

EXTRAGALACTIC ULTRAVIOLET BACKGROUND RADIATION

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Abstract. We describe observations of the cosmic background in the far ultraviolet. If the Voyager upper limit on the cosmic diffuse ultraviolet background at 1100 Å at some locations is accepted as correct, the spectrum of the high-galactic latitude background is most remarkable, featuring an abrupt rise at about 1216 Å. Such a rise suggests an origin in redshifted Lyman α recombination radiation, but that explanation requires the existence of an ionization source such as the radiative decay of massive neutrinos to maintain the ionization. We therefore explore a more conservative origin in the scattered light of galactic plane OB stars. This explanation is fraught with difficulties: a dust population specially invented for the purpose seems to be required. This *ad hoc* explanation may be preferred by some; a perhaps somewhat exotic extragalactic origin by others. Quite simple additional observations should clarify matters considerably.

1. INTRODUCTION

The subject of our paper is the *extragalactic* far ultraviolet background radiation. We start, therefore, by describing the observations at high galactic latitudes; and we also start by simply *assuming* that the observed signals are extragalactic in origin. Having explored various possible origins, in relation to the observations, we then consider the observations at lower galactic latitudes; at this point we examine carefully whether the high-latitude observations themselves might be galactic in origin, rather than extragalactic. Finally, we summarize our conclusions.

2. THE ULTRAVIOLET BACKGROUND AT HIGH LATITUDE

The observations of the diffuse ultraviolet background at high galactic latitudes are collected in Figure 1. The figure caption contains references to the sources of the various observations. We will, for now, assume that this radiation is extragalactic.

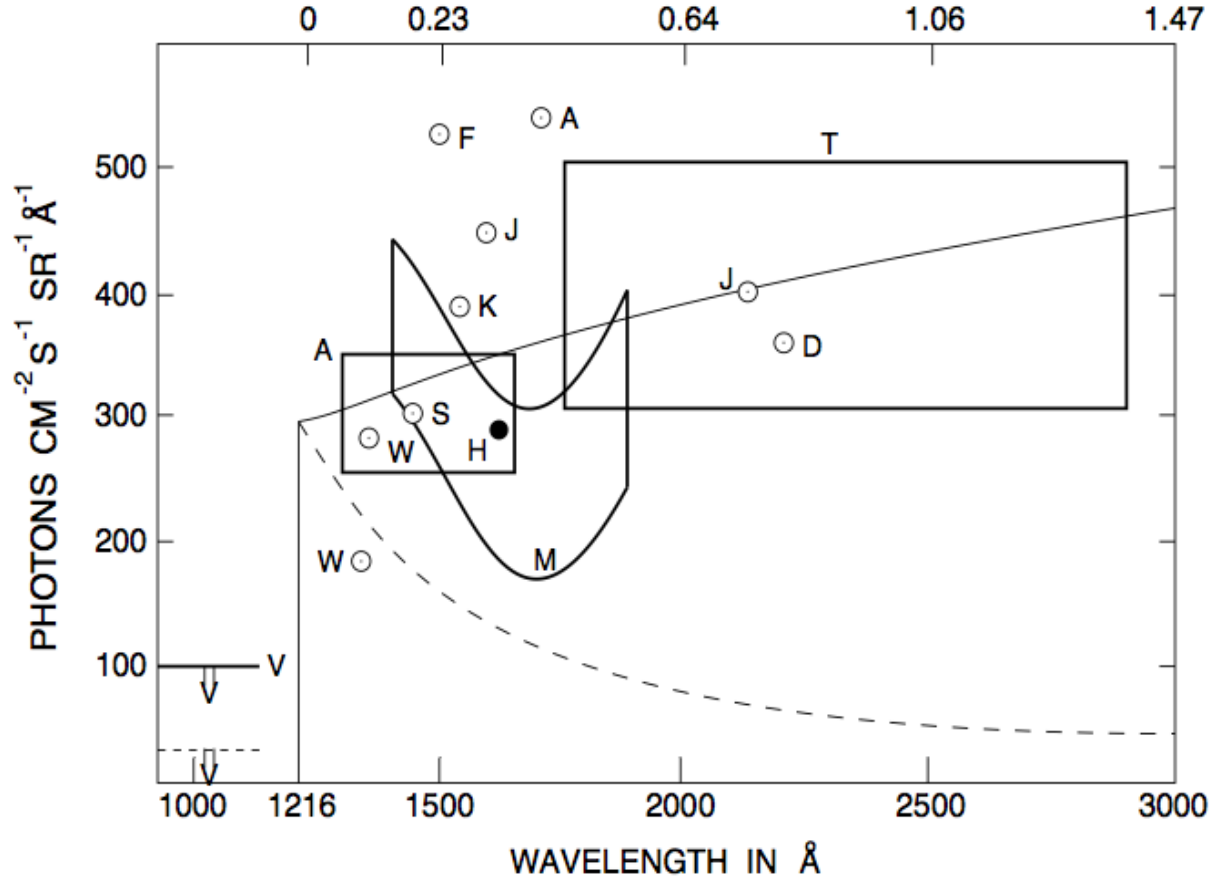


Figure 1. The plotted observations of (assumed) extragalactic diffuse cosmic ultraviolet background radiation (letters in Figure) have been reviewed by Henry (1991). The intensity in units is plotted against the wavelength of observation in Å. Superposed on the observations are predicted spectra of the recombination radiation from ionized intergalactic clouds (solid line, clouds that are expanding as the universe expands; dashed line, gravitationally bound clouds). Neutrino decay radiation would also produce a spectrum shaped like the dashed line. The observation V, shortward of Lyman α (1216 Å), is the Voyager upper limit of Holberg (1986; solid line: calibration of Holberg et al. 1982, dashed line: calibrations of Brune et al. 1979 and Cook et al. 1989). The observations longward of $L\alpha$ are all positive detections, not upper limits. They include spectroscopy (boxes, and filled point): A (Anderson et al. 1979), M (Martin and Bowyer 1990), T (Tennyson et al. 1988), H (Hurwitz et al. 1990), and photometric observations (open circles): W (Weller 1983), S (Paresce et al. 1979), J (Jakobsen et al. 1984), K (Onaka 1990), A (Anderson et al. 1979), D (Joubert et al. 1983), F (Fix et al. 1989). We have omitted the Apollo 17 observation of Henry et al. (1978), which agrees with the others at 1500 Å, but which shows a decline at longer wavelengths that is surely spurious.

First, we note that the extragalactic background shortward of $\text{Ly}\alpha$ (1216 Å) is less than 100 photons $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{Å}^{-1}$ (units that will be called “units” hereafter) if the calibration of Holberg *et al.* (1982) is used (solid line in figure), or still less (dashed line) if the calibration of Brune *et al.* (1979) or Cook *et al.* (1989) is used. In contrast, all of the observations in Figure 1 longward of 1216 Å are positive detections of ≥ 200 units, not upper limits.

We stress that the scatter that appears in the observations of Figure 1 demonstrably reflects a *spatial* variation in overall intensity of the ultraviolet background on the sky, rather than either uncertainties in the observations or gross (or detailed) *spectral* variations. This is demonstrated most clearly by examining individual spectra, for example Figure 10 of Anderson *et al.* (1979). Such examination makes clear that the ultraviolet background longward of 1216 Å (*at a given location*) shows *no trace* of a decline toward shorter wavelengths. The decline is *abrupt*, and occurs near 1216 Å.

What is the interpretation of the remarkable spectrum of Figure 1? The striking feature of course is the ledge: no detectable radiation short of about 1216 Å; strong, well-observed radiation longward of that wavelength. Now, a ledge of just this character has been searched for ever since de Rújula and Glashow (1980) suggested that the dark matter might be massive neutrinos that might decay with the emission of an ultraviolet photon. A ledge of exactly this character was predicted, and has been vigorously searched for. For example Stecker (1980) identified a ledge in the fragmentary observations of the time, and suggested the possibility that neutrino decay radiation had actually been observed. While that particular ledge is no more, interest in the general subject remains keen (Kimble *et al.* 1981, Henry and Feldman 1981, Murthy and Henry 1987).

However, while we have now located an excellent ledge, the shape of the spectrum toward longer wavelengths does not fit an origin in neutrino decay radiation. The expected spectrum is given in Equation 1, as a function of redshift z (for the same equation in terms of wavelength, see Kimble *et al.* 1981).

$$I_{\lambda > 1216 \text{ Å}} = \frac{n_{\nu} c}{\lambda_{e\lambda} 4\pi\tau H_0 (1+z)^2 (1+\Omega z)^{1/2}} \text{ units} \quad (1)$$

where n_{ν} is the local density of neutrinos of the type that decay with the emission of a photon, $\lambda_{e\lambda}$ is the wavelength of the emitted radiation, τ is the lifetime of the neutrinos against radiative decay, $c = 3 \times 10^{10} \text{ cm s}^{-1}$, the Hubble parameter $H_0 = 50 h_{50} \text{ km s}^{-1} \text{ Mpc}^{-1}$, $1+z = \lambda/1216 \text{ Å}$ is the redshift due to the expansion of the universe, and $\Omega = 1$ (from inflation, but see also Dekel *et al.* 1993).

The spectrum of Equation 1 is shown in Figure 1 as a dashed line. The decline to longer wavelengths is $\sim \lambda^{-5/2}$ and clearly such a decline is not supported at all by the observations. The only hope of preserving this origin would be to hypothesize that some other (galactic?) source was filling in at longer wavelengths, but if this were the case, the observations (see the figure) would provide no evidence at all for the neutrino decay radiation itself. There is therefore no support whatever for the idea that neutrino decay radiation has been detected.

Had we been able to conclude that the observed radiation actually was neutrino decay radiation, we would have had to attribute the fact that the ledge occurred at a wavelength very close to that of Lyman α to chance. Let us next look at another potential origin where again we would ascribe the wavelength of the ledge to coincidence: an origin in the redshifted light of galaxies. In particular, could the ledge be the Lyman limit to the light from a tremendous burst of star formation in starburst galaxies?

To have the ledge occur near 1216 \AA requires that the starbursts occurred at a redshift of 0.33, and the sharpness of the ledge requires that the activity have begun and ended rather abruptly. None of this is very palatable. Even more important, Martin, Hurwitz, and Bowyer (1991) have looked very carefully and critically at the idea that the diffuse background spectrum observed longward of 1216 \AA could originate in starburst activity, and do not succeed in reconciling the observations with a dominant contribution from unclustered starburst galaxies at low redshift.

Finally, we consider the idea that we are seeing redshifted extragalactic hydrogen recombination radiation and that the fact that the ledge occurs near 1216 \AA is not a coincidence. The expected spectral shape for the case of gravitationally-bound clouds of ionized hydrogen is identical to that of neutrino decay radiation, and so that case may be rejected immediately on observational grounds.

The spectrum for intergalactic clouds that are expanding as the universe expands is given in Equation 2.

$$I_{\lambda > 1216 \text{ \AA}} = \frac{\alpha x^2 n_0^2 c C (1+z)}{\lambda_{e\text{\AA}} 4\pi H_0 (1+\Omega_z)^{1/2}} \text{ units} \quad (2)$$

where $\alpha = 2.8 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ is the effective recombination coefficient (recombination to $n = 1$ generates no $L\alpha$ radiation), $x = 0.746$ is the fraction of baryons that are hydrogen nuclei, the local density of ionized hydrogen nuclei $n_0 = 2.83 \times 10^{-6} h_{50}^2 \Omega_g$, $\lambda_{e\text{\AA}} = 1216$, C = the clumping factor (which is independent of z in this model). We take the gas temperature (which affects α) to be 8000 K, for reasons that are given below; our results are very insensitive to the temperature.

The spectrum of Equation 2 appears in Figure 1 as the solid line, which fits the data acceptably well, considering that the data are obtained at many different locations at high galactic latitudes. The parameter Ω_g is the contribution to Ω that is due to ionized intergalactic gas. If we attribute the jump at $z = 0$ of 300 units that is shown by the observations (Figure 1) to intergalactic recombination radiation, we find that

$$\Omega_g^2 h_{50}^3 C = 180 \quad (3)$$

describes the observations.

At this point, we recapitulate facts that bear directly on the possibility of detecting redshifted Lyman α recombination radiation from ionized intergalactic gas.

The very small spatial fluctuations observed by COBE indicate that the dark matter was an essential ingredient in the formation of structure among the baryons following recombination. The structured dark matter was already there, and following recombination the neutral hydrogen and helium fell into the potential wells, creating the structure we observe today.

Intergalactic space was left free of neutral hydrogen. Indeed, intergalactic space is astonishingly free of neutral hydrogen, the density being $< 4.5 \times 10^{-14} h_{50} \text{ cm}^{-3}$ (Steidel and Sargent 1987). This means that in a volume of 50 cubic megaparsecs, where there is on average one galaxy, of mass 8×10^{10} solar masses (Allen 1973), there are $< 50,000$ solar masses of (smoothly distributed) neutral intergalactic gas. Galaxy formation gathered up all of the baryons except a fraction $< 6 \times 10^{-7}$, an efficient process indeed—unless intergalactic hydrogen is highly ionized. Observations of the cosmic microwave background (Mather *et al.* 1990) show that such intergalactic hydrogen cannot be at very high temperatures (Rogers and Field 1991). At lower

temperatures, recombination becomes more efficient, especially if the intergalactic gas is clumped. The clumping $C = \langle n_e^2 \rangle / \langle n_e \rangle^2 = 1.5 \times 10^7$ for galaxies, and is unknown for ionized intergalactic gas.

The final fact that bears directly on the search for recombination radiation is that only a small part of the expected baryonic matter is accounted for by matter that has already been detected. For example Persic and Salucci (1992) estimate the baryon mass density of the universe due to the stars in galaxies and hot gas in clusters and groups of galaxies. They find $\Omega_b = 0.003$, which is less than 10 percent of the lower limit predicted by standard primordial nucleosynthesis which implies that the great majority of the baryons in the universe are as yet unseen.

We are now prepared to explore the consequences of equation 3. Persic and Salucci quote Kolb and Turner (1990) and Peebles *et al.* (1991) in giving $\Omega_b h_{50}^2 = 0.06$ as the most probable value for the baryon density from nucleosynthesis. We take $\Omega_g = \Omega_b$, that is, essentially all of the baryons are intergalactic ionized hydrogen. Insertion into equation 3 then gives $C/h_{50} = 50,000$. Notice that this clumping is vastly less than for the visible matter (galaxies) in the universe. The clumps of ionized baryons in the universe are much larger in relation to their separation than are galaxies.

We have seen that the intergalactic medium is unquestionably highly ionized. What causes this ionization? There is some controversy over this. Meiksin and Madau (1993) provide several models in which the observed QSOs can provide the required ionizing photons at early epochs, and we accept their conclusion.

However, our highly clumped ionized intergalactic medium has much more severe problems. For $h_{50} = 1$, the recombination time of our clouds is only 1.3×10^7 years, and for $h_{50} = 2$ the recombination time is 6.3×10^6 years. Thus, if this interpretation of the diffuse high galactic latitude diffuse background is correct, a strong additional source of ionizing photons is required. Just such a source, radiative decay of neutrinos, has been proposed by Sciama (1993, *e.g.*, in which Sciama references defenses of his neutrinos against the conclusions of Davidsen *et al.* 1991, who failed to observe a neutrino decay line from the cluster of galaxies A665). Sciama's neutrinos decay with the emission of photons that are just capable of ionizing hydrogen (hence our assumed temperature, above, of ~ 8000 K). Sciama's neutrinos, in our present picture, would be the dark matter into which the baryons all fell following recombination. In every potential well, most (or rather, in most cases, all) of the hydrogen was re-ionized by Sciama's neutrinos. In exceptional cases dissipation occurred and quasars and galaxies formed. In most cases, in contrast, the hydrogen simply re-ionized and expanded out of the well, forming our present clouds that are expanding with the universe. Such clouds would be extremely hard to detect, either in emission or absorption, because of the very large velocity dispersion that is expected.

In the present picture there is no way of avoiding Sciama's neutrinos (or their equivalent). If we assume that all of closure density ($\Omega=1$) is ionized gas (that is, we ignore the nucleosynthesis argument), we obtain present-day recombination times that are of the order of the Hubble time, but the recombination time earlier (when the clouds were denser) would still be too short.

We conclude that if the high-galactic latitude diffuse ultraviolet background is extragalactic in origin, then its observed spectrum implies all of: *a*) detection of the baryonic dark matter; *b*) detection of the effects of the non-baryonic dark matter (Sciama neutrinos); and *c*) evidence for new physics beyond the standard model of elementary particle physics (Sciama neutrinos). As that would be an important set of discoveries indeed, we now turn to the observations at lower galactic latitudes in an effort to account for the high galactic latitude signal as being galactic, rather than extragalactic, in character.

3. OBSERVATIONS OF DIFFUSE BACKGROUND GENERALLY

The overall observational situation concerning ultraviolet background radiation has been reviewed recently by Henry (1991), and also by Bowyer (1991). Here we will survey progress since 1991, and try to resolve differences in interpretation of the existing data which have occurred.

Galactic sources that have been posited for diffuse background include fluorescence of interstellar molecular hydrogen (Martin, Hurwitz, and Bowyer 1990), atomic emission lines from hot gas in the interstellar medium and/or galactic halo (Feldman *et al.* 1981, Martin and Bowyer 1990), two-photon emission from the ionized component of the interstellar medium (Deharveng *et al.* 1982), and the light of hot stars scattering from interstellar dust grains (many authors).

There has been no recent change in the situation regarding molecular hydrogen fluorescence. The spectrum (Jakobsen 1986, Sternberg 1989) is sufficiently structured that there is no possibility that the signal at high galactic latitudes could be dominated by this source, which in any case continues strongly shortward of Lyman α .

There has also been no change in the situation regarding two-photon emission. The expected intensity from galactic sources can be accurately predicted by using the H α measurements of Reynolds (1986). No sharp break is expected at 1216 Å of course, and the average intensity is predicted to be well below the observed level longward of 1216 Å.

For the other two sources there is more to say on developments since 1991, and we devote separate sections, below, to each.

4. LINE EMISSION FROM THE INTERSTELLAR MEDIUM

Until recently, the situation concerning detection of line emission from hot gas has been murky. The tentative detection by Feldman *et al.* (1981) was not confirmed by Murthy *et al.* (1989). Martin and Bowyer (1990) present a spectrum for one of their UVX targets that contains a quite impressive and convincing CIV 1549 Å line, and a much less impressive O III] 1663 Å line. For their other targets, for some of which similar line emission was claimed, Martin and Bowyer present only tiny portions of their spectra, at the location of the claimed lines. The full spectra of all targets should be published.

The recent development on this topic is detection of very strong line emission in the Eridanus region by Murthy, Im, Henry, and Holberg (1993) using the Voyager spacecraft. Figure 2 shows the spectrum of their Target B, which shows strong emission lines of O VI 1032/1038 Å and C III 977 Å radiation. The lines are extremely strong, and predicted associated lines (see figure) should be detectable even with IUE. The region involved is one where there is a very strong soft X-ray enhancement (Burrows *et al.* 1993) and based on our other Voyager spectra is not typical of the general interstellar medium. What this suggests is that when a high-sensitivity sky survey (*e.g.* Kimble *et al.* 1990) is finally carried out, what will be revealed is a highly patchy structured hot interstellar medium.

Of course the highly structured character of the spectrum of Figure 2 shows that there is no possibility that the background at high latitudes is line emission. (To verify this, the reader should consult the individual spectra from the relevant references in Figure 1, rather than rely on Figure 1 itself.)

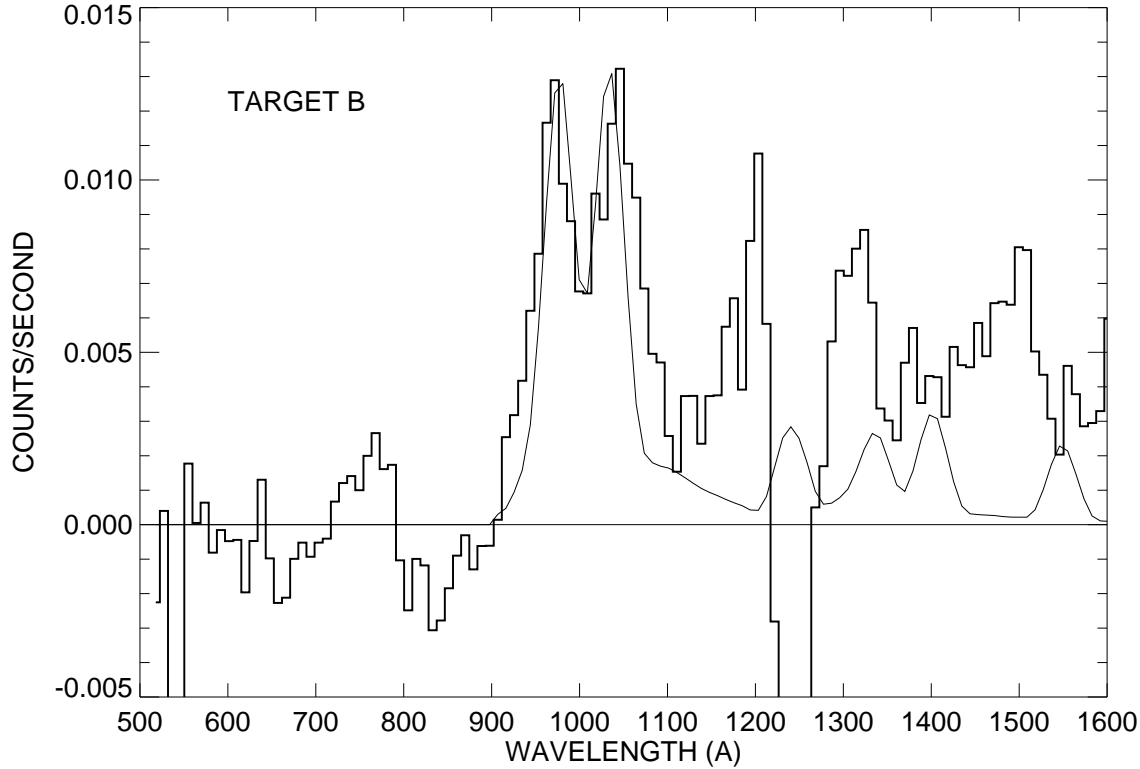


Figure 2. Spectrum of a region in Eridanus observed by Murthy, Im, Henry, and Holberg (1993). Strong solar system Lyman α (1216 \AA) has been subtracted. Emission lines of C III (977 \AA) and O VI ($1032/1038 \text{ \AA}$) are seen. The solid line shows the emission that is expected (Hartigan et al. 1987) from a shock with a velocity of 180 km s^{-1} , including two photon emission, plus appropriate dust-scattered light. The sensitivity of Voyager above 1200 \AA is too low to allow detection of additional predicted lines of N V, C II, Si IV, O IV, and C IV, but those lines should be accessible to IUE and to the Hopkins Ultraviolet telescope.

5. STARLIGHT SCATTERING FROM INTERSTELLAR DUST

This is a critical topic in regard to our effort to identify the source of the diffuse cosmic background at high galactic latitudes. The interstellar radiation field in the far ultraviolet has been directly measured by Henry, Anderson, and Fastie (1980), and it is found to be flat when expressed in units. Our spectrum, Figure 1, is also consistent with being flat longward of 1216 \AA , and if the Voyager measurement is dismissed (we will briefly discuss its likely validity below), then on spectral grounds there obviously is strong reason to hope that the light that is seen at high galactic latitudes is simply starlight scattering from interstellar dust.

The two recent reviews of the diffuse ultraviolet background (Bowyer 1991, Henry 1991) reached very different conclusions concerning the subject of diffuse galactic light (starlight scattering from dust). New developments, and careful reconsideration of earlier discussions, allow us to resolve most of the controversy.

The most important new development is the measurement of the Henyey–Greenstein (1941) scattering parameter g in the ultraviolet by Witt *et al.* (1992). This parameter g characterizes the scattering pattern of the interstellar grains: $g = 1$ means complete forward scattering, $g = 0$ is isotropic scattering, and $g = -1$ represents complete back-scattering. The Henyey–Greenstein function has no physical basis, it is simply an heuristic tool for model-building. The reason that the value of g is so critical to our present concern is that if the albedo of the grains is high and if g is zero or at least has not too large a positive value, then the dust which is known to exist at high galactic latitudes (*eg*, from IRAS cirrus observations) would backscatter sufficient light to account for the high latitude observations longward of 1216 Å.

The state of our knowledge of the value of g in 1991 can be gleaned from the excellent summary by Bowyer (1991, his Table 2). Values are widely divergent. The new observation by Witt *et al.* is of the nebula NGC 7023. The authors show an ultraviolet photograph, taken using UIT on the *Astro* mission, that shows the scattered light. Their analysis produces a fairly model-independent measurement of $g = 0.75$, which corresponds to very strong forward scattering. Their value for the albedo at 1400 Å is 0.65. In the light of all the controversy there has been over the value of g , it is important to note that Witt *et al.* indicate that their conclusion that $g_{\text{uv}} > g_{\text{vis}}$ is based on general radiative transfer principles and on the observational data alone. The value therefore should be quite secure. Let us now develop a simple model to use these values to predict what we should see at the highest galactic latitudes.

There is considerable dust at high galactic latitudes; for example Hauser *et al.* (1984) report, from their study of IRAS cirrus observations, that $A_V = 0.1$ mag at high latitudes. Stark *et al.* 1992 show $2 \times 10^{20} \text{ cm}^{-2}$ as a typical column density of neutral hydrogen at the highest galactic latitudes. Use of $E_{\text{B-V}} = N_{\text{H}}/5 \times 10^{21}$ (Knapp and Kerr 1974) then gives $A_V = 0.12$. If $E_{1500\text{-V}} / E_{\text{B-V}} = 5.3$ (Bless and Savage 1972, for ζ Oph), we then get $\tau_{1500\text{Å}} = 0.921$ $A_V = 0.3$. We adopt $A_V = 0.1$ and $\tau_{1500\text{Å}} = 0.255$. Also, there are many bright OB stars in or near the galactic plane. For our simple model for the scattered light of these stars, we integrate the Henyey–Greenstein (1941) scattering function

$$H(\theta) = (1 - g^2) / 4\pi (1 + g^2 - 2g \cos \theta)^{-3/2} \quad (4)$$

over the back-scattering directions, $\pi/2$ to π , obtaining

$$B = 1/2 - 1/(2g) + (1 - g^2) / (2g\sqrt{1 + g^2}) \quad (5)$$

for B , the fraction of the scattered light that is backscattered. Our model is, then, that at high latitudes we expect a scattered intensity $S = B G a \tau$, where G is the local far-ultraviolet interstellar radiation field ($\sim 10,000$ units: Henry, Anderson, and Fastie 1980), a is the grain albedo (~ 0.65 at 1500 Å: Witt *et al.* 1992), and $\tau = 0.255$ is the far-ultraviolet optical thickness of the high galactic latitude scattering layer.

For detailed study of scattered light at any particular region of the sky, one unquestionably wants to use a detailed model. However, such models are often complex and not generally available. The only competing simple model is that of Jura (1979), which predicts the scattered light as a function of five variables: the source function in the disk (roughly our G), τ_0 (~ 0.85 , Joubert *et al.* 1983) the optical thickness of the galaxy in the ultraviolet, a , g , and the galactic latitude b . Use of Jura's model is illustrated nicely in Joubert *et al.* 1983. We prefer our model: because of its simplicity (no evaluation of an exponential integral is required); because it is valid for

all values of g (Jura's model fails for large values of g); and because it does *not* give a galactic latitude dependence: the source function shows asymmetry in galactic longitude that is very strong (Henry 1977), equaling that in latitude (just more than 78% of the source function originates at $|b| < 21^\circ$ while 78% of the source function originates at $180^\circ < l < 360^\circ$).

A crude estimate using our model is, however, very revealing. In Table 1 we present (as a function of the Henyey–Greenstein scattering parameter g) the predicted high galactic latitude flux, from our model and from that of Jura (for $b = 90^\circ$), using the values that were specified above for the necessary parameters.

Table 1.
Backscattered Light S (Units) at $b = 90^\circ$ as a Function of g

g	B	S (present)	S (Jura)	S (Onaka & Kodaira)
0.98	0.004	7	(-53)	
0.90	0.023	38	(7)	41
0.80	0.051	84	81	90
0.75	0.067	110	118	
0.70	0.084	139	155	151
0.60	0.124	205	229	222
0.40	0.225	372	378	394
0.30	0.286	473	452	494
0.00	0.500	828	675	741
-0.90	0.977	1619	1342	

The observed level of cosmic background reported at moderate and high latitudes by large numbers of observers is about 300 units (Henry 1991, and also Figure 1). A glance at Table 1 shows that if the value of g in the ultraviolet is, say, 0.7 or greater, then the cosmic high-latitude background is not scattered starlight and is presumably extragalactic.

The final column in Table 1 is the prediction at high galactic latitudes of the sophisticated model of Onaka and Kodaira (1991), which takes into account the variation with galactic *longitude* of the galactic source function. We have used $a = 0.65$ and $\tau = 0.255$ in this application of the Onaka and Kodaira model. Note the excellent agreement among all these closely-related models.

That there is a very significant variation with galactic longitude of the source function for scattered light is of the greatest importance for interpretation of the diffuse galactic light. If one simply considers the distribution of the TD-1 stars (Figure 3), it is easy to mistakenly conclude that the source function is dependent on galactic latitude, and is independent of galactic longitude. That both of these conclusions are wrong, is demonstrated in Figure 4, which shows the integrated 1565 Å emission from the same stars that appear in Figure 3. There are profound effects due to absorption by the interstellar medium: also, the presence of Gould's Belt, which is tipped 19° with respect to the galactic plane, is very apparent. The model of Onaka and Kodaira, which takes some of these effects explicitly into account, will be very useful to us below.

If the background at high latitudes is not the back-scattered light of galactic plane stars, our rather exotic extragalactic model must perhaps be taken seriously. Before we do so, however, we must ask why Bowyer (1991) came to an opposite conclusion, concluding that most of the light, even at the highest galactic latitudes, is galactic in origin. Bowyer relied mostly on the result of

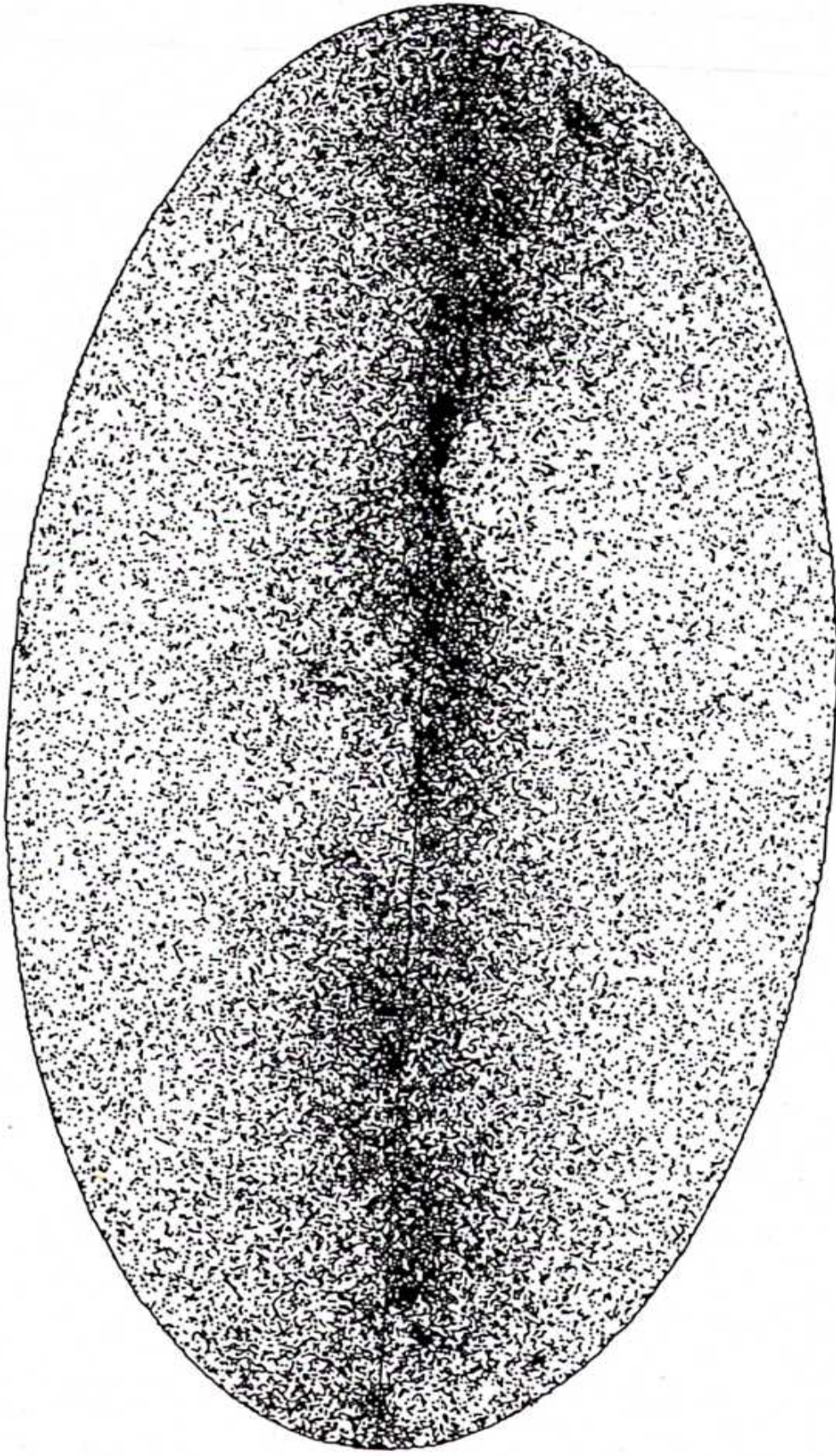


Figure 3. The ultraviolet (1656 Å) stars from the TD-1 catalog. The north galactic pole is at the top, and the galactic center at the center. Galactic longitude increases to the left. The TD-1 stars are concentrated to the galactic plane, and they are reasonably evenly distributed in galactic longitude, when simply number of stars (shown) is considered. When the flux from these same stars is considered, instead, the result is dramatically different, as is shown in Figure 4 and 5.

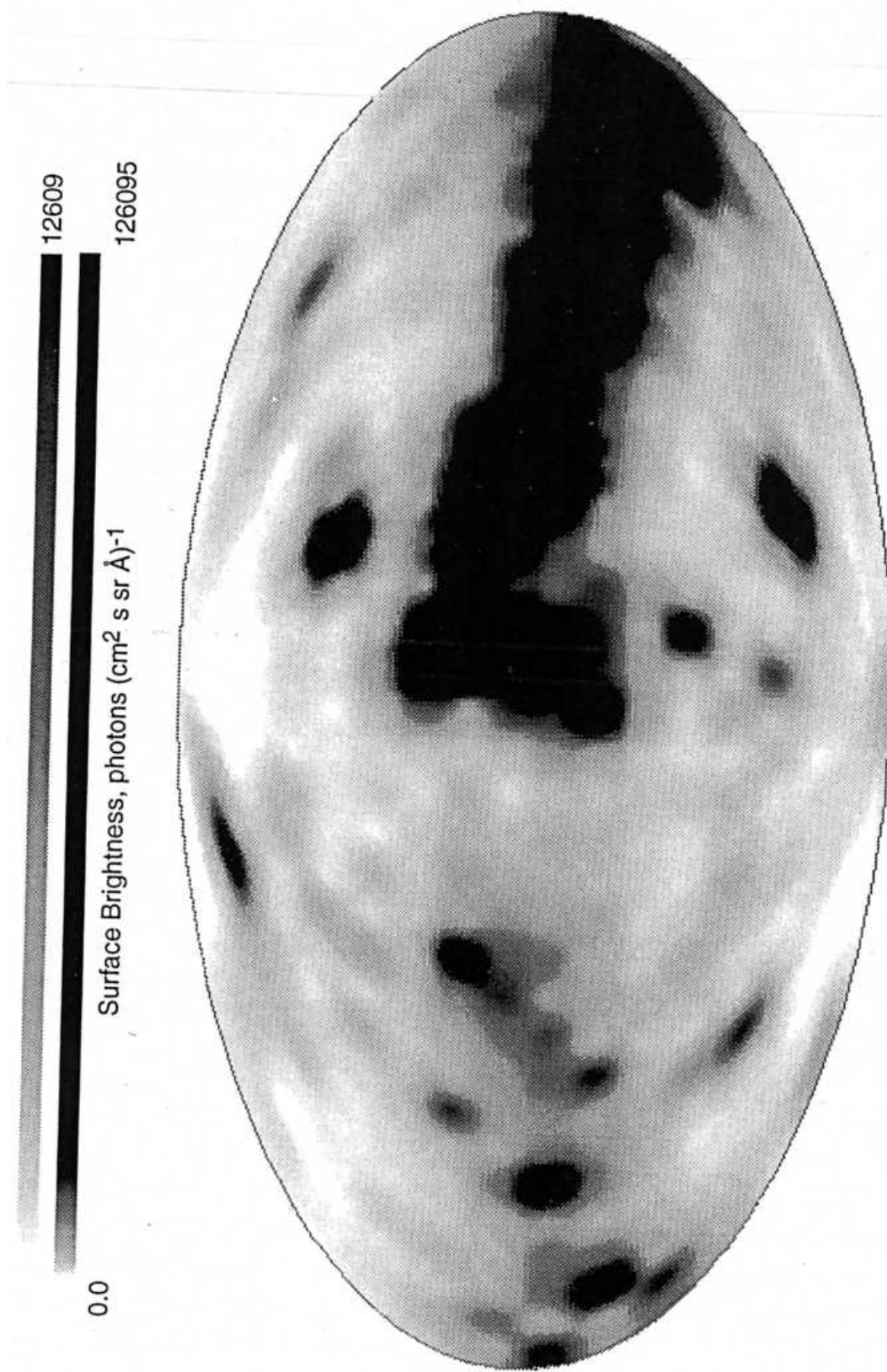


Figure 4. A linear, but saturated by a factor of ten, “photograph” of the sky at 1565 Å constructed from the TD-1 observations. This image contains only the light of the stars; that is, of the source function for scattering. The north galactic pole is at the top, and the galactic center is at the center. Just more than 78% of the source function originates between galactic longitudes 180° and 360°.

Hurwitz, Bowyer, and Martin (1991) in reaching this conclusion. The result of Hurwitz, Bowyer, and Martin was that in the far ultraviolet, the interstellar grains have albedo $0.1 < a < 0.3$ and Henyey–Greenstein scattering parameter is $0 < g < 0.4$, which numbers differ drastically from the values quoted above, and which if correct would give a scattered starlight signal at high galactic latitudes of as much as 340 units. As long as there is any possibility that Hurwitz *et al.* are correct, our extragalactic model must be rejected.

Unfortunately it is easy to show that the Hurwitz *et al.* analysis is suspect. It is based on the Berkeley UVX measurements. The locations of the nine UVX pointings are shown in Figure 5, superimposed on an unsaturated map of the source function for scattered light, the TD-1 stars (that is, Figure 5 is simply an unsaturated version of Figure 4, shifted in longitude). The Hurwitz *et al.* determination of the albedo relies mostly on their analysis of the signal seen during scan number 6 (see Figure 5), which was a scan from moderate galactic latitude to low galactic latitude in which the signal was interpreted as being saturated. We have organized Figure 5 so that this critical scan (at $l = 135^\circ$) is centered in the figure. The potential flaw in their analysis is their assumed source function: they assumed that the interstellar radiation field arises from a smooth galactic-plane-parallel distribution of emitting (and absorbing) media. That this is not the case is dramatically apparent from Figures 4 and 5. The Hurwitz *et al.* model was scaled to match the TD-1 results for the sky-averaged interstellar radiation field at 1550 \AA in the galactic plane. Now in fact 78% of the source function occurs in the hemisphere $180^\circ - 360^\circ$, far removed from scan 6. Thus, the light illuminating the dust of scan 6 was coming from quite different angles than assumed in their model. In particular, if g were large and positive (as the Witt *et al.* result suggests) then the dust in the direction of scan 6 could not be expected to backscatter significant amounts of light *regardless* of the value of the albedo. The Hurwitz *et al.* determination of g follows directly from their determination of the albedo a : they infer g from the high galactic latitude UVX observations, after fixing a . If a is low, then of course scattering must be isotropic if it is to provide the observed high latitude flux. If instead, the albedo is high as the analysis of Witt *et al.* 1992 suggests, then it follows from their data (and from our own UVX data, Murthy *et al.* 1990) that g must be large, or too high a flux would be seen at high latitudes.

We emphasize that the asymmetry of the source function that is shown in Figure 5 is not in the least controversial (see, *e.g.*, Gondhalekar *et al.* 1980). It has been clear for quite some time that to extract accurate values of a and g from mapping of the scattered light at moderate and high galactic latitudes will require rather sophisticated models. A beginning for such a model was used by Murthy, Henry, and Holberg (1991) in interpreting Voyager observations of the diffuse background at 1100 \AA . In Figure 6 we show a preliminary version of their model, to re-emphasize our point that a sophisticated model is required. In particular, for g large (and the observation of Witt *et al.* suggests that g is indeed large), models that take into account individual stars clearly will be necessary.

[Since the above was written, we have performed a reanalysis of the UVX data (Henry and Murthy 1993) in which we show that these data are in fact quite compatible with values of the albedo ~ 0.65 , and of the scattering asymmetry parameter $g \sim 0.75$, if an extragalactic component of 300 ± 100 units exists.]

A number of works (Bowyer 1991, Henry 1991) report correlations between purported measurements of the diffuse ultraviolet background and either galactic latitude or hydrogen column density. On this front, there has been a certain amount of progress since 1991. Wright (1992) has criticized the approach, often used, of noting that such correlations when extrapolated to zero column density always leave an unexplained residual. He points out that ionized and molecular hydrogen are also present and should have associated dust. Wright's reanalysis of the data of Fix *et*

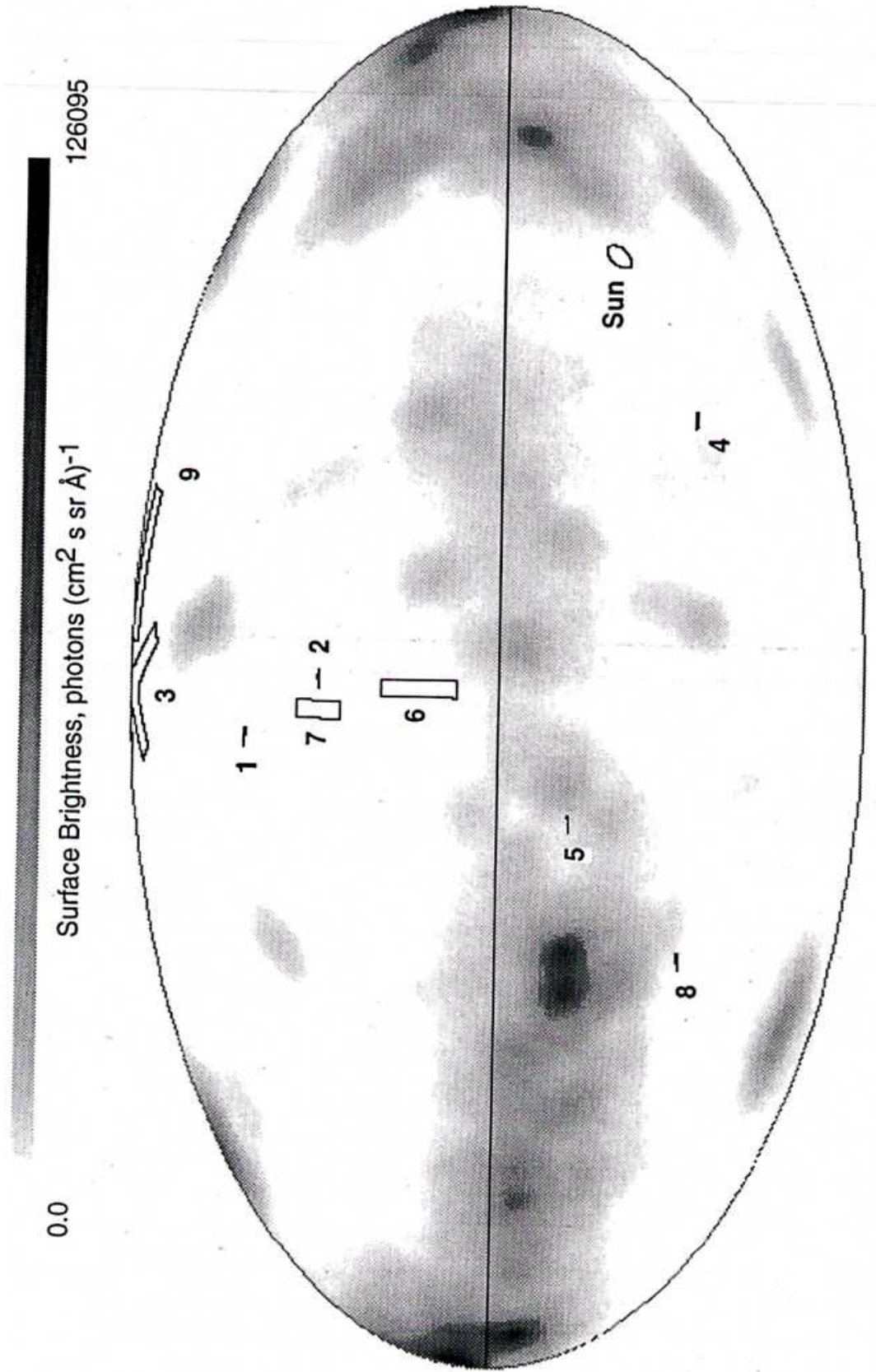


Figure 5. Integrated emission from the TD-1 stars. Dark regions in the figure are bright regions in the sky. The figure is linear and is just saturated at the darkest point. Also shown (numbered) are the regions observed by Johns Hopkins and Berkeley during the UVX mission. Targets are identified by number as specified in Murthy et al. (1989). Target 4 was a failed attempt to observe Comet Halley, and produced no data useful for the present analysis. The north galactic pole is at the top, while the center of this Aitoff all-sky image is at galactic longitude $l = 135^\circ$ so as to demonstrate clearly how poorly illuminated the dust is at the location of UVX scan number six, called GRADIENT by Murthy et al. (1989).

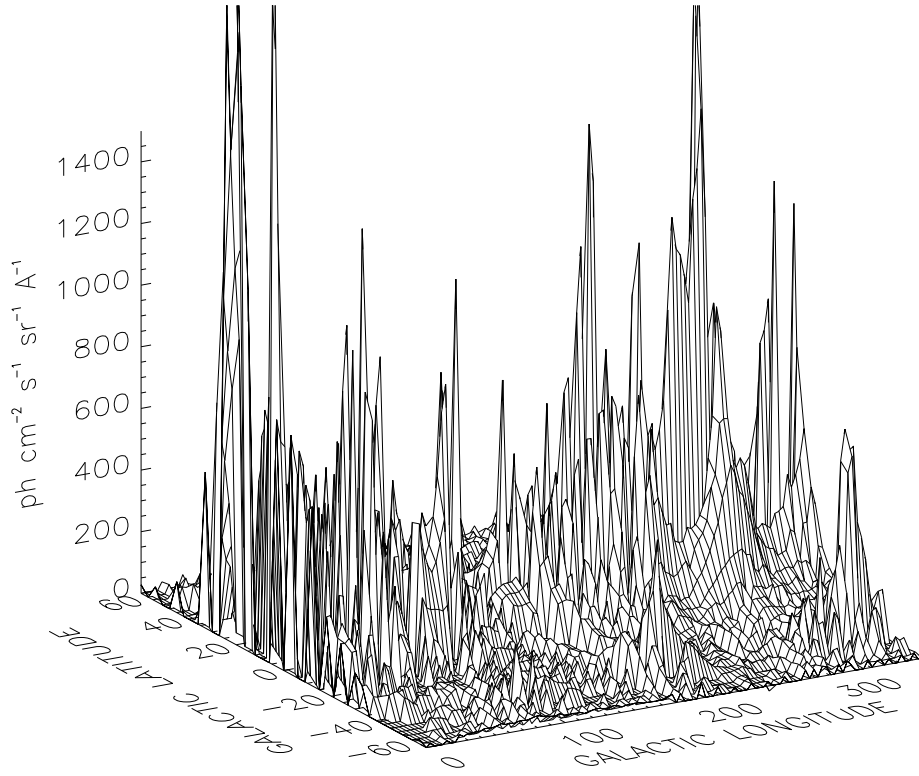


Figure 6. The model of ultraviolet scattered light of Murthy, Henry, and Holberg (1991) for the case $a = 0.1$, $g = 0.9$. The model scales linearly with a . The very sharp spikes are diffuse halos around stars that are predicted by this model. The figure shows only the scattered light; the source (the stars) is not shown (the source appears in Figures 3 and 4).

al. (1989) yields $a = 0.42 \pm 0.06$, $g = 0.44 \pm 0.18$, and an extragalactic component of no larger than 500 units. However, Witt and Petersohn (1994) have reconsidered Wright's analysis, and they find that the Fix *et al.* data show, instead, that the albedo $a \sim 0.5$, $g \sim 0.9$, and the extragalactic component is 300 ± 80 units.

Onaka and Kodaira (1991) have now reported in detail their rocket study of diffuse far-ultraviolet radiation at high galactic latitudes. They find, using their model that contains a dependence on galactic longitude of the source function for the scattered starlight, that

$$a(1 - 1.04 g) = 0.18 \pm 0.03 \quad (6)$$

which agrees at the 2σ level with the a and g values of Witt *et al.* (1991), and which also agrees within 2σ with the values of Wright (1991). They find that their regression line of intensity against hydrogen column density intercepts the ordinate at 200 to 300 units, a somewhat lower value than appears in Figure 1. A plot of their data against $\csc b$ (as recommended by Wright 1991) yields an "extragalactic" component of about 400 units.

Finally, Péroult *et al.* (1991) have re-examined the D2B-AURA measurements of the diffuse ultraviolet background of Joubert *et al.* (1983). The reexamination strongly justifies the skeptical attitude that was taken toward these data by Henry (1991). In the new analysis, the strong galactic latitude dependence of the “diffuse” flux is found to be dominated by direct starlight and starlight diffused in the instrument. They estimate that 1/2 to 2/3 of the ultraviolet flux is due to factors other than single scattering off dust. Péroult *et al.* believe that the major additional factor is light scattering in the instrument.

We now turn to the Voyager observations, and in particular, to the question of the reality of the jump in the high latitude background at 1216 Å.

6. VOYAGER OBSERVATIONS OF THE DIFFUSE BACKGROUND

In his review of the diffuse background Henry (1991) consistently took an extremely skeptical attitude toward claims of the detection of diffuse ultraviolet radiation, and particularly toward works that claimed to understand the physical source of the radiation absent a spectrum. In particular, it was only in the case of the Voyager observation of extended diffuse emission in Ophiuchus by Holberg (1990) that Henry felt that there was a very strong case for the assertion that ultraviolet starlight scattered from dust had been detected. There is now a second very strong case: Murthy, Henry, and Holberg (1993) have detected extremely strong scattered starlight in the direction of the Coalsack nebula (see Figure 7). Detailed modeling shows that this is not light backscattered from the Coalsack, but rather is the forward-scattered light of three very bright ultraviolet stars near the Coalsack. The spectral dependence of this diffuse emission is (as can be seen by our model fit) exactly that of the illuminating early B stars. Unless g is varying with wavelength in such a way as to fortuitously exactly cancel changes in a , we can conclude that the albedo of the grains is as high at 1000 Å as it is at 1350 Å. In fact, exactly the same phenomenon can be seen in Figure 2 of Holberg (1990), where the geometry of the dust relative to the source star is not so clear, but is unlikely to be the same as for the Coalsack observation.

This is an important result, highly relevant to the question of what is happening at high galactic latitudes. Voyager, with its low sensitivity longward of Lyman α , could not be expected to detect the background that appears in Figure 1. But it should definitely detect 300 units in the range 1000 Å to 1100 Å if it is there, and furthermore, the data of Figure 7 suggest that if what is being seen at high latitudes at longer wavelengths by many independent observers is starlight scattered from dust, the spectrum should continue strongly down to 912 Å. Voyager shows that it does not.

We have seen, in Figure 1, the Voyager upper limit of 100 units at 1100 Å. The extragalactic radiation field at slightly shorter wavelengths has been measured by Kulkarni and Fall (1993) by applying the proximity effect to Lyman α forest lines in the spectra of nearby quasars. They find an intensity of one unit, well below the Voyager upper limit at 1100 Å.

Holberg (1986, 1990) and Murthy, Henry, and Holberg (1991) present the evidence for the validity of the Voyager upper limit. There is a great deal more that can be done with the Voyager archive, and Murthy, Henry, Hall, and Holberg have been funded in an archival research program to carry out this project, which is under way. In Figure 12 of his review Henry (1991) indicated that every Voyager diffuse background observation above 20° latitude was only an upper limit. We have subsequently learned (Holberg, private communication) that the *Voyager* targets selected for analysis included only those that showed no evidence of a signal. That does not change any conclusions: there is still the same considerable number of locations at moderate and high galactic latitudes that show only an upper limit (which does *not* occur at wavelengths longward of Lyman α , Figure 1), and those locations where a signal *is* present may all contain point sources (the

overwhelming majority of Voyager pointings were toward known point sources). The new situation does leave open the possibility, however, that diffuse emission might still be detected at high

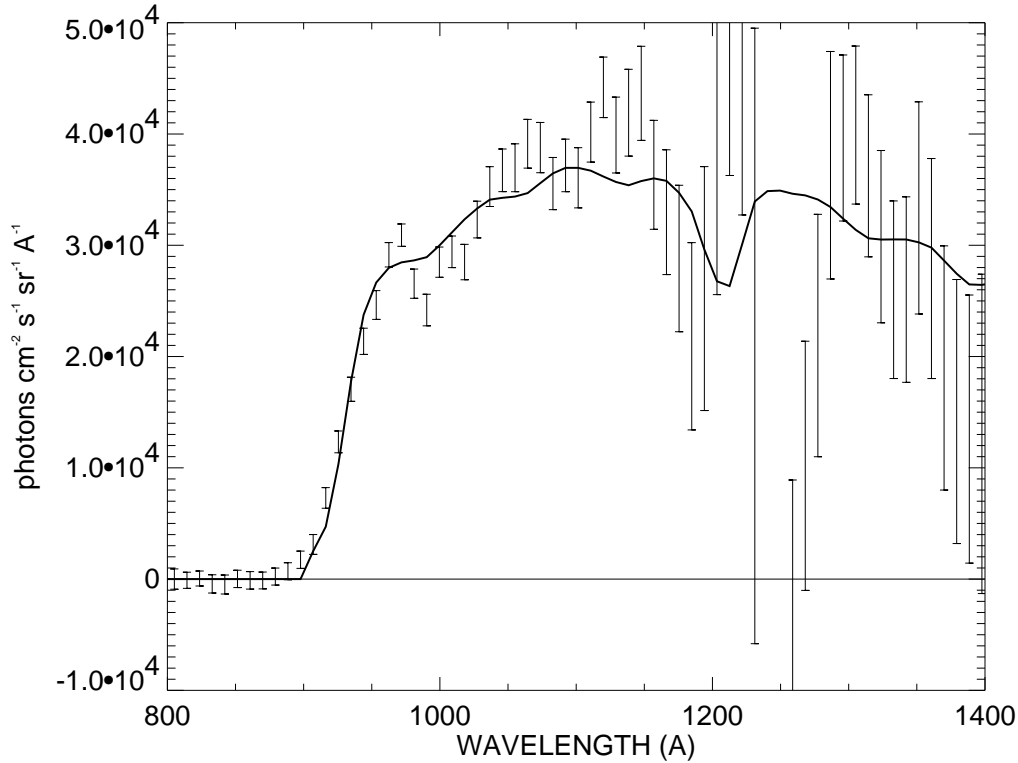


Figure 7. *Spectrum of the Coalsack nebula as observed by Murthy, Henry, and Holberg 1993. This is the brightest cosmic diffuse ultraviolet radiation ever reported in the night sky. The radiation is the forward-scattered light of three extremely bright ultraviolet-emitting stars, α Cru, β Cru, and β Cen. A large subtraction has occurred at Lyman α (1216 Å). The dark solid line represents our best fit model, after subtraction of interplanetary lines. Notice that no break occurs in this spectrum of dust-scattered starlight between wavelengths longward of Lyman α and wavelengths shortward of Lyman α .*

latitudes near 1100 Å using Voyager. Indeed, if g and a are both large, we would predict a significant signal at high latitudes near the location of bright ultraviolet stars (see Figure 6).

Figure 8 shows the Voyager upper limits of Holberg (1990) and of Murthy, Henry, and Holberg (1991) superposed on a map of the expected scattered light above $b = 40^\circ$ predicted using the model of Onaka and Kodaira (1991). We used $\tau = 0.4 \csc b$ in making this plot, with the albedo

taken as 0.65 and $g = 0.9$ (northern hemisphere) and $g = 0.8$ (southern hemisphere), to illustrate the model. We have evaluated the reduced χ^2 for these data (treated as detections, each with a standard deviation of 100 units) against this model as a function of a and g . A plot of the reduced χ^2 appears in Figure 9. An albedo of 0.65 is seen to require that $g > 0.8$. A sufficiently low albedo will also explain the data.

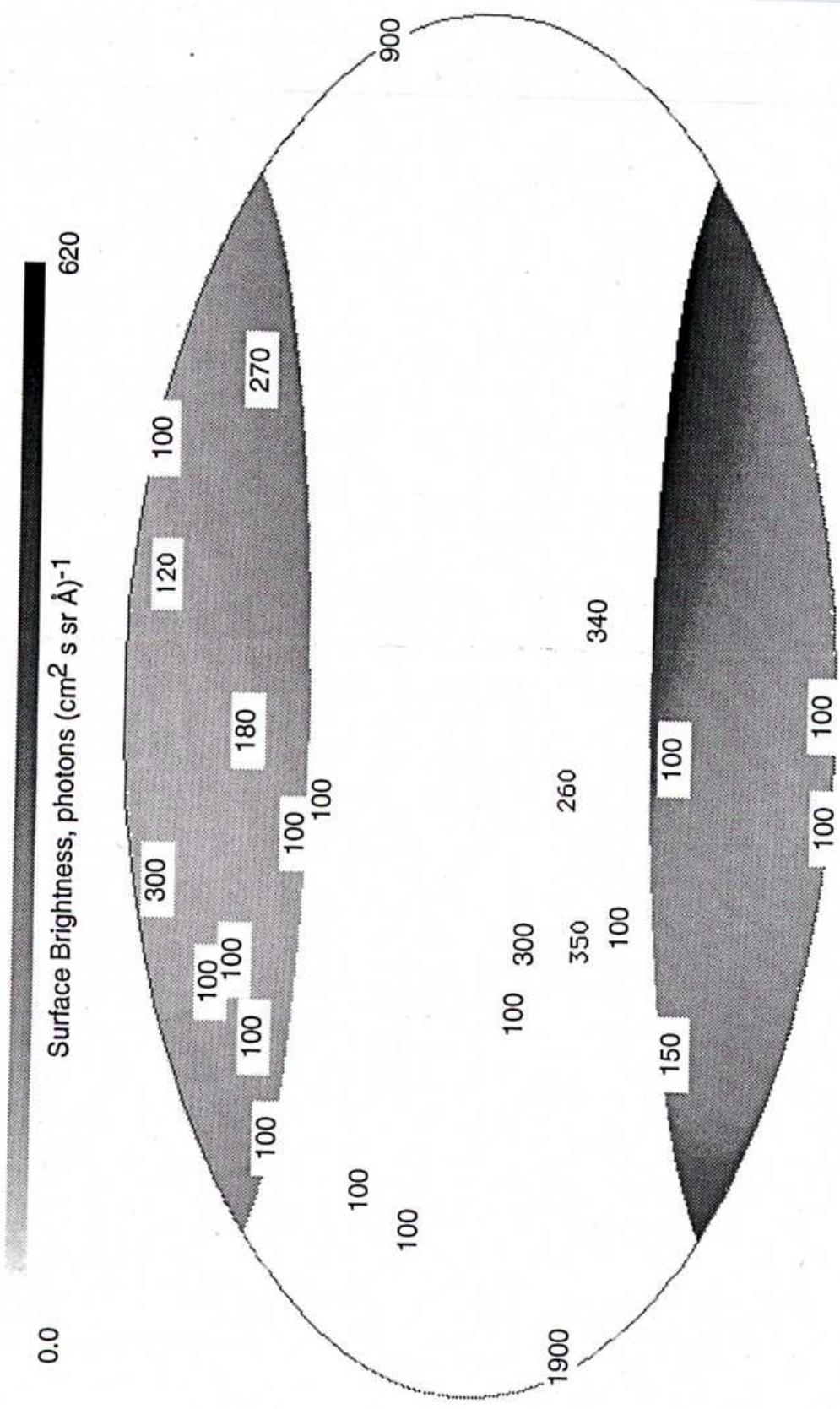
The new work already done on Voyager data that bears most directly on the present discussion is a new observation by Murthy, Henry, and Holberg of the extended dust patch at high galactic latitudes that was discovered by Sandage (1976). Sandage's Plate 1 shows very clear evidence for dust at $b = +38^\circ$. Our Voyager observation shows nothing but an upper limit of 100 units, and our measurement is so clean that we have included it as part of our data-reduction template for "no astrophysical signal" (Murthy, Im, Henry, and Holberg 1993). The importance of this observation is that Sandage deduces that $A_V = 0.3$ mag, from the 21 cm observation of Heiles (1975). This translates into an optical depth τ at 1100 Å of 1.0 mag, using the E_{1100-V}/E_{B-V} of York *et al.* (1973). Use of the model of Onaka and Kodaira for Sandage's location and value of τ shows that for an albedo of 0.65 we require $g > 0.9$ to explain our Voyager result. (Another possible explanation would be a *low* albedo for the grains: this of course would also suggest that the high galactic latitude signal at longer wavelengths is extragalactic.) The Sandage region was also scanned at longer ultraviolet wavelengths by Murthy *et al.* (1989, 1990), and also by Martin, Hurwitz, and Bowyer (1990). No enhancement of background as the line of sight passed over the Sandage region was noted by any of the various UVX spectrometers.

7. DISCUSSION

The absence of a signal from the Sandage region discussed in the last section is perhaps the most powerful indication that the signal at longer wavelengths is not back scattered starlight, and hence is extragalactic. It is not proof, however. The new information that we presented in the previous section showing that the albedo of grains continues high into the farthest astronomical ultraviolet is not conclusive, as g could be varying with wavelength to compensate. If one is desperate to avoid concluding that the radiation is extragalactic, one can postulate that for *backscattered* light the shape of the scattering function changes abruptly near 1216 Å. There is nothing sacred, after all, about the Henyey–Greenstein scattering form. One could also simply postulate an arbitrary additional previously-unknown dust population having the needed optical properties.

In this context it is interesting to note that Martin, Hurwitz, and Bowyer (1991) concluded (ignoring entirely the Voyager data) that what is observed at the highest galactic latitudes indicates "either the existence of a hitherto unidentified dust component, or ... a large enhancement in dust scattering efficiency in low-density gas." They reached their conclusion from the striking resemblance between their highest-latitude UVX spectrum and a lower-latitude spectrum that they believed was dust-scattered light. That is, their evidence for dust reflection at high latitudes is its exact resemblance to dust at low latitudes, but then they are forced to conclude that it is anomalous dust, and that the resemblance is therefore fortuitous.

What would it take to resolve the matters that we have discussed in this paper? A good deep ultraviolet image of the Sandage region at 1500 Å would be a great step forward. If the Sandage region is not clearly seen, that would be virtually conclusive evidence that the high-latitude background is not due to scattering by normal dust. Also, with the Hopkins Ultraviolet Telescope (Davidsen 1993) it ought to be possible to obtain a spectrum of the dust-scattered light in the



Onaka/Kodaira Model of Dust-scattered Light

Figure 8. The shading shows the predicted scattered light as a function of galactic longitude and latitude as predicted using the model of Onaka and Kodaira (1991). We have used albedo $a = 0.65$, and $\tau = 0.4 \csc(b)$, and we have used $g = 0.9$ for northern galactic latitudes, and $g = 0.8$ for southern galactic latitudes, simply to exhibit the results of the model.

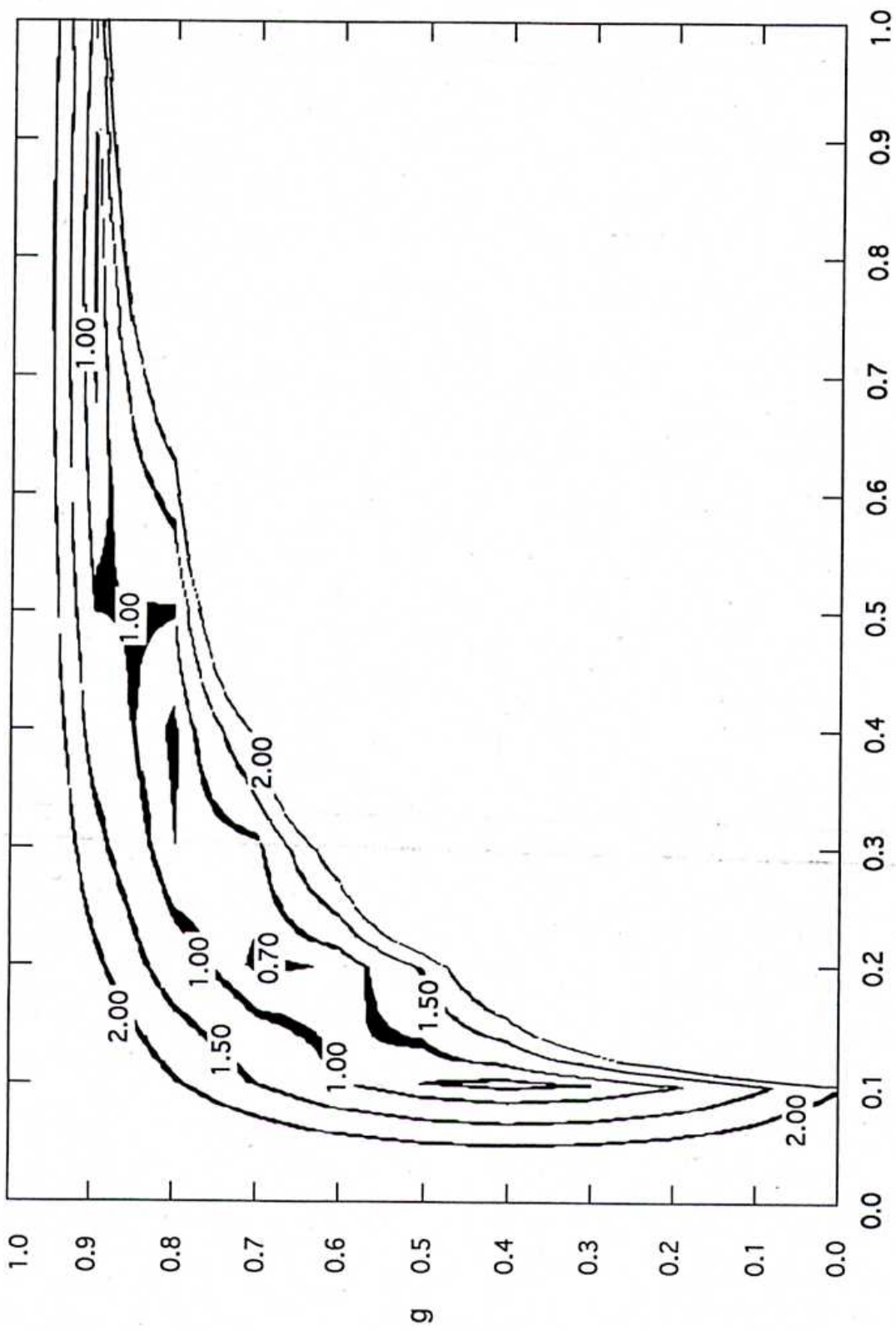


Figure 9. Reduced χ^2 for the fit of the Voyager observations of Holberg (1990) and Murthy, Henry, and Holberg (1999) to the sophisticated model of scattered starlight of Onaka and Kodaira (1991). The Henyey–Greenstein (1941) scattering parameter g is plotted against the interstellar grain albedo a . Contours of reduced $\chi^2 = 2.0, 1.5, 1.0$, and 0.7 are shown. The width of the contour at any point reflects the function's slope.

direction of the Coalsack that has high enough signal to noise that a comparison is possible with the rather structured high galactic latitude spectrum of Martin and Bowyer (1990). Certainly the interstellar radiation field (Henry *et al.* 1980) that is incident on the putative high latitude dust does not have the observed cosmic background spectral character reported by Martin and Bowyer; the Coalsack observation, while not decisive (it would not be *back* scattered light), could be extremely suggestive one way or the other.

To disprove the existence of an anomalous dust component specially designed to account for the observations would be difficult. A very long exposure indeed might, if the light is scattered starlight, reveal the spectral structure (absorption lines) that is expected in an integrated B-star dust-reflection spectrum.

8. CONCLUSION

No definite conclusion is possible. An interesting possibility is raised, however, that deserves observational and theoretical exploration. The intergalactic clouds of ionized hydrogen that we postulate might be related to the objects that produce the Lyman α forest, and the extrapolated spectrum of the radiation approximates the integrated light of the faint blue “galaxies” discovered by Tyson (1988). Perhaps Tyson’s objects are not galaxies at all, but our gaseous objects, radiating and dissipating.

Diffuse ultraviolet background study today is in the same state that study of the diffuse infrared background was before IRAS and COBE: fragmentary, often conflicting observations. What is needed is an all-sky survey in the ultraviolet, involving both imaging and spectroscopy.

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DISCUSSION

J. Peebles: Very simply, what sky coverage would you have [using the Hopkins Ultraviolet Background Explorer]?

Henry: The Hopkins Ultraviolet Background Explorer (HUBE; see Kimble, Henry, and Paresce 1990), which was described by me briefly in my verbal presentation, is a candidate Small Explorer mission that was under consideration by NASA for possible selection. What we would have had in this proposed experiment would be a complete survey of the entire sky, as far as imaging is concerned, in the wavelength range longward of Lyman α . Spectroscopically, HUBE involved a partial survey of the sky: each time we took an image, we would get a spectrum of the central region, typically with 5 Å resolution. The spectrum would have covered from 800 Å all the way to 1800 Å. Unfortunately, HUBE was not selected by NASA. HUBE is currently one of seven "finalists" to fly on the SAC-D spacecraft of Argentina.

V. Khersonsky: If I understand correctly, your conclusion about light scattering is strongly dependent on the size of dust particles. In particular, the properties of scattering are dependent on grain sizes, and we know that the sizes of grains cover approximately 3 orders, maybe even 4 orders of magnitude. How do you take this into account in your considerations? Maybe it is not important.

Henry: It is certainly important in terms of actually understanding the grains. I am afraid I do tend to regard the interstellar grains as simply a source of noise or interference, and so I tend to take a rather pragmatic view, which is to treat the grains, regardless of their actual nature, as being simply governed by two numbers: an albedo a and a Henyey–Greenstein scattering phase parameter g . It is true that the Henyey–Greenstein scattering pattern is totally arbitrary. It was picked for its rather beautiful mathematical properties, and it might be that the actual pattern is very different. For example, Adolf Witt et al. (1992) get $g=0.7$ in NGC 7023, and he may be completely correct; but it may also be that there is three or four times more backscattering with that same forward pattern than there is in the Henyey–Greenstein function, and that is just the way the grains are, in which case some of what I said just does not mean anything. So, ultimately one is going to have to understand what is going on, on the basis of observations over the galactic cap itself. Peebles' question concerning how thoroughly I hoped to map the sky is very apropos because what you want to do is really see the scattered light; you should see it! If it is backscattered light, we should see it in spades, because the cirrus is up there, right? So we know where the dust is. And if we see this coincidence with the cirrus, there will be absolutely no question: it is backscattered light from dust. Now in connection with that, Alan Sandage made an observation published in A.J. in 1976. From the ground he photographed a nebosity about 50° north and interpreted it as starlight in the visible, scattered from interstellar dust. So this is a nice prototype area you would like to look at. Now, one of those four Voyager observations we made at the highest galactic latitudes was of that region, and we see absolutely nothing.

C. Norman: Can I just come back to a simple question of units and numbers? That is, there are other estimates of the background UV flux from the integrated light of quasars and also estimates by Carrie *et al.* from high velocity clouds, etc. Are these 300 counts roughly equivalent to what they estimate?

P. Jakobsen: The 300 photon units that people like to use in the far UV are, in comparison with the result deduced from the proximity effect for local ionizing flux, about an order of magnitude higher. I'll get into that in my talk. Quasars can provide nothing to the extragalactic far-UV background. The point is that 300 photon units is an enormous flux, even compared to galaxies.