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ULTRAVIOLET BACKGROUND RADIATION

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ABSTRACT

We have reanalyzed the UVX measurements of the surface brightness of the diffuse ultraviolet background above $|b| = 40°$ using the dust-scattering model of Onaka & Kodaira (1991), which explicitly takes into account the variation of the source function with galactic longitude. The range of allowed values of interstellar grain albedo *a*, and scattering asymmetry parameter *g*, is considerably expanded over those of a previous analysis. The new χ^2 probability contours come close to, but do not include, the values of *a* and *g* found for the interstellar grains by Witt et al. (1992) using the Ultraviolet Imaging Telescope on the Astro-1 mission. If we hypothesize in addition to the dust-scattered light an extragalactic component of 300 ± 100 photons cm^{-2} s^{-1} sr^{-1} $\mathrm{Å}^{-1}$, attenuated by a cosecant *b* law, the new reduction of the UVX data gives complete consistency with the Witt et al. determination of the optical parameters of the grains in the ultraviolet.

Subject headings: dust, extinction — Galaxy: halo — reflection nebulae — ultraviolet: general — ultraviolet: interstellar

1. INTRODUCTION

The UVX experiment was carried on the Space Shuttle Columbia between 1986 January 12 and 19 (STS-61C). Several ultraviolet spectrometers were used to obtain measurements of the diffuse ultraviolet background at eight locations in the sky. The measurements are discussed extensively by Bowyer (1991) and Henry (1991); detailed references are given in those reviews.

One of the aims of the analysis of the UVX data was the determination of the optical constants of the interstellar grains in the far-ultraviolet (~1500 Å). The relevant analyses are presented by Murthy et al. (1990), who found, from the Johns Hopkins data, no correlation of ultraviolet light intensity with neutral hydrogen column density, and by Hurwitz, Bowyer, & Martin (1991), who found, from the Berkeley data, an excellent correlation. These different results hang largely on the discrepantly high dark currents in the Murthy et al. data.

Since publication of the UVX data, there have been two important and highly relevant additions to our knowledge. First, there is the measurement of the phase function asymmetry parameter in the ultraviolet by Witt et al. (1992). The asymmetry parameter characterizes the scattering pattern of the interstellar grains. Astronomers usually select, from the many phase functions in common use (van de Hulst 1980), the Henyey-Greenstein (1941) scattering parameter *g*; where $g = 1$ means complete forward scattering, $g = 0$ is isotropic scattering, and $g = -1$ represents complete backscattering. The state of our knowledge of the value of *g* in 1991 can be gleaned from the excellent summary by Bowyer (1991; see his Table 2), to which should be added the determination of Henry (1981). Values are widely divergent. The new observation by Witt et al. (1992) is of the nebula NGC 7023. The authors show an ultraviolet photograph, taken using the Ultraviolet Imaging Telescope (UIT) on the Astro-1 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 1440 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 $g_{\mathrm{UV}} > g_{\mathrm{vis}}$ is based on general radiative transfer principles and on the observational data alone. The value therefore should be quite secure.

The second development is the creation by Onaka & Kodaira (1991) of a sophisticated model for the dust-scattered light above $b = 40°$. Their model takes into account the variation of the source function with Galactic longitude that is described by Gondhalekar, Phillips, & Wilson (1980); their model is therefore greatly superior to that of Jura (1979).

Happily, the two discordant UVX measurements are the only two that are below the $b = 40°$ limit of the Onaka–Kodaira model. In this *Letter*, we report reanalysis of the rest of the UVX data using the Onaka–Kodaira model.

2. ANALYSIS

The UVX data were extracted from the papers cited above. The two Johns Hopkins spectrometers (Murthy et al. 1989, 1990) were given equal weight and were each assigned standard deviations of 200 photons cm^{-2} s^{-1} sr^{-1} $\mathrm{Å}^{-1}$. The higher signal-to-noise Berkeley data were given double weight (standard deviation of 100 photons cm^{-2} s^{-1} sr^{-1} $\mathrm{Å}^{-1}$). These error bars should reflect reasonably well both the systematic and the statistical errors in the three experiments.

The Onaka–Kodaira model requires us to know the optical depth at the relevant wavelength in any given direction. We know that 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 2×10^{20} cm^{-2} as a typical column density of neutral hydrogen at the highest Galactic latitudes. Use of $E_{B-V} = N_{\mathrm{H\,I}}/5 \times 10^{21}$ (Knapp & Kerr 1974) then gives $A_V = 0.12$. If $E_{1500-V}/E_{B-V} = 5.3$ (for ζ Oph; see Bless & Savage 1972), we then get $\tau_{1500\,\mathrm{Å}} = 0.921 A_\lambda = 0.3$. We adopt $A_V = 0.12$ and $\tau_{1500\,\mathrm{Å}} = 0.3$, and we assume that $\tau = 0.3 \csc b$. Finally, to the Onaka–Kodaira model we add an extragalactic

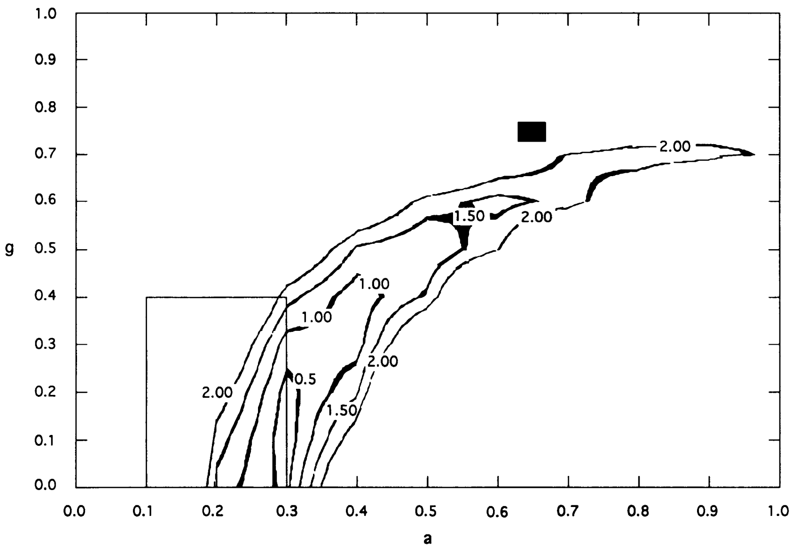

FIG. 1.—Contours of reduced χ^2 are plotted as a function of interstellar grain albedo a and Henyey-Greenstein (1941) scattering parameter g. The range of values of these optical parameters of the interstellar grains that is allowed by the UVX data is expanded from the previous determination (Hurwitz et al. 1991) (box at $a = 0.2$) to larger values of a and g, but there is still not good agreement with the values as determined from light scattered from the nebula NGC 7023 as measured by Witt et al. (1992), indicated by the black rectangle.

term: a flat radiation field attenuated by the extinction of the same dust that provides the scattered-light component.

The result of comparing the data with the model, with the extragalactic component set to zero, is shown in Figure 1. The contours showing allowed values of a and g include certain of the values determined in the analysis by Hurwitz et al. (1991), but in addition, larger values of a and g are found to be permitted. This result comes closer to showing consistency between the determination of the grain optical properties by Witt et al. (1992) and the UVX results. The new result is also consistent with the analysis by Onaka & Kodaira (1991) of their own data: they concluded that the albedo a is greater than 0.32 and the scattering phase asymmetry factor g is greater than 0.5.

It is interesting to see why the present analysis permits a wider range of dust optical constants than does the analysis of Hurwitz et al. (1991). Figure 2 (Plate L1) shows the locations of the nine UVX pointings, superposed on an unsaturated map of the source function for scattered light, the *TD-1* stars (Henry et al. 1988). The previous UVX determination of the albedo (Hurwitz et al. 1991) relies mostly on the analysis of the signal seen during scan 6 (see Fig. 2), 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 2 so that this critical scan (at $l = 135°$) is centered in the figure. In the analysis by Hurwitz et al. it was 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 Figure 2. In fact, 78% of the source function occurs in the hemisphere 180°–360°, far removed from scan 6. Thus, the light illuminating the dust of scan 6 was coming from quite different angles than was assumed in the model. In particular, if g were large and positive (as the Witt et al. 1992 result suggests), then the dust in the direction of scan 6 could not be expected to scatter back much light *regardless* of the value of the albedo. The previous determination of g follows directly from their determination of the albedo a: viz., g is inferred 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 that g must be large otherwise too high a flux would be seen at high latitudes.

One might ask whether our larger range of allowed values of a and g results mostly from use of the Onaka–Kodaira model or mostly from our exclusion of the lowest latitude UVX observations. To explore this, we have first repeated our analysis identically, but using the model of Jura (1979). The result is very similar to Figure 1. However, we have also run the Jura model (which is advertised as valid down to galactic latitude 10°, which includes all of the UVX pointings) for *all* of the UVX data. For the two low-latitude targets, we used only the Berkeley observations. The result is again similar to Figure 1, suggesting that it is not exclusion of the low-latitude points, but some other aspect of the Berkeley model, that is responsible for the difference. (This work with the Jura model is useful only for diagnostics, as the model of Jura has the major defect of having no source-function longitude variations.)

There are actually independent reasons for wishing to exclude scan 6 from the analysis in any case. Danly (1989) showed that the general region of scan 6 is very disturbed, in fact, uniquely so in the galaxy, having large amounts of intermediate and high velocity H I emission. In all of the galaxy, this is the most clear site of disk-halo interaction. The analysis of 21 cm hydrogen by Kuntz & Danly (1993) shows that the region of scan 6 itself contains substantial amounts of intermediate-velocity hydrogen. The dust associated with such hydrogen may be a factor of 3 or more lower in abundance compared with low-velocity hydrogen (Wakker & Boulanger 1986); if the ultraviolet observation is not saturated, this would lead to an underestimate of the grain albedo.

Finally, we note that there are observations that indicate that the intensity of diffuse light is highly variable from place to place: Holberg (1990) reports two locations with intensities of $\sim$2000 photons cm^{-2} s^{-1} sr^{-1} Å^{-1}, while Murthy, Henry & Holberg (1993) report diffuse radiation of 10,000 to 40,000

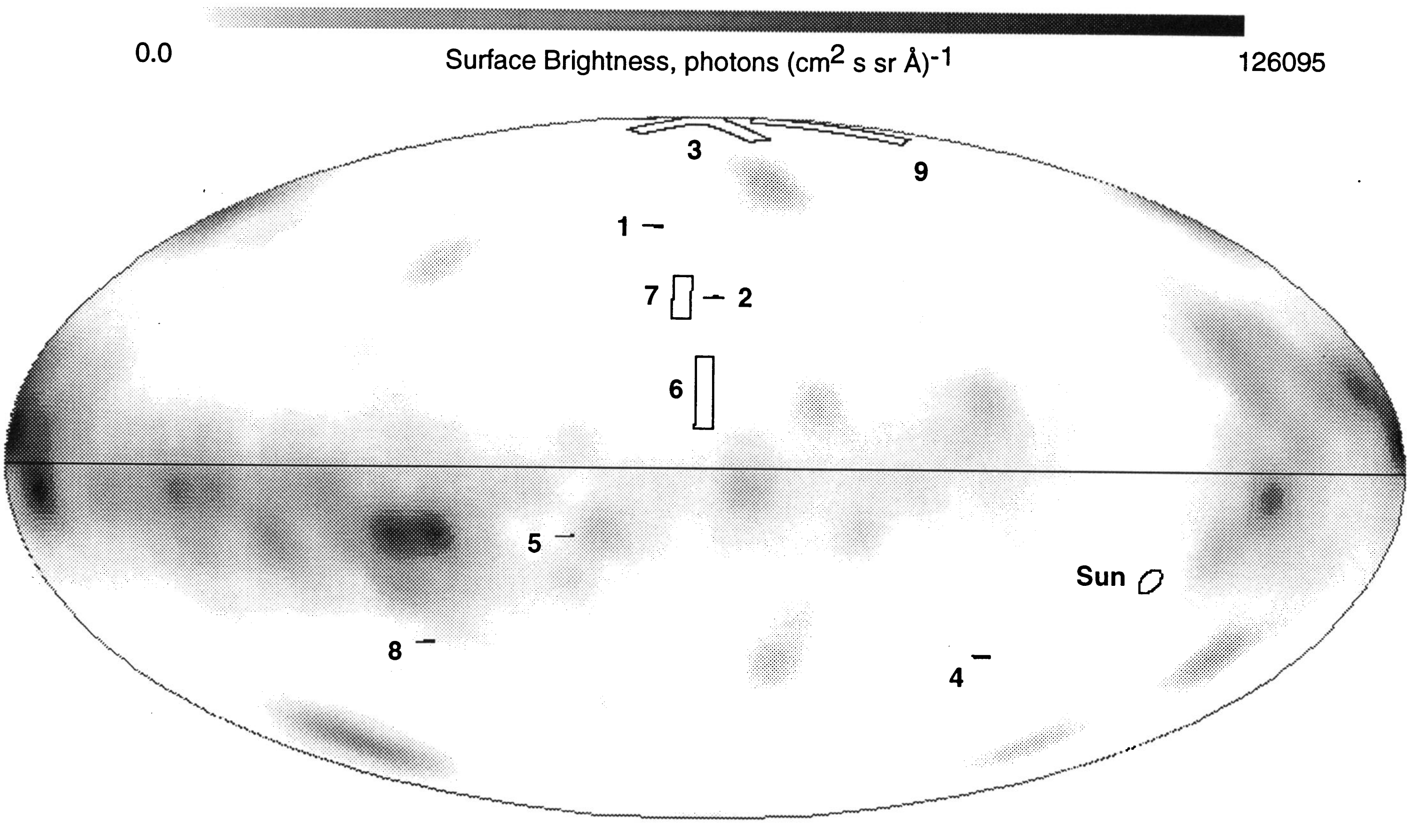

FIG. 2.—Integrated emission from the *TD-1* stars. Dark regions in the figure are bright regions in the sky. The figure is linear and is just saturated at the darkest point. Also shown (*numbers*) are the regions observed by Johns Hopkins and Berkeley during the UVX mission. Targets are identified by 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 $l = 135°$, so as to demonstrate clearly how poorly illuminated the dust is at the location of UVX scan 6, called GRADIENT by Murthy et al. (1989).

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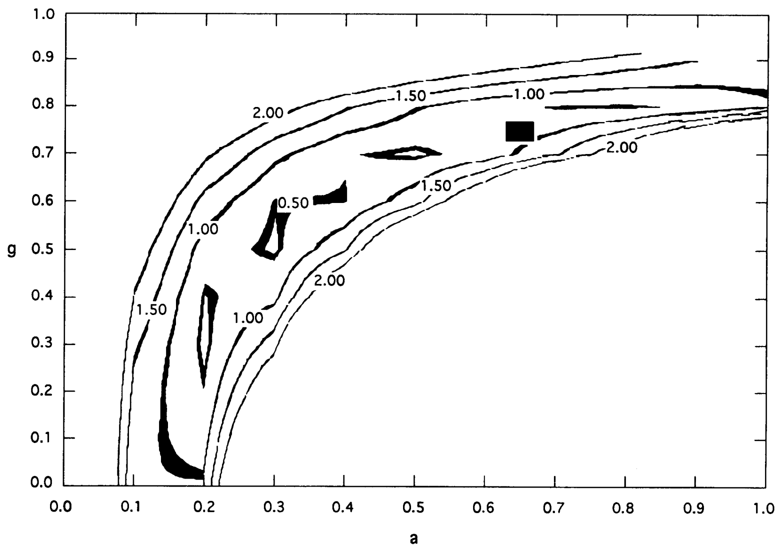

FIG. 3.—When an attenuated extragalactic component of 300 photons cm^{-2} s^{-1} sr^{-1} Å^{-1} is included in the model, the contours of χ^2 now include the measurement of Witt et al. (*black rectangle*), reconciling the UVX and UIT determinations of interstellar grain properties.

photons cm^{-2} s^{-1} sr^{-1} Å^{-1} near the Coalsack. These are all much larger intensities than the Berkeley intensities for the two low-latitude UVX targets.

It can be seen from Figure 1 that there is still a significant disagreement between the values of a and g resulting from our reanalysis of the UVX data and the values obtained by Witt et al. We therefore reran the model, now increasing the extragalactic term from zero to larger values. For assumed $a = 0.65$ and $g = 0.75$, the reduced χ^2 has a minimum at 300 units, allowing us to conclude (if our other assumptions are correct) that there is an extragalactic component of 300 ± 100 photons cm^{-2} s^{-1} sr^{-1} Å^{-1}. Our result for this best-fit value is shown in Figure 3, where we now see complete consistency between the UVX and UIT determinations of the optical properties of the interstellar grains in the ultraviolet.

3. DISCUSSION

The present result needs to be set in a context. The ultraviolet background was reviewed by Henry (1991). Subsequent to that review, Pérault et al. (1991) have reexamined the D2B-AURA measurements of the diffuse ultraviolet background of Joubert et al. (1983). Their 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 one-half to two-thirds of the ultraviolet flux is due to factors other than single scattering off dust. Pérault et al. believe that the major additional factor is light scattering in the instrument.

In another recent development, Wright (1992) has reanalyzed the data of Fix et al. (1989). The final word on this data set is almost certainly that of Witt & Petersohn (1994), who reconsider the approach of Wright and conclude that the data set implies a high value for a (~ 0.5), a high value for g (~ 0.9), and an extragalactic component of 300 ± 80 units, in excellent agreement with the present result.

4. CONCLUSION

Henry (1981), by comparing the interstellar far-ultraviolet radiation fields from *Apollo 17* (Henry, Anderson, & Fastie 1980) and *TD-1* (Gondhalekar et al. 1980), determined that the grain optical parameters are $a > 0.5$ and $g > 0.7$ in the ultraviolet. We now see considerable convergence on these values. In particular, we conclude that there is now complete consistency between the UVX results and the Witt et al. (1992) results concerning the optical properties of the interstellar grains in the ultraviolet. The price paid for actual agreement is the existence of an extragalactic flux of ~300 units. We have described a potential source for such radiation elsewhere (Henry 1991; Henry & Murthy 1993). Of course this conclusion depends on the grains in a nebula (NGC 7023) having optical properties that are similar to those of high Galactic latitude interstellar dust grains, which may not actually be the case.

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