THE ASTROPHYSICAL JOURNAL, 512:521–526, 1999 February 20
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PHOTODISINTEGRATION OF ULTRA–HIGH-ENERGY COSMIC RAYS: A NEW DETERMINATION

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Received 1998 August 11; accepted 1998 September 22

ABSTRACT

We present the results of a new calculation of the photodisintegration of ultra–high-energy cosmic-ray (UHCR) nuclei in intergalactic space. The critical interactions for energy loss and photodisintegration of UHCR nuclei occur with photons of the 2.73 K cosmic background radiation (CBR) and with photons of the IR background radiation (IBR). We have reexamined this problem, making use of a new determination of the IBR based on empirical data primarily from IRAS galaxies, which is consistent with direct measurements and upper limits from TeV γ-ray observations. We have also improved the calculation by including the specific threshold energies for the various photodisintegration interactions in our Monte Carlo calculation. With the new smaller IBR flux, the steepness of the Wien side of the now relatively more important CBR makes their inclusion essential for more accurate results. Our results indicate a significant increase in the propagation time of UHCR nuclei of a given energy over previous results. We discuss the possible significance of this for UHCR origin theory.

Subject headings: cosmic microwave background — cosmic rays — diffuse radiation — intergalactic medium

1. INTRODUCTION

Shortly after the discovery of the cosmic microwave background radiation (CBR), it was shown that cosmic-ray protons above ~ 60 EeV (6×10^{19} eV) should be attenuated by photomeson interactions with CBR photons (Greisen 1966; Zatsepin & Kuzmin 1966; Stecker 1968). It was later calculated that heavier cosmic-ray nuclei with similar *total* energies would also be attenuated but by a different process, viz., photodisintegration interactions with IR background radiation (IBR) photons (Puget, Stecker, & Bredekamp 1976, hereafter PSB).[1] We will refer to such cosmic rays of total energies above 10 EeV as ultra–high-energy cosmic rays (UHCRs).

In the more conventional scenario, UHCRs are charged particles that must be accelerated to ultra-high energies by electromagnetic processes at extragalactic sites, both because there are no known sites in our Galaxy that can accelerate and magnetically contain them, and most of the observed UHCR air shower events arrive from directions outside of the Galactic plane. Although such acceleration of charged particles to energies above 100 EeV in cosmic sources pushes our present theoretical ideas to their extreme, it has been suggested that it may occur in hot spots in the lobes of radio galaxies (Biermann & Strittmatter 1987; Takahara 1990).

The detection of the two highest energy air shower events yet observed, with energies of ~ 200 (between 170 and 260) EeV (Hayshida et al. 1994) and 320 ± 90 EeV (Bird et al. 1995), has aggravated both the acceleration and propagation problems for cosmic-ray physicists. (Very recently, the Akens Giant Air Shower Array group has presented a total of six events of energies between ~ 100 and ~ 200 EeV, including the one cited above, observed since 1990; Takeda et al. 1998.) How does nature accelerate particles to these extreme energies, and how do they get here from extragalactic sources (Elbert & Sommers 1995)? To answer these questions, new physics has been invoked, involving the formation and annihilation of topological defects (TDs) that may have been produced in the very earliest stages of the big bang, perhaps as a result of grand unification. A TD annihilation or decay scenario has unique observational consequences, such as the copious production of UHCR neutrinos and γ-rays (Sigl 1996 and references therein; Bhattacharjee, Shafi, & Stecker 1998). A new ground-based detector array experiment named after Pierre Auger (Cronin 1992) and an interesting satellite experiment called *OWL* (*Orbiting Wide-Angle Light Collectors*; Ormes et al. 1997) have been proposed to look for such consequences.

2. PROPAGATION OF UHCR NUCLEI

A UHCR *proton* of energy ~ 200 EeV has a lifetime against photomeson losses of $\sim 3 \times 10^{15}$ s; one of energy 300 EeV has a lifetime of about half that Stecker (1968). These values correspond to linear propagation distances of ~ 30 and 15 Mpc, respectively. Even shorter lifetimes were calculated for Fe nuclei based on photodisintegration off the IBR (PSB). Recent estimates of the lifetimes of UHCR γ-rays against electron-positron pair production interactions with background radio photons give values below 10^{15} s (Protheroe & Biermann 1996). Within such distances, it is difficult to find candidate sources for UHCRs of such energies.

In this paper, we reexamine a part of the propagation problem by presenting the results of a new calculation of the photodisintegration of UHCR *nuclei* through the CBR and IBR in intergalactic space. In order to do this, we have made use of a new determination of the IBR based on

[1] For earlier work and other considerations involving the photodisintegration of extragalactic high-energy cosmic-ray nuclei, see Stecker (1969), Tkaczyk, Wdowczyk, & Wolfendale (1975), and Karakula & Tkaczyk (1993).

empirical data primarily from IRAS galaxies recently calculated by Malkan & Stecker (1998).[2]

They calculated the intensity and spectral energy distribution (SED) of the IBR based on empirical data, some of which was obtained for almost 3000 IRAS galaxies. It is these sources that produce the IBR. The data used for the new IBR calculation included (1) the luminosity-dependent SEDs of these galaxies, (2) the 60 μm luminosity function for these galaxies, and (3) the redshift distribution of these galaxies. The magnitude of the IBR flux derived by Malkan & Stecker (1998) is considerably lower than that used in PSB in their extensive examination of the photodisintegration of UHCR nuclei.

A search for absorption in the high-energy γ-ray spectra of extragalactic sources can also be used to help determine the value of the IBR or to place constraints on the magnitude of its flux (Stecker, De Jager, & Salamon 1992; Stecker, & De Jager 1993). The observed lack of strong absorption in the γ-ray spectra of the active galaxies Mrk 421 (McEnery et al. 1997) and Mrk 501 (Aharonian et al. 1997) up to an energy greater than $\sim$5–10 TeV is consistent with the new, lower value for the IBR used here (Stecker & De Jager 1997, 1998; Stanev & Franceschini 1998; Biller et al. 1998).

The SED calculated by Malkan & Stecker (1998) agrees with direct estimates of the far-IR background obtained from the *COBE*/FIRAS observations (Puget et al. 1996; Fixsen et al. 1997, 1998). Recent fluxes reported from *COBE*/DIRBE observations at 140 and 240 μm (Hauser et al. 1998) are roughly a factor of 2 higher than the Malkan & Stecker (1998) predictions but are consistent with them if one considers the systematic uncertainties in the observational results (Dwek et al. 1998).

In justifying our reexamination of the photodisintegration problem using the new IBR SED, we point out that it may reasonable to expect that the highest energy cosmic rays may be nuclei. This is because the maximum energy to which a particle can be accelerated in a source of a given size and magnetic field strength is proportional to its charge, Ze. That charge is 26 times larger for Fe than it is for protons. Although some composition measurements in the energy range 0.1–10 EeV appear to indicate a transition from heavier to lighter nuclei with increased energy (Gaisser et al. 1993), this and other data appear to be consistent with a "mixed" composition of both protons and heavier nuclei (Hayashida et al. 1995; Dawson, Meyhandan, & Simpson 1998). In any case, at the "lower" energies for which composition measurements have been attempted, most of the cosmic rays may be Galactic in origin.

3. CALCULATIONS

We have now done a full Monte Carlo calculation similar to that presented in PSB but using the new intergalactic infrared spectrum given by Malkan & Stecker (1998). In this new calculation, we have also specifically included the threshold energies of the various nuclear species to photodisintegration. The reason this is now important is that with the CBR playing a relatively more important role, interactions of the steeply falling cosmic-ray spectrum near threshold with the Wien tail of the CBR become important relative to the much flatter IBR photon spectrum. In fact, as we will show, taking account of the measured higher threshold energies (as opposed to the artificial value of 2 MeV taken by PSB) increases the value of the cutoff energy for heavy UHCR nuclei.

Our intent is both to update and improve the PSB results and to determine whether the highest energy cosmic-ray events seen by the Fly's Eye and Akeno groups are consistent with their being heavy nuclei that have propagated to us from candidate active galactic nuclei (Stecker 1998). The energy loss from photodisintegration has a much stronger dependence on Lorentz factor than on atomic weight and increases strongly with Lorentz factor γ (PSB). Therefore, to maximize the propagation distance for a given total particle energy, $E = \gamma AM$ (where M is the nucleon mass), one takes the largest possible mass number. Given the abundances of the elements, this nucleus is Fe. Therefore (as PSB have done), we chose to examine the propagation history of UHCR nuclei originating as ^{56}Fe, as this nuclide offers the best chance for providing a conventional explanation for the UHCR events.

3.1. *Cross Sections*

The nuclear photodisintegration process is dominated by the giant dipole resonance (GDR), which peaks in the γ-ray energy range of 10–30 MeV (nuclear rest frame). Experimental data are generally consistent with a two-step process: photoabsorption by the nucleus to form a compound state, followed by a statistical decay process involving the emission of one or more nucleons from the nucleus (Levinger 1960). The photoabsorption cross section roughly obeys a Thomas-Reiche-Kuhn (TRK) sum rule, viz.,

$$\Sigma_d \equiv \int_0^\infty \sigma(\epsilon) d\epsilon = \frac{2\pi^2 e^2 \hbar}{Mc} \frac{NZ}{A} = 60 \frac{NZ}{A} \text{ mbar-MeV} , \quad (1)$$

where A is the mass number, Z is the nuclear charge, $N = A - Z$, M is the nucleon mass, and ϵ is the photon energy in the rest system of the nucleus. The TRK sum rule is not exact, however, because of the presence of nuclear exchange forces (Feenberg 1936), as can be seen in Table 1 of PSB (which is based on the data tabulations of Fuller et al. 1973; related material supplied by E. Fuller.)

PSB approximated the GDR cross section for a given nuclide (Z, A) with the parameterization

$$\sigma_i(\epsilon) = \xi_i \Sigma_d W_i^{-1} e^{-2(\epsilon - \epsilon_{p,i})^2/\Delta_i^2} \Theta(\epsilon - \epsilon_{\text{thr}}) \Theta(\epsilon_1 - \epsilon) ; + \zeta \Sigma_d \Theta(\epsilon - \epsilon_1) \Theta(\epsilon_{\max} - \epsilon)/(\epsilon_{\max} - \epsilon_1) , \quad (2)$$

where the Z and A dependence of the width Δ_i, the peak energy $\epsilon_{p,i}$, and the dimensionless integrated cross sections ξ_i and ζ are understood and are listed in Table 1 of PSB. $\Theta(x)$ is the Heaviside step function, and the normalization constants W_i are given by

$$W_i = \Delta_i \sqrt{\frac{\pi}{8}} \left[\text{erf}\left(\frac{\epsilon_{\max} - \epsilon_{p,i}}{\Delta_i/\sqrt{2}} \right) + \text{erf}\left(\frac{\epsilon_{p,i} - \epsilon_1}{\Delta_i/\sqrt{2}} \right) \right] . \quad (3)$$

[2] In a recent paper (Stecker 1998), one of us considered such photodisintegration interactions, using the new estimate of the extragalactic IR spectral energy distribution by (Malkan & Stecker 1998), which yielded an extragalactic IR photon density even lower than the low-IR estimate used in PSB. That paper, however, neglected the fact that the lower IR flux used in the new calculation would imply that interactions with CBR photons would now be dominant above an energy of roughly 130 EeV rather than 300 EeV (see Fig. 8 in PSB). Thus, as pointed out by Epele & Roulet (1998), it is important to include interactions with CBR photons in the calculation.

The index i takes the values 1 or 2, corresponding to single- or double-nucleon emission during the photodisintegration reaction. For energies $\epsilon < \epsilon_1 = 30$ MeV, the measured cross sections are dominated by single [(γ, n) or (γ, p)] or double [$(\gamma, 2n)$, (γ, np), $(\gamma, 2p)$] nucleon loss, since the threshold energies for the emission of larger numbers of nucleons are close to or exceed ϵ_1 (Forkman & Petersson 1987). From ϵ_1 to $\epsilon_{max} = 150$ MeV, the cross section is approximated as flat, normalized so the integrated cross section matches experimental values. The probability of emission of k nucleons in this region is given by a distribution function that is independent of the γ-ray energy (see Table 2 of PSB). Above ϵ_{max}, detailed cross section data are more scarce; we follow PSB by approximating this smaller residual cross section by zero. Interactions with photons of energy greater than ϵ_{max} will have a negligible contribution to the photodisintegration process for UHCR energies below 1000 EeV, owing to the fact that the density of the background photons seen by the UHCR near the peak of the GDR cross section falls rapidly with energy (exponentially along the Wien tail of the CBR and roughly as ϵ^{-2} in IR-optical region), along with the fact that the photodissociation cross section is about 2 orders of magnitude lower in the γ-ray energy region from ϵ_{max} to ~ 1 GeV than at the GDR peak (Jonsson & Lindgren 1973, 1977). We have verified by numerical tests that interactions with photons of energy greater than ϵ_{max} indeed have a negligible effect on our calculation.

In the PSB calculation the GDR threshold energies were taken to be $\epsilon_{thr} = 2.0$ MeV for *all* reaction channels. This value is far smaller than the true thresholds; single-nucleon emission has a typical threshold of ~ 10 MeV, while the double-nucleon emission energy threshold is typically ~ 20 MeV. Table 1 lists the energy thresholds for the (γ, n), (γ, p), $(\gamma, 2n)$, (γ, np), $(\gamma, 2p)$, and (γ, α) channels for each nuclide in the ^{56}Fe decay chain (taken from Forkman & Petersson 1987). Owing to the increased importance of the CBR relative to the IBR that follows from the new, lower IBR estimates and the presence of the Wien tail that exponentially increases the target photon density at the GDR threshold (see Fig. 1), increasing this threshold energy may significantly lengthen the propagation distance of a highly relativistic nucleus. Therefore, we have used the measured threshold energies for a subset of the reaction channels given in Table 1.

Unfortunately, photodisintegration cross section data are incomplete. For many reaction channels, $\sigma(\epsilon)$ data do not exist. Also, integrated cross section strengths are not available for all of the exclusive channels. The most complete compilation of the world's GDR cross section data exists in the 15 volumes of Fuller & Gerstenberg (1983). In these volumes GDR cross section data for ^{56}Fe, for example, are given only for the (γ, pX) channel and the inverse channels (α, γ) and (p, γ).

One cannot perform the Monte Carlo calculations in such a way as to distinguish a (γ, n) interaction from a (γ, p) reaction when the relative branching ratios are not known. Instead, we separately consider only single-nucleon emission (as a single channel) and double-nucleon emission (as a single channel) in the GDR region up to ϵ_1. We take the conservative approach of choosing the energy threshold for single-nucleon emission to be the *lowest* of the two for (γ, n) and (γ, p) for each nuclide in the decay chain, with a similar choice for the double-nucleon emission channel. Along most of the decay chain from ^{56}Fe to ^{1}H there is only one stable isotope for a given mass A. Since the radioactive decay time to the line of stability is less than the one-nucleon photodisintegration loss time for all but three unstable nuclei, ^{53}Mn, ^{26}Al, and ^{10}Be, we assume that decay has brought the daughter nucleus to the line of stability before the next photon collision, so for any given mass A there is a unique charge Z. This clearly is not the case for mass values $A = 54$, 50, 48, 46, 40, and 36, where more than one stable isotope exists, but the absence of cross section data for each of these isotopes makes this a moot point.

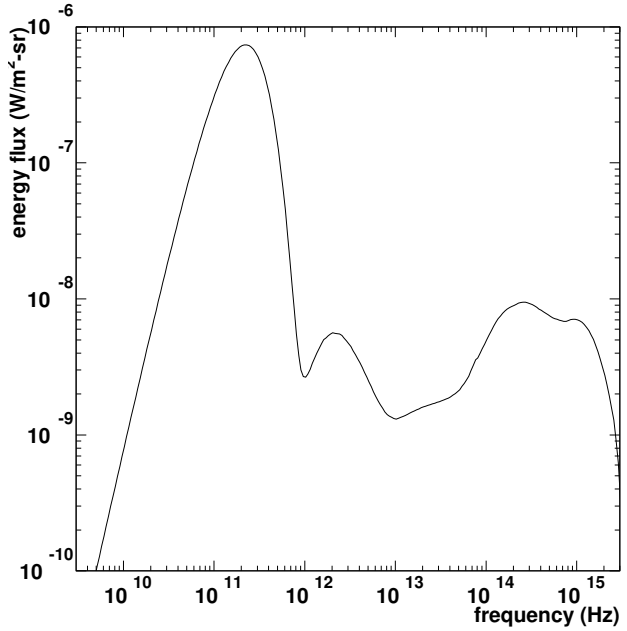

FIG. 1.—Energy flux spectrum (SED) of the diffuse, intergalactic soft photon background used in these calculations.

We also note that although the thresholds are lowest for α emission (because of the α's large binding energy), the integrated cross section for α emission from ^{56}Fe, for example, is over 2 orders of magnitude lower than the Σ_d value for that nuclide (Skopic, Asai, & Murphy 1980; see also Fuller & Gerstenberg 1983). We therefore neglect the α emission channels entirely in our calculation.

3.2. *Reaction Rates*

For a UHCR nucleus with Lorentz factor $\gamma = E/AM$ propagating through an isotropic soft-photon background with differential number density $n(\epsilon)$, the photodisintegration rate R (lab frame) is given by (Stecker 1969):

$$R = \frac{1}{2} \int_0^\infty d\epsilon \, \frac{n(\epsilon)}{\gamma^2 \epsilon^2} \int_0^{2\gamma\epsilon} d\epsilon' \epsilon' \sigma(\epsilon') \, , \tag{4}$$

where σ is the total cross section summed over the number of emitted nucleons.

In our calculations we construct the soft-photon background by summing three components: (1) the $T = 2.73$ K CBR from lab frame energies of $\epsilon = 2.0 \times 10^{-6}$–$4.0 \times 10^{-3}$ eV, (2) the IBR estimated by Malkan & Stecker (1998) from $\epsilon = 3.0 \times 10^{-3}$ to 0.33 eV (using the two "best estimates" shown by heavy lines in their Fig. 2, which we denote as the "high-IBR" and "low-IBR" cases), and (3) the optical to UV diffuse, extragalactic photon background estimated by Salamon & Stecker (1998; taking their no–metallicity-

TABLE 1

PHOTODISINTEGRATION ENERGY THRESHOLDS (IN MEV) FOR ONE-NUCLEON, TWO-NUCLEON, AND α EMISSION FOR ALL ISOTOPES IN THE DECAY CHAIN OF ^{56}Fe

Z	A	(γ, n)	(γ, p)	$(\gamma, 2n)$	(γ, np)	$(\gamma, 2p)$	(γ, α)
26.....	56	11.2	10.2	20.5	20.4	18.3	7.6
26.....	54	13.4	8.9	24.1	20.9	15.4	8.4
25.....	55	10.2	8.1	19.2	17.8	20.4	7.9
24.....	54	9.7	12.4	17.7	20.9	22.0	7.9
24.....	53	7.9	11.1	20.0	18.4	20.1	9.1
24.....	52	12.0	10.5	21.3	21.6	18.6	9.4
24.....	50	13.0	9.6	23.6	21.1	16.3	8.6
23.....	51	11.1	8.1	20.4	19.0	20.2	10.3
23.....	50	9.3	7.9	20.9	16.1	19.3	9.9
22.....	50	10.9	12.2	19.1	22.3	21.8	10.7
22.....	49	8.1	11.4	19.8	19.6	20.8	10.2
22.....	48	11.6	11.4	20.5	22.1	19.9	9.4
22.....	47	8.9	10.5	22.1	19.2	18.7	9.0
22.....	46	13.2	10.3	22.7	21.7	17.2	8.0
21.....	45	11.3	6.9	21.0	18.0	19.1	7.9
20.....	48	9.9	15.8	17.2	24.2	29.1	14.4
20.....	46	10.4	13.8	17.8	22.7	22.7	11.1
20.....	44	11.1	12.2	19.1	21.8	21.6	8.8
20.....	43	7.9	10.7	19.4	18.2	19.9	7.6
20.....	42	11.5	10.3	19.8	20.4	18.1	6.2
20.....	40	15.6	8.3	29.0	21.4	14.7	7.0
19.....	41	10.1	7.8	17.9	17.7	20.3	6.2
19.....	40	7.8	7.6	20.9	14.2	18.3	6.4
19.....	39	13.1	6.4	25.2	18.2	16.6	7.2
18.....	40	9.9	12.5	16.5	20.6	22.8	6.8
18.....	38	11.8	10.2	20.6	20.6	18.6	7.2
18.....	36	15.3	8.5	28.0	21.2	14.9	6.6
17.....	37	10.3	8.4	18.9	18.3	21.4	7.8
17.....	35	12.6	6.4	24.2	17.8	17.3	7.0
16.....	36	9.9	13.0	16.9	21.5	25.0	9.0
16.....	34	11.4	10.9	20.1	21.0	20.4	7.9
16.....	33	8.6	9.6	23.7	17.5	18.2	7.1
16.....	32	15.0	8.9	28.1	21.2	16.2	6.9
15.....	31	12.3	7.3	23.6	17.9	20.8	9.7
14.....	30	10.6	13.5	19.1	22.9	24.0	10.6
14.....	29	8.5	12.3	25.7	20.1	21.9	11.1
14.....	28	17.2	11.6	30.5	24.6	19.9	10.0
13.....	27	13.1	8.3	24.4	19.4	22.4	10.1
12.....	26	11.1	14.1	18.4	23.2	24.8	10.6
12.....	25	7.3	12.1	23.9	19.0	22.6	9.9
12.....	24	16.5	11.7	29.7	24.1	20.5	9.2
11.....	23	12.4	8.8	23.5	19.2	24.1	10.5
10.....	22	10.4	15.3	17.1	23.4	26.4	9.7
10.....	21	6.8	13.0	23.6	19.6	23.6	7.3
10.....	20	16.9	12.8	28.5	23.3	20.8	4.7
9	19	10.4	8.0	19.6	16.0	23.9	4.0
8	18	8.0	15.9	12.2	21.8	29.1	6.2
8	17	4.1	13.8	19.8	16.3	25.3	6.4
8	16	15.7	12.1	28.9	23.0	22.3	7.2
7	15	10.8	10.2	21.4	18.4	31.0	11.0
7	14	10.6	7.6	30.6	12.5	25.1	11.6
6	13	4.9	17.5	23.7	20.9	31.6	10.6
6	12	18.7	16.0	31.8	27.4	27.2	7.4
5	11	11.5	11.2	19.9	18.0	30.9	8.7
5	10	8.4	6.6	27.0	8.3	23.5	4.5
4	9	1.7	16.9	20.6	18.9	29.3	2.5
3	7	7.3	10.0	12.9	11.8	33.5	2.5
3	6	5.7	4.6	27.2	3.7	26.4	1.5
2	4	20.6	19.8	28.3	26.1	...	...
2	3	7.7	5.5	...	...	...	...
1	2	2.2	...	...	...	...	...

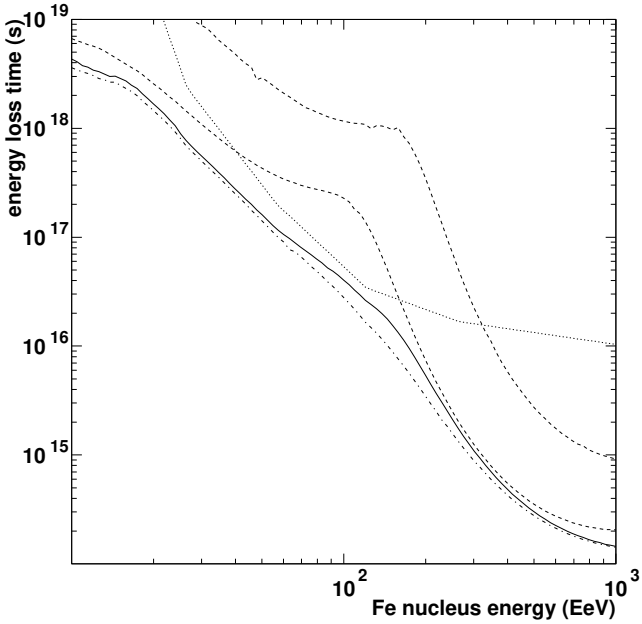

FIG. 2.—Energy-loss times for single-nucleon emission (*lower dashed line*), double-nucleon emission (*upper dashed line*), pair production (*dotted line*), and their total (*solid line*). The dot-dashed line shows the energy-loss time using $E_{\rm thr} = 2$ MeV for all photodisintegration rates, as was done in PSB.

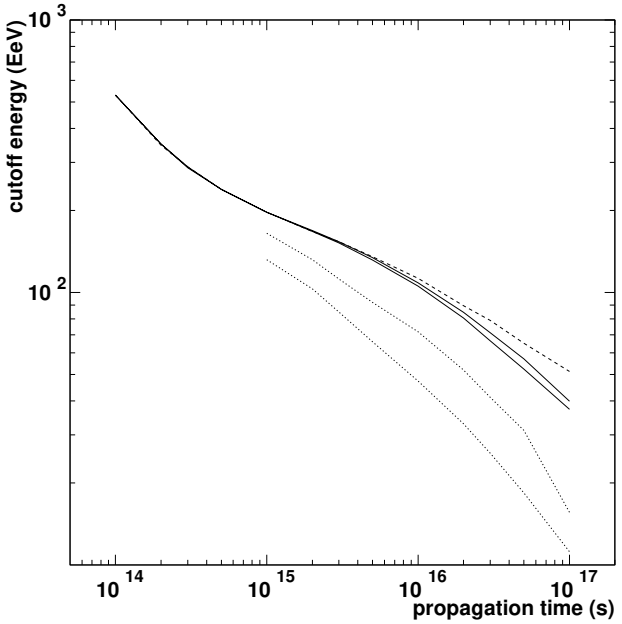

FIG. 4.—Cutoff energy vs. propagation time for UHCR nuclei starting out as ^{56}Fe. The solid lines are for our new calculations using the two IBR SEDs from Malkan & Stecker (1998) and the higher threshold energies. The dashed line is calculated using only the CBR (no IBR). The dotted lines are the results from Fig. 16 of PSB and are shown for comparison. The lower the IBR, the higher the cutoff energy curve.

correction case) from $\epsilon = 0.33$ to 13 eV. Figure 1 shows the SED of the entire low-energy background radiation. A salient feature of this figure is the roughly constant energy flux down to the dramatic rise of the Wien tail of the CBR. For UHCR nuclei with Lorentz factors large enough that the CBR photons are above the photodisintegration threshold, most of the reaction rate R is dominated by collisions with CBR photons. This is particularly true with the new, smaller IR photon background levels, compared with those used by PSB.

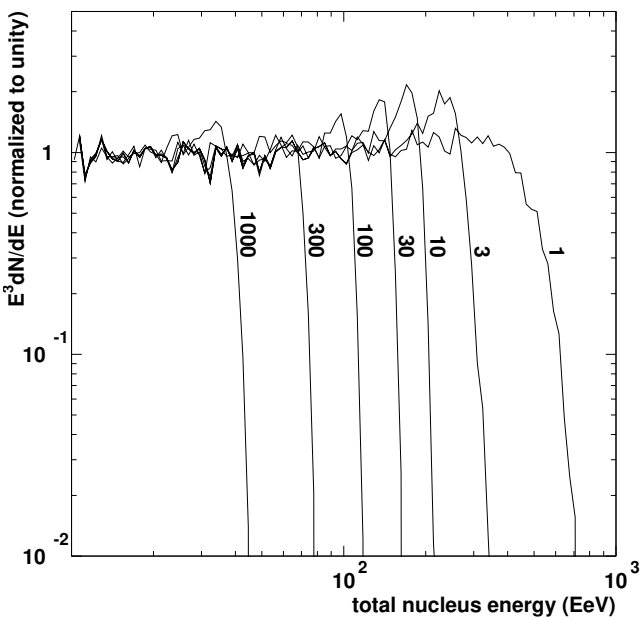

FIG. 3.—Differential spectra of UHCR nuclei that started out as ^{56}Fe after propagation over the distance (in Mpc) indicated for each curve. The source spectrum is taken to be a power law, E^{-3}, over the interval 10–1000 EeV.

The energy-loss time τ is defined as

$$\tau^{-1} \equiv \frac{1}{E}\frac{dE}{dt} = \frac{1}{\gamma}\frac{d\gamma}{dt} + \frac{R_1}{A} + \frac{2R_2}{A} + \frac{\langle \Delta A \rangle R_k}{A}, \qquad (5)$$

where R_1, R_2, and $R_{\rm k}$ are the reaction rates for one- and two-nucleon emission, and $R_{\rm k}$ is the reaction rate for $\langle \Delta A \rangle > 2$ nucleon loss. The reduction in γ comes from two effects: nuclear energy loss due to electron-positron pair production off the CBR background and the γ-ray momentum absorbed by the nucleus during the formation of the excited compound nuclear state that preceeds nucleon emission. This latter effect is much smaller (of order $\sim 10^{-2}$) than the energy loss from nucleon emission and will therefore be neglected. For the former mechanism, we use the results given in Figure 3 of Blumenthal (1970), which gives the loss rate for relativistic nuclei off the CBR calculated in the first Born approximation. (We note that the Coulomb corrections to the Born approximation [Davies, Bethe, & Maximon 1954; Jauch & Rohrlich 1980] have a negligible effect on the pair production loss rate for ultrarelativistic Fe nuclei.)

Figure 2 shows the energy-loss rates due to single-nucleon, double-nucleon, and pair production processes for ^{56}Fe as a function of energy, along with the total energy-loss rate. Also shown is the total energy-loss rate when the photodisintegration thresholds $\epsilon_{\rm thr}$ are all set to 2 MeV; this indicates the effect of incorporating more realistic threshold energies in the Monte Carlo calculation, compared with those of PSB.

3.3. *Results*

Figure 3 shows the spectra of UHCR nuclei ($Z > 1$) that started out as ^{56}Fe after propagating linear distances from 1 to 1000 Mpc (corresponding to lifetimes between 10^{14} and

10^{17} s), assuming a source differential energy spectrum $\propto E^{-3}$ over the energy interval 10–1000 EeV. The effect of the CBR "wall" at the Wien side of the 2.73 K blackbody spectrum is to produce a sharp cutoff at a rather well-defined energy, E_c.

Figure 4 shows the cutoff energy as a function of propagation time, where E_c is defined as the cosmic-ray energy at which the propagated differential flux is $1/e$ that of the unpropagated flux. For comparison, the cutoff energies calculated by PSB are also shown. It can be seen that (except for energies above ~ 200 EeV) for a given energy the propagation time increases by a substantial factor over that calculated by PSB, assuming larger IBR fluxes and a 2 MeV threshold for all photodisintegration interactions. We also note that our new results do not differ significantly for the two SEDs adopted from Malkan & Stecker (1998) and, except for the longest propagation times, they do not differ significantly from the no-IBR case shown in the figure. This is because the new values obtained for the IBR are so low.

4. DISCUSSION AND CONCLUSIONS

As can be seen from Figure 4, our use of the new, lower values for the intergalactic IR photon flux, together with the explicit inclusion of the measured threshold energies for photodisintegration of the individual nuclides involved in the calculation, has the effect of increasing the cutoff energy (for a given propagation time) of heavy UHCR nuclei over that originally calculated by PSB. This increase may have significant consequences for understanding the origin of the highest energy cosmic-ray air shower events.

Stanev et al. (1995) and Biermann (1998) have examined the arrival directions of the highest energy events. They point out that the ~ 200 EeV event is within 10° of the direction of the strong radio galaxy NGC 315. NGC 315 lies at a distance of only ~ 60 Mpc from us. For that distance, our results indicate that heavy nuclei would have a cutoff energy of ~ 130 EeV, which may be within the uncertainty in the energy determination for this event. The ~ 300 EeV event is within 12° of the direction of the strong radio galaxy 3C134. The distance to 3C134 is unfortunately unknown because its location behind a dense molecular cloud in our Galaxy obscures the spectral lines required for a measurement of its redshift. It may be possible that *either* cosmic-ray protons (Stecker 1968) *or* heavy nuclei originated in these sources and produced the highest energy air shower events.

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