

CMB Anisotropy in the Decaying Neutrino Cosmology

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ABSTRACT

It is attractive to suppose for several astrophysical reasons that the universe has close to the critical density in light (~ 30 eV) neutrinos which decay radiatively with a lifetime of $\sim 10^{23}$ sec. In such a cosmology the universe is reionized early and the last scattering surface of the cosmic microwave background significantly broadened. We calculate the resulting angular power spectrum of temperature fluctuations in the cosmic microwave background. As expected the acoustic peaks are significantly damped relative to the standard case. This would allow a definitive test of the decaying neutrino cosmology with the forthcoming MAP and PLANCK surveyor missions.

Key words: cosmology: dark matter, reionization, microwave background

1 INTRODUCTION

The absence of Gunn-Peterson absorption by diffuse neutral hydrogen in quasar spectra (Gunn & Peterson 1965) indicates that the intergalactic medium (IGM) is highly ionized, out to a redshift of at least 5 (Giallongo et al. 1994). The integrated flux of ionizing UV photons due to quasars themselves is believed to be inadequate for this purpose (Giroux & Shapiro 1996; Madau 1998). It has been proposed that the required flux can arise from the radiative decays of relic neutrinos of mass ~ 30 eV which would also provide the critical density in dark matter (Rephaeli & Szalay 1981; Sciama 1982). This hypothesis can naturally account for the temperature of Lyman- α clouds (Sciama 1991) as well as explain an anomaly found in the abundance of He I in three high-redshift Lyman-limit systems of the QSO HS 1700+6416 (Sciama 1994). Moreover, the decays of the neutrinos in galactic halos such as ours can account for the observed ionization of the interstellar medium, which again is difficult to account for by conventional sources (Sciama 1993). Various astrophysical and cosmological constraints can then pin down the parameters of the decaying hot dark matter (HDM) cosmology rather precisely (Sciama 1997a):

$$m_\nu = 27.4 \pm 0.2 \text{ eV} \implies \Omega_\nu h^2 = 0.293 \pm 0.003, \quad (1)$$

$$\tau_\nu \simeq (1 - 2) \times 10^{23} \text{ sec}, \quad (2)$$

$$h = 0.548 \pm 0.003, \quad \text{for } \Omega_\nu + \Omega_B = 1.$$

(Here Ω_ν and Ω_B denote the fraction of the critical density in neutrinos and baryons, respectively, and h is the Hubble constant in units of $100 \text{ km sec}^{-1} \text{ Mpc}^{-1}$. We note that most dynamical estimates of the clustered mass density upto supercluster scales (Peebles 1993) as well as recent observations of Type Ia supernovae at high redshift (Perlmutter et

al. 1998; Garnavich et al. 1998) actually suggest $\Omega \sim 0.3-0.4$ (with a possible cosmological constant). The decaying neutrino cosmology can, in principle, accommodate this as long as the constraint (1) is respected, i.e. for a high value of h .) Direct searches for the expected UV line at $E_\gamma = 13.7 \pm 0.1$ eV (i.e. $\lambda = 905 \pm 7 \text{ \AA}$) have so far proved unsuccessful but new results are expected soon from the EURD detector on the Spanish MINISAT 01 satellite (Sciama 1997b).

As is well known, large-scale structure formation is problematic in a HDM cosmology because the primordial density perturbation is severely damped on small scales due to neutrino free-streaming (Bond, Efstathiou & Silk 1980). This would lead to supercluster-size objects forming first and smaller objects forming subsequently through their fragmentation, which is in conflict with a variety of observations (Peebles 1993). However the problem may be solved if there is an additional source of small-scale fluctuations, e.g. from a network of cosmic topological defects (Villumsen, Scherrer & Bertschinger 1991; Gratsias et al. 1993).

It had been noted some time ago (Bond & Efstathiou 1984) that reionization of the IGM, e.g. by early star formation, leads to suppression of the anisotropy in the cosmic microwave background (CMB) on angular scales smaller than the horizon size at the reionization epoch. This would then appear to provide a potential test of the decaying HDM cosmology. Although much work has been done on reionization in cold dark matter (CDM) and (isocurvature) baryonic dark matter (BDM) models (Sugiyama, Silk & Vittorio 1993; Hu & Sugiyama 1994; Dodelson & Jubas 1995; De Bernardis et al. 1997), these results are not directly applicable to the present case where the universe is *gradually* reionized by the decaying neutrinos. (An exception is the work of Dodelson & Jubas (1995) who considered a variety of possible ion-

ization histories and estimated the CMB fluctuation signal expected in specific experiments.) Hence it is necessary to make a specific study of the problem. Such a calculation has been performed already by Tuluie, Matzner and Anninos (1995) (see also Anninos et al. 1991) who numerically simulated the growth of structure in a HDM universe and followed photon trajectories in the reionized universe in order to construct CMB temperature maps. However these authors fixed the amplitude of the initial density perturbation by requiring that the autocorrelation function of the dark matter particles should equal the observed value for clusters ($\zeta(r) = (r/r_0)^{-1.8}$) at a redshift of $z = 0$ for separations $r \sim 25h^{-1}$ Mpc. Since the COBE discovery of super-horizon scale CMB fluctuations this is no longer appropriate and the primordial density perturbation should be normalized via the COBE quadrupole. It is then seen that the HDM model has too little power on cluster and smaller scales to match observations and, as mentioned earlier, some other source of small-scale power must be sought. Since this issue is model-dependent, the effects of reionization on the CMB anisotropy ought to be computed without specific reference to the manner in which structure was generated.

In this Letter we first make the necessary connection between the ionization history of the IGM and the lifetime of the decaying neutrinos. We then incorporate this in a numerical code which computes the CMB anisotropy with high precision. To compare with observational data, we normalize the primordial density perturbation to COBE and present the results as an angular power spectrum.

2 REIONIZATION IN THE DECAYING NEUTRINO COSMOLOGY

In the standard cosmology the universe (re)combines at a redshift of $z_{\text{rec}} \sim 1300$ (Peebles 1968, 1981). In particular the last scattering surface (LSS) of the relic blackbody photons is well approximated by a gaussian of width $\Delta z = 78$ located at a redshift $z \sim 1065$ (Jones & Wyse 1985). The presence of decaying neutrinos generates UV photons which reionize the IGM, thus significantly broadening the LSS (Scott, Rees & Sciama 1991). We study the ionization history from early times by direct integration of the rate equation for the ionization fraction of hydrogen, $x_{\text{H}} \equiv n_{\text{e}}/n_{\text{H}}$, following previous work (Salati & Wallet 1984; Asselin, Girardi & Salati 1988; Dodelson & Jubas 1992).

At high temperatures both helium and hydrogen are fully ionized and $x_{\text{H}} \approx 1$. Helium (re)combines while hydrogen is still fully ionized and this process can be approximated by the Saha ionization equilibrium equation, quite independently of the subsequent evolution. The evolution of the free electron fraction through hydrogen (re)combination and reionization is driven by two distinct processes — transitions via excited states, and transitions directly to the ground state,

$$-\frac{dx_{\text{H}}}{dt} = a \left(\alpha_{1s} \frac{n_{\text{e}}^2}{n_{\text{H}}} - \sigma_{\text{I}} \frac{n_{1s} n_{\text{I}}}{n_{\text{H}}} \right)_{ep \rightarrow \text{H}_{1s}} + aC \left(\alpha \frac{n_{\text{e}}^2}{n_{\text{H}}} - \beta \frac{n_{1s}}{n_{\text{H}}} e^{-B_1/kT_B} \right)_{ep \rightarrow \text{H}^* \rightarrow \text{H}_{1s}}, \quad (3)$$

where α_{1s} and α are the recombination rates to the 1s level

and excited states respectively, β is the ionization rate from the ground state, C is a correction factor (Peebles 1968, 1981) and $B_1 = 13.6$ eV is the ground state binding energy. In the standard picture of (re)combination of hydrogen, the first component is negligible because every combining electron–proton pair releases a photon which immediately ionizes another neutral hydrogen atom. However it cannot be neglected when there is an additional injection of ionizing photons from the decaying neutrinos at a rate

$$\left(\frac{dn_{\text{I}}}{dt} \right)_{\text{decay}} = \frac{n_{\nu}}{\tau_{\nu}}, \quad (4)$$

where n_{I} and n_{ν} are the number density of ionizing photons and neutrinos respectively and τ_{ν} is the neutrino lifetime. Then, including the effect of dilution due to expansion and the redshifting below the Rydberg energy, n_{I} evolves in time according to

$$\frac{dn_{\text{I}}}{dt} + \left[\sigma_{\text{I}} n_{1s} + \left(3 + \frac{B_1}{kT} \right) H \right] n_{\text{I}} = \alpha_{1s} n_{\text{e}}^2 + \frac{n_{\nu}}{\tau_{\nu}}, \quad (5)$$

so the equilibrium value of n_{I} is

$$(n_{\text{I}})_{\text{eq}} = \frac{\alpha_{1s} n_{\text{e}}^2 + n_{\nu} \tau_{\nu}}{[\sigma_{\text{I}} n_{1s} + (3 + B_1/kT)H]}. \quad (6)$$

Except for a small region when x_{H} is close to unity, n_{I} is well approximated by its equilibrium value (Dodelson & Jubas 1992). It is also a good approximation to replace the number density n_{1s} of hydrogen atoms in the 1s state by $(1 - x_{\text{H}})n_{\text{H}}$. Equation (3) then reads

$$-\frac{dx_{\text{H}}}{dt} = a \left[\alpha_{1s} x_{\text{H}}^2 n_{\text{H}} - \sigma_{\text{I}} (1 - x_{\text{H}}) \left(\frac{\alpha_{1s} x_{\text{H}}^2 n_{\text{H}}^2 + n_{\nu} / \tau_{\nu}}{\sigma_{\text{I}} (1 - x_{\text{H}}) n_{\text{H}} + (3 + B_1/kT) H} \right) \right] + aC \left(\alpha x_{\text{H}}^2 n_{\text{H}} - \beta (1 - x_{\text{H}}) e^{-B_1/kT_B} \right). \quad (7)$$

In addition we must follow the evolution of the matter and radiation temperatures. We modify the standard evolution as incorporated in the computer code COSMICS (Ma & Bertschinger 1995) by including the energy, $E_{\nu} - B_1$, released by the decaying neutrinos (as long as there is neutral hydrogen present to capture the photons).

We integrate Equation (7) numerically using a semi-implicit method. The resulting ionization fraction, optical depth and cumulative visibility function ($= \int_0^z e^{-\tau} (dt/dz) dz$) are shown in Figure 1. For the Hubble parameter we use $h = 0.55$ (Sciama 1997a). The baryon density obtains from taking $\Omega_{\text{B}} h^2 = 7 \times 10^{-3}$ as indicated by the primordial abundance of ${}^4\text{He}$ inferred from observations of blue compact galaxies by Olive, Skillman & Steigman (1997), the high D abundance measured in quasar absorption systems (Songaila, Wampler & Cowie 1997; Webb et al. 1997) and the abundance of ${}^7\text{Li}$ in Pop II stars (Bonifacio & Molaro 1997). If however we adopt the higher ${}^4\text{He}$ abundance obtained by Izotov, Thuan & Lipovetsky (1998) in conjunction with the lower D abundance of Burles & Tytler (1998) then the appropriate value is $\Omega_{\text{B}} h^2 = 1.88 \times 10^{-2}$. Both values for the baryon density, viz. $\Omega_{\text{B}} = 0.023, 0.062$ yield a good χ^2 for the fit to the theoretical expectations (Fiorentini et al. 1998). We also consider two values for the neutrino lifetime, $\tau_{\nu} = 10^{23}, 2 \times 10^{23}$ sec. It is seen that the IGM is fully ionized for a redshift below ~ 30 although the optical depth reaches unity only at a redshift exceed-

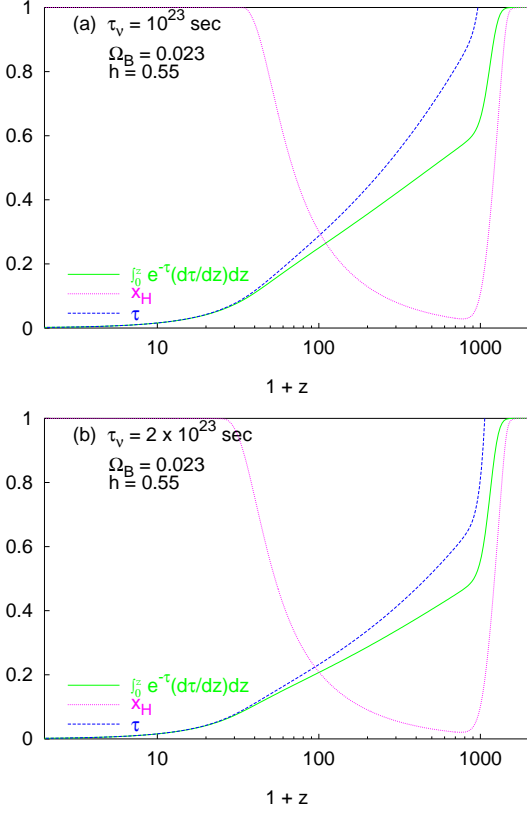


Figure 1. The fractional ionization, optical depth and cumulative visibility function in the decaying neutrino cosmology for a neutrino lifetime of (a) 10^{23} sec and (b) 2×10^{23} sec.

ing ~ 1000 . The LSS is significantly broadened as is evident from the slow growth of the cumulative visibility function.

It had been argued (Zeldovich & Sunyaev 1969) that the universe must have been neutral during the epoch $300\Omega_B^{-7/9} < z < z_{\text{rec}}$ in order not to induce a “y” distortion in the blackbody spectrum of the CMB. However this assumed that all matter is constituted of baryons. Allowing for non-baryonic dark matter, this argument is evaded and the universe is not required to have (re)combined (Bartlett & Stebbins 1991). We have checked that there is no conflict in the decaying HDM cosmology with even the very restrictive bound $y < 2.5 \times 10^{-5}$ from the COBE FIRAS data (Fixsen et al. 1991).

3 CALCULATION OF THE CMB ANISOTROPY

As mentioned earlier, the anisotropy in the CMB will be damped as a result of the broadening of the last scattering surface. To calculate this we use the CMBFAST code (Seljak & Zaldarriaga 1996) incorporating the ionization fraction evolution described above. The primordial density perturbation is assumed to be scale-invariant and is normalized on super-horizon scales to the CMB quadrupole moment measured by COBE: $Q_{\text{RMS-PS}} \simeq 18 \mu\text{K}$ (Bennett et al. 1996).

The calculated angular power spectrum is shown in Figure 2. As expected the acoustic peaks are damped by reionization, with the extent of damping decreasing as the neu-

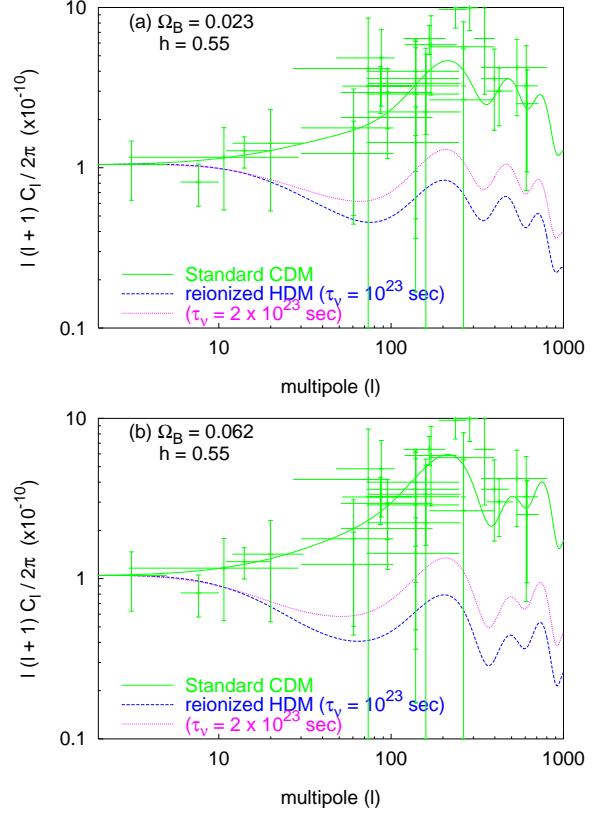


Figure 2. Angular power spectrum of CMB anisotropy in the decaying neutrino cosmology for (a) $\Omega_B = 0.023$ and (b) $\Omega_B = 0.062$, with $\tau_\nu = 10^{23}$, 2×10^{23} sec.

trino lifetime increases. (We stress that the damping effect is largely due, not to the reionization itself, but rather the presence of more free electrons at all redshifts which widens the last scattering surface. In particular, sudden reionization at a late redshift would not result in significant damping.) An increase in the assumed baryon density alters the relative level of damping of the second and third acoustic peaks. A selection of data from recent ground-based and balloon-borne experiments is also shown for comparison.

To obtain a quantitative measure of the (dis)agreement of the decaying neutrino prediction with present observations we perform a χ^2 analysis (Lineweaver et al. 1997) after convolving the predicted CMB power spectrum with the experimental window functions. The χ^2 for the decaying HDM model ranges between $\sim 500 - 700$ for the allowed range of τ_ν and Ω_B , for 29 degrees of freedom (32 data points - 2 fitted parameters - 1 COBE normalization). Since there is less than 0.5% probability of obtaining a χ^2 exceeding 52.34, the decaying HDM theory clearly does not fit the trend in the present data. However it would be premature to draw any strong conclusion from this, given that there may still be large systematic uncertainties in the present data. A definitive test will however be possible with the forthcoming MAP and PLANCK all-sky surveyor satellite missions, which are expected to reliably measure the small-scale anisotropy with an accuracy of a few per cent (Smoot 1997). Moreover these experiments will also measure the CMB polarization, thus providing an independent constraint on the ionization history (Keating et al. 1998).

4 CONCLUSIONS

We have computed, in a consistent manner, the angular power spectrum of CMB anisotropy to be expected in the decaying HDM cosmology. The damping of the acoustic peaks due to the gradual reionization of the IGM is shown to provide a clear test of the model.

Other possible observational signatures of reionization have been considered. With regard to the CMB, although large angular-scale fluctuations are damped, new fluctuations are generated on arcminute-scales by the motions of the ionized gas — the Vishniac effect (Ostriker & Vishniac 1986; Vishniac 1987). This has been studied in some detail for both CDM and BDM models and various constraints inferred from observational limits on small angular-scale fluctuations (Efstathiou 1988; Hu, Scott & Silk 1994; Dodelson & Jubas 1995; Hu & White 1996). For HDM, the small-scale power in the primordial (inflationary) density perturbation is generically suppressed which would normally imply a negligible Vishniac effect. However as we have noted some additional source of small-scale power such as cosmic topological defects is needed in any case to allow galaxies to form in an HDM universe. Lacking a precise knowledge of such fluctuations, it is not possible to make a model-independent calculation of the Vishniac effect in the present case.

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