Can Neutrino Decay Driven Mock Gravity Save Hot Dark Matter?

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ABSTRACT

The radiative decay of a 30 eV neutrino with a lifetime of order 10^{23-24} sec has recently been shown to yield a satisfactory explanation of a wide range of problems in astrophysics. Melott in 1985 showed how such a decay can explain morphological features of dwarf satellite galaxies. Melott, McKay, and Ralston in 1988 demonstrated that such a decay process can ionize the IGM to the Gunn-Peterson limit. Finally, in a series of papers Sciama has addressed the issue of radiative neutrino decay and successfully applied it to an even broader range of problems.

In this paper we investigate whether the photon flux generated by the radiative decay of a massive neutrino is capable of generating sufficient radiation pressure to cause a "mock gravitational" collapse of primordial hydrogen clouds. We show that when using neutral hydrogen as a source of opacity for mock gravity the timescale for mock gravitational collapse is significantly larger than the expansion timescale. Thus, the model fails as a source of galactic seed perturbations. Furthermore, we argue that non-linear feedback mechanisms will be unable to increase the collapse rate of the cloud under mock gravity.

Subject headings: cosmology - dark matter - galaxies:clustering - galaxies:formation

I. INTRODUCTION

Spitzer (1941) was the first to point out that absorbing particles in an isotropic radiation field will experience a net attractive force. This attractive force has become known as mock gravity. In 1986 Hogan and White revived mock gravity as a possible way to generate large-scale structure in the universe. A subsequent study by Wang and Field (1989) taking into account additional effects yielded a less optimistic picture of structure formation using mock gravity. In the work of Hogan and White (1986) and Wang and Field (1989) the source of the radiation field was the sub-millimeter background, and dust was the source of opacity. Further, both groups assumed that the dust did not evolve as it was subjected to the UV photon flux. In this paper, we wish to modify the previous work on mock gravity by using radiative neutrino decay as the source of UV photons and neutral hydrogen as the source of opacity.

The first experimental announcements of a 30 eV neutrino by Reines, *et al.* (1980) and Lubimov, *et al.* (1980) led to a flurry of activity in cosmology considering such a neutrino as a dark matter candidate. A number of these first studies were concerned with a possible decay mode of the neutrino into a lighter neutrino and a photon. These studies (see, for instance DeRújula and Glashow [1980], Kimble, Bowyer and Jakobsen [1981], and Stecker [1980]) tended to focus on using the known UV flux to constrain the lifetime of the neutrinos. On the other hand, about the same time Raphaeli and Szalay (1981) began considering the astrophysical implications of such a neutrino mass, lifetime and decay mode. They concluded that such a neutrino could reionize the universe and erase small-scale irregularities in the microwave background.

In recent years a body of evidence has been accumulating for the existence of a 30 eV neutrino that has a radiative decay mode. In 1985 Melott was able to show using the decay of $\approx 10^{24}$ sec neutrinos in the dark matter halo of a parent galaxy could explain the tendency for dwarf elliptical galaxies to lie closer to the parent galaxy and exhibit significantly less star formation than the gas rich irregulars which tend to populate the peripheral regions. More recently, in a series of papers Sciama (1990a-f) has explored the astrophysical consequences of the radiative decay of a long lived massive neutrino. He has found that a neutrino with mass of order 30 eV and a lifetime of $\tau \approx 10^{23}$ sec is capable of solving a wide range of problems in astrophysics and cosmology. In addition, Melott, McKay and Ralston (1988) found that such a decaying neutrino could also very easily explain the ionization level found in the IGM, something that Shapiro and Giroux (1987) have argued cannot be accomplished with QSOs. Therefore, any model should have the capability of making contact with at least one observational constraint, the Gunn-Peterson limit. In addition, Sciama (1990b) has found that the decaying neutrino model can explain very nicely the constancy of the free electron density in HI regions near the Sun. Despite the speculative nature of neutrino decay as far as standard particle physics is concerned, Gabbiani, Masiero, and Sciama (1990) have been successful at constructing a supersymmetric theory with unbroken R-parity that predicts the existence of neutrino decay with a lifetime consistent with the requirement that $\tau \approx 10^{23}$ sec. In addition, Ralston, McKay and Melott (1988) have constructed an extension of the standard model which includes a charged, weak-singlet which can induce an electron-neutrino magnetic moment large enough to implement the Voloshin-Vysotski-Okun solution to the solar neutrino problem and predict a radiative decay of the neutrino with a lifetime of about 10^{23-24} sec.

Recently, several groups have made attempts to observe the photon flux directly with IUE and the Astro I mission (see, Fabian, Naylor, Sciama [1991] and Davidsen, *et al* [1991]).

Both missions have been unsuccessful although their results may not be conclusive; cold neutral hydrogen along the line of sight could easily obscure the photon flux. Furthermore, Miralda-Escudé and Ostriker (1991) have recently considered the absence of an absorption trough due to He absorption in quasars. They found that if the background spectrum were as soft as the Sciama model suggests then the absence of such an absorption trough can be used to rule out neutrino decay, unless the He I in the Lyman limit system is ionized by a local source.

The principle problem with hot dark matter (HDM) is that it may possess too little power on small scales, due to free streaming of the neutrinos. One possible way to correct that problem is to produce density fluctuations not from inflation, but from seed perturbations. Seeded hot dark matter models have been studied by a large number of people (for instance, Villumsen, Scherrer and Bertschinger [1990], Scherrer, Melott, and Bertschinger [1989]). Traditionally, in these studies the seed perturbations have been taken to be either primordial black holes or cosmic strings, and have been quite successful at improving the small-scale power relative to the standard hot dark matter models. In a less model dependent fashion Lilje (1990) has studied HDM models in a more generic way without specifying the physical processes that are responsible for generating the small scale structures. He found that the properties of the HDM model that are due to a large wavenumber cutoff are retained in his models, in addition to the small-scale structure generated by the unknown physical processes. In this paper we wish to introduce a simpler method of generating seed perturbations in hot dark matter models, which utilizes the radiation pressure generated by the radiative decay of the dark matter neutrinos to drive a mock gravitational collapse, where the source of opacity is primordial neutral hydrogen.

This paper is laid out in the following manner: section I is a general introduction to mock gravity and the idea of a radaitive neutrino decay; section II discusses recombination in the presence of radiative neutrino decay and in section III we take the results of section II and use them to make estimates of the growth rate of the perturbations under mock gravity. In section IV we discuss the results, and explain why the model fails to successfully generate seed perturbations.

II. RECOMBINATION IN THE PRESENCE OF MASSIVE NEUTRINO DECAY

To be more precise, the reaction we are considering is

$$\nu_H \rightarrow \nu_L + \gamma,$$

where $m_{\nu_H} \approx 30\ eV$, $m_{\nu_L} \approx 0\ eV$, and $E_\gamma \approx \frac{1}{2} m_{\nu_H} \approx 15\ eV$. Furthermore, the lifetime of the heavy neutrino is long compared to the Hubble time; in fact we will choose the lifetime to be $O(10^{23})$ *sec*. The length of the neutrino lifetime ensures that most of the neutrinos are still around today to act as dark matter, and that we do not violate isotropy limits on the microwave background. In addition, for our purposes we insist that $m_{\nu_H} > 27.2\ eV$, this will guarantee that upon decay the daughter photon can ionize neutral hydrogen. If the neutrinos are the dark matter and their abundance is such that $\Omega_0 = 1$, then we may set an interesting limit first derived by Cowsik and McClelland (1972),

$$\Omega_\nu h_0^2 = \frac{m_\nu}{91.5eV},$$

where h_0 is the current value of the Hubble constant in the units 100 $km\ Mpc^{-1}\ sec^{-1}$. Now if we require that $\Omega_0 = \Omega_B + \Omega_\nu$, the Hubble constant can be written in terms of Ω_B, Ω_0, and m_ν;

$$h = \left[\left(\frac{m_\nu}{91.5}\right)\frac{1}{\Omega_0 - \Omega_B}\right]^{1/2}.$$

With these ideas in mind let us continue in our study of recombination.

Raphaeli and Szalay (1981) were one of the first groups to consider the effect of the radiative neutrino decay on standard recombination. They were one of the first groups to argue such a decay process may allow the universe to reionize and subsequently erase small-scale microwave background inhomogeneities. Salati and Wallet in 1984 extended the Raphaeli and Szalay calculation so that they could explicitly compute how standard homogeneous recombination will proceed in the presence of the radiative decay of a light-ino (or in our case a light neutrino). More recently, Asselin, *et al* (1988) have improved upon the original calculations of Salati and Wallet. It is this second paper that we will take as the basis of our recombination calculation. The set of equations which we will be required to integrate in order to determine the ionization level are,

$$-\frac{d\chi_e}{dt} = C[\alpha_c n_B \chi_e^2 - \beta_c(1-\chi_e)e^{-(B_1-B_2)/kT}] + \alpha_{1S} n_B \chi_e^2, \tag{1}$$
$$-c(1-\chi_e)\sigma_I n_I - <\sigma v> n_B \chi_e (1-\chi_e),$$

$$\frac{dT_m}{dt} = \frac{8\sigma_T a T^4}{3m_e c}\chi_e(T - T_m) - 2HT_m + \frac{2}{3}\frac{c(1-\chi_e)\sigma_I(\frac{1}{2}m_\nu c^2 - B_1)n_I}{k}, \tag{2}$$

$$\frac{dn_I}{dt} = -[\sigma_I c n_B(1-\chi_e) + (3 + B_1/kT)H]n_I + \alpha_{1S} n_B^2 \chi_e^2 + \frac{n_\nu}{\tau}, \tag{3}$$

where χ_e is the fractional ionization, defined as $\chi_e \equiv n_e/n_B$, T_m is the matter temperature, n_I is the number density of ionizing photons, $<\sigma v>$ is the collisional ionization cross-section, n_B is the number density of baryons, B_1 is the binding energy of the hydrogen $1s$ state, B_2 is the binding energy of the hydrogen $2s$ state, σ_I is the photoionization cross-section of hydrogen, and α_c is the recombination coefficient to all but the ground state. In addition, H is the Hubble constant, m_ν is the neutrino mass, n_ν is the number density of neutrinos, and τ is the neutrino lifetime. For a more detailed discussion of the origins of these equations see, Peebles (1968) for standard recombination and either Asselin, *et al* (1988), or Salati and Wallet (1984) for the modifications required by the addition of a radiatively decaying particle species.

The additional factors are defined by

$$C = \frac{1 + K\Lambda_{2s,1s} n_B (1 - \chi_e)}{1 + K(\Lambda_{2s,1s} + \beta_c) n_B (1 - \chi_e)}, \tag{4}$$

$$K = \frac{\lambda_\alpha^3 a}{8\pi \dot{a}}, \tag{5}$$

and

$$\beta_c = \alpha_c e^{-B_2/kT} (2\pi m_e kT)^{3/2} h^{-3}, \tag{6}$$

where λ_α is the wavelength of Lyman α, $\Lambda_{2s,1s}$ is the transition rate from the $2s$ to the $1s$ state.

In the present work a number of modifications have been made on the set of equations that was used by Asselin, *et al.* (1988). First, in the expression for the evolution of n_I Asselin, *et al.* (1988) assume that $n_I = 0$, while this is true for a significant part of the universe's history it breaks down at small redshift. To try and obtain a solution valid for smaller redshifts we have relaxed this restriction and included equation (3) for the evolution of the number density of ionizing photons. The photoionization heating term also has a different form, than what was used in Asselin, *et al* (1988). In their work, they choose the heating term to be proportional to $n_\nu(1/2m_\nu - B_1)/\tau$. This term cannot be correct because as the universe grows more ionized the heating term should turn off since there is less hydrogen to ionize, and thus, photoionizational heating becomes increasingly inefficient. To make these statements more quantitative, the photoionization heating rate can be expressed as (see, for instance Rybicki and Lightman [1979], or Osterbrook [1989])

$$\Gamma = c n_H \int_{\nu_{edge}}^{\infty} N_\nu (h\nu - B1) d\nu \approx c n_H (\frac{1}{2} m_\nu c^2 - B_1) n_I, \tag{7}$$

where $n_H = n_B(1 - \chi_e)$ is the number density of hydrogen, N_ν is the number density of photons per frequency interval, ν_{edge} is the frequency at the absorption edge (i.e., at 13.6 eV), and m_ν is the neutrino mass, with all other quantities defined as they were previously. This expression is true as long as the mean free time for an ionizing photon is short compared to the expansion timescale, which is the case for nearly all redshifts except for a small range near $z \approx 0$. In addition, we have also kept the term describing recombination directly to the $1s$ hydrogen state. In standard recombination this term does not contribute, because such a recombination generates a 13.6 eV photon. This photon then very quickly ionizes another neutral hydrogen atom. Thus, there is no net change in the ionization level, assuming there is sufficient hydrogen present, a condition which is stated above as whenever the mean free time for an ionizing photon is short compared to the expansion timescale. On the other hand when neutrino decay is included, the universe now becomes gradually more ionized. At some point the universe will become sufficiently ionized so that the universe becomes transparent to these UV photons. At that point they no longer interact with neutral hydrogen. The decay photons then contribute to the number density of ionizing photons and should be included. We should also note that recently Dodelson and Jubas (1991) have obtained similar results using a more sophisticated approach based upon integrating the full Boltzmann equation for the photon spectrum.

Results from the integration of the above equations can be found in figures 1,2, and 3, for a particular neutrino mass and lifetime consistent with the estimates of Sciama (1990a-f). Figure 1 is a plot of the log of the fractional ionization versus redshift for a neutrino of mass 27.7 eV and a lifetime of 10^{23} sec. As expected the universe goes through a short neutral phase from about a redshift of a 1000 to several hundred. After this short neutral phase the universe rapidly approaches a fractional ionization of 1. Figure 2 is the log of the fractional neutrality $(1 - \chi_e)$ versus redshift. In this plot we see that the universe very rapidly ionizes at a redshift of about 30, and slowly levels out to a fractional neutrality of order 10^{-6} at $z \approx 2$. This model does satisfy the Gunn-Peterson limit at a redshift of 2.64 as determined by Steidel and Sargent (1987). The third plot is a graph of the matter temperature versus redshift. In this final plot, we see for large redshifts the matter temperature follows an adiabatic law, until near a redshift of 50 when the temperature begins increasing. The matter temperature increases until a redshift of about 5 at which point the neutral hydrogen density must become too small to allow photoionizational heating to continue, and the matter begins cooling. The evolution of the fractional ionization is consistent with the results of Scott, Rees and Sciama (1991).

The numerical integrations were performed using a specialized subroutine designed especially for the integration of systems of stiff differential equations. The subroutine was written by Alan Hindmarsh at Lawrence-Livermore National Laboratory and is named LSODE. Initial conditions are imposed at $z \approx 2000$. The following process,

$$\text{electron} + \text{proton} \rightleftharpoons \text{neutral hydrogen} + \text{photon}$$

is in thermal and chemical equilibrium at $z \approx 2000$. This is Saha equilibrium. Thus, the fractional ionization is chosen to satisfy the Saha equation. Since the matter and radiation are in close thermal contact at this era we can choose the matter temperature to equal the radiation temperature. Finally, the number density of ionizing photons is chosen to satisfy the condition $dn_I/dt = 0$. Since the above process is in equilibrium it is natural to expect that there is no net production of ionizing photons.

III. GROWTH RATE OF FLUCTUATIONS USING MOCK GRAVITY

With our simplified study of the ionization state of the IGM complete we can now proceed to study whether the mock gravitational collapse will play any role in the formation of seed perturbations. As stated previously, absorbing particles in a homogeneous and isotropic radiation field will experience an r^{-2} attractive force due to the mutual shadowing of of incident photons. Assume the perturbation is optically thin. This is required for mock gravity to be an efficient process. If the medium is not optically thin then the mutual shadowing of photons cannot occur and mock gravity will not work. Consider two hydrogen atoms, A and B, separated by a distance r, then the solid angle subtended at B due to absorption at A is $\Omega = \sigma_I/r^2$. The radiation momentum flux that is missing due to the presence of atom A is $\Omega\epsilon/4\pi = \sigma_I\epsilon/4\pi r^2$, where ϵ is the energy density of the radiation field. The momentum flux incident on atom A from 180° away is not shielded, so atom A experiences a net force which equals σ_I multiplied by the momentum flux,

$$F = \frac{\sigma_I^2 \epsilon}{4\pi r^2}. \tag{8}$$

Further, one can define an "effective gravitational" constant due to mock gravity as

$$G_{eff} = \frac{\sigma_I^2 \epsilon}{4\pi m_H^2}. \tag{9}$$

Clearly, the model depends upon several factors in crucial ways. First, we require that the radiation pressure must be larger than the matter pressure. This guarantees that the cloud will collapse rather than diffuse away. Secondly, an adequate supply of neutral hydrogen must exist to provide the opacity needed for mock gravity. Lastly and not independent of the above two conditions is that the growth rate of the perturbations under mock gravity must be larger than the expansion rate. This ensures that the perturbations will not be smeared out by expansion before they can collapse.

Now we consider each of the above points separately. In figure 4, we present for the particular model that we have been considering the matter and radiation pressure as a function of redshift. Clearly, for a range of redshifts between about 30 and 5 the above condition is true. Over the range of redshifts between 30 and 5 we see from figure 2 that the fractional neutrality is quite small, thus possibly pointing out a possible stumbling block. The last condition can be easily written down in a more qualitative form. The characteristic expansion timescale is $t_{exp} \approx (G\rho_{crit})^{1/2}$. In a similar fashion the characteristic timescale scale for mock gravitational collapse is $t_{mg} \approx (G_{eff}\rho_H)^{1/2}$. A comparison of the ratio of the expansion timescale to the mock gravitational collapse timescale is given in figure 5. In this figure we see that for redshifts after about 30, the ratio t_{exp}/t_{mg} decreases. Thus, the mock gravitational timescale, t_{mg}, exceeds the expansion timescale and expansion is wiping out the fluctuations faster than mock gravity can affect the collapse.

IV. CONCLUSIONS

In previous studies of mock gravity (for instance, Hogan and White [1986] or Wang and Field [1989]) it has been assumed that the source of opacity does not evolved with time. In the case we have been considering here the sources of opacity, the neutral hydrogen, does. In fact, the fundamental problem with the model is clear. It requires only a single photon to ionize a neutral hydrogen atom. After the atom has been ionized the cross-section for its interaction with photons decreases dramatically. Thus, as the hydrogen clouds become more ionized it becomes increasingly difficult to push the hydrogen into coherent clouds that may undergo collapse due to the radiation field. The problem is compounded by the fact that it is the radiation field that is required by mock gravity that is causing the ionization in the first place. Thus, the model which appears so appealing on the surface primarily due to its ability to explain the Gunn-Peterson limit and a number of other interesting related astrophysical problems (e.g. see Sciama [1990a-f]) seems to contain the seeds of its own demise.

Since hydrogen has failed as a natural source of opacity one may consider an alternative source of opacity to be helium. Helium is also quite appealing since about 25% of the baryons are bound into helium. Thus, the baryonic fraction in helium does not differ substantially from hydrogen. Unfortunately, the lowest excited state of helium lies at $\approx$ 21 eV, far too high to be reached with the photons that we are considering here. Thus, helium also fails as an adequate source of opacity.

Lastly, we would like to consider the role of feedback mechanisms. One possible objection to the model is that we have worked entirely in the linear regime. Thus, non-linear feedback mechanisms will not play any role since we are not locally perturbing the fractional ionization, matter temperature and the number density of ionizing photons. For instance, as a perturbation collapses the density increases. The increase in density will increase the recombination rate locally, thus producing more neutral hydrogen locally and possibly increasing the mock gravitational collapse rate. What we would like to consider briefly is an estimate of the importance of such a mechanism. We will do so by estimating the ratio of the perturbed recombination rate and the perturbed ionization rate. This quantity should give us a measure of the importance of such a feedback mechanism. The recombination rate is $\Gamma_{rec} = \alpha_c n_B \chi_e^2$, and the ionization rate is $\Gamma_{ion} = \sigma_I c n_I (1 - \chi_e)$. During the redshifts of interest the medium is relatively ionized, therefore the expression for n_I that is needed is equation (4.12) of Dodelson and Jubas (1991). We then compute the lowest order changes in the rates due to the local non-linearities in the perturbations. Using their expression for n_I in an ionized medium we can compute the ratio of the recombination rate to the ionization rate to lowest order. We find that the ratio is,

$$\frac{\delta\Gamma_{rec}}{\delta\Gamma_{ion}} \approx 7.9(10)^{-5}\Omega_B h_0^2 \tau_{23} \chi_e (1+z) \tag{10}$$

where τ_{23} is the lifetime of the neutrino in units of 10^{23} *sec*. Over the redshift range of the most interest, $2 \leq z \leq 30$, the recombination rate is always much smaller than the ionization rate. Therefore, the recombination rate does not increase significantly enough in the collapsing hydrogen cloud to affect the rate of collapse due to mock gravity.

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FIGURE CAPTIONS

Figure 1 - Fractional Ionization as a function of redshift for the cosmological model, $\Omega_B = 5(10)^{-2}$, $h_0 = 0.559$, and neutrino properties, $m_\nu = 27.7\ eV$, $\tau = 10^{23}\ sec.$

Figure 2 - Fractional neutrality $(1-\chi_e)$ as a function of redshift for the cosmological model, $\Omega_B = 5(10)^{-2}$, $h_0 = 0.559$, and neutrino properties, $m_\nu = 27.7\ eV$, $\tau = 10^{23}\ sec.$

Figure 3 - Matter temperature as a function of redshift for the cosmological model, $\Omega_B = 5(10)^{-2}$, $h_0 = 0.559$, and neutrino properties, $m_\nu = 27.7\ eV$, $\tau = 10^{23}\ sec.$

Figure 4 - Plots of the radiation and matter pressure as a function of redshift for the cosmological model $\Omega_B = 5(10)^{-2}$, $h_0 = 0.559$, and neutrino properties, $m_\nu = 27.7\ eV$, $\tau = 10^{23}\ sec.$ The radiation pressure is the upper dotted line while the solid lower line is the matter pressure.

Figure 5 - Log of the ratio of the expansion timescale to the mock gravitational collapse timescale as a function of the log of the redshift for the cosmological model, $\Omega_B = 5(10)^{-2}$, $h_0 = 0.559$, and neutrino properties, $m_\nu = 27.7\ eV$, $\tau = 10^{23}\ sec.$

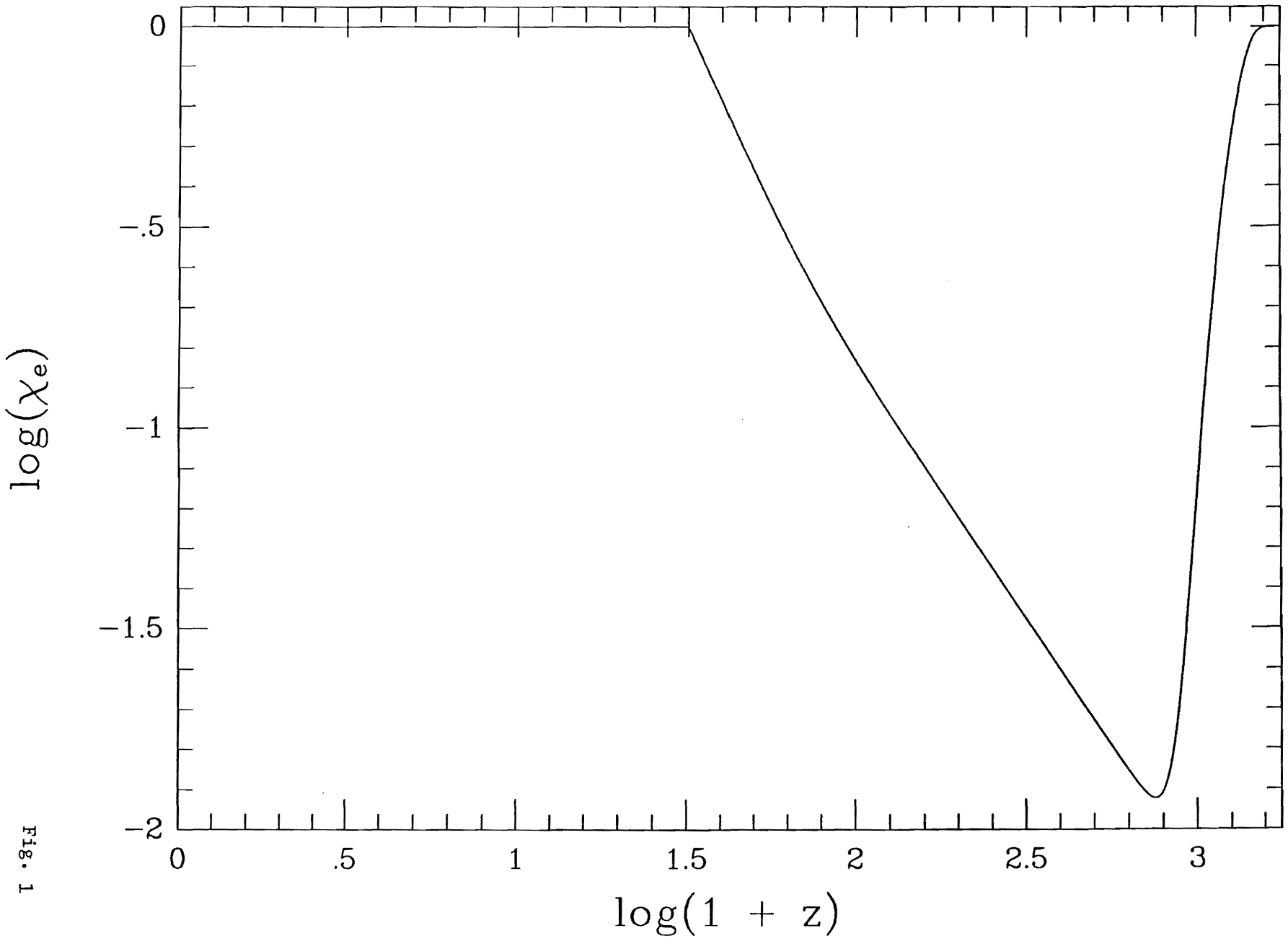

Fig. 1

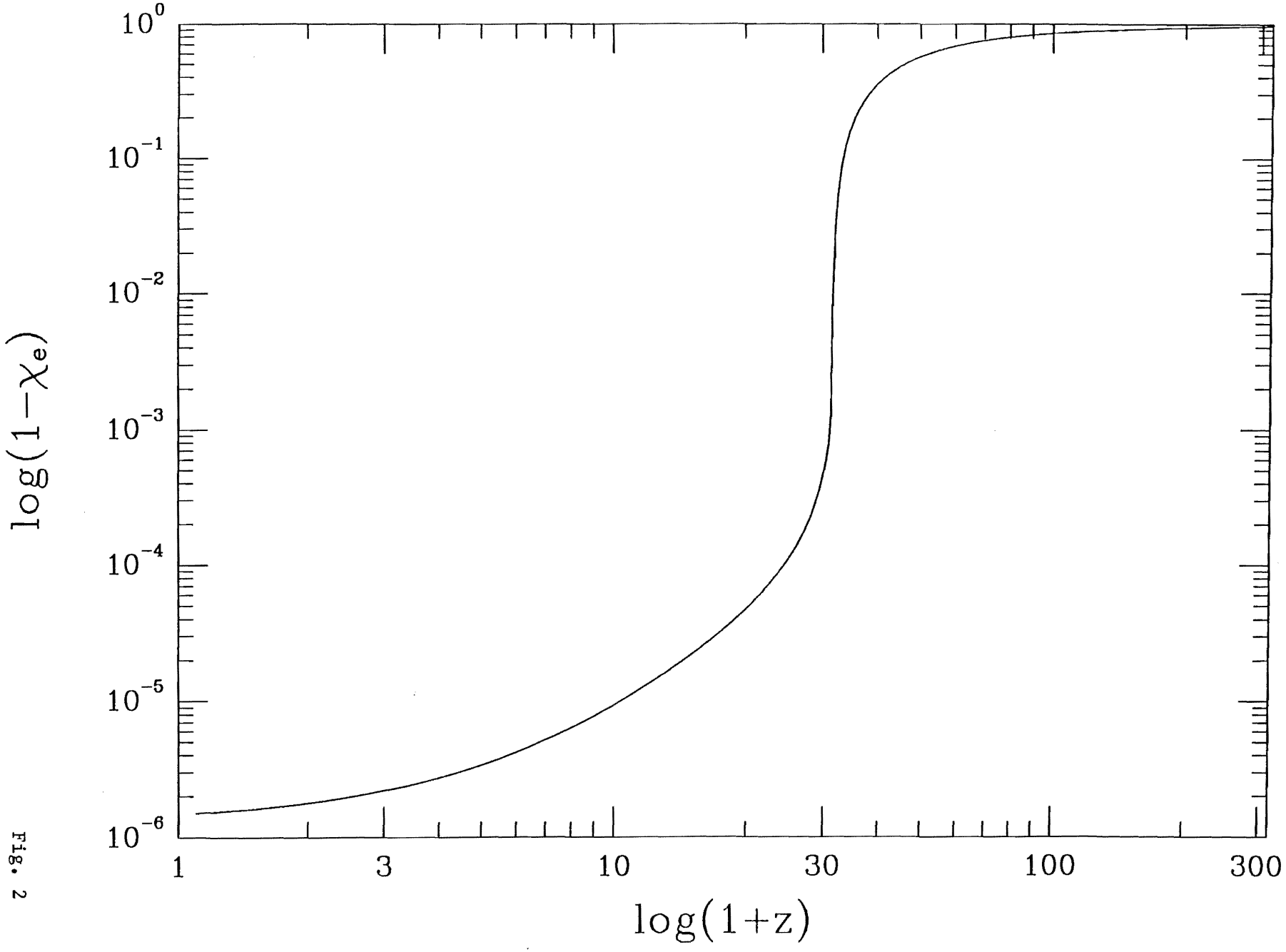

Fig. 2

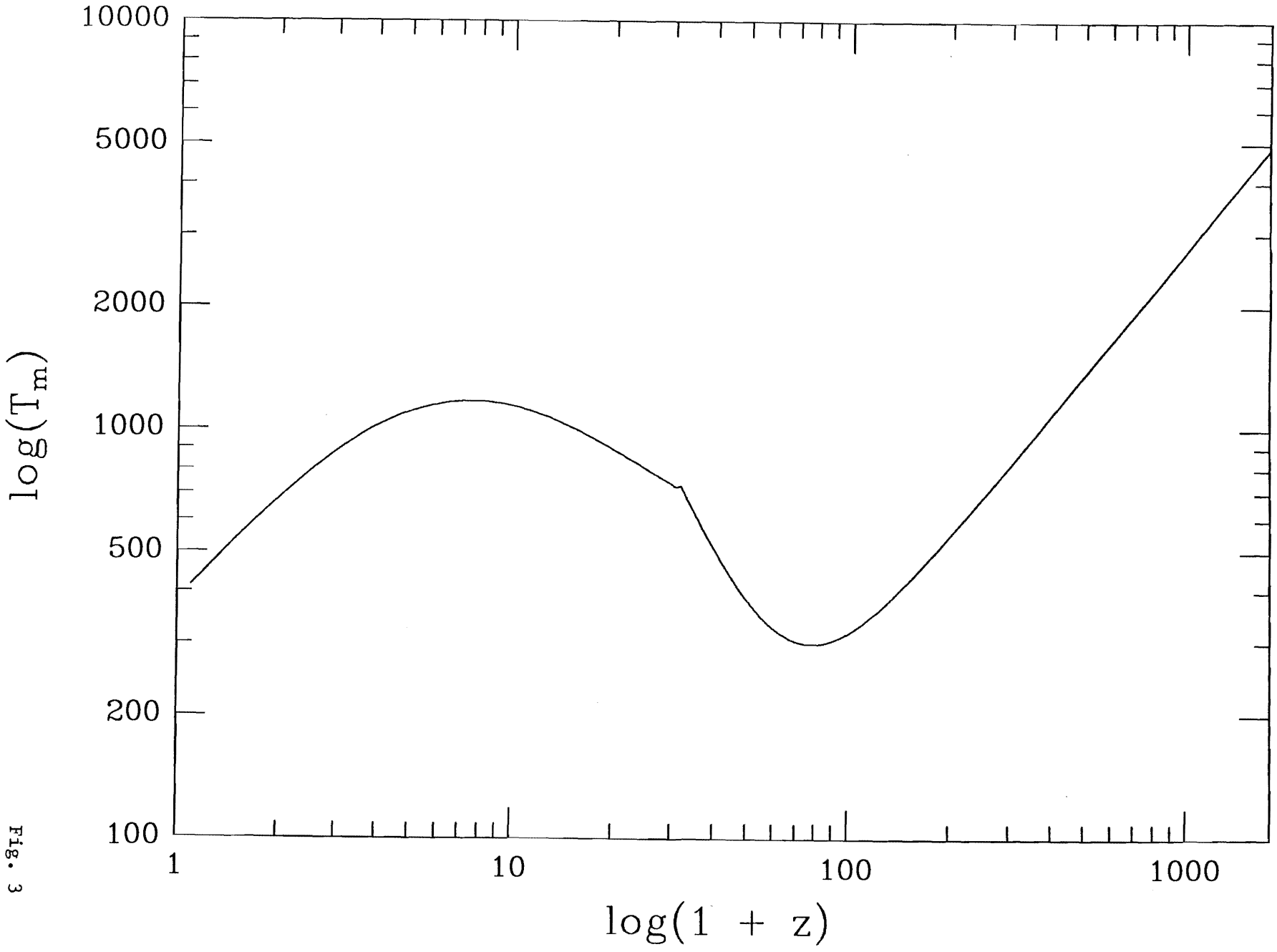

Fig. 3

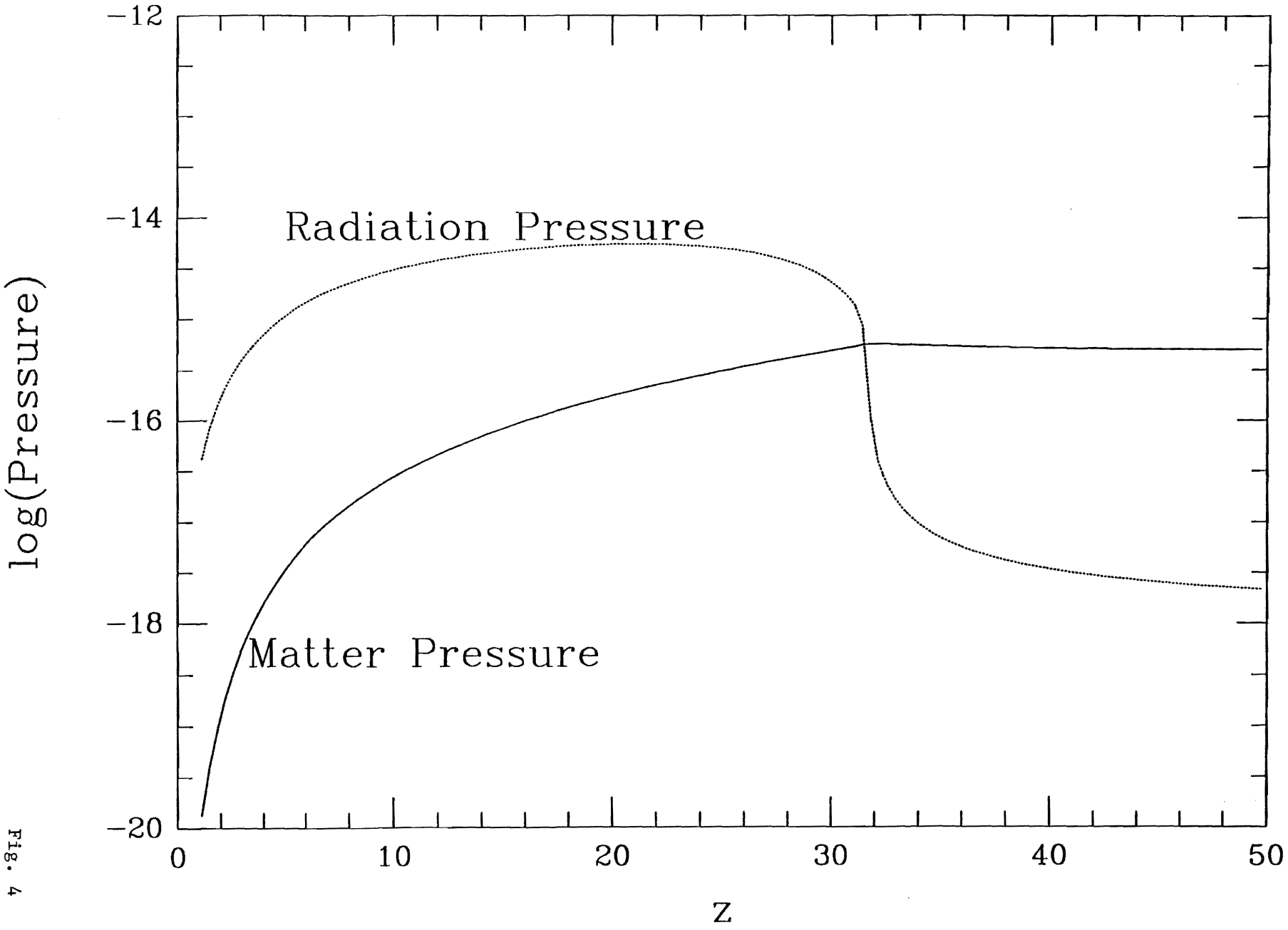
Radiation Pressure
Matter Pressure
log(Pressure)
z
−12
−14
−16
−18
−20
0
10
20
30
40
50

Fig. 4

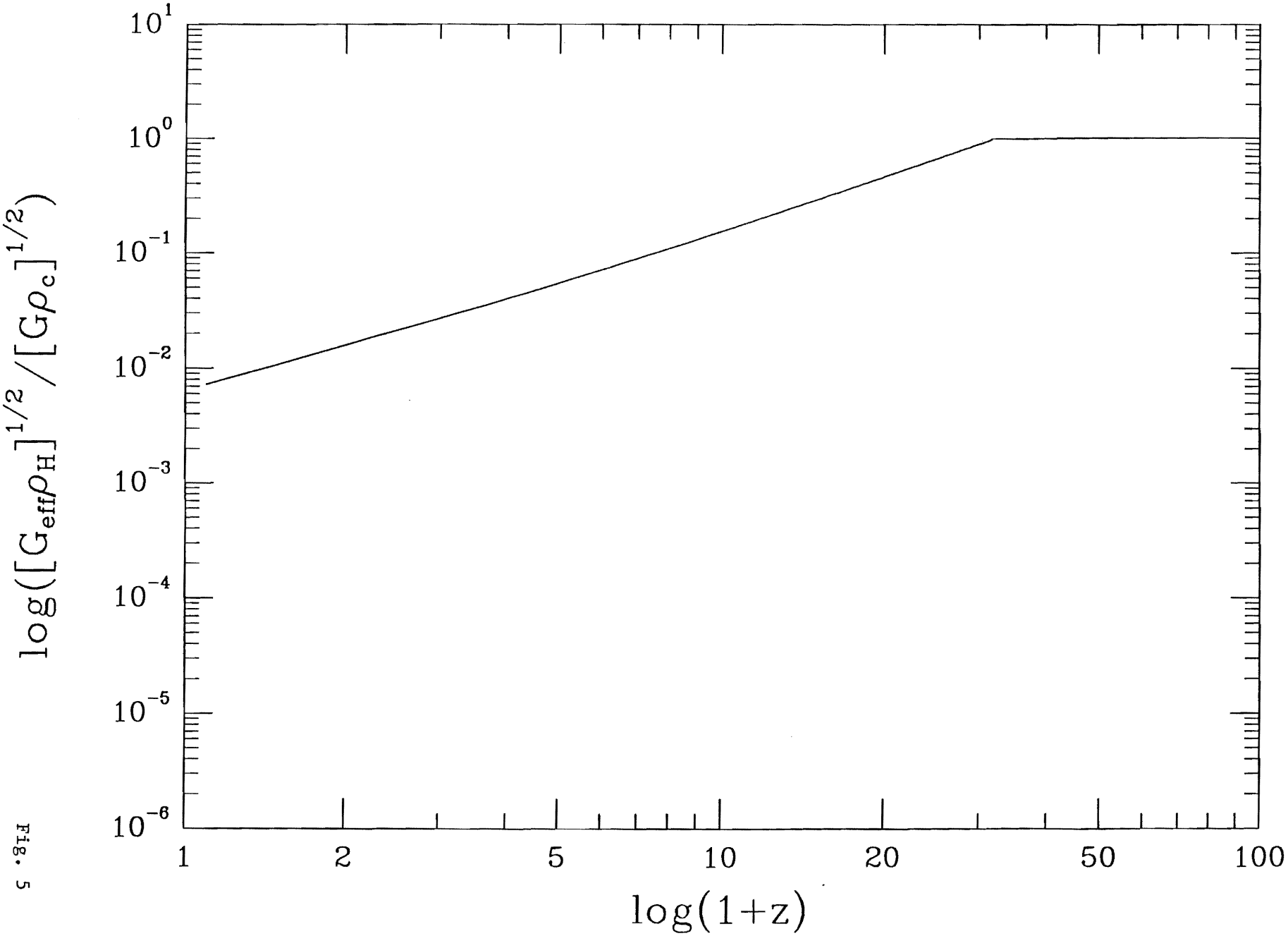
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\log([G_{eff}\rho_H]^{1/2}/[G\rho_c]^{1/2})$
1
2
5
10
20
50
100
log(1+z)

Fig. 5