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Could intergalactic dust obscure a neutrino decay signature?

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Abstract. Following recent results from the Super-Kamiokande experiment which indicate that neutrinos may have finite masses and provide at least part of the dark matter in the Universe, we re-examine the decaying neutrino hypothesis of Sciama, including for the first time the effects of absorption by intergalactic dust. We consider several dust models, including one designed to optimize ultraviolet extinction for a given dust-to-gas ratio. Dust absorption is insufficient to reconcile the theory with observational upper limits on the intensity of the diffuse ultraviolet background reported recently by Murthy et al. The theory remains marginally compatible with other diffuse background measurements.

Key words: cosmology: dark matter – cosmology: diffuse radiation – ISM: dust, extinction

1. Introduction

Cosmic ray showers as observed with the Super-Kamiokande observatory (Fukuda et al. 1998) have lent strong new support to the hypothesis of nonzero neutrino masses. While there is at present no consensus on the actual values of these masses (Valle 1998), various extensions of the standard model of particle physics imply τ neutrino rest masses (for instance) of order $m_\tau \sim$ 0.07 eV (Glashow et al. 1998), 4 eV (Foot 1998), and even 15–100 eV (Shi & Fuller 1999). This is of great interest for cosmology, since neutrinos near the upper end of this mass range could collectively provide enough hot dark matter to close the Universe (Gawiser & Silk 1998). The most direct connection between cosmology and particle physics is via background radiation, since massive dark matter particles will in general decay, adding photons to the intergalactic radiation field, about which we have good data in various wavebands. Specifically, in Sciama's theory neutrinos with rest masses of about 30 eV decay and contribute to the extragalactic background light (EBL) at ultraviolet wavelengths (see for review Sciama 1997). In a previous study (Overduin & Wesson 1997; hereafter "OW") we showed that the strength of this neutrino decay signal was at or near upper limits on EBL intensity, especially at far ultraviolet (FUV) wavelengths. We did not include the effects of absorption by *dust* in that study, since preliminary work indicated that this would be of little importance compared to absorption by neutral hydrogen. Recent developments, however, have prompted us to revisit this issue. In particular, it appears that intergalactic dust may consist of smaller particles than has usually been assumed in the past (Duley & Seahra 1998, Zubko et al. 1999, Weingartner & Draine 1999), and these would be more efficient at absorbing short-wavelength ultraviolet radiation. There are also tighter new *observational limits* on the intensity of the FUV EBL, based on a re-analysis of data from the Voyager spacecraft (Murthy et al. 1999, Henry 1999). Taken together, we believe that the Super-Kamiokande results, the change in thinking on dust, and the new observational data warrant a new look at the question of decaying neutrinos and the EBL. We will find that Sciama's theory appears inconsistent with the new Voyager numbers, but that other data do not rule it out.

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2. Contributions of neutrino decay to the EBL intensity

The spectral intensity of the neutrino decay signal at observed wavelength λ_0 (including the effects of extinction) is given by Eqs. (12) and (17) of OW:

$$I_\lambda(\lambda_0) = I_0 \int_0^{z_{\max}} \exp\Bigg[-\frac{1}{2}\left(\frac{\lambda_0/(1+z)-\lambda_\gamma}{\sigma}\right)^2 - \tau(\lambda_0,z)\Bigg]\,(1+z)^{-9/2}\,dz, \quad (1)$$

where z refers to redshift and we have assumed an Einstein-de Sitter cosmology, as befits the fact that neutrinos in Sciama's theory provide enough dark matter to close the Universe.

The parameters in Eq. (1) are given as follows: $z_{\max}$ is the redshift beyond which neutrino contributions to the observed EBL become negligible. It may be confirmed numerically (by evaluating the integral for various values of $z_{\max}$) that $z_{\max} \sim 1.4$ for the neutrinos and waveband of interest here; we take $z_{\max} = 2$ in our calculations. (The fact that the signal is dominated by nearby neutrino decays plays a crucial role in limiting the effects of obscuration by intergalactic dust, since the latter in most cases becomes important only at $z \sim 3$ and higher.) In Sciama's theory (Sciama 1997), each decay [of lifetime $(2\pm1)\times10^{23}$ s] produces a 14.4 ± 0.5 eV photon, implying a peak decay wavelength $\lambda_\gamma = 861$ Å. To this we associate a 3σ uncertainty of 30 Å (OW). The (redshifted) waveband of interest therefore stretches across the FUV region, from $\lambda_0 \approx 900$ Å to about 2000 Å.

The mean number density of ~ 30 eV neutrinos required to close the Universe is about 100 cm^{-3}; whereas the number density of neutrinos responsible for the ionization of the local interstellar medium in Sciama's theory is about 10^7 cm^{-3}. This implies that a significant fraction of the decaying neutrinos are bound in galactic halos. The integral (1) must therefore incorporate contributions from both bound and free-streaming neutrinos. Since we are concerned only with the total extragalactic background signal, however, the two components may be pulled out of the integral and absorbed into the constant I_0; ie, $I_0 = I_{\rm bound} + I_{\rm free}$. It turns out that $I_{\rm free}$ is much greater than $I_{\rm bound}$, partly because the free-streaming neutrinos are more numerous, and partly because many of the decay photons from bound neutrinos are absorbed within their host galaxies before they can contribute to the EBL. More detailed investigation (OW) leads to the expressions $I_{\rm bound} = (1.0\times10^{-8}{\rm erg\ cm^{-2}s^{-1}sr^{-1}Å^{-1}})h_0^2 f_{\rm h} f_\epsilon f_\tau^{-1}$ and $I_{\rm free} = (3.7\times10^{-7}{\rm erg\ cm^{-2}s^{-1}sr^{-1}Å^{-1}})h_0^{-1} f_{\rm f} f_\tau^{-1}$ respectively, where the f_i are factors reflecting various uncertainties in the model. In particular, $f_{\rm h} = 1.00\pm0.25$, $f_\epsilon = 1.00\pm0.04$, $f_\tau = 1.0\pm0.5$ and $f_{\rm f} = 1.00\pm0.08$ refer to the mass of galactic dark matter halos, the extent to which decay photons given off by bound neutrinos are absorbed by neutral hydrogen in their host galaxies, the neutrino decay lifetime, and the neutrino rest energy, respectively. We will allow these factors to take their upper and lower limits in order to arrive at minimum and maximum possible EBL contributions from neutrino decay. We also allow the Hubble parameter h_0 to vary within the narrow range 0.57 ± 0.02, consistent with a critical density in the context of Sciama's theory.

The total extinction $\tau(\lambda_0, z)$ also arises from two distinct sources: hydrogen gas ($\tau_{\rm gas}$) and dust ($\tau_{\rm dust}$) along the line of sight. The gas contribution is fairly well-understood. We take:

$$\tau_{\rm gas}(\lambda_0,z) = \begin{cases} \tau_0(\lambda_0/\lambda_{\rm L})^{3/2}\ln[(\lambda_{\rm L}/\lambda_0)(1+z)] & \text{if} \lambda_{\rm L} < \lambda_0 < \lambda_{\rm L}(1+z) \\ \tau_0(\lambda_0/\lambda_{\rm L})^{3/2}\ln(1+z) & \text{if} \lambda_0 \le \lambda_{\rm L} \\ 0 & \text{if} \lambda_0 \ge \lambda_{\rm L}(1+z), \end{cases} \qquad (2)$$

where $\lambda_{\rm L} = 912$ Å and $\tau_0 = 2.0$ (Zuo & Phinney 1993, Model 1, assuming $z_{\rm obs} = 0$).

A new feature of our analysis is $\tau_{\rm dust}$. Little is known about the distribution of dust between galaxies, and we proceed to discuss this critically before presenting our model. The simplest possibility, and the one which should be most effective in obscuring a diffuse signal like that considered here, would be for dust to be spread uniformly through intergalactic space. A quantitative estimate of opacity due to a proposed uniform dusty intergalactic medium has in fact been suggested (Ostriker & Cowie 1981), but is regarded as an extreme upper limit because it would lead to excessive reddening of quasar spectra (Wright 1981). Subsequent discussions have tended to treat intergalactic dust as clumpy (Ostriker & Heisler 1984), with significant debate about the extent to which such clumps would redden and/or hide background quasars, possibly helping to explain the "turnoff" in quasar population at around $z \sim 3$ (Wright 1986, Wright & Malkan 1987, Heisler & Ostriker 1988, Wright 1990). Most of these models assume a critical density of matter ($\Omega_0 = 1$) with no cosmological term ($\Omega_\Lambda = 0$). There is evidence that $\Omega_0 < 1$ and/or $\Omega_\Lambda > 0$ might enhance the effects of dust obscuration (Heisler & Ostriker 1988). We will ignore this possibility here, because neutrinos (not Λ) are assumed to make up the critical density in Sciama's theory.

3. Dust opacity model

We adopt a recent model for intergalactic extinction in which dust is clumped into damped Lyα absorption systems whose numbers and density profiles are sufficient to obscure a portion of the light reaching us from $z \sim 3$, but not to account fully for the turnoff in quasar population (Fall & Pei 1993; hereafter "FP"). The *mean* opacity at observed wavelength λ_0 due to these dusty clumps (out to redshift z) is:

$$\bar{\tau}_{\rm dust}(\lambda_0, z) = \int_0^z \frac{\tau_*(z')(1+z')}{(1+\Omega_0 z')^{1/2}}\,\xi\left(\frac{\lambda_0}{1+z'}\right)dz'. \qquad (3)$$

Here $\tau_*(z)$ is the comoving dust density in units of optical depth per Hubble radius and $\xi(\lambda)$ is the ratio of extinction at wavelength λ to that in the B-band (4400 Å). Earlier treatments (Ostriker & Cowie 1981, Ostriker & Heisler 1984) took $\tau_*(z)$ = constant and $\xi(\lambda) \propto \lambda^{-1}$, so that $\bar{\tau}_{dust}(\lambda_0, z) \propto \lambda_0^{-1}[(1+z)^3 - 1]$ or $\lambda_0^{-1}[(1+z)^{2.5} - 1]$, depending on cosmology. We follow the more sophisticated approach of FP, in which dust opacity depends on redshift:

$$\tau_*(z) = \tau_*(0)\,(1+z)^\delta, \qquad (4)$$

where $\tau_*(0)$ and δ are fixed by observational data on extinction due to hydrogen at $z = 0$ and (for damped Lyα systems) at $z = 2.4$, together with estimates of dust-to-gas ratios (see FP for discussion). The data are consistent with *lower limits* of $\tau_*(0) = 0.005$, $\delta = 0.275$ (model A), *best-fit values* of $\tau_*(0) = 0.016$, $\delta = 1.240$ (model B), or *upper limits* of $\tau_*(0) = 0.050$, $\delta = 2.063$ (model C), assuming a critical density $\Omega_0 = 1$.

To calculate the extinction $\xi(\lambda)$ in the 300–2000 Å range, we use numerical Mie scattering routines in conjunction with various interstellar dust models. In performing these calculations, we have tacitly assumed that intergalactic and interstellar dust are similar in nature, which is a reasonable assumption that is, of course, very difficult to test. Many people have constructed dust grain models that reproduce the average interstellar extinction curve for $\lambda > 912$ Å (as given by Mathis 1990, for example), but there have been far fewer studies of the optical properties of the diffuse interstellar medium (DISM) at shorter wavelengths. One such study is that of Martin & Rouleau (1991; hereafter "MR"). These authors extended the silicate/graphite grain synthetic extinction curves produced by Draine & Lee (1984) to photon

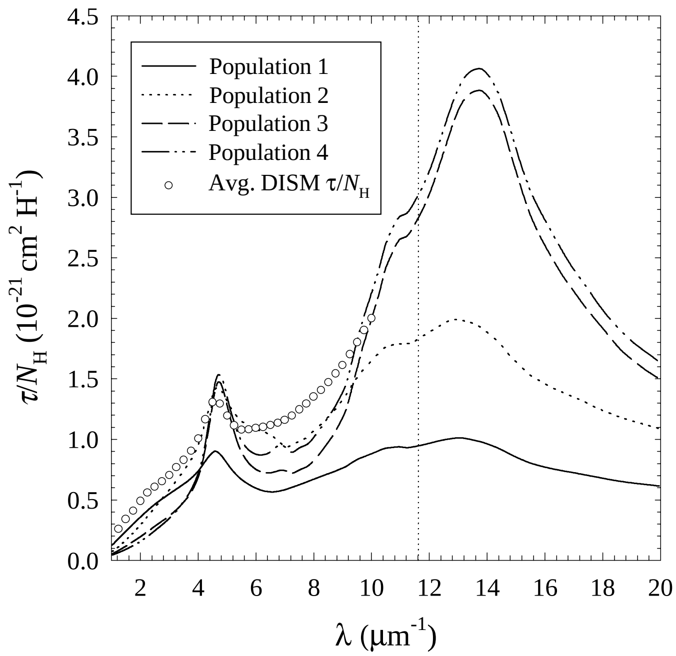

Fig. 1. The extinction produced by several different grain models in the visible, UV and FUV wavebands. See text for descriptions of populations 1 – 4. Also shown is the average interstellar extinction curve (open circles; Mathis 1990) and the location of the neutrino decay peak at 861 Å(vertical dotted line).

energies in excess of 100 eV. Like Draine & Lee, they assumed: (1) two populations of homogeneous spherical dust grains composed of graphite and silicates respectively; (2) a power law size distribution of the form $a^{-3.5}$ where a is the grain radius; (3) the range of grain radii is 50–2500 Å; and (4) an interstellar abundance of carbon and silicon relative to hydrogen that was the same as that for the Sun (as given by Meyer 1979). It has recently been discovered that the heavy element abundances in the DISM are significantly lower than the Solar values. For example, Snow & Witt (1996) report interstellar abundances of carbon and silicon to be 214×10^{-6}/H and 18.6×10^{-6}/H respectively. This represents a ∼50% reduction in the elemental abundances used by Draine & Lee and MR, which imposes a severe handicap on the simple silicate/graphite model's ability to reproduce the observed DISM extinction curve.

These difficulties have prompted us to perform fresh extinction calculations based on new grain models. Since we are primarily interested in obtaining the most conservative bounds possible on the neutrino decay hypothesis, we have attempted to find dust grain populations with optimal extinction efficiency in the neighborhood of 861 Å. In so doing, we *do not* aim to create a comprehensive new dust model, or to reproduce the average interstellar extinction curve to a high degree of accuracy over all wavelengths. However, the average characteristics of interstellar dust do provide reasonable constraints on intergalactic dust which we try to adhere to as closely as possible.

In the interests of simplicity, the materials used to comprise our grain populations are characterized by the graphite and "astronomical silicates" dielectric functions provided by Draine (1995). In calculating the extinction profiles of spherical graphite particles, we employ the 1/3–2/3 approximation discussed in Draine & Malhotra (1993). Due to the lack of standard dielectric functions in the FUV we do not consider contributions due to amorphous carbon (AC), hydrogenated amorphous carbon (HAC), glassy carbons or other materials. We first considered a grain model identical to that of MR as a test of our code. We successfully reproduced the shape of their extinction curves, although the absolute intensity of our results somewhat weaker (presumably due to differences in the new dielectric functions). Having satisfied ourselves with the functionality the Mie scattering algorithm, we then calculated the extinction due to the same grain model, but now with the DISM abundances given by Snow & Witt (1996) and the maximum possible depletions of C and Si from the gas phase. The results of this calculation are plotted in Fig. 1 as the continuous solid line (population 1). We have also plotted the average interstellar extinction curve (open circles; Mathis 1990) for reference, along with the position of the neutrino decay peak (the vertical dotted line). The inadequacies of the old dust model are apparent from this figure; while the shape of the average curve is well approximated, the magnitude of the synthetic extinction is far too low. The amount of extinction in the vicinity of the neutrino decay peak is also relatively weak (the largest FUV extinction is $\tau_{\rm peak} \sim 0.9 \times 10^{-21}{\rm cm}^2{\rm H}^{-1}$), making this grain model a rather poor mechanism for hiding excess EBL intensity.

It has recently been suggested that the heavy element abundance crisis in the DISM might be resolved by the presence of "fluffy" grains (Mathis 1996). In these models, the bare silicate grains are replaced with composite grains consisting of silicates and carbonaceous materials like AC or HAC with a high porousity or void fraction. By suitable variation of the model parameters, very good fits to the average interstellar curve are possible. To study the extinction characteristics of such model in the FUV, we modify the previous population by replacing the ordinary silicate grains by silicate grains with a 45% void fraction as in Mathis (1996). The dielectric function of fluffy silicates is obtained using the Bruggmann effective medium approximation (Bohren & Huffmann 1983, Eq. 8.51). We have also modified the size distribution of the graphite grains to include only small particles (a = 50–250 Å) and decreased the carbon depletion to 60% to better match the average curve. Following Dwek (1997), we assume a Si abundance of 32.5×10^{-6}/H for this population alone. The result is the dotted (population 2) curve of Fig. 1. This grain population has much better success in matching the shape of the average curve and shows significantly more FUV extinction than population 1 ($\tau_{\rm peak} \sim 2.0 \times 10^{-21}{\rm cm}^2{\rm H}^{-1}$). The fit to the average curve would be improved by the inclusion of AC in the fluffy grains.

It has also been recently suggested that the carrier of the 2175 Å absorption bump is not a population of spherical graphite particles with radii ∼50 Å, but rather polycyclic aromatic hydrocarbon (PAH) nanoparticles. These structures are thought to be consist of stacks of PAH-like molecules resembling coronene, circumcoronene and larger species in various states of edge hydrogenation. There are several attractive prop-

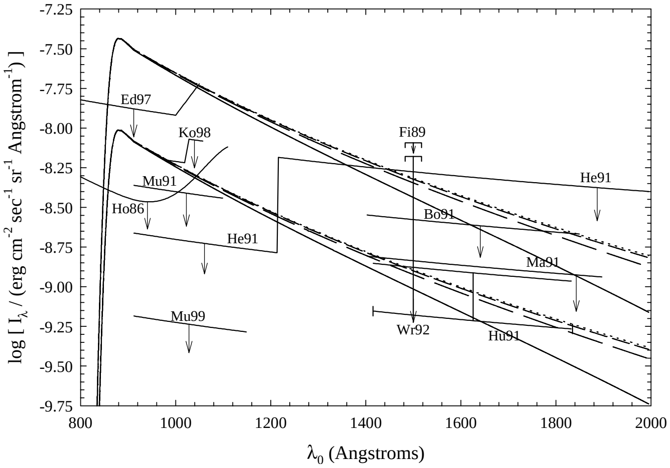

Fig. 2. Comparison of predicted strength of a neutrino decay signal (heavy solid, dashed and dotted lines) with observational upper limits on the intensity of the FUV EBL (labelled lines), assuming dust grains of standard size. The two sets of predicted curves correspond to upper and lower limits, obtained by adjusting the free parameters of Sciama's theory to their minimum and maximum values, as appropriate.

erties of this model, including a very good fit to the 2175 Å feature shape and position (Duley & Seahra 1998) and an explanation of the unidentified infrared emission (UIR) bands detected in the DISM at 3.4–25 μm (Dwek 1997, Seahra & Duley, in prep.). Also, PAH nanoparticles could be responsible for the extended red emission (ERE) observed in nebular environments (Seahra & Duley 1999) and 3.4 μm infrared absorption in in the DISM (Duley & Seahra, in prep.). Now, these particles have sizes of ∼7–30 Å, much smaller than the canonical graphite grain populations. However, as discussed in Duley & Seahra (1998), the dielectric function of PAHs should be similar to that of graphite with the major difference coming from the free π-electron characteristics of each material. In the $\omega \to \infty$ limit, the two dielectric functions merge (see Fig. 1 of Duley & Seahra 1998). So as a first approximation to the extinction curves produced by nanoparticle populations, we use spherical graphite particle populations with very small radii. A truly rigorous calculation would use the discrete dipole array (DDA) formalism of Draine (1988), but this is computationally expensive at FUV wavelengths.

We treat the bounds on the power-law size distribution of the PAH nanostructures as variable parameters in order to maximize the FUV extinction. We find the optimal extinction in the neighborhood of the neutrino decay peak is achieved for a PAH population with radii ranging from 3–150 Å. On Fig. 1, the dashed line (population 3) reflects the extinction produced by such a PAH nanoparticle population with a silicate population identical to that of population 1. The dash-dot-dot-dashed line on Fig. 1 (population 4) represents the same nanoparticle population with a "fluffy" silicate population identical to that of population 3 except for a 45% porousity. Both populations 3 and 4 give poor fits to the average interstellar curve, as expected since the Mie scattering formalism is not expected to reproduce the behaviour of the nanoparticles near the 2175 Å resonance. Also, the lack of opaque materials such as AC reduces the synthetic extinction in the visible and near UV part of the spectrum. However, in the FUV region, we see a doubling in the magnitude of the extinction peak at ∼14 μm^{-1} compared to that of population 2 ($\tau_{\rm peak} \sim 4.1 \times 10^{-21} {\rm cm}^2 {\rm H}^{-1}$). Evidently, the small particles are much more efficient at extinguishing light at shorter wavelengths. This is partly the reason that there is little difference between populations 3 and 4; the extinction curves are dominated by small particle contributions, so the void fraction of the silicates does not have a large effect.

Fig. 1 shows that population 1 and population 3 (or 4) dust models lead to lower and upper limits respectively on dust extinction in the FUV waveband. We therefore use these populations to obtain conservative constraints on the decaying neutrino hypothesis (regardless of the fact that they do not produce a perfect fit to the average extinction curve). We do not consider possible secondary scattering of photons back *into* the line of sight. This is a comparatively small effect at the wavelengths of interest here (Martin & Rouleau 1991). Moreover, neglect of this factor can only enhance the overall dust opacity along the line of sight, strengthening our conclusions further.

4. Comparison with observation

To begin with we adopt the population 1 dust grains, identical to those considered in MR, and the new abundance numbers of Snow & Witt (1996). Inserting $\xi(\lambda) = \tau(\lambda)/\tau_{\rm B}$ into Eq. (3), and substituting this into the intensity integral (1) along with the gas extinction (2), we obtain the results shown in Fig. 2 (after OW). In this plot the dashed, long-dashed and heavy solid lines are predicted intensities of the EBL due to decaying neutrinos (after absorption by gas and dust) for dust opacity models A, B and C respectively. There are two groups of lines; these have been obtained by letting the model parameters and theoretical uncertainties in Sect. 2 take their maximum and minimum possible values, as appropriate. The faint dotted line is included for comparison purposes and illustrates the effects of ignoring dust (absorption by hydrogen gas only). The remaining curves (labelled) are observational upper limits on EBL intensity in this waveband reported by Bowyer (1991; "Bo91"), Edelstein et al. (1997; "Ed97"), Fix et al. (1989; "Fi89"), Henry (1991; "He91"), Holberg (1986; "Ho86"), Hurwitz et al. (1991; "Hu91"), Korpela & Bowyer (1998; "Ko98"), Martin et al. (1991; "Ma91"), Murthy et al. (1991; "Mu91"), Murthy et al. (1999; "Mu99") and Wright (1992; "Wr92"). Most of these limits have been discussed in OW. The curve marked "Ed97" has come down somewhat from that based on preliminary data (OW, "Ed96"), however. And one important new limit has been included: that of Murthy et al. (1999), who have re-analyzed the data from Voyager and now find a 1σ upper limit of 30 continuum units (photons cm^{-2} s^{-1} sr^{-1} Å^{-1}) over the waveband 912–1150 Å. This is by far the strongest limit yet reported on the intensity of the EBL at FUV wavelengths (see Henry 1999 for discussion).

Several things can be noted about Fig. 2. Firstly, the overall picture has not changed significantly from that described in OW, despite the inclusion of dust extinction. This is particu-

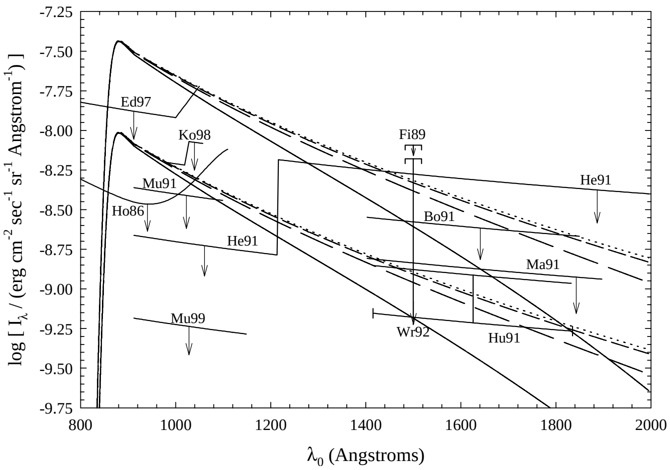

Fig. 3. Comparison of predicted strength of a neutrino decay signal (heavy solid, dashed and dotted lines) with observational upper limits on the intensity of the FUV EBL (labelled lines), assuming nanoparticle-sized dust grains. The two sets of predicted curves correspond to upper and lower limits, obtained by adjusting the free parameters of Sciama's theory to their minimum and maximum values, as appropriate.

larly true for dust models A and B, the lower limit and best-fit models. For model C, which represents an upper limit on the amount of dust compatible with observation (FP), the neutrino decay signal is noticeably reduced at wavelengths longward of 1216 Å. Constraints on the theory in this region were already weak, however, in comparison to those at shorter wavelengths (OW). Constraints shortward of Lyα are hardly affected at all by dust, essentially because dust extinction only becomes important at large redshifts: $z > 10$ for model A, $z \sim 5$ for model B, and $z \sim 2$ for model C.

Next, we move to the population 3 dust grains, with very small radii [as an approximation to the nanoparticle populations discussed by Duley & Seahra (1998)]. This model, with its strong FUV extinction, is able to hide a good deal more of the neutrino decay signal and should thus lead to the most conservative constraints on Sciama's model. Inserting $\xi(\lambda) = \tau(\lambda)/\tau_{\rm B}$ into Eq. (3), and substituting this into the intensity integral (1) along with the gas extinction (2), we obtain the results shown in Fig. 3. The format of this figure is exactly the same as that of Fig. 2 (see description above). As expected, reductions in EBL intensity are significant. Longward of Lyα, in particular, we find that the strength of the neutrino decay signal is cut (at 1600 Å) by 4%, 17% and 56% for dust models A,B and C respectively. At these wavelengths, we therefore approach the factor-two reduction in intensity attributed to dust extinction by Sciama (1992) – *if* one adopts the upper limits on dust density consistent with quasar obscuration (FP, model C), and *if* the dust grains are extremely small.

Shortward of 1216 Å, the neutrino decay signal is cut (at 1000 Å) by only 1%, 3% and 10% respectively. This is not enough to alter the findings in OW. As before, *our ability to rule out Sciama's hypothesis stands or falls on the validity of the Voyager limits*. The new limit derived by Murthy et al. (1999),

Table 1. Lower limits on neutrino lifetime ($\times 10^{23}$ s), with extinction due to dust grains of standard size (population 1)

Model A	Model B	Model C	Ref. (Fig. 2)
29.1±8.8	28.8±9.0	28.0±9.5	Mu99
8.3±3.1	8.2±3.1	8.0±3.3	He91(<Lyα)
4.7±3.1	4.6±3.1	4.6±3.1	Ho86
4.6±1.1	4.5±1.2	4.4±1.2	Mu91
2.4±0.7	2.4±0.7	2.3±0.7	Ko98
2.5±0.9	2.3±0.9	1.8±0.9	Hu91
2.2±0.9	2.1±0.9	1.6±1.0	Ma91
1.5±0.7	1.5±0.7	1.4±0.7	Ed97
1.3±0.5	1.2±0.5	0.9±0.5	Bo91
0.8±0.5	0.8±0.5	0.6±0.5	He91(>Lyα)

Table 2. Lower limits on neutrino lifetime ($\times 10^{23}$ s), with extinction due to very small dust grains (population 3)

Model A	Model B	Model C	Ref. (Fig. 3)
28.9±8.9	28.3±9.2	26.4±10.2	Mu99
8.3±3.1	8.1±3.2	7.5±3.5	He91(<Lyα)
4.6±3.1	4.6±3.1	4.5±3.2	Ho86
4.5±1.1	4.5±1.2	4.2±1.3	Mu91
2.4±0.7	2.3±0.7	2.2±0.7	Ko98
2.4±0.9	2.1±0.9	1.2±0.8	Hu91
2.2±0.9	1.9±0.9	1.1±0.8	Ma91
1.5±0.7	1.4±0.7	1.4±0.7	Ed97
1.2±0.5	1.1±0.5	0.6±0.4	Bo91
0.8±0.5	0.7±0.5	0.5±0.5	He91(>Lyα)

in particular, is crucial – if valid, it is more than an order of magnitude below the minimum intensity consistent with the theory. The only non-Voyager data in this region (Korpela et al. 1998) remains marginally consistent with the theory. New observations by the EURD instrument aboard Spain's MINISAT 01 satellite (Bowyer et al. 1999) could help settle the issue decisively.

By comparing the minimum predicted intensities in Figs. 2 and 3 to the observational upper limits, one can obtain constraints on the neutrino decay lifetime. Results are summarized in Table 1 (for standard grain sizes, 50–2500 Å) and Table 2 (for the nanoparticle-sized grains, 3–150 Å). These figures – especially the ones in Table 2 – are conservative lower limits, and may be compared with the neutrino decay lifetime of $(2 \pm 1) \times 10^{23}$ s required in Sciama's theory (Sciama 1997). Tables 1 and 2 confirm that the strongest constraints come from the new limit of Murthy et al. (1999). This is inconsistent with the decaying neutrino hypothesis, even assuming the most conservative dust model (C) and the smallest possible dust grains (population 3). The other limits, however, do not rule out the theory under these assumptions. Assuming the best-fit (B) or least conservative model (A), the theory is inconsistent with three of the Voyager-based limits (Mu99,He91 below Lyα, and Mu91), but remains compatible with the other data (for both standard and small sized dust grains).

5. Conclusions

Motivated by recent results from the Super-Kamiokande experiment which indicate that neutrinos may have finite masses and provide at least part of the dark matter in the Universe, we have re-examined the decaying neutrino hypothesis of Sciama, including for the first time the effects of absorption by intergalactic dust. Earlier constraints have been weakened, especially in the case of very small dust grains (for which there is independent evidence). However, this is not enough to alter the conclusion that the model is only marginally consistent with observational data. The strongest constraints come from a new analysis of Voyager data by Murthy et al. (1999), which appear to rule out the theory, but ideally should be confirmed by further experiments. At best, Sciama's theory suggests that dust grains may be considerably smaller than has so far been assumed in most studies, and that their collective density is at the upper end of the range suggested by reddening and obscuration of quasars. At worst, the theory with more conventional dust data is incompatible with observation.

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