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Setti and Woltjer[1] have recently discussed a universal model for cosmic rays. This model is based on an earlier paper[2] in which the same authors assumed that the infrared background at submillimeter wavelengths[3,4,5] is universal, resulting from the superposed contributions of the infrared luminosities of Seyfert galaxies at large redshifts. If the cosmic ray and infrared outputs of these galaxies are about equal, the cosmic ray energy density in metagalactic space is comparable to the energy density in infrared photons. Since the latter could be as large as a few (eV cm^{-3})[6,7], this model, in principle, is capable of accounting for the observed energy density of cosmic rays near earth.

One of the principal observable features of the cosmic radiation is its energy spectrum. Since cosmological effects leave the cosmic ray spectrum invariant at relativistic energies only, it is of some interest to investigate the effects of an expanding universe with evolving sources on low energy cosmic rays.

Let $(t_o/t)^{m+3}$ q(p) dp be the volume emissivity of cosmic rays measured in particles per cm^3 per second at some epoch t, where t_o is the present epoch and p is the particle momentum at epoch t. The function $(t_o/t)^{m+3}$ represents possible evolutionary effects, with m ranging from 0 (no evolution) up to perhaps m = 6.5[2].

The expansion of the universe leads to a variation of p with time which is given by[8]

$$p(t)\,R(t) = \text{const} \tag{1}$$

where R (t) is the time-dependent scale factor of the universe determined from Einstein's field equations. If cosmic rays are freely moving particles in metagalactic space (i.e., the effects of matter and magnetic fields are negligible), the differential cosmic ray intensity, $I(p_o)$, resulting from particle production in the space-time element dt dV can be written as

$$I(p_o) = \frac{(t_o/t)^{m+3}}{4\pi R^2(t_o)\,\eta^2}\, q(p)\, \frac{dp}{dp_o}\,\frac{dt\,dV}{dt_o\,d\Omega} \tag{2}$$

where $p = p_o R(t_o)/R(t)$, $\eta = r/R$ is a dimensionless radial coordinate, $dV = R^2(t)\eta^2 R(t)\,du\,d\Omega$, and

$$u = \int_t^{t_o} \frac{dt'\,c\beta(t')}{R(t')} \tag{3}$$

is the invariant distance between two points embedded in the metric and traversed by a particle of velocity $c\beta(t')$. Since u does not depend on the expansion of the universe, we have that $dt/dt_o = \beta(t_o)/\beta(t)\; R(t)/R(t_o)$. Furthermore, $dV = R^2(t)\eta^2 c\beta(t)\,d\Omega$, so that equation (2), integrated over all space-time, becomes

$$I(p_o) = \frac{c\beta_o}{4\pi}\int_{t_m}^{t_o} \left(\frac{t_o}{t}\right)^{m+3} q\!\left[p_o \frac{R(t_o)}{R(t)}\right] \frac{R^2(t)}{R^2(t_o)}\,dt \tag{4}$$

where $\beta_0 = \beta(t_0)$ and t_m is the epoch at which cosmic-ray sources began to be formed.

Except for the factor β_0, equation (4) is the same as the corresponding expression for photons[9]. In particular, if $q(p) \propto p^{-\Gamma}$, $I(p_0) \propto \beta_0 p_0^{-\Gamma}$, i.e., a power law spectrum is modified by the factor β_0 at low energies. This result is independent of cosmological model or evolutionary effects.

An interesting departure from this simple behavior could be caused by spatial inhomogeneities in the cosmic ray source distribution. Let us assume that there is a minimum invariant distance u_{min}, such that at all epochs t, $t_m < t < t_0$, there have been no sources between us and u_{min}. In this case, the integral in equation (4) has to be cut off at an upper limit $t_r < t_0$. The time t_r is momentum dependent and is determined by solving the integral

$$u_{min} = \int_{t_r}^{t_0} \frac{c\,\beta(t')\,dt'}{R(t')} \qquad (5)$$

In order to associate this cutoff with an observable quantity, we consider photons emitted by a source at u_{min} with redshift z_{min},

$$u_{min} = \int_0^{z_{min}} (1+z)\,\frac{dt}{dz}\,dz \quad . \qquad (6)$$

The quantities dt/dz in equation (6) and R(t) in equations (4) and (5) depend on the cosmological model. In a zero-pressure Friedmann universe $dt/dz = -1/H_0\,(1+z)^{-2}(1+2q_0 z)^{-1/2}$ [10], where $q_0 = 4\pi G n_0/3H_0^2$, n_0 is the mean matter density, and H_0 is Hubble's constant at the present epoch. Furthermore, as discussed by Setti and Woltjer[1], a universal theory of cosmic rays is tenable only if the metagalactic density is less than about 10^{-7} cm^{-3}, since otherwise the diffuse gamma ray background at $\gtrsim$ 100 MeV would exceed the observed upper limits[11]. We have to use, therefore, a low-density model for which $q_0 \simeq 0$ and $dt/dz \simeq -1/H_0(1+z)^{-2}$. By changing the variable of integration in equation (4) to $z = R(t_0)/R(t) - 1$ and by combining equations (5) and (6) we find that

$$I(p_0) = \frac{c\beta_0}{4\pi H_0} \int_{z_r}^{z_{max}} dz\, q\left[p_0(1+z)\right] (1+z)^{m-1} \tag{7}$$

where

$$z_r = \frac{\left(p_0 + \sqrt{p_0^2+1}\right)^2 (1+z_{min})^2 - 1}{2p_0\left(p_0+\sqrt{p_0^2+1}\right)(1+z_{min})} - 1 \quad . \tag{8}$$

The quantity z_r is given in Figure 1 for various values of p_0 and z_{min}. For $p \ll 1$, $z_r \simeq z_{min}(1+z_{min}^2/2)/(p_0(1+z_{min}))$, whereas for $p \gg 1$, $z_r \to z_{min}$. The value of the cutoff momentum p_c is obtained by equating z_r and z_{max}. In the non-relativistic region

$$p_c \simeq \frac{z_{min}}{z_{max}} \left(\frac{1+z_{min}}{1+z_{min}^2/2} \right) \tag{9}$$

We have evaluated equation (7) for $q(p) \propto p^{-2.5}$, $z_{max} = 2.5$[2] and z_{min} = 0, 0.5 and 1. The results are shown in Figures 2 and 3, for m = 0 and 6.5, respectively. As can be seen, the low energy cutoffs are independent of m, but above the cutoff, the spectrum steepens with increasing m because, by increasing the evolutionary effects, the number of relativistic particles that are redshifted to low energies is correspondingly increased.

Setti and Woltjer[2] have evaluated the energy density w_{ir} of the far infrared background due to Seyfert galaxies in a cosmological model with $q_o = 1/2$. We can get similar results for $q_o = 0$ by using equation (7) with $\beta_o = 1$ and $q(p) = \rho_o L(p)/p$, where ρ_o and $L_o = \int L(p)\,dp$ are the assumed density and luminosity of Seyfert galaxies at the present epoch. The energy density in infrared photons is then given by

$$w_{ir} = \frac{\rho_o L_o}{H_o} \int_{z_{min}}^{z_{max}} dz\,(1+z)^{m-3} \tag{10}$$

We have evaluated w_{ir} for[2] $\rho_o = 10^{-77}\,cm^{-3}$, $L_o = 2.5 \times 10^{46}\,ergs\,sec^{-1}$ and z_{max} = 2.5, and various values of m and z_{min}. The results are given in Table 2. As can be seen, even though the variation of w_{ir} with z_{min} is large for m = 0, it becomes negligible if the evolutionary effects are large. The same effect can also be seen by comparing the spectra in Figures 2 and 3 at relativistic energies. Since on energy grounds, a universal theory for the infrared background as well as for the cosmic rays requires large evolutionary effects, we conclude that independent of the energy densities in both infrared photons and cosmic rays, a spatial inhomogeneity in the source distribution will produce a low energy cutoff in the spectrum of the cosmic rays.

Cosmic ray spectra with low energy cutoffs are not inconsistent with direct observations near earth. Goldstein et al.[12] have shown that because of energy loss in the interplanetary medium, cosmic ray particles below ~ 100 MeV/nucleon are prevented from reaching earth. It is, therefore, not possible to sample the cosmic ray spectrum at low energies near the orbit of earth, and the cutoffs derived in this paper may in fact exist.

Although there are no compelling arguments for a metagalactic model of cosmic rays, such a model cannot be ruled out on the basis of existing observations. A possible exception is the issue of the ionization and thermal state of the interstellar medium. In equilibrium, the rate of ionization of the interstellar gas ζ should not exceed about 2.5×10^{-15} (H atom sec)$^{-1}$[13]. For a cosmic ray intensity with the spectral shape given in Figures 2 or 3 for $z_{min} = 0$ and normalized to direct measurements at earth at high energies, $\zeta \simeq 5 \times 10^{-16}/\varepsilon$ (H atom sec)$^{-1}$, where ε is kinetic energy in MeV. In order not to overheat the interstellar medium, a cutoff is required at about 0.2 MeV. If this cutoff is produced by the mechanism suggested in this letter, from equation (9) with $z_{max} = 2.5$, we find that $z_{min} = 0.05$. A higher value of z_{min} would be required if the source spectrum is steeper than $p^{-2.5}$. Conversely, if the source spectrum is flatter or possesses an intrinsic low energy cutoff, z_{min} could be smaller than 0.05 or could in fact be zero.

Finally, if the bulk of the cosmic ray are metagalactic but are cut off at low energies, galactic supernovae could still produce large fluxes of low energy nuclei which would heat and ionize the interstellar medium, as discussed recently by Ramaty et al.[14]. In addition, in a metagalactic model of cosmic rays, the role of galactic supernovae would be limited to the production of cosmic electrons (and nuclei to about 1% of their observed energy density) and possibly, to the generation of certain short lived ultraheavy nuclei which would be present in the cosmic rays[15].

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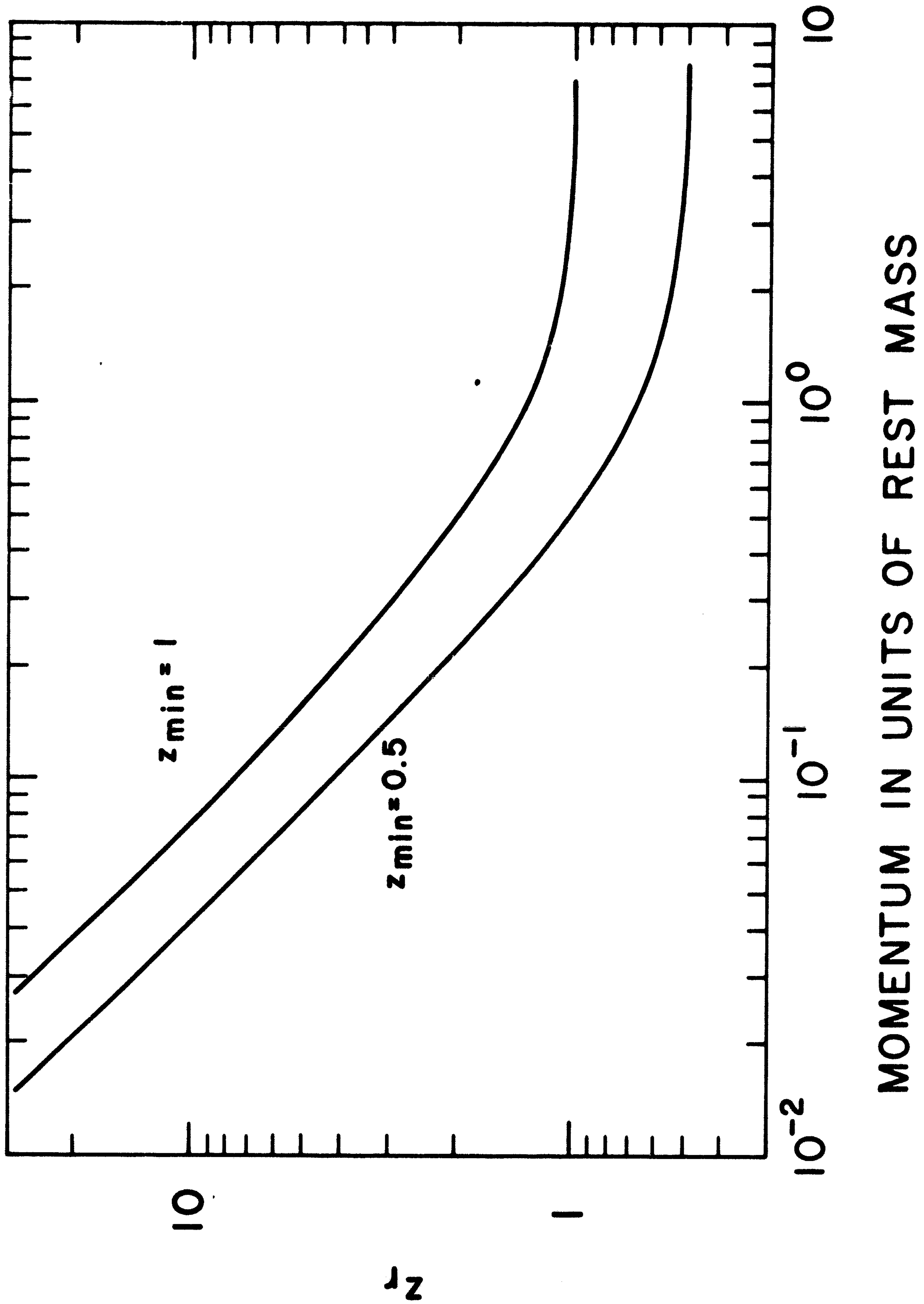
TABLE 1

M \ Z_{min}	0	0.5	1
0	.03	.01	.005
3	0.15	.13	.09
6.5	3.73	3.66	3.44

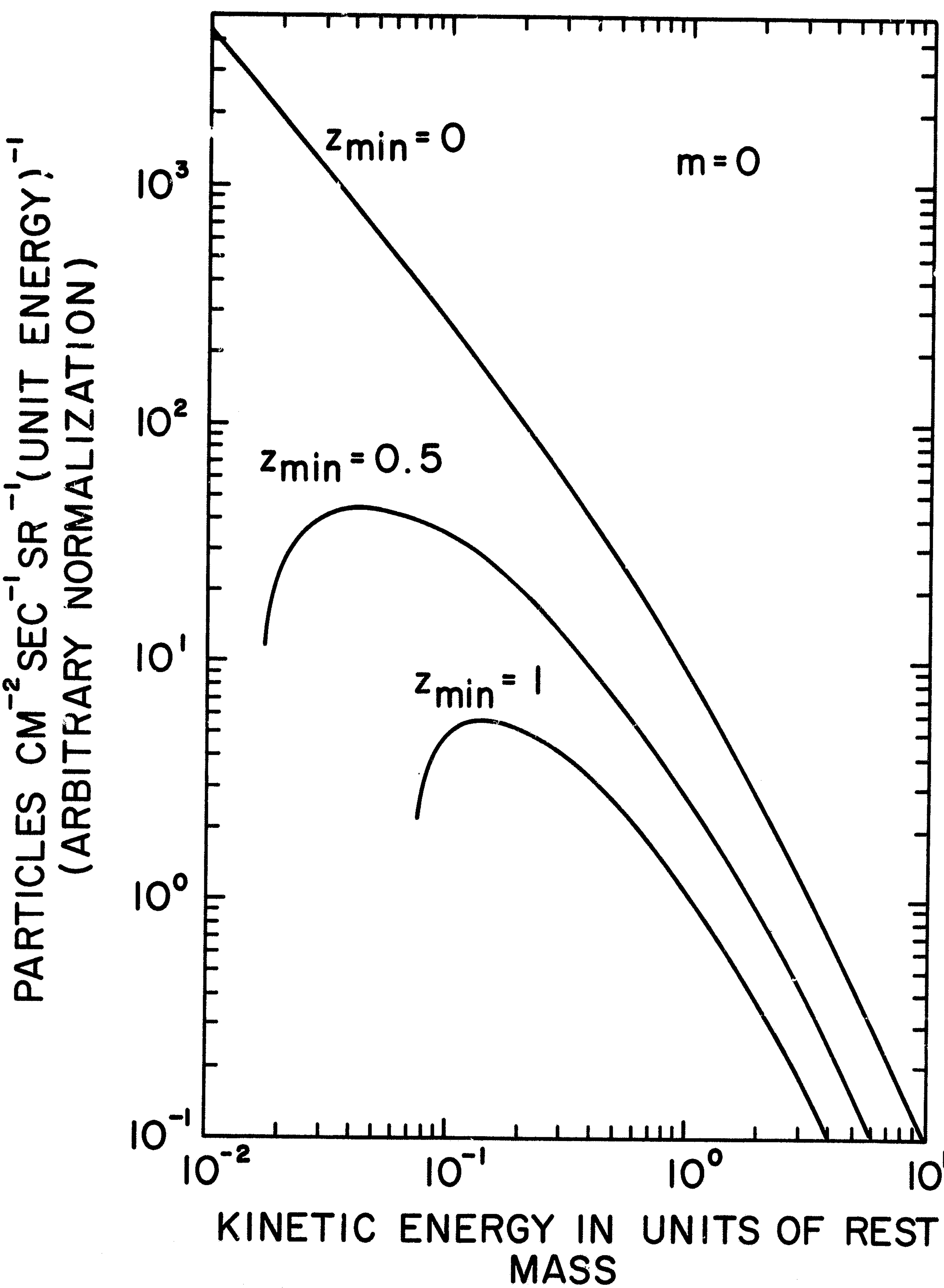
Figure Captions

1. The variation of Z_r, defined in equation 8, with momentum.
2. Differential energy spectra for $m = 0$.
3. Differential energy spectra for $m = 6.5$.



10
1
z r
10⁻²
10⁻¹
10⁰
10¹
MOMENTUM IN UNITS OF REST MASS
z min = 1
z min = 0.5

FIGURE 1



PARTICLES CM^{-2}SEC^{-1}SR^{-1}(UNIT ENERGY)$^{-1}$
(ARBITRARY NORMALIZATION)
$z_{min}=0$
m = 0
$z_{min}=0.5$
$z_{min}=1$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-1}
10^0
10^1
KINETIC ENERGY IN UNITS OF REST MASS

FIGURE 2

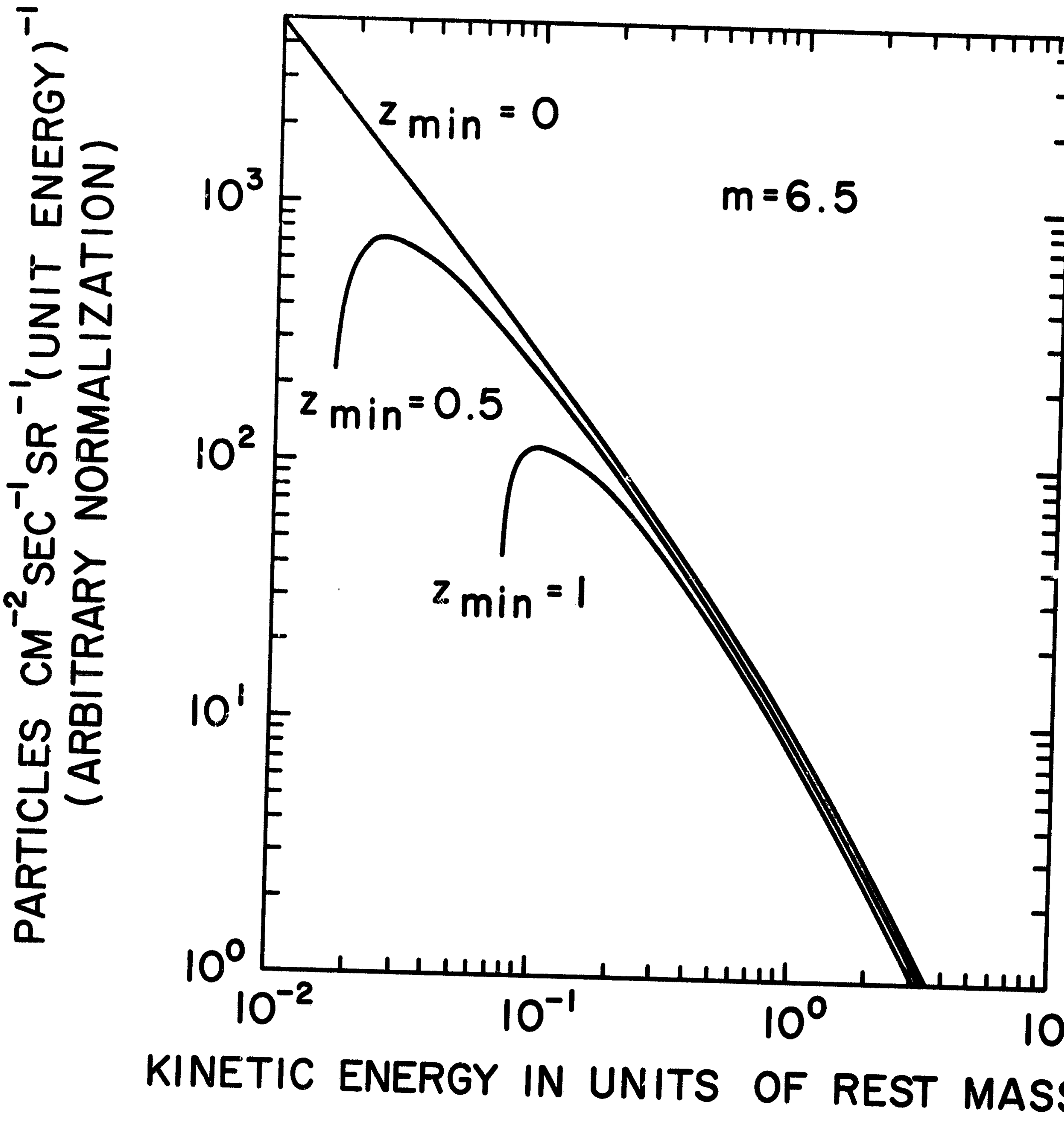

PARTICLES CM^{-2}SEC^{-1}SR^{-1}(UNIT ENERGY)$^{-1}$
(ARBITRARY NORMALIZATION)
z_{min} = 0
m=6.5
z_{min}=0.5
z_{min} = 1
10^3
10^2
10^1
10^0
10^{-2}
10^{-1}
10^0
KINETIC ENERGY IN UNITS OF REST MAS

FIGURE 3