $E_0 \simeq 10^{20} eV$, one obtains from eq.7, for $E \simeq E_0$, that

$$E^3 \frac{dn}{dE} \simeq (\beta - 2) S E_0 \left(\frac{E}{E_0}\right)^{1-\beta} \sim 4 \times 10^{20} eV^2 m^{-2} s^{-1} sr^{-1}. \tag{8}$$

This value is smaller by four orders of magnitude than the observed value (e.g., Takeda et al. 1998), $E^3 dn/dE \simeq 5 \times 10^{24} eV^2 m^{-2} s^{-1} sr^{-1}$ around $E \sim 10^{20}\ eV$.

5. COSMIC RAYS FROM BEAMED CGRBs ?

The above luminosity problems can be solved by postulating that GRBs emit isotropically more than 10^{55} erg in UHECR, which is very unlikely for compact stellar objects, or by jetting the GRB ejecta (Dar et al. 1998; Dar 1998; Dar and Plaga 1998). Note that ΔE, the kinetic energy release in GRBs, if they are associated with the birth of compact stellar objects, is bounded by their gravitational binding, and probably it is one or two orders of magnitude smaller, because of neutrino and gravitational wave emission, as observed, for instance, in SNe. But, the "isotropic" energy emission, which is inferred from the measured γ-ray fluence F_γ of GRBs their measured redshift z and their luminosity distance d_L,

$$E_{isot} \equiv 4\pi\Delta E_\gamma/\Delta\Omega \simeq 4\pi d_L^2 F_\gamma/(1+z), \qquad (9)$$

can exceed even $M_\odot c^2 \simeq 1.8 \times 10^{54}\ erg$ by a large factor. E.g., if the GRB ejecta is narrowly collimated into a jet (plasmoid) with a bulk motion Lorentz factor $\Gamma \sim 10^3$ (e.g., Dar and Plaga 1998) then its radiation is beamed into a solid angle $\Delta\Omega \sim \pi/\Gamma^2$ and $E_{isot} \equiv 4\pi(\Delta E/\Delta\Omega) = (4\pi/\Delta\Omega)\Delta E \sim 4 \times 10^6(\Gamma/10^3)^2\Delta E$, is much larger than ΔE, the true energy release in GRBs. Thus, while the total luminosity of CGRBs in γ-rays (eq.4) is independent of the unknown beaming angle, $E_{isot}[CR]$ can be much larger than that assumed by Waxman (1995), Vietri (1995) and Usov and Milgrom (1996). However, extragalactic UHECR must show the GZK "cutoff" unless there is a "cosmic conspiracy". Namely, either the large scale local magnetic fields conspire to trap the extragalactic UHECR at the GZK "cutoff" energy for a time which is exactly equal to their attenuation time in the background radiation (Sigl et al. 1998), or the GRB source spectrum below the GZK "cutoff" energy is suppressed by exactly the attenuation factor above it or GRBs produce new particles with a flux that is fine tuned to produce a smooth CR spectrum at the GZK cutoff. Such fine tuned "cosmic conspiracies" seem very improbable and unnatural: Observational limits on extragalactic magnetic fields, from limits on Faraday rotation of radio waves from distant powerful radio sources (e.g., Kronberg 1994) and from limits on intergalactic synchrotron emission, imply Larmor radius for $4 \times 10^{19} eV$ protons in typical extragalactic magnetic fields, ($B < nG$), that is much larger than the typical coherence length ($\lambda < 1\ Mpc$) of these fields. Moreover, magnetic trapping is completely ruled out if the arrival directions of UHECR coincide with the directions of cosmological GRBs (Usov and Milgrom 1995) or if the arrival directions of extragalactic UHECR are clustered (Hayashida et al. 1996). Fermi or collisionless shock acceleration normally produce smooth power-law source spectra and not ad hoc imposed thresholds. Thus, jetting the ejecta of GRBs may solve the energy problem but does not seem to explain the absence of the GZK cutoff.

Moreover, UHECR have a Larmor radius, $R_L \sim 100(E/10^{20}eV)(ZB/nG)^{-1}\ Mpc$, that is much larger than the coherence length, $\lambda \sim 1\ Mpc$ and $\lambda \sim 1\ kpc$, of, respectively, the intergalactic and the halo turbulent magnetic fields (Kronberg 1994). Therefore, they suffer only small random deflections along their arrival trajectories from a typical distances $kD \sim 30 Mpc$. This implies that the arrival directions of the UHECR point back in the directions of nearby ($kD < 50\ Mpc$) galaxies, i.e. in the direction of the Virgo cluster and the Super galactic plane, which is not observed (e.g., Hayashida et al. 1996). Furthermore, the spread in their arrival direction with respect to the source direction has r.m.s. angular deviation,

$$\Delta\theta \sim 2^0 \left(\frac{E}{10^{20}}\right)^{-1} \left(\frac{kD}{50Mpc}\right)^{1/2} \left(\frac{\lambda}{Mpc}\right)^{1/2} \left(\frac{B}{nG}\right), \tag{10}$$

and arrival times that are spread with r.m.s. value

$$\Delta t \sim 7 \times 10^4 \left(\frac{E}{10^{20}}\right)^{-2} \left(\frac{kD}{50Mpc}\right) \left(\frac{\lambda}{Mpc}\right) \left(\frac{B}{nG}\right)^2\ y. \tag{11}$$

The number of GRBs within distance of $d \leq 50\ Mpc$ during this spread of arrival times is $N_{GRB} \simeq (\rho_L/L_{MW})(4\pi/3)d^3 R_{MW}[GGRB]\Delta t < 1$. Consequently, all UHECR with energy above $10^{20}\ eV$ should point back to one or two sources with an angular spread of $\sim 2^0$, which is inconsistent with their observed wide sky distribution (Takeda et al. 1998).

6. CONCLUSION

The above arguments can be repeated for UHECR nuclei that are photodissociated by cosmic background photons, and for UHECR photons that are attenuated by pair production. Both have attenuation lengths shorter than that of UHECR. Then, it leads to the conclusion that if the CR that are observed near Earth are long lived normal CR particles, their source is not extragalactic GRBs. However, if GRBs are narrowly collimated, then Galactic GRBs can produce the cosmic rays which are observed near Earth, including those with the highest observed energies (Dar and Plaga 1998).

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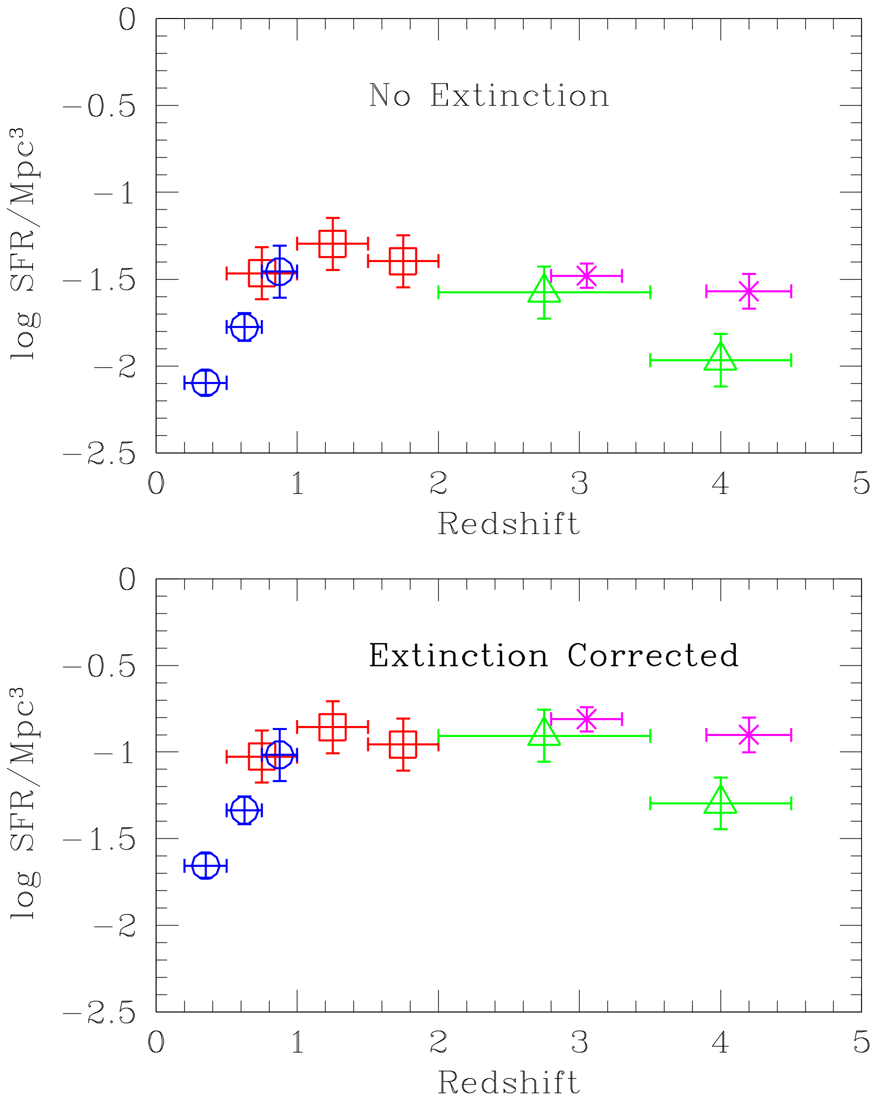

Fig. 1.— The star formation rate per comoving volume as a function of redshift, assuming $H_0 = 50$ kms Mpc^{-1} and $q_0 = 0.5$, uncorrected and corrected for extinction by Steidel et al. 1998. The different points are from Lilly et al. 1996 [circles], Connolly et al. 1997 [squares], Madau et al. 1997 [triangles], and Steidel et al. 1998 [crosses].

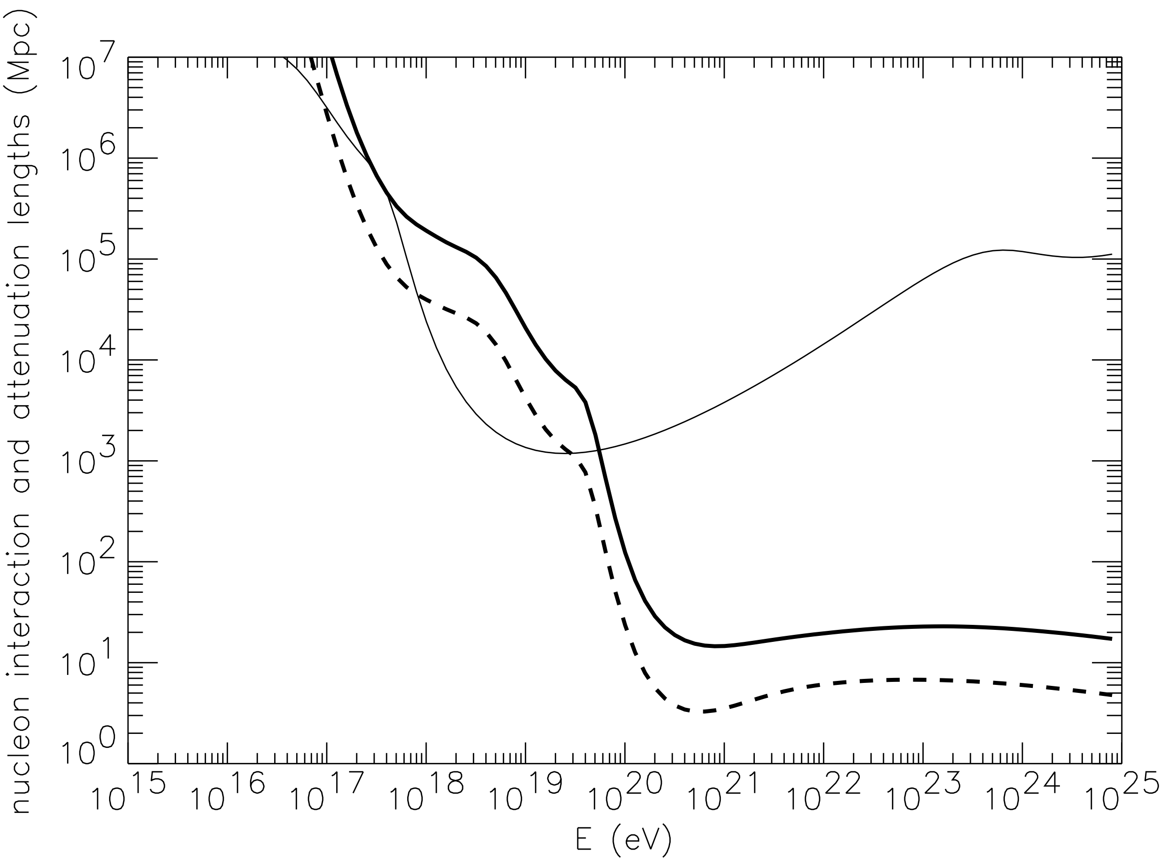

Fig. 2.— The proton interaction length (dashed line) and attenuation length (heavy line) for inverse photoproduction on the cosmic background radiation, and the proton attenuation length due to pair production (thin line), as calculated by Lee 1998.

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