Astron. Astrophys. 321, 1–7 (1997)

ASTRONOMY
AND
ASTROPHYSICS

Comparison of stars and decaying neutrinos as additional sources of the intergalactic UV background

Luis Masperi[1] **and Sandra Savaglio**[2]

[1] Centro Atómico Bariloche and Instituto Balseiro, Comisión Nacional de Energía Atómica and Universidad Nacional de Cuyo, 8400 S.C. de Bariloche, Argentina
[2] European Southern Observatory, Karl-Schwarzschildstr. 2, D-85748 Garching bei München, Germany

Received 29 April 1996 / Accepted 5 September 1996

Abstract. A numerical calculation of properties of finite absorbers and of intergalactic medium based on photoionization equilibrium is performed to confront alternative UV sources in addition to quasars.

It is seen that a spectrum including a large peak around the HI ionization energy due to decaying neutrinos is too soft in the region up to the HeI edge to explain the relatively small observed ratio of neutral He and H densities in Lyman-limit systems if their size is of the kpc order. The recently proposed decrease of the contribution from unstable neutrinos solves this problem but tends to spoil the consistence between IGM and Lyman-α clouds, which requires a large ratio of fluxes for the HI and HeII ionization frequencies, unless there is a very fast decline of quasars above $z = 3$.

On the other hand, the addition of stars to quasars may produce a spectrum sufficiently hard between HI and HeI and thereafter soft up to HeII to allow a reasonable agreement of the properties of denser absorbers with those of IGM. This model seems to favour cold dark matter with additional cosmological constant.

Key words: dark matter – galaxies: intergalactic medium – quasars: absorption lines – diffuse radiation

1. Introduction

The reionization of the Universe is a subject of deep experimental and theoretical study for its implication on galaxy formation and on the consistence of small scale anisotropies with cosmological models. The different possible sources of UV background may give some information on the identity of dark matter.

It has been seen from the bounds on Gunn-Peterson (GP) effect (Gunn & Peterson 1965) for neutral H and single-ionized He that the frequency UV spectrum seems to be softer than that due to quasars (QSO) (Madau 1992), requiring therefore additional sources which might be stars.

Another suggested possibility has been that decaying neutrinos (Sciama 1990a), in addition to QSOs, may ionize HI in the intergalactic medium (IGM), clouds and other systems. This decaying dark matter (DDM) would be hot (HDM) and might be in difficulty to explain the formation of structures unless cosmic strings are the seed of primeval fluctuations (Zanchin et al. 1996). Since this is a delicate subject, it is interesting to see whether the sole properties of reionization are able to support this hypothesis or not.

The observations whose validity we will assume for our analysis are the ratio of densities of neutral He and H in Lyman-limit systems (LLS) (Reimers & Vogel 1993), the bound of GP effect for HI (Giallongo et al. 1994) considered as due to photoionization and the estimation of the same effect for HeII (Jakobsen et al. 1994; Tytler et al. 1995; Davidsen et al. 1996).

We will calculate the He ionization fractions for absorbers of given density due to UV fluxes corresponding to the different alternatives to inspect their agreement with the observations of LLS. Additionally, from the expressions of GP effect for HI and HeII we will obtain a bound for the ionization fraction of the latter in IGM to compare its consistence with that of Lyman-α clouds (LC) for the various possibilities of flux.

In Sect. 2 we will describe the possible sources of UV radiation whose difference is roughly that QSOs ionize HI, HeI and HeII, stars just HI and HeI and decaying neutrinos only HI. The contribution of stars will be fixed by recent determinations of the proximity effect (Giallongo et al. 1996) and that of DDM requiring that it is capable to ionize alone the HI and NI of the Milky Way (Sciama 1990b) or that the decay photons have not enough energy to ionize NI (Sciama 1995).

In Sect. 3 the numerical calculation will be presented for absorbers of different density with the alternative UV fluxes to determine the ionization of He and other properties and see their compatibility with observations in LLS.

Sect. 4 will be devoted to compare GP effect for HI and HeII with the different models estimating the fraction of the latter in

---

Send offprint requests to: Luis Masperi homogeneous IGM to evaluate through approximate formulae if it is consistent with the numerically calculated properties of LC.

The conclusions will be given in Sect. 5 indicating the possible relation of the UV ionizing flux with different cosmological models.

2. Sources of UV background

Recent determinations of bounds for GP effect for HI and estimations for HeII give, under the assumption of photoionization to explain the ratio of the optical depths

$$\tau^{GP}_{HeII}/\tau^{GP}_{HI} = 0.45\ J_{HI}/J_{HeII}\ , \tag{1}$$

a ratio of the effective UV fluxes at the corresponding ionization frequencies of at least

$$S_L = J_{HI}/J_{HeII} = 100 \tag{2}$$

for $z = 3.3$. Even if the GP effect is masked by line blanketing, the above ratio is maintained rather high with the estimation $S_L \geq 40$ (Madau & Meiksin 1994) or $S_L \geq 65$ (Sethi 1995). On the other hand, from metallicity abundance it is found that $S_L \sim 70$ at $z \sim 3.2$ (Songaila et al. 1995) and even $S_L > 100$ for $z = 3.5 - 3.8$ (Savaglio et al. 1996).

This ratio S_L seems to exceed that due to QSOs which was evaluated as ~ 30 (Madau & Meiksin 1994; Haardt & Madau 1996) in agreement with the declining quasar population for $z > 3$ (Pei 1995). It appears therefore necessary to fill the difference with another UV source.

If one adds stars of primeval galaxies (Miralda-Escudé & Ostriker 1990) they may ionize HI and HeI with a spectrum similar to that of QSOs but which afterwards drops abruptly so that HeII is ionized only by the latter source. If one fits the resulting flux of QSOs in the range between HI and HeI as $J \sim \nu^{-\alpha}$ with $\alpha \leq 1$, it follows that for the total flux

$$J_{HI}/J_{HeI} \leq 2\ . \tag{3}$$

Another possibility is the addition to QSOs of DDM thought (Sciama 1993) as neutrinos of mass around 30 eV which could correspond to close the universe with HDM. This model is alternative to the first since HDM delays galaxy formation so that stars would be excluded. According to the details of the decaying neutrinos the relation of Eq. 3 may be altered.

Our analysis will be based on considering three models for UV fluxes: that due to QSOs alone and the alternatives of adding either stars or decaying neutrinos. We will consider them at $z = 2$ and 4 because the former redshift corresponds to the observations of LLS, and the latter to the range of GP estimations for HI and HeII (see Fig. 1).

Using for the effective UV flux the normalization $J = J_{-22} \times 10^{-22}$ erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}, the evaluation of the QSO contribution has increased doubling the earlier values (Madau 1992) to reach at $1Ry$ a maximum of $J_{-22} \sim 3$ for $z \geq 2$ when dust obscuration is taken into account (Haardt & Madau 1995) and diminishing for larger redshifts so that we estimate $J_{-22} \sim 2$ at $z \sim 4$. According to the discussed values of S_L due to QSOs, and considering that this ratio increases with z, one evaluates as maximum contribution at $4Ry$ $\ J_{-22} \sim 0.05$ at $z = 4$ and slightly above 0.1 at $z = 2$, which will coincide with the total flux at this frequency in all the alternative models. We will denote this scheme as the strong QSO model (sQSO).

Stars give a slightly softer spectrum in the range HI – HeI and we normalize the total flux in the QSO+star model at $1Ry$ as $J_{-22} \sim 5$ to agree with recent determinations from proximity effect $J_{-22} = 5 \pm 1$ at $1Ry$ which show no evolution in the range $2 < z < 4$ (Giallongo et al. 1996). In this way it will be noted that the ratio of Eq. 2 is satisfied for $z \sim 4$ and that of Eq. 3 reasonably fulfilled in the range $2 < z < 4$. To explore the situation $S_L = 200$ at $z \sim 4$ we will also consider the weak QSO contribution (wQSO) corresponding to take 50% of the above quoted values, always keeping the normalization $J_{-22} = 5$ at $1Ry$ for the total QSO+star flux.

It must be remarked that the fluxes denoted as J_{HI}, J_{HeI} and J_{HeII} are the average over frequency weighted with the corresponding ionization cross section. In the QSO and QSO+star cases they differ only slightly from the flux J_ν at $\nu = 1Ry$ etc, because of the fast decrease of the cross section. E.g.

$$J_{HI} = \frac{\int_{1Ry}^{\infty} J_\nu\,(\sigma_{HI}/\nu)\,d\nu}{\int_{1Ry}^{\infty}(\sigma_{HI}/\nu)\,d\nu}\quad . \tag{4}$$

On the other hand for the QSO+DDM model the only difference from QSOs alone is a large peak around $1Ry$ so that this maximum of J_ν will be much greater than the averaged J_{HI}. From the requirement (Sciama 1990b) that decaying neutrinos are able to ionize the H of the Milky Way their lifetime must be $\tau_\nu \sim 2 \times 10^{23}$ s. Correspondingly, the intergalactic flux expressed in number of photons per cm^2 and s at $z \sim 0$ would be

$$F = \frac{n_\nu}{\tau_\nu}\frac{c}{H_0}\frac{\epsilon}{13.6} \tag{5}$$

with photon energy $E_\gamma = (13.6 + \epsilon)$ eV, and where n_ν is density of neutrinos and H_0 present Hubble constant. Assuming (Sciama 1993) that decay photons are able to ionize NI, the neutrino mass must be $m_\nu \sim 29$ eV and consequently $F \sim 6 \times 10^5$ which corresponds to $J_{-22} \sim 24$. Since according to this model the flux due to neutrinos increases with redshift as $(1 + z)^{3/2}$, we would have $J_{-22} \sim 120$ at $z = 2$.

The ionization cross-section has the frequency behaviour $\sigma \sim \nu^{-3}$ so that for a peak of width ϵ additional to the spectrum due to QSOs one has, according to Eq. 4,

$$J_{HI} = J^{DDM}\frac{3\,\epsilon}{13.6} + J^{QSO}_{1Ry}\frac{3}{3+\alpha}\quad . \tag{6}$$

For the above values, using strong QSO contribution, one would obtain

$J_{HI,-22} \sim 27$ at $z = 2$ which is extremely large. Considering a reduction of the flux due to absorption by clouds, one may estimate at $1Ry$ $J_{-22} \sim 80$ for $z = 2$, case which we will

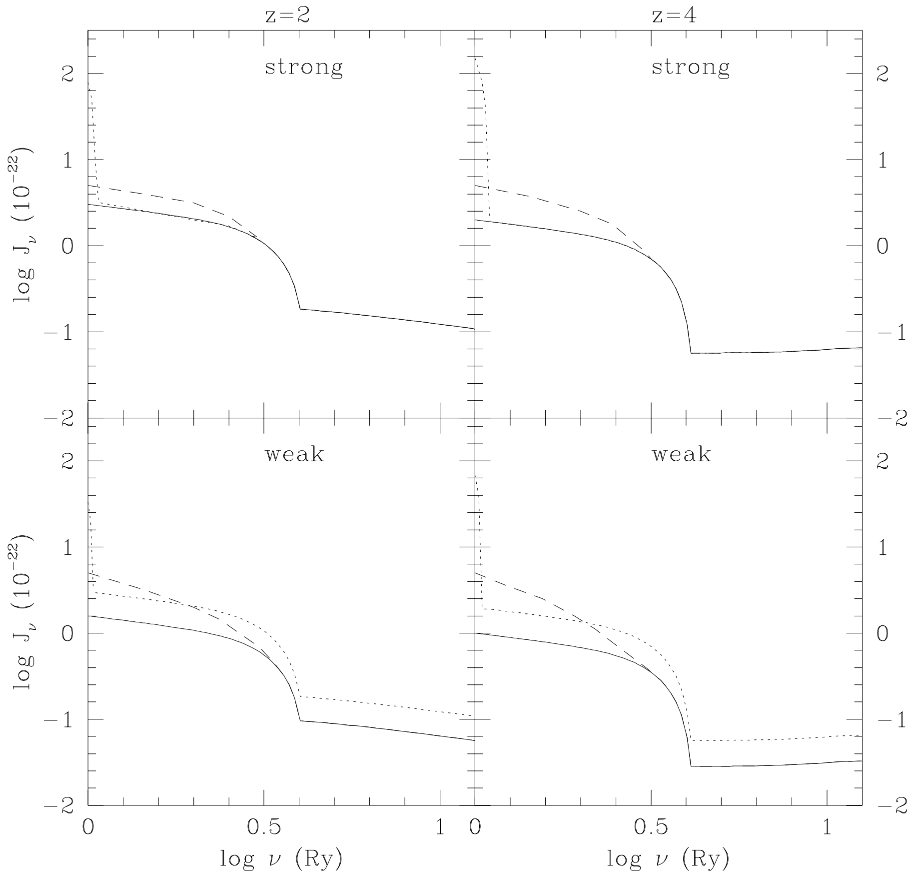

Fig. 1. The UV ionizing source as function of the frequency (in Rydberg) for two different redshifts. The continuum line is for QSO sources only, the dashed line is the same with the addition of stars, the dotted line is with the addition of decaying dark matter (DDM) photons. The upper two plots represent the UV flux in case of strong contribution by the QSOs (sQSO), and in case of the QSO+DDM model, of strong contribution by the DDM (sQSO+sDDM). The lower two panels are for weak QSO contribution (wQSO) and, in the case of the DDM model, for strong QSO contribution, but weak DDM contribution (sQSO+wDDM).

denote as strong DDM model (sDDM). As a consequence, the averaged flux for QSO+DDM will be $J_{HI,-22} \sim 18$ and we may establish a typical ratio (Sciama 1994) at $z = 2$ for this standard QSO+DDM model

$$J_{HI}/J_{HeI} \sim 8 \ . \qquad (7)$$

For $z = 4$ the same strong DDM contribution will be $J_{-22} \sim 150$ which gives an averaged flux $J_{HI,-22} \sim 30$ for sQSO+DDM and therefore a ratio S_L much larger than that of Eq. 2. It is seen that the flux due to neutrinos is higher than the large initial observations of proximity effect at $z \sim 2.5$ (Bajtlik et al. 1988) and even beyond the upper quoted values (Bechtold 1994). Other determinations give smaller fluxes which either would be consistent with QSOs alone (Williger et al. 1994; Lu et al. 1996) or correspond to the value we have taken to normalize the QSO+star model (Giallongo et al. 1996). Therefore for the described QSO+DDM case a non-standard interpretation of the proximity effect must be invoked (Sciama 1991).

But recently a modified decaying neutrino has been proposed (Sciama 1995) due to an estimation of the metagalactic flux F at $z \sim 0$ four times smaller than that given by $m_\nu \sim 29$ eV. Therefore, keeping the value of the lifetime, from Eq. 5 ϵ must not exceed 0.2 and the decay photons cannot ionize NI. The maximum fluxes due to this weak DDM (wDDM) would be $J_{-22} \sim 30$ at $z = 2$ and $J_{-22} \sim 67$ at $z = 4$ which would be roughly compatible with the highest estimations from proximity effect. Due to the fact that the peak is now smaller and narrower, from Eq. 6 the averaged flux for the modified DDM+sQSO model turns out to be $J_{HI,-22} \sim 4.4$ at $z = 2$ and $J_{HI,-22} \sim 5$ at $z = 4$. Therefore the bound (3) is almost respected and that of Eq. 2 exactly satisfied. We note that we have performed a more accurate relation between neutrino mass and flux of decay photons than that done in Miralda-Escudé & Ostriker 1992.

Since the standard QSO+sDDM model satisfies the Eq. 7 whereas the QSO+star alternative as well as QSOs alone and the modified QSO+wDDM model correspond to a ratio (3), one may test their consistence using them in the ratio of neutral densities which follows from photoionization equilibrium for HI and HeI (Miralda-Escudé & Ostriker 1992; Sciama 1994)

$$\frac{n_{HeI}}{n_{HI}} = 0.044 \frac{J_{HI}}{J_{HeI}} \chi_{HeII} \ . \qquad (8)$$

χ_{HeII} is the fraction of single-ionized He and the numerical coefficient is independent of temperature and density of the system. Moreover, information from GP effect which involves HI and HeII does not support QSOs as the only UV source and may distinguish between QSO+star model and the modified QSO+wDDM possibility.

3. Lyman-limit systems and Lyman-α clouds

For LLS a ratio $n_{HeI}/n_{HI} \sim 1/30$ has been observed (Reimers & Vogel 1993) for $z \simeq 2$. If one takes the standard

QSO+sDDM alternative of Eq. 7, Eq. 5 would require that for $z \simeq 2$ $\chi_{HeII} \simeq 0.1$ the rest being almost all HeIII. On the contrary if one chooses either the fluxes of QSOs alone or those of QSO+star or modified QSO+wDDM models, it follows from Eq. 3 that $\chi_{HeII} \geq 0.5$.

To obtain the fractions of ionized He, we have performed a numerical calculation for absorbers using the standard photoionization code CLOUDY (Ferland 1991).

As input for the LLS we have taken the HI column density $N_{HI} \sim 10^{17}$ cm^{-2}, the metallicity as $1/100$ of the solar value and the H density $n_H \sim 10^{-2}$ cm^{-3}. This last figure corresponds to the lower bound (Steidel 1990; Lanzetta 1991) consistent with sizes smaller than 15 kpc.

For the LC we have fixed $N_{HI} \sim 10^{14}$ cm^{-2}, $n_H \sim 10^{-4}$ cm^{-3} and metallicity 1/1000 of the solar value, which correspond to their commonly accepted sizes (Meiksin & Madau 1993). Lower limits to the transverse size of the LC observed in the gravitational lensed spectra of HE1104-1805 (Smette et al. 1995) is of the order of 50 h^{-1} kpc at 2σ level for spheroidal clouds at $z \sim 2$, where $h = H_0/(100$ km s^{-1} Mpc$^{-1})$. Similar results have been found (Dinshaw et al. 1995) from the cross correlation of absorption lines in the close quasar pair 1343+2640A and B deriving sizes larger than 40 h^{-1} kpc at $z = 1.8$.

We have assumed that the UV background radiation is the only ionizing source and we used for the flux the different shapes and intensities according to Fig. 1. Results are summarized in Tables 1 and 2.

Considering LLS, it turns out that at $z = 2$ $\chi_{HeII} > 0.5$ for the three models. In particular for the modified decaying neutrino in addition to the sQSO contribution, the values of χ_{HeII} turn out to be similar to those of the sQSO+star model. Therefore $\chi_{HeII} \sim 0.1$ is excluded with all the models for the chosen value of the density n_H.

One must remark that the observation of n_{HeI}/n_{HI} in LLS was accompanied by that of ionized states of C, N and O (Reimers & Vogel 1993) which would be consistent with a large He ionization, i.e. $\chi_{HeII} \sim 0.1$. This led to the explanation of the whole set of observations with the standard decaying neutrino (Sciama 1994) using the large ratio (7) of J_{HI}/J_{HeI}. But to obtain $\chi_{HeII} \sim 0.1$ it is necessary to decrease the density n_H in such a way that the sizes of LLS would be larger than 100 kpc which is an unattractive possibility. This has suggested that the heavy elements are collisionally ionized in hot regions (Giroux et al. 1994) different from those where H and He are photoionized. This is the scenario adopted for our analysis.

Therefore we may state that QSO+star model, QSOs alone and also the modified sQSO+wDDM alternative are consistent with the observation of n_{HeI}/n_{HI} at $z = 2$. From the tables we may see that the CLOUDY calculation predicts a smaller He ionization at $z = 4$ as it is generally expected.

For further considerations it is convenient to use approximate expressions assuming photoionization equilibrium for HI and HeII in a thin absorber of size R expressed in kpc and column density given in cm^{-2}, which allow to write (Miralda-Escudé & Ostriker 1992)

$$\chi_{HeII} = \left(\frac{N_{HI}\ J_{HI,-22}}{R} \right)^{1/2} \frac{2.7 \times 10^{-10}}{J_{HeII,-22}} \ , \tag{9}$$

where the numerical figure includes the square root of the recombination coefficient whose temperature dependence is (Spitzer 1978) $\alpha(T) \sim T^{-3/4}$ and, defining $T = T_4\ 10^4\ K$, $T_4 \sim 2$ has been taken. It is possible to check the densities for which the approximate expressions are valid so that also IGM can be included in the comparison.

For a thicker absorber like LLS the left-hand side of Eq. 9 must be replaced in principle by $\chi_{HeII}/(1 - \chi_{HeII})$ since the right-hand side gives n_{HeII}/n_{HeIII}. But in this way the obtained χ_{HeII} will be a lower bound because self-shielding for He should be already included for LLS, diminishing the value of J_{HeII}. Another source of approximation of Eq. 9 is the fact that instead of the detailed flux spectrum, the averaged values are included what is particularly relevant in J_{HI} for the QSO+DDM case, as indicated in the previous section.

Comparing with our more accurate results of Table 1 for LLS, it is easily seen that the approximate formula gives typically a value of χ_{HeII} lower in 0.1 for QSOs and a slightly larger difference for QSO+star and QSO+DDM models. In fact for $z = 2$ CLOUDY gives e.g. for sQSO, sQSO+star, sQSO+sDDM and sQSO+wDDM models (Table 1) sizes $R \simeq 1.4$, 2.4, 5.2 and 2.2 kpc respectively, with a temperature $T_4 \sim 2$. The difference can be understood if in the approximate formula J_{HeII} is reduced around 40% in the QSO case because of self-shielding, around 50% in the QSO+star and QSO+wDDM models and even more than 60% for QSO+sDDM due to the increasing size of the absorber which results from CLOUDY.

For thin absorbers like LC, one expects that both CLOUDY and the approximate Eq. 9 give similar results because the absorber becomes thick to J_{HeII} only at $N_{HI} \sim 10^{15}$ cm^{-2} (Miralda-Escudé & Ostriker 1990). In fact CLOUDY gives for LC a ionization larger than for LLS with a typical $\chi_{HeII} \geq 0.01$ at $z = 4$ (Table 2). One may check that Eq. 9 gives the same values of χ_{HeII} once the numerical coefficient is changed in correspondence with the different T. For this comparison we must quote that CLOUDY for $z = 4$ gives for sQSO, sQSO+star, sQSO+sDDM and sQSO+wDDM models $R \simeq 17$, 37, 160 and 47 kpc respectively with $T_4 \sim 4.5$.

CLOUDY has produced rather large temperatures for LC which might result from thermal evolution of collapsed systems (Miralda-Escudé & Rees 1994) and that correspond to Doppler broadening in the range 25 km s^{-1} $\lesssim b \lesssim 32$ km s^{-1}, which is marginally consistent with the measured values obtained from high resolution QSO spectra. This would require gravitational confinement of LC in a colder IGM.

Considering only the photoionization equilibrium for HeII, it is also possible to check the consistency of predictions for different thin absorbers through

$$\frac{\chi_{HeII}}{1 - \chi_{HeII}} = \frac{\alpha(T)\, n_e}{J_{HeII}\, \sigma_{HeII}} \ . \tag{10}$$

Table 1. Fraction of HeII and HeIII for different UV background models (as shown in Fig. 1) in the LLS.

Model	$z = 2$			$z = 4$		
	$J(1Ry)_{-22}$	χ_{HeII}	χ_{HeIII}	$J(1Ry)_{-22}$	χ_{HeII}	χ_{HeIII}
sQSO	3	0.60	0.40	2	0.78	0.22
wQSO	1.6	0.70	0.29	1	0.86	0.14
sQSO+star	5	0.67	0.33	5	0.84	0.15
wQSO+star	5	0.79	0.20	5	0.91	0.09
sQSO+sDDM	80	0.79	0.21	150	0.94	0.06
sQSO+wDDM	33	0.67	0.33	69	0.87	0.12

Table 2. Fraction of HeII and HeIII for different UV background models (as shown in Fig. 1) in the LC.

Model	$z = 2$			$z = 4$		
	$J(1Ry)_{-22}$	χ_{HeII}	χ_{HeIII}	$J(1Ry)_{-22}$	χ_{HeII}	χ_{HeIII}
sQSO	3	0.004	0.996	2	0.013	0.987
wQSO	1.6	0.009	0.991	1	0.029	0.971
sQSO+star	5	0.004	0.996	5	0.013	0.987
wQSO+star	5	0.008	0.992	5	0.026	0.974
sQSO+sDDM	80	0.004	0.996	150	0.015	0.985
sQSO+wDDM	33	0.004	0.996	69	0.014	0.986

Eq. 10 is one of the ingredients which lead to Eq. 9 and involves only the density and temperature of the medium so that it is valid also for homogeneous IGM.

Since for LLS and LC CLOUDY gave the results of Tables 1 and 2, it is clear that the discrepancies in the use of Eq. 10 to compare these absorbers must come from self-shielding effects in LLS. Thinking in principle that UV flux and ionization cross section are common properties, the ratio of Eq. 10 for LLS and LC should be

$$[\chi_{HeII}/\chi_{HeIII}]_{LLS}\ [\chi_{HeIII}/\chi_{HeII}]_{LC} =$$

$$(n_{H_{LLS}}/n_{H_{LC}})\ (T_{LC}/T_{LLS})^{3/4}\ . \tag{11}$$

If we take the values of Tables 1 and 2 for QSO, QSO+star and QSO+DDM models at $z = 2,\ 4$ being typically $T_4 \sim 2$ for LLS and 5 for LC, the left-hand side of Eq. 11 is larger than the right-hand side in an amount which is explained by the same reduction of J_{HeII} for LLS that we discussed in connection with the discrepancies of Eq. 9.

Therefore we conclude that the approximate expressions based on photoionization equilibrium work well for thin absorbers so that we may use them to compare LC with the less dense homogeneous IGM.

4. Homogeneous intergalactic medium

We anticipate that the results of this section cannot be too precise due to the large uncertainties in the properties of homogeneous IGM.

As a first step we consider GP effect for HI which, if the ionization is due entirely to UV radiation, will correspond to the optical depth

$$\tau_{HI}^{GP} = 23\left(\frac{\Omega_{IGM}h^2}{0.015}\right)^2\left(\frac{0.5}{h}\right)\left(\frac{1+z}{5}\right)^6\frac{H_0}{H(z)}\frac{T_4^{-0.7}}{J_{HI,-22}} \tag{12}$$

where Ω_{IGM} is the fraction of critical density in the homogeneous IGM.

From the bound (Giallongo et al. 1994) at $z = 4.3$ $\tau_{HI}^{GP} \leq 0.02$ we will obtain the bounds on density of IGM for different UV models which then, through GP for HeII, will allow to estimate χ_{HeII} .

We start with the sQSO+star model with $S_L = 100$ at $z = 4$, taking $T_4 \sim 2$ which corresponds to inhomogeneous photoionization (Miralda-Escudé & Rees 1994). We adopt the value of the Hubble constant $h = 0.7$ which seems to emerge recently (Freedman et al. 1994; Riess et al. 1995; Tanvir et al. 1995), though also smaller values have been obtained (Tammann et al. 1996; Branch et al. 1996), that suggests the presence of the cosmological constant (Krauss & Turner 1995). Since for $\Omega_\Lambda \sim 0.6$ plus CDM, model denoted as ΛCDM, the ratio $H(4)/H_0 \simeq 7.1$ is obtained (Reisenegger & Miralda-Escudé 1995), the estimation $\Omega_{IGM} \leq \frac{1}{5}\Omega_B$ follows from the bound of Eq. 12 where we have taken the average of the quoted values of the baryonic density $\Omega_B = 0.015/h^2$. It is interesting that this agrees with simulations for ΛCDM giving 80% of baryons in collapsed form (Miralda-Escudé et al. 1995).

We now pass to GP for HeII whose optical depth is

$$\tau_{HeII}^{GP} =$$

$$2.5 \times 10^5\left(\frac{\Omega_{IGM}h^2}{0.015}\right)\left(\frac{0.5}{h}\right)\left(\frac{1+z}{4}\right)^3\frac{H_0}{H(z)}y_{HeII} \tag{13}$$

where $y_{HeII} = n_{HeII}/n_H$. The observations (Jakobsen et al. 1994; Tytler et al. 1995; Davidsen et al. 1996) and their interpretation (Shapiro 1995) allow to estimate
$\tau^{GP}_{HII} \sim 1$ at $z = 3.3$.

With the above parameters and saturating the bound for Ω_{IGM} the QSO+star model gives from Eq. 13 $y_{HeII} \simeq 1.7 \times 10^{-4}$ and, using the cosmological ratio between H and He, $\chi_{HeII} \simeq 2 \times 10^{-3}$. A similar prediction results from the addition of modified decaying neutrinos to QSOs. For QSOs alone the flux $J_{HI,-22} \sim 2$ at $z \sim 4$ would produce instead a larger fraction $\chi_{HeII} \simeq 3 \times 10^{-3}$.

For the standard QSO+sDDM alternative if one takes the averaged flux
$J_{HI,-22} \sim 30$ at $z = 4$, $T_4 \sim 1$ due to the lower temperature of homogeneous photoionization and the rest of parameters as required by the decaying neutrino model (Sciama 1990a) $\Omega = 1$, $H(z)/H_0 = (1+z)^{3/2}$, $h = 0.56$ (which would coincide with the measurement of Tammann et al. 1996 and Branch et al. 1996), from Eq. 12 it turns out $\Omega_{IGM} \leq \frac{2}{5}\Omega_B$. The saturation of this bound for Ω_{IGM} would be in agreement with the delayed formation of structures predicted by HDM which requires $\Omega_{IGM} \geq \frac{1}{3}\Omega_B$ (Williger et al. 1994). In this way one would obtain from Eq. 13 $y_{HeII} \simeq 0.9 \times 10^{-4}$ and $\chi_{HeII} \simeq 1.1 \times 10^{-3}$.

We now compare these results for IGM with those for LC of Table 2 using Eq. 10 from which

$$\frac{\chi_{HeII_{LC}}}{\chi_{HeII_{IGM}}} = \frac{n_{H_{LC}}}{n_{H_{IGM}}} \left(\frac{T_{IGM}}{T_{LC}}\right)^{3/4} \quad . \qquad (14)$$

Taking as average the properties of IGM at $z \sim 4$ it seems clear that the spectrum of QSOs alone is excluded because, since $n_{H_{IGM}} \sim 10^{-5}\,\Omega_{IGM}/\Omega_B\,\mathrm{cm}^{-3}$ (Madau & Meiksin 1994), inserting the rest of parameters in Eq. 14 the left-hand side is one order of magnitude smaller than the right-hand side. This conclusion is consistent with the fact that the UV spectrum must be softer than that of QSOs to agree with the estimations of GP as seen in Eq. 1.

With the QSO+star model the left-hand side of Eq. 14 increases because $\chi_{HeII_{IGM}}$ is smaller, and the right-hand side decreases because $n_{H_{IGM}}$ is larger so that the disagreement diminishes. A similar situation applies to the addition of modified decaying neutrinos to QSOs. One must note that this conclusion is independent of the chosen value of $h\,H(z)/H_0$ since both χ_{HeII} and n_H for IGM turn out to depend on the square root of it.

For the sQSO+sDDM alternative the comparison of both sides of Eq. 14 is reverted because, to the further modifications of χ_{HeII} and n_H for IGM, one must add its predicted smaller temperature so that the left-hand side becomes almost twice larger than the right-hand side. This indicates that S_L may be too large in this case.

It is interesting to note that for the QSO+star model the increase of S_L should improve the agreement of Eq. 14. In fact with our reduction of 50% of the flux due to QSOs which gives $S_L = 200$ at $z = 4$, χ_{HeII} for IGM increases in 100% because one would expect $\tau^{GP}_{HeII} \sim 2$. But looking at Eq. 9 χ_{HeII} for LC increases more because, apart from the influence of J_{HeII}, a smaller global flux decreases R and T giving a further enhancing factor. However the improvement is not fast for $S_L = 200$ as seen in Table 2.

We must note that the same procedure of using a weak QSO contribution cannot be applied to the modified decaying neutrino because, in doing so, one would obtain a ratio J_{HI}/J_{HeI} at $z = 2$ which would clearly exceed the bound of Eq. 3. Therefore the only way to improve the comparison of the QSO+wDDM model with homogeneous IGM would be to accept a decline of QSO contribution for $z > 3$ more marked that the generally estimated $exp[-0.69(z-3)]$ assumed here.

Apart from the modification of decaying neutrinos obtained diminishing slightly its mass, one could keep this value to allow NI ionization and increase its lifetime. Relaxing the condition that neutrinos ionize alone the HI in the Milky Way (Dodelson & Jubas 1994) one might assume the ν to be more stable in one order of magnitude $i.e.$ $\tau_\nu \sim 10^{24}$ s.

Several models for massive decaying neutrinos give the dependence of lifetime on mass and magnetic moment

$$\tau_\nu \simeq \left(\frac{29\,eV}{m_\nu}\right)^3 \left(\frac{10^{-14}\,\mu_B}{\mu}\right)^2 \; 0.8 \times 10^{23}\,s \qquad (15)$$

and in particular the minimal supersymmetric standard model with couplings which violate the R parity allows easily (Roulet & Tommasini 1991) $m_\nu \sim 29$ eV and
$\mu \sim 10^{-14}\,\mu_B$. To increase the lifetime to $\tau_\nu \sim 10^{24}$ s one must decrease slightly these coupling constants and, to keep the value of m_ν , correspondingly increase the scale of supersymmetric partners above 100 GeV. This is perfectly possible in the range of the theoretically admissible parameters.

The averaged DDM flux would be similar to that of the wDDM previously described so that again, added to that of sQSO model, the properties of LLS would be reproduced but the consistence between LC and IGM would be difficult because of not high enough S_L.

It seems that the most convenient shape of UV spectrum for a general agreement is one where the flux decreases gently between HI and HeI ionization frequencies and then drops abruptly towards the HeII edge. A modification of DDM that might give this result is to further increase τ_ν above 10^{24} s and simultaneously double the neutrino mass to allow the ionization of both HI and HeI, which would be admissible if $h > 0.74$ (Bradford & Hogan 1996), but since this implies a major change of the model we will not analyze in detail its consequences here.

Obviously all our discussion related to homogeneous IGM is based on assuming photoionization as seen in Eq. 12. Whereas for densities $n \sim 10^{-2} - 10^{-4}$ cm^{-3} collisional ionization is not important (Haardt & Madau 1995), it may be relevant in low density IGM if the temperature is higher than what assumed here. In this case the conclusions regarding UV sources would not apply to IGM.

5. Conclusions

Using a photoionization code for absorbers we have seen that the QSO+star model for UV sources is able to reproduce the bulk of properties of homogeneous IGM, LC and LLS, requiring that $S_L > 100$ at $z \sim 4$ in agreement with what emerges from recently observed metallicity abundance. For the comparison with IGM it would be crucial to determine its temperature with more precision. These same properties are not easily reconciled assuming the addition to QSOs of neutrinos of mass ~ 29 eV which would complete the critical Universe mass with only HDM. In fact if one takes the lifetime $\tau_\nu \simeq 2 \times 10^{23}$ s, there is a rough agreement between LC and IGM but properties of LLS are not reproduced. On the other hand if one reduces the neutrino mass to 27.6 eV or increases its lifetime in one order of magnitude, the LLS difficulty is solved but the matching of LC and IGM properties becomes questionable unless there is a very fast decline of QSOs for $z > 3$.

It is interesting that the original model of decaying neutrinos gives, through GP bounds, the large density of non-collapsed baryonic matter predicted by HDM. In the same way the QSO+star model is consistent with the scenario of CDM with cosmological constant $\Omega_\Lambda = 0.6$ convenient to explain the X-ray emitting intracluster gas, as well as old galaxies at large redshift (Krauss 1996), but in difficulty with recent measurement of the deceleration parameter (Dodelson et al. 1996). Therefore it seems that when GP effect and properties of absorbers will be better determined, the observed properties of the reionization of Universe will give definite hints, regarding the models which originated the structures, at a redshift intermediate between the one of recombination age and that of formation of bulk of galaxies.

Acknowledgements. We are deeply indebted to Prof. D.W. Sciama for comments related to modified decaying neutrinos. S.S. thanks heartily the hospitality at the Osservatorio Astronomico di Roma where part of this research was performed. L.M. acknowledges partial financial support from CONICET of Argentina through grant PID 339650092.

References

Bajtlik S., Duncan R.C. & Ostriker J.P., 1988, ApJ 327, 570
Bechtold J., 1994, ApJS 91, 1
Bradford E. & Hogan C., 1996, ASTRO-PH 960475, ApJ, in press
Branch D., Fischer A., Baron E. & Nugent P., 1996, ASTRO-PH 9604006
Davidsen A.F., Kriss G.A. & Zheng W., 1996, Nature 380, 47
Dinshaw N., Impey C.D., Foltz C.B., Weymann R.J. & Morris S.L., 1995, Nature 373, 223
Dodelson S. & Jubas J.M., 1994, MNRAS 266, 886
Dodelson S., Gates E.I. & Turner M.S., 1996, ASTRO-PH 9603081 (submitted to Science)
Ferland G.J., 1991, OSU Astronomy Dept. Internal Rept. 91-01
Freedman W.L., Madore B.F., Mould J.R., Hill R., Ferrarese L. et al.: 1994, Nature 371, 757
Giallongo E., D'Odorico S., Fontana A., McMahon R., Savaglio S. et al.: 1994, ApJ 425, L1
Giallongo E., Cristiani S., D'Odorico S., Fontana A. & Savaglio S., 1996, ApJ 466, 46
Giroux M.L., Sutherland R.S. & Shull J.M., 1996, ApJ 435, L97
Gunn J.E. & Peterson B.A., 1965, ApJ 142, 1633
Haardt F. & Madau P., 1996, ApJ 461, 20
Jakobsen P., Boksenberg A., Deharveng J.M., Greenfield P., Jedrzejewski R. et al.: 1994, Nature 370, 35
Krauss L.M., 1996, ASTRO-PH 9607103
Krauss L.M. & Turner M.S., 1995, J. Gen. Rel. Grav. 27, 1137
Lanzetta K.M., 1991, ApJ 375, 1
Lu L., Sargent W.L.W., Womble D.S. & Takada-Hidai M., 1996, ASTRO-PH 9606033, ApJ, in press
Madau P., 1992, ApJ 389, L1
Madau P. & Meiksin A., 1994, ApJ 433, L53
Meiksin A. & Madau P., 1993, ApJ 412, 34
Miralda-Escudé J. & Ostriker J.P., 1990, ApJ 350, 11
Miralda-Escudé J. & Ostriker J.P., 1992, ApJ 392, 15
Miralda-Escudé J. & Rees M.J., 1994, MNRAS 266, 343
Miralda-Escudé J., Cen R., Ostriker J.P. & Rauch M., 1995, ASTRO-PH 9511013
Pei Y.C., 1995, ApJ 438, 623
Reimers D. & Vogel S., 1993, A&A 276, L13
Reisenegger A. & Miralda-Escudé J., 1995, ApJ 449, 476
Riess A.G., Press W.H. & Kirschner R.P., 1995, ApJ 445, L91
Roulet E. & Tommasini D., 1991, Phys. Lett. B 256, 218
Savaglio S., Cristiani S., D'Odorico S., Fontana A., Giallongo E. et al.: 1996, ASTRO-PH 9606063, A&A, in press
Sciama D.W., 1990a, Phys. Rev. Lett. 65, 2839
Sciama D.W., 1990b, ApJ 364, 549
Sciama D.W., 1991, ApJ 367, L39
Sciama D.W., 1993, *Modern Cosmology and the Dark Matter problem* (Cambridge University Press)
Sciama D.W., 1994, ApJ 422, L49
Sciama D.W., 1995, ApJ 448, 667
Sethi S.K., 1995, ASTRO-PH 9507116
Shapiro P.R., 1995, *The physics of the interstellar medium and intergalactic medium* ASP Conference Series 80, 55
Smette A., Robertson J.G., Shaver P.A., Reimers D., Wisotzki L. et al.: 1995, A&AS 113, 199
Songaila A., Hu E.M. & Cowie L.L., 1995, Nature 375, 124
Spitzer L., 1978, *Physical processes in the interstellar medium* (John Wiley & Sons, New York).
Steidel C., 1990, ApJS 74, 37
Tammann G.A., Labhardt L., Federspiel M., Sandage A., Saha A. et al.: 1996, *Science with the Hubble Space Telescope*, Eds. P. Benvenuti, F.D. Macchetto & J. Schreier
Tanvir N.R., Shanks T., Ferguson H.C. & Robinson D.R.T., 1995, Nature 377, 27
Tytler D., Fan X.-M., Burles S., Cottrell L., David C. et al.: 1995, *Proceedings of the ESO Workshop on Quasars Absorption Lines*, Ed. G. Meylan (Springer, Heidelberg) p. 289
Williger G.M., Baldwin J.A., Carswell R.F., Cooke A.J., Hazard C. et al.: 1994, ApJ 428, 574
Zanchin V., Lima J.A.S. & Brandenberger R., 1996, ASTRO-PH 9607062

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.