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# DIFFUSE BACKGROUND RADIATION

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## ABSTRACT

A new determination of the upper limit to the cosmic diffuse background radiation, at ∼110 nm, of 300 photons $s^{-1}$ $cm^{-2}$ $sr^{-1}$ $nm^{-1}$ is placed in the context of diffuse background measurements across the entire electromagnetic spectrum, including new optical, infrared, visible, and gamma-ray background measurements. The possibility that observed excess diffuse *visible* radiation is due to redshifted cosmological Ly$\alpha$ recombination radiation is explored. Also, a new standard of units for the display of spectra is advocated.

*Subject headings:* cosmology: observations — diffuse radiation — methods: data analysis

## 1. INTRODUCTION

We have recently reported (Murthy et al. 1999) a new and sharply lower value for the upper limit to the background radiation from the universe at ∼110 nm. Here I place our new measurement in the context of diffuse background measurements that have been made at *all* frequencies from radio to gamma ray and, in this way, bring out the potential significance of the new measurement. I also gather other new diffuse background measurements that have been reported recently in the microwave, in the far-infrared, in the visible, and in the gamma-ray spectral regions. The visible background, in particular, may be directly related in its origin to a mechanism that is strongly suggested by our new ultraviolet background upper limit.

Display of the broad spectrum of the cosmic background radiation apparently began with Longair & Sunyaev (1969), who unfortunately chose a display method (the plotting of log $I_\nu$, with $I_\nu$ expressed in units of ergs $s^{-1}$ $cm^{-2}$ $sr^{-1}$ $Hz^{-1}$) that exaggerates the importance, in terms of energy per decade of frequency, of the radio background (compared with the gamma-ray background) by a factor of as much as $10^{17}$. This inferior method of plotting was also used by Henry (1991), and a similar plot appears as Figure 5.5 of Kolb & Turner (1990, p. 143), which is taken from the comprehensive review by Ressell & Turner (1990).

If one is interested in *energy content*, the most meaningful units in which to display the spectrum of diffuse radiation are, remarkably enough, photons $s^{-1}$ $cm^{-2}$ $sr^{-1}$ $nm^{-1}$. If there is an *equal* amount of energy present in every logarithmic interval of frequency, then these units have the virtue of assuming a *constant* value, which I will now demonstrate.

For clarity, I omit "$cm^{-2}$ $s^{-1}$ $sr^{-1}$" from the units. I use constants $h = 6.6261 \times 10^{-27}$ ergs s and $c = 2.9979 \times 10^{10}$ cm $s^{-1}$. If we have $N$ photons $nm^{-1}$, then in a 1 nm passband, we have $(Nhc/\lambda_{nm})\,10^{-7}$ ergs. But $\Delta\nu_{Hz} = (-c/\lambda_{nm}^2 10^{-7}) \times \Delta\lambda_{nm}$. So $N$ photons $nm^{-1}$ corresponds to $Nh\lambda_{nm}$ ergs $Hz^{-1}$ = $Nhc/(\nu 10^{-7})$ ergs $Hz^{-1} \equiv I_\nu$ ergs $Hz^{-1}$ = $N\,(1.9864 \times 10^{-9})$ ergs $Hz^{-1}/\nu \simeq N/(5 \times 10^8)$ ergs $Hz^{-1}/\nu$. If $N$ is independent of frequency (a flat spectrum), then

$$\int_\nu^{b\nu} N \text{ photons nm}^{-1}\, d\nu = \int_\nu^{b\nu} \frac{Nhc}{\nu 10^{-7}} \text{ ergs Hz}^{-1}\, d\nu$$
$$= \frac{Nhc}{10^{-7}} \ln b \text{ ergs}.$$

This demonstrates that, whatever the frequency from which we integrate, as long as we integrate over a specified factor $b$ in frequency, we will obtain the same amount of energy. Note that it does not matter what you plot your value *against*—constant is constant. It would be most consistent to plot your values against the natural logarithm of the frequency; however, in Figure 1, logarithms to base 10 are used. If you wish the *area of paper* on your graph to be proportional to energy, you must create a plot that is *linear* in the proposed units, against the logarithm of the frequency (or energy).

It was recognized during the 1960s that some truer method than the plotting of $I_\nu$ is needed for the display of spectra. The method adopted, however, was *not* the use of the presently advocated units; instead, it was in effect reasoned that, if the spectrum is $N$ photons $nm^{-1}$, then $I_\nu = Nhc/\nu 10^{-7}$ ergs $Hz^{-1}$, and if $N$ is independent of $\nu$ (meaning, as we see above, constant energy per decade), then $\nu I_\nu = Nhc/10^{-7}$ ergs is independent of $\nu$: so one should plot *that*, because it is *flat*! Gehrels (1997) points to many recent references that employ such plots, showing that the use of plots of $\nu I_\nu$ may be on its way to becoming an unfortunate new standard. Clearly, instead, one should simply plot $N$ photons $nm^{-1}$ (or, in full, $N$ photons $s^{-1}$ $cm^{-2}$ $sr^{-1}$ $nm^{-1}$), which I do, in Figure 1, for the background radiation spectrum of the universe.

This plotting method has the great advantage that what is plotted is the detected "quantity," "per passband" (i.e., it is a *spectrum*), whereas $\nu I_\nu$ is simply energy. Note that the first and last parts of the last equation can be written as

$$\int_\nu^{b\nu} N \text{ photons nm}^{-1}\, d\nu = \nu I_\nu \times \ln b \text{ ergs},$$

and note the presence, on the right-hand side, of the factor ln $b$. It has been emphasized by Gehrels (1997) that *none* of those who use the increasingly ubiquitous plots of $\nu I_\nu$ (vs. "whatever") include that factor, which is therefore unity by implication, and so the "constant quantity" that is plotted is energy *per natural logarithmic frequency*, again by implication. Gehrels points out that, frequently, authors incorrectly state in such papers that what is plotted is energy per decade or energy per octave. Gehrels also points out that the integration of $\nu I_\nu$ is tricky, which is hardly surprising, considering that it is an already integrated quantity itself. Now, *none* of these considerations are present if, instead, what is plotted is what I have

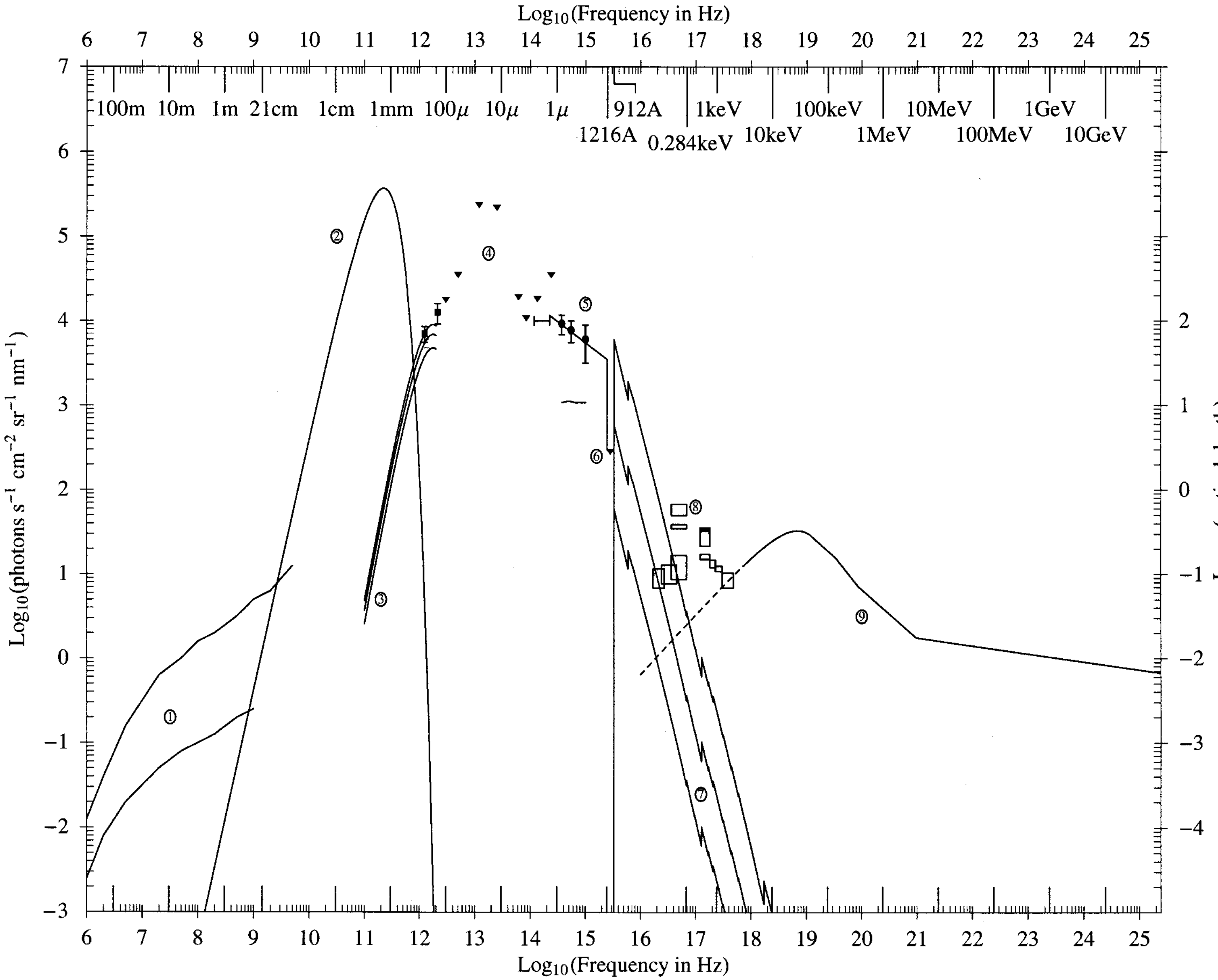


FIG. 1.—The background radiation spectrum of the universe: (1) radio, (2) cosmic microwave background, (3) FIRAS excess (Fixen et al. 1998), (4) DIRBE background (*points with error bars*) and DIRBE upper limits (Hauser et al. 1998), (5) optical background (Bernstein 1998), (6) ultraviolet background (Murthy et al. 1999; Henry & Murthy 1994; Henry 1991), (7) the interstellar medium photoionization optical depth (*right-hand scale*) for $10^{19}$, $10^{18}$, and $10^{17}$ H atoms $cm^{-2}$, (8) soft X-ray background, and (9) high-energy background. In this diagram, an equal plotted value means an equal amount of energy per logarithmic interval of frequency. The new *Voyager* upper limit between 912 and 1216 Å of Murthy et al. (1999) suggests that the transition from the high background in the visible to the low background in the X-ray may occur at 1216 Å, which in turn would suggest that the ultraviolet and visible background at high galactic latitudes is redshifted Ly$\alpha$ recombination radiation.

*advocated* be plotted, namely, the integrand in the first part of the last equation. In view of its many defects, the use of $\nu I_\nu$ should be permanently abandoned.

None of what I say should be taken to suggest that it is not *sometimes* appropriate to plot diffuse background (or other) spectra in other units. Mather et al. (1990) display the 2.7 K background spectrum in units that, entirely appropriately, exaggerate the highest energy part of the spectrum, which is where they made their brilliant measurements. Figure 6.2 of Peebles (1993, p. 133) offers a complementary example of constructive display.

## 2. THE BACKGROUND SPECTRUM

I have assembled the background radiation spectrum of the universe in Figure 1. The various contributions are discussed as follows:

*Radio background*.—The radio background spectra shown are from the Galactic pole and the Galactic plane, from Allen (1973). The curvature of the spectra is due (Yates & Wielebinski 1967) to free-free absorption of the synchrotron radiation by the partially ionized Galactic disk.

*Microwave background*.—The microwave background is shown for a temperature of 2.714 K (Fixen et al. 1994).

*FIRAS excess*.—The spectrum (Fixsen et al. 1998), with a $\pm 1\ \sigma$ error range, of the extragalactic microwave background in excess of the 2.714 K blackbody background is shown. This represents a major discovery, comprising as it does about 20% of the total intensity expected from the energy release from nucleosynthesis throughout the history of the universe.

*Infrared* (*DIRBE*).—I present the infrared background (detections at 140 and 240 $\mu$m are shown with error bars; the other points are all upper limits) of Hauser et al. (1998). The two highest upper limits are at 25 and 60 $\mu$m, where the interplanetary dust is brightest. As just mentioned, these positive detections represent a major discovery for cosmology. The fact that these DIRBE detections, and the FIRAS detections previously mentioned, are in agreement is of course very satisfactory.

*Optical background*.—The optical background as evaluated by Bernstein (1998) is shown as filled circles with error bars. Bernstein points out that the level she finds is "at least a factor 2 or 3" above the Hubble Deep Field–integrated brightness of galaxies, which is shown in Figure 1 as the line below Bernstein's points. Populations of galaxies entirely below the surface brightness threshold may be ruled out as the explanation for the excess radiation by the important finding of Vogeley (1997) that the background of the Hubble Deep Field is smooth and cannot be made up of the integrated light of fainter galaxies. The thin solid line through Bernstein's observational points is the extrapolation of the ultraviolet background radiation to longer wavelengths, as we discuss next.

*Ultraviolet background*.—The ultraviolet background radiation has been reviewed by Henry (1991), and a figure giving the detailed spectral observations appears in Henry & Murthy (1994). The new *Voyager* upper limit by Murthy et al. (1999) of 300 photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$ nm$^{-1}$ is shown in our Figure 1 as a filled triangle, joined to the ultraviolet observations longward of Ly$\alpha$ by a vertical line at 121.6 nm. The ultraviolet observations longward of Ly$\alpha$ (Henry & Murthy 1994) are summarized here simply by a solid line. That line is the model of Henry & Murthy (1994), which is the spectrum of redshifted Ly$\alpha$ recombination radiation from ionized intergalactic clouds. These clouds must be substantially clumped, and their ionization must be maintained by unknown means (although the suggestion by Sciama 1997 that neutrinos decay with the emission of an ionizing photon would do the job). The horizontal "error bar" at $\sim 10^{14}$ Hz is identified by Gnedin & Ostriker (1997) as the redshifted L$\alpha$ frequency interval ($z$ = 10–20) where maximum Ly$\alpha$ emission is expected because of the reheating (leading to the reionization) of the universe.

*Extreme-ultraviolet: optical depth*.—In the extreme ultraviolet, the interstellar medium is very opaque, and instead of showing the observed background, which is entirely local, I choose to show (right-hand scale in Fig. 1) the logarithm of the photoionization optical depth (for hydrogen columns of $10^{19}$ cm$^{-2}$, $10^{18}$ cm$^{-2}$, and $10^{17}$ cm$^{-2}$), obtained using the cross sections of Morrison & McCammon (1983).

*Soft X-ray background*.—The soft X-ray background has been reviewed by McCammon & Sanders (1990); their reports of the measurements are shown as the seven small boxes that are at the lowest intensities. The width of each box has no meaning, while the height of each box is the *range* of observed values, from low to high Galactic latitudes (excluding special regions).

Above these seven boxes, the earliest observations of the soft X-ray background are plotted. The highest box is that of Bowyer, Field, & Mack (1968) showing their extrapolation to extragalactic intensity, which, they stated, may reasonably be interpreted as a continuation of the background spectrum already observed above 1 keV. The observed intensity of Henry et al. (1968) is below their box, and they correctly identified it as a new component of X-ray emission, but they incorrectly attributed it to emission from intergalactic gas. The observation (*very small filled box*) of Henry et al. (1971) is at slightly higher energy: the emission was again attributed to emission from intergalactic gas, this time, perhaps, correctly (Wang & McCray 1993). The box contiguous below is the confirming observation of Davidsen et al. (1972), which is in reasonable agreement with that reported by McCammon & Sanders (1990).

*High-energy background*.—From log $\nu$ = 18, I plot the X-ray background spectrum of Boldt (1987), in addition extrapolating his spectrum to longer wavelengths (*dashed line*) in order to make clear just how *extraordinary* is the excess, which was first recognized by Henry et al. (1968), that occurs in the soft X-ray region. Superposed on Boldt's spectrum, and extending to higher energy, is the fit to the data of Gruber that is quoted by Fabian & Barcons (1992). Finally, above log $\nu$ = 19.6, I have plotted the high-energy background data and upper limits that are presented by Sreekumar et al. (1998); the famous "MeV bump" (Fichtel, Simpson, & Thompson 1978) has now vanished.

## 3. DISCUSSION

A virtue of having the entire background radiation spectrum of the universe presented in a single diagram, in units that allow comparison of relative energy content, is that the parts may be seen in relation to the whole and that possible connections may be examined. The X-ray background that was discovered by Giacconi et al. (1962) has very slowly been revealed as largely due to the integrated radiation of faint point sources (Ueda et al. 1998). The background below $10^{18}$ Hz is clearly of independent origin. Henry et al. (1968) failed to focus on the most important aspect of their observation, the detection of strong soft X-ray emission at *low* Galactic latitudes. That no such radiation existed was sufficiently strongly believed, at that time, that Bowyer et al. (1968) subtracted out all of their low-latitude signal as particle contamination.

The main focus of the present Letter is the relation of the soft X-ray background to the ultraviolet and visible backgrounds. Note the very large jump in background intensity from $10^{17}$ to $10^{15}$ Hz. Where exactly this jump occurs is unclear, but the fact that our observed intensity between 91.2 and 121.6 nm is only an upper limit may be revealing. The sharp jump at precisely 121.6 nm is clearly extremely important if real, as we believe it to be.

## 4. CONCLUSION

I conclude that a new possible origin for the diffuse visible background has been identified, the extension of the observed ultraviolet background. A new upper limit to the background shortward of 121.6 nm reveals the ultraviolet (and visible) backgrounds to be *perhaps* redshifted Ly$\alpha$ recombination radiation from an ionized intergalactic medium. If this is so, additional support is provided for the idea of Sciama (1997) that much of the nonbaryonic dark matter is massive neutrinos that decay with the emission of an ionizing photon. While intriguing, none of these ideas can be accepted as facts yet; a definitive measurement of the diffuse ultraviolet background radiation spectrum is called for before any secure conclusions can be adopted.

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