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Implications of The Fly's Eye Ultra-High Energy Cosmic Ray Spectrum

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Abstract

We discuss the potential implications of the recent results of the Fly's Eye detector on the ultra high energy spectrum. The data suggest that the observed slope flattening immediately prior to the cutoff appears to be a recoil proton pile-up associated with an $E^{-2.5\pm.2}$ injection spectrum. We discuss the induced neutrino spectrum and its detectability in Fly's Eye and DUMAND detectors.

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Recently the Fly's Eye experiment has presented data on the ultra-high energy cosmic ray spectrum[1] in which there is strong evidence of a spectral flattening above 10^{19}ev from a differential index of 2.94±.02 to 2.42±.27. Above 7×10^{19}ev there is evidence of a cut-off. Though it is true that the detector acceptance is energy dependent and, of course, this data consists of only 62 events, nonetheless this structure survives numerous experimental self-consistency checks (for example, the shape remains if cuts with range from the center of the detector are made on the data). It should be noted that, except for the last few highest energy bins, the Fly's Eye results are in general accord with those of Haverah Park. Thus, in the present letter we will discuss the implications of these results.

As is well known, shortly after the discovery of the 2.7^{o}K microwave background radiation, Greisen[2] and independently Kuzmin and Zatsepin[3] remarked that above energies of order 7×10^{19}ev the intergalactic medium must become opaque to protons on scales of tens of Mpcs. due to photomeson production. Stecker, Berezinsky and others[4] gave the first accounts of this mechanism using experimental laboratory data. Nonetheless, there has not been incontrovertible evidence for the Greisen-Zatsepin cut-off until the Fly's Eye's new results. The implication of this is then striking: the UHE cosmic rays must be extra-galactic and have traversed at least a few interaction lengths (~20 Mpc).

Previous analyses were essentially "zeroth moment" approximations to the actual transport evolution of the spectrum in traversing the microwave background. In the past two years we undertook a much more detailed analysis involving the direct integration of the photomeson production Ginzburg-Syrovatsky equation[5]. We were surprised to see several new effects as depicted in Fig.(1) appropos an $E^{-2.5}$ injection spectrum. We note (i) the recoil protons are not thrown to arbitrarily small energies but rather accumulate immediately below the cut-off in a range of order $3x10^{19}$ev to $6x10^{19}$ev; (ii) with much greater range (exceeding 100Mpc) there onsets a dip at 10^{19}ev due to the peaking of energy losses due to e^+e^- pair production (this analysis was based upon Blumenthal[6]). (iii) By 3000 Mpc (the Hubble range) the spectrum cut-off has fallen to $\sim 10^{19}$ev.

The observed bump in the Fly's Eye data cannot be interpreted as the recoil proton pile up of the $E^{-3.0}$ spectrum. This follows simply by considering the total number of events above 10^{19}ev which is 62 compared to ~40 expected for an $E^{-3.0}$ pile-up. Thus one is seeing one of two possible phenomena: (i) the emergence of a flatter extra-galactic component which is crossing over the steeper, presumably galactice $E^{-3.0}$ spectrum seen below 10^{19}ev or (ii) the pile-up of an arbitrary injection spectrum above $E \sim 10^{20}$ev, e.g. a monoenergetic spike of a sufficiently distant object after several interaction lengths can produce this structure.

It is reasonable that up to energies of order 10^{19}ev we are seeing primarily a galactic spectrum, possibly Fe-group rich, which is governed by an injection spectrum and a diffusion trapping time which is energy dependent. Thus the observed galactic spectrum would follow an $E^{-\gamma_i} t(E)$ shape and for the sake of argument we shall assume γ_i=2.5 and $t(E) \sim E^{-.5}$. The spectrum outside the galaxy is not trapped, but is essentially line of sight (or "trapped" on a scale of the age of sources or age of the Universe) and will therefore have the form $E^{-\gamma_i}$. Thus at some energy we may expect a crossover from the steeper galactic spectrum to the flatter extragalactic one.

Assuming all galaxies are roughly equivalent to our own, that an extra-galactic crossover occurs at 10^{19}ev, and that contributing sources range out to some distance L, we may estimate L. We take for the normalization of the universal injection spectrum the observed CR spectrum at 10^{16}ev. Then, for an idealized disk structure of our galaxy (the solar system on the periphery) we obtain the local flux:

$$J_L = \omega d \rho_s \eta_s \, (E_o/E)^{\gamma_i} \, (E_o/E)^{.5} \tag{1}$$

where ρ_s is the galactic source density, η_s is the activity per source (particles/time), d the width of the galaxy and ω a geometric factor of order unity. The sum over extragalactic sources to distance L then gives:

$$\begin{aligned} J_E &= \int_0^L \rho_s \eta_s \, (\pi R^2 d) \rho_G \, (E_o/E)^{\gamma_i} \, dl \\ &= \rho_s \eta_s \rho_G L \, (\pi R^2 d)(E_o/E)^{\gamma_i} \end{aligned} \tag{2}$$

where ρ_G is the density of galaxies $(\sim .03/\mathrm{Mpc}^3)$, and R the galactic radius (~10kpc). Thus, equating these fluxes at 10^{19}ev gives L:

$$L \sim \omega/(\pi R^2 \rho_G)\ (E_0/E')^{.5} \tag{3}$$

where E' is $\sim 10^{19}$ev. If we assume γ_i=2.5 then L is of order 100 Mpc. This corresponds to between 15 and 20 interaction lengths (i.l.; 1i.l. = 6Mpc). We emphasize that this model will have the dominant contribution due to sources at L. Thus, superimposing the 15 to 20 i.l. curves upon an $E^{-3.0}$ spectrum gives the composite seen in Fig.(1).

In this model we have assumed that the dominant contribution below 10^{19}ev is given by relatively local extragalactic sources. In ref.(5) we assumed the dominant contribution below 10^{19}ev is given by distant, large redshift sources. In the latter case we predicted a dip should occur at 10^{19}ev because such distant sources would be cut-off at that energy and the cross-over energy is emphasized (it may be possible to consider other linear combinations in which the dip would be reduced). Evidence from the Fly's Eye with relatively good statistics does not indicate a dip; we therefore believe that Hillas-Blumenthal models in which the spectrum below 10^{19}ev is large red-shift cosmological in origin are disfavored.

We emphasize that the pile-up structure can also be due to an arbitrary initial injection spectrum, such as a delta-function "spike" above $\sim 10^{20}$ev, accumulating below the cut-off[5,7].

The composite spectrum of Fig.(1) is in good agreement with the Fly's Eye data for the simple model considered. L is a typical scale for the local supercluster. The abundance should swing from a galactic composition below 10^{19}ev to a principally proton rich spectrum at the peak of the bump. This prediction would seem to be universally true for even an iron rich injection spectrum. The anisotropy would seem to be associated with the local supercluster in this model. It is very difficult in any model with a Greisen cut-off to understand a galactic associated anisotropy to our knowledge (it would be of considerable interest to consider local steering of an incoming extra-galactic spectrum; evidently some anisotropy of the extragalactic spectrum would be required).

If the Fly's Eye bump above 10^{19} eV is a bare measurement of the extragalactic cosmic ray component, it can be used to calculate the flux of ultra-high energy neutrinos necessarily arising from the photomeson production causing such a feature. The cosmic ray spectrum measured by Fly's Eye above 10^{19} eV is best fit by a power law of the form:

$$J_N(E) = a\,(E)^{-\gamma_i}\;; \qquad \begin{cases} a = 34\pm 17\ \mathrm{Eev}^{-1}\mathrm{km}^{-2}\mathrm{sr}^{-1}\mathrm{yr}^{-1} \\ \gamma_i = 2.47\pm 0.27 \end{cases} \tag{4}$$

with a cut-off above 7×10^{19} eV. The resultant integrated extragalactic flux above 10^{18} eV is then:

$$I_N(>10^{18}\ \mathrm{eV}) = a/(\gamma-1) = 23.9\pm 12.8\ \ \mathrm{km}^{-2}\mathrm{sr}^{-1}\mathrm{yr}^{-1} \tag{5}$$

Following the analysis of ref.(5), the minimum neutrino flux associated with these cosmic rays is:

$$I_{\nu_e}^{min}(>0)/I_N(>10^{18}eV) = c(\gamma_i,E_o)/2 \tag{6}$$

and:

$$J_{\nu_e}^{min}(E) = (2.04\times10^{-4} I_N(>10^{18}eV))\ J_o^{min}(E) \tag{7}$$

where $c(\gamma_i,E_0) \sim 4.35\times10^{-3}$ for γ_i=2.5 and the differential neutrino spectrum, $j_0(E)$, is shown in Fig.(2). Combining Eqs. (5)-(7) we have for the minimum neutrino flux:

$$I_{\nu_e}^{min}(>10^{18}eV) = (52.1\pm27.9)10^{-3}\ km^{-2}sr^{-1}yr^{-1} \tag{8}$$

and:

$$J_{\nu_e}^{min}(E) = (4.9\pm2.6)\times10^{-3}\ J_o^{min}(E) \tag{9}$$

We say "minimum" because we have not yet scaled the flux by a factor R_H/L which takes into account the fact that we see neutrinos from photomeson production at Hubble length scales while only sampling cosmic rays originating from the scale L. For the same reason, there can be an enhancement of the neutrino spectrum relative to the cosmic ray spectrum due to bright phase scenarios of galactic evolution.

We envision two possible methods for the detection of such an ultra-high energy neutrino flux. An EAS detector, like the Fly's Eye, would look for upward going air showers produced by these neutrinos after passing thru the earth, while the DUMAND detector could see these neutrinos as contained interactions in 10^{14}cm^3 of sea water.

In both cases, the event rate is given by:

$$\Gamma(yr^{-1}) = \int J_{\nu_e}(E)A_{eff}P(E)\; S(E,\Omega)\; dE\; d\Omega \tag{10}$$

Here A_{eff} is the effective cross sectional area the detection region presents to incoming neutrinos ($\sim 10^2\text{km}^2$ for Fly's Eye and $\sim 0.1\ \text{km}^2$ for DUMAND), $P(E)$ is the probability that a neutrino passing through the detection region interacts with a nucleon:

$$A_{eff}P(E) = A_{eff}\langle L_{det}\rangle/L_{\nu N} \sim 10^{-6}\ \sigma_{34}(E)\ \text{km}^2 \tag{11}$$

for both Fly's Eye and DUMAND (here $\langle L_{det}\rangle$ is the average linear dimension of the detection region (m.w.e.), $L_{\nu N} \sim 10^8/\sigma_{34}$ m.w.e., and we have taken $\sigma_{34} \equiv \sigma/10^{-34}\text{cm}^2 \sim \ln E_{Tev}$. For $s \gg M_W^2$ ($E_\nu \gg M_W^2/2m_N \sim 3.6$ TeV), the total νN cross section is given by:

$$\sigma_{\nu N} = \sigma_{\bar{\nu}N} = \frac{G_F^2}{(2\pi)}\, M\ \ln\left(\frac{s}{M_W^2}\right) \sim \left(6\times10^{-35}\right)\ln\left(\frac{E_\nu}{3.6\ \text{TeV}}\right)\text{cm}^2 \tag{12}$$

which for the EeV energies considered here has the approximate value $\sigma_{\nu N} \sim 7\text{x}10^{-34}\ \text{cm}^2$. $S(E,\Omega)$ is a factor which accounts for shadowing of the neutrino flux by the earth:

$$S(E,\Omega) = e^{-n\sigma L} = e^{-\alpha(E)\cos(\theta)}; \quad \alpha(E) = .3\sigma_{34}(E) \tag{13}$$

where L is the slant depth of the incoming neutrino and θ is the angle between $\vec{L}$ and detector zenith. Integration of S over the earth (assuming ~2π detector coverage) yields a factor $2\pi(1-e^{-\alpha})/\alpha$. The upward and downward (S=1) rates are given by:

$$\Gamma(yr^{-1}) = \begin{cases} (2\times10^{-5}) \int_{E_0}^{E} J_{\nu_e}(E)\ (1-e^{-\alpha})\ dE & \text{(upward)} \\ (6\times10^{-6}) \int_{E_0}^{E} J_{\nu_e}(E)\ \sigma_{34}(E)\ dE & \text{(downward)} \end{cases} \tag{14}$$

the upward rate corresponding to Fly's Eye and the sum of downward and upward rates corresponding to DUMAND.

In accordance with Fig.(2), we approximate the bright phase neutrino spectra as

$$J_{\nu_e}^{BP}(E) \sim A^{BP}(\bar{z})\ J_{\nu_e}^{min}(E)/E^3 \tag{15}$$

where the bright phase normalization, $A^{BP}(\bar{z})$, takes values of ~10^2, 10^4, and 10^6 for $\bar{z} \sim 2$, 4, and 7 respectively, and $j_{\nu_e}^{min}(E)$ is taken to be a step function in energy (the larger $\bar{z}$ calculations are normalized at 2×10^{17}eV). With these approximations, the interaction rates take the following form:

$$\Gamma(yr^{-1}) = \begin{cases} \text{Minimum} & \text{Bright Phase} \\ 2\times10^{-5} I_V(E_0); & 10^{-7} A^{BP} \bar{z}(z) \int_{E_0'}^{E_c} \frac{(1-e^{-\alpha})}{E^3}\, dE \text{ (upward)} \\ 8.4\times10^{-5}\left[I_V(E) + 3.6\times10^{-4} \int_{E_0}^{E_c} E\, dE \right]; & 3\times10^{-8} A^{BP}(\bar{z})\times \int_{E_0'}^{E} \sigma_{34}(E)\, \frac{dE}{E^3} \text{ (downward)} \end{cases} \quad (16)$$

In Table I we give a compilation of these rates. In calculating the bright phase rates we have taken into account that A_{eff} decreases by a factor of ~70 when E_o' is taken to be 2×10^{17}eV. We see that, in most cases, the yearly rate of Fly's Eye bump neutrino interactions is not observable, but the rates can be brought into the observable regime by including galactic evolution effects with the epoch of maximum activity occurring at $\bar{z}\gtrsim6$ along with extending the incoming neutrino energies down to 2×10^{17}eV. We point out that the event rates listed are somewhat uncertain but that this "bright phase threshold" is accurate to $\bar{z}\pm1$. In addition there is an upper bound to $\bar{z}$ from the diffuse X-ray background at $\bar{z}\sim7$ for the $1/E^3$ bright phase spectra.

Presently we comment upon the astrophysical implications of detectable neutrinos as described by these models. The validity of "bright phase" models may well rest with the determination of the shape and evolution of the luminosity function for quasars (QSO's) and the epoch of galaxy formation. If extragalactic cosmic ray (EGCR) production is associated with active galactic nuclei (AGN) then one would expect large z enhancements in EGCR fluxes to be reflected in the evolution of the average co-moving luminosity of young QSO's. There is some evidence that although the total number of QSO's per co-moving volume decreases with increasing z[8], the increase in the number of bright QSO's is such that $\langle L \rangle_{co\text{-}moving}$ increases with increasing z[9]. We should point out that limits on the X-ray production of young QSO's indicate a cut-off in the increase of $\langle L \rangle_{co\text{-}moving}$ at a z_{max} of ~5[9]. However, one might also expect enhances EGCR production during the epoch of galaxy formation. Optical searches designed to look for the continuum emission from these primeval galaxies (large redshift galaxies in the throes of initial star formation) indicate galaxy formation occuring at $z > 5$[10]. In any case the observation of a flux of 10 EeV neutrinos would be an indication of robust cosmic ray production in the past and could possibly open a new window to the early history of galactic evolution.

Table I: A compilation of Γ's for $(E_0, E_c) = (1,70)$EeV (increasing E_0 to 10EeV decreases the bright phase rates by $\sim 10^3$, but has little effect on the minimum rates). We list the minimum rate, R_h/R_L (~20) times the minimum rate, and R_H/R_L times the bright phase for $\bar{z}$=2,4, and 7.

	Minimum (xR_H/R_L)	Bright Phase ($\bar{z}$=2,4,7)
Γ_{down}(DUMAND)	$10^{-5}(2\times10^{-4})\ yr^{-1}$	$2\times10^{-4,\ -2,\ 0}\ yr^{-1}$
Γ_{up}(Fly's Eye)	$10^{-6}(2\times10^{-5})\ yr^{-1}$	$2\times10^{-5,\ -3,\ -1}\ yr^{-1}$

Figure (1): The superposition of the evolved $E^{-2.5}$ extragalactic spectrum and an $E^{-3.0}$ local spectrum for 6 and 48 interaction lengths. Solid curves are fit to low energy ($<10^{19}$eV) data while the dashed curve is a 6 I.L. fit to the peak at 5×10^{19}eV. The dotted curve assumes a local $E^{-3.0}$ component due to the superposition of large z sources. The Fly's Eye data is shown with error bars[1].

Figure (2): Bright phase differential neutrino spectra normalized so that $j_0(E)=1$ at 10^{17}eV. We estimate that spectra falling below the horizontal line at 10^5 would not be observable in the Fly's Eye or DUMAND detectors.

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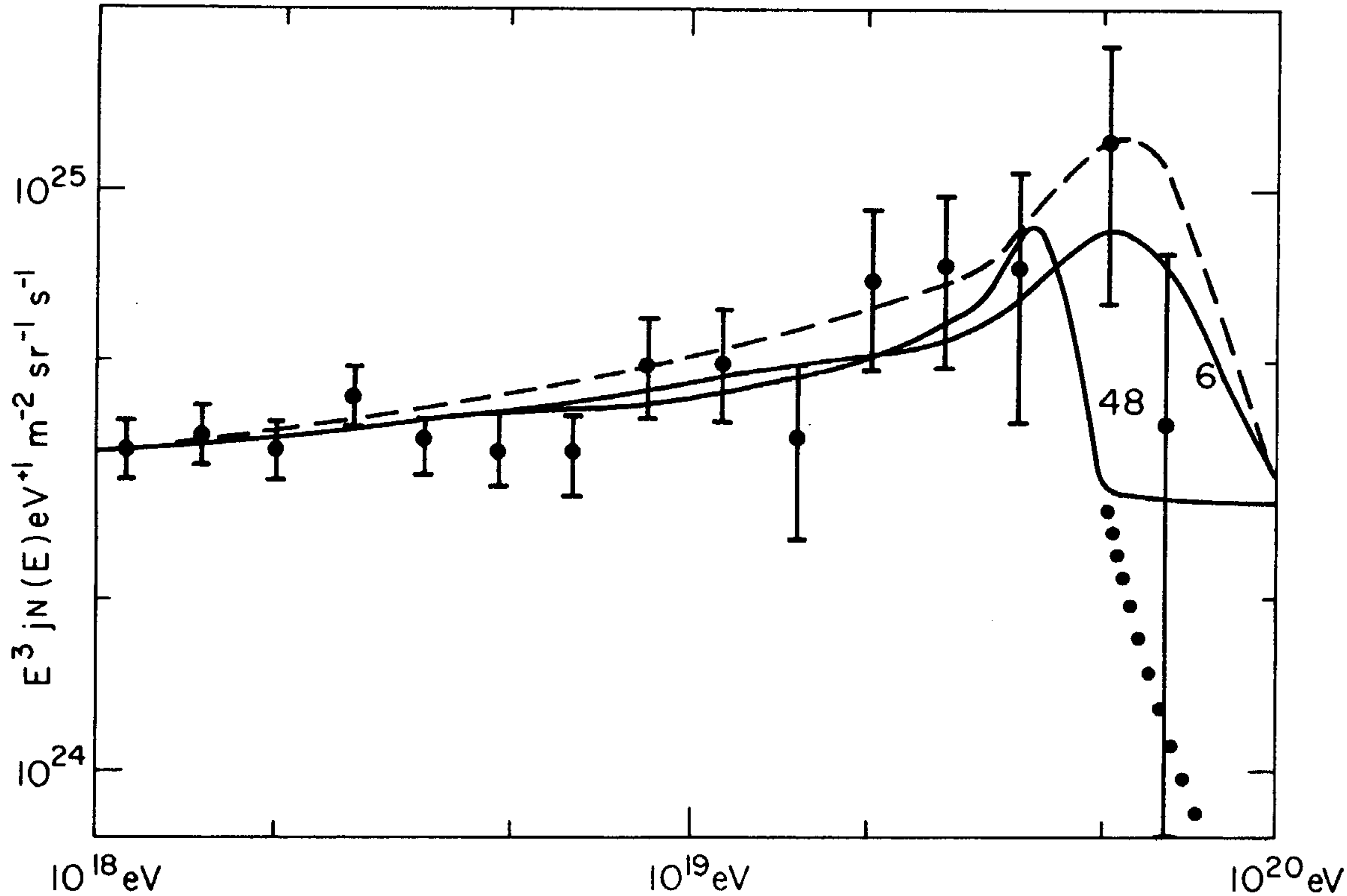
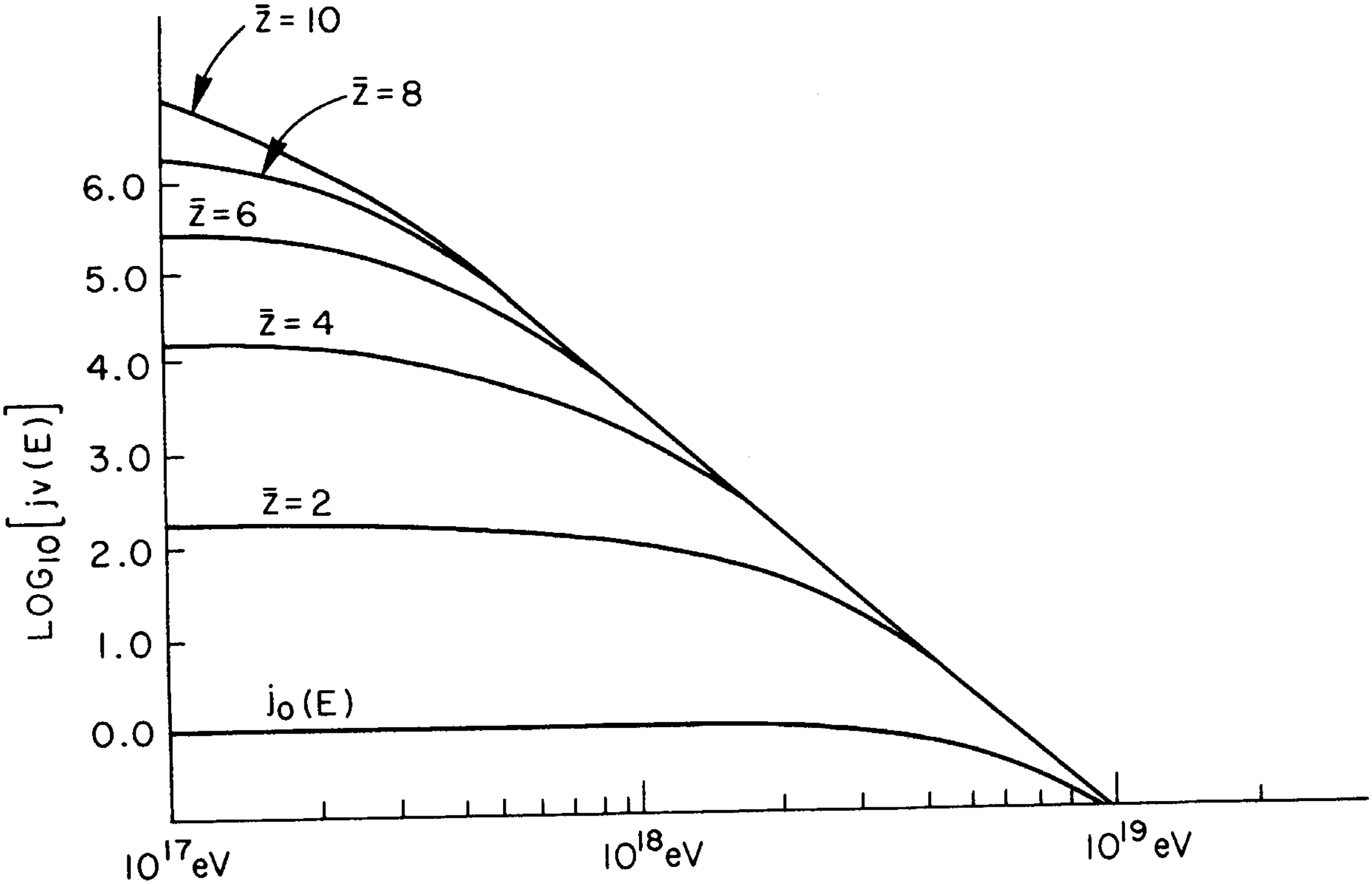


Fig. 1



z̄ = 10
z̄ = 8
z̄ = 6
z̄ = 4
z̄ = 2
j0 (E)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
LOG10 [jv(E)]
10^17 eV
10^18 eV
10^19 eV

Fig. 2