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HOPKINS ULTRAVIOLET TELESCOPE OBSERVATIONS OF FAR-ULTRAVIOLET SCATTERING IN NGC 7023: THE DUST ALBEDO

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ABSTRACT

We have obtained the first sub-Lyα spectroscopic observations of the reflection nebula NGC 7023 and its illuminating star, HD 200775, using the Hopkins Ultraviolet Telescope during the Astro-1 mission in 1990 December. The ratio of the nebular to stellar flux is virtually flat between 1100 and 1860 Å, indicating that σ_a, the cross section for absorption, must rise sharply with decreasing wavelength. Independent of any model, this means that much of the far-ultraviolet rise in the extinction curve is due to an increase in absorption rather than scattering. If, in addition, we assume a spherical geometry, we derive an albedo of 0.5 at 1100 Å with somewhat higher values at longer wavelengths. If the geometry is not spherical, lower values of the albedo may be obtained.

Subject headings: dust, extinction — ISM: individual objects (NGC 7023) — reflection nebulae — ultraviolet: stars

1. INTRODUCTION

Studies of extinction curves and scattered starlight provide complementary methods for determining the optical properties of interstellar dust. However, uncertainties in both data and models have led to considerable variations in the parameters derived from the scattering observations, and standard grain models (e.g., Draine & Lee 1984) simply attempt to match the extinction curve. A thorough discussion of interstellar dust may be found in the review by Mathis (1990).

As one of the brightest reflection nebulae in the sky, NGC 7023 has been observed extensively from the ultraviolet to the far-infrared (see Casey 1991 for additional references). Although the structure of the nebula is actually quite complex (Casey 1991), its appearance in the UV is quite smooth (Witt et al. 1992), which, it is hoped, will simplify the modeling necessary to extract information about the optical properties of the dust grains. The central star, HD 200775 ($l = 104°$, $b = 14°$) is visible through the nebulosity as a 7.25 mag B3 Herbig Ae/Be star with $E(B-V) = 0.52$ (Casey 1991).

Based on a series of images of NGC 7023 obtained with the Ultraviolet Imaging Telescope (UIT) and on optical observations of dust scattering, Witt et al. (1992) have recently deduced an albedo (a) of about 0.65 and a phase function (g) of 0.7 at wavelengths greater than 1400 Å. We present here spectra between the Lyman limit (912 Å) and 1860 Å of both HD 200775 and a position offset by 22″ in the nebula obtained with the Hopkins Ultraviolet Telescope (HUT). From these spectra, which provide one of the very few (and certainly the highest quality) observations of scattering below Lyα obtained to date, we have constrained the albedo of the dust down to about 1100 Å, where the reddened stellar spectrum vanishes.

2. OBSERVATIONS

The Hopkins Ultraviolet Telescope (HUT) flew aboard the space shuttle Columbia in 1990 December on the Astro-1 mission. HUT consists of a 0.9 m mirror that feeds a prime-focus spectrograph with a microchannel plate intensifier and Reticon detector. First-order sensitivity covers the region from 830 to 1860 Å at 0.51 Å pixel^{-1} with ~3 Å resolution. Details of the spectrograph and telescope can be found in Davidsen et al. (1992), and an overview of the Astro Observatory, which included UIT, is given by Blair & Gull (1990).

The 18″ diameter circular aperture of the HUT spectrograph was placed on HD 200775 on the night of 1990 December 5 for 660 s and then offset 22″ northwest to a point in the nebula for another 1432 s. This nominal location for the nebular pointing had been chosen to correspond to the observation made using the *International Ultraviolet Explorer* (*IUE*) satellite (Witt et al. 1982); however, postflight analysis indicates that the actual pointing was at a location 25″–32″ from the star. On 1990 December 9 a second observation of HD 200775 was made with an exposure time of 2622 s, again at night. There was a considerable amount of pointing jitter in the first observation of the star, and so only the second stellar observation was used. This spectrum is plotted in Figure 1*a* with the nebular spectrum plotted in Figure 1*b*. From analysis of other HUT observations made near bright stars, we can place an upper limit of about 0.1% on the amount of instrumentally scattered light from HD 200775, or about 10% of the observed nebular flux. The fluxes obtained in this work are in good agreement with both the UIT (Witt et al. 1992) and *IUE* (Witt et al. 1982) fluxes, with the exception that the nebular flux is somewhat higher in the corresponding UIT image, probably due to contamination from the overexposed image of HD 200775.

The intense geocoronal Lyα (1216 Å) line is prominent in both spectra, and other airglow lines are identified in Figure 1. Absorption features of C IV λ1549 and Si IV $\lambda\lambda$1393, 1402, characteristic of B3 stars, are seen in the spectra, as well as absorption by interstellar and stellar H I Lyα λ1216. Finally, the Lyman and Werner bands of nebular H_2 are observed in absorption in the stellar spectrum.

The ratio of the nebular surface brightness (S) at the location observed with HUT to the observed stellar flux (F_*) is virtually constant from 1100 to 1860 Å (Fig. 2), despite the rapidly decreasing optical depth in the nebula. This is our primary

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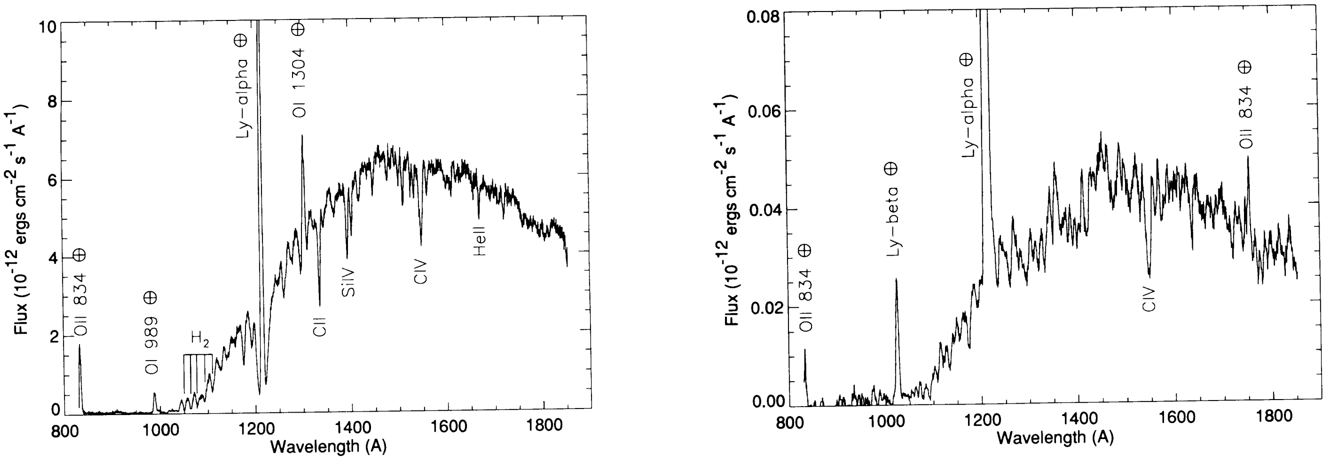

FIG. 1*a* FIG. 1*b*

FIG. 1.—(*a*) Spectrum of HD 200775 observed for 2622 s with the Hopkins Ultraviolet Telescope (HUT). (*b*) HUT spectrum of a point offset by 25″–32″ (pointing uncertainty rather than jitter) from HD 200775 in NGC 7023. Emission lines from the terrestrial atmosphere can be seen in both spectra and are identified in the stellar spectrum. Also observed are several stellar absorption features, such as C IV λ1550 and absorption by the Lyman and Werner bands of nebular H_2. The nebular spectrum has been smoothed over 5 bins.

observational result, and we will discuss its implications in § 4 after describing our model and its underlying assumptions.

3. ANALYSIS

Following Witt et al. (1982, 1992), we have used a Monte Carlo simulation of multiple scattering from a star centrally located in a spherically symmetric cloud to model the emission from the reflection nebula. We have assumed a uniform density distribution and a phase factor (g) of 0.7 (which was derived by Witt et al. 1992), since we cannot independently derive either of these parameters from our single observation. However, in practice, the ratio of the integrated nebular flux to the stellar flux, which is the observable we model, depends almost entirely on the albedo and the optical depth. It can be shown that, for a spherical geometry with predominantly forward-scattering grains, $F_N/F_* \approx a^m(1 - e^{-\tau})e^{\tau}$ (Witt et al. 1992), where m is the number of scatterings per photon. The dependence on geometry and g is now hidden in m, which is typically between 1.25 and 1.75 for this model.

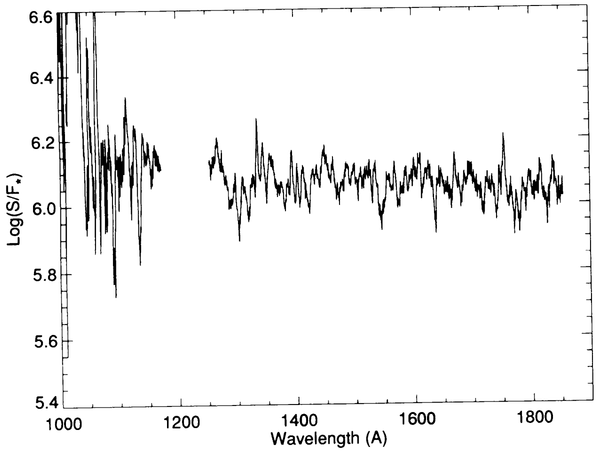

FIG. 2.—Logarithm of the ratio of the nebular surface brightness (S) at the location of the HUT 18″ aperture to the stellar flux (F_*) smoothed over 5 bins. The region around Lyα is dominated by the geocoronal line and has been excised. There is too little flux below about 1100 Å to allow the data to be used. The main observational result of this paper is the constancy of the ratio S/F_*.

Although infrared and radio observations of NGC 7023 have revealed a very complex and clumpy structure (Casey 1991; Sellgren, Werner, & Dinerstein 1992), we have assumed a spherical geometry for the nebula, primarily because of the difficulty in modeling any other situation. The morphology may be much simpler to model in UV than at other wavelengths because of the large optical depth at short wavelengths. We will effectively observe scattering from material within only about one optical depth of the surface, thus hiding nonuniformities in the interior of the nebula. The UIT images of the nebula are, in fact, quite smooth and symmetric (Witt et al. 1992), lending support to our use of spherical geometry. As a cautionary note, Chlewicki & Greenberg (1984) have shown that use of inappropriate geometries can lead to considerable errors in the optical constants derived (see below).

In order to obtain the optical depth in the nebula, we have derived an extinction curve to HD 200775, using a Kurucz (1979) model of effective temperature 18,000 K for the stellar spectrum. We obtain an excellent fit with $E(B-V) = 0.57$, using the formulation of Cardelli, Clayton, & Mathis (1989), consistent with the value 0.52 derived by Casey (1991). This total reddening can be divided into three parts: that intrinsic to the star: an ISM contribution (which will redden both the stellar and the nebular fluxes equally), and that actually in the nebula, which is responsible for the observed scattering. Witt et al. (1982, 1992) have assumed an optical depth at 1440 Å of 1.25 in the nebula, corresponding to $E(B-V) = 0.14$, with the rest divided between the star and the intervening ISM, to be consistent with the infrared radiation emitted by the grains (Casey 1991).

We have assumed the same optical depth at 1440 Å as used by Witt et al. ($\tau = 1.25$) and scaled to other wavelengths using the observed extinction curve. If we assume a spherical geometry, then this is the only model which is consistent with both the IR and the UV total fluxes. However, most of the observed emission in the UV will be from the first optical depth into the nebula with little contribution from dust farther in, unlike the IR, where the entire nebular contribution is important, because of the low optical depth in that spectral region. Hence, an alternative scenario might be to place the star just behind a hemispherical cloud. For a given column density in

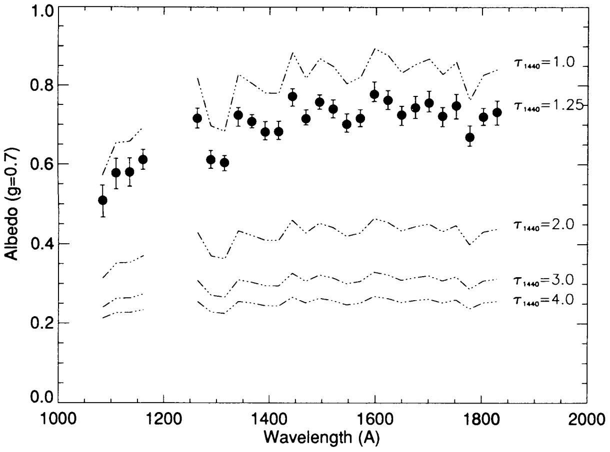

FIG. 3.—Albedo using $E(B-V) = 0.14$ in the nebula (the value assumed by Witt et al. 1982, 1992) plotted as filled circles with $\pm 1\ \sigma$ error bars. The spectra of Fig. 1 have been binned in groups of 50 to increase the signal-to-noise ratio. Also shown are a number of other models (*dashed lines*) corresponding to different amounts of extinction in the nebula. We have calculated these albedos assuming spherical models of the appropriate column density in front of the star. Although the IR constraints rule out these specific models, hemispherical models of the same optical depth (in front of the star) may be allowed (see text).

front of the star, the UV scattering would be unaffected, as the back of the cloud is hidden from view, while the IR emission would be halved. Thus we could make an albedo of as low as 0.3 at 1100 Å consistent with the observations (see Fig. 3).

4. DISCUSSION

Figure 3 exhibits our calculated albedos (*filled circles*), corresponding to a spherical geometry with $E(B-V) = 0.14$ in the nebula itself. As might be hoped, we derive an albedo consistent with that of Witt et al. (1992) in the region of spectral overlap. At shorter wavelengths, where τ increases, the albedo drops to a minimum of about 0.5 at 1100 Å. In the plot, we have binned F_N/F_* in groups of 50 points ($\sim$25 Å) and calculated error bars using the uncertainty in the mean for each group of 50 points. We have also shown a number of other curves corresponding to models in which more of the total reddening is associated with the nebula NGC 7023 itself. While these are calculated in the spherical case (when they would violate the IR constraint on the total flux) we do not expect the behavior of the albedo to change significantly for a hemispherical cloud, as discussed above. Note that the infrared luminosities predicted for a spherical nebula will range from 1800 to 3600 $L_\odot$ for optical depths (τ_{1440}) of between 1 and 4, respectively, compared with the observed luminosity of 900–1800 $L_\odot$ (Casey 1991; Whitcomb et al. 1981). If the back half of the nebula is removed, the predicted luminosities will be halved, in agreement with the observed values.

Much lower albedos have been derived through studies of the scattered starlight. Hurwitz, Bowyer, & Martin (1991) have found an albedo of about 0.2 at 1500 Å based on an experiment aboard the Space Shuttle, while Murthy, Henry, & Holberg (1991) placed an upper limit of 0.1 on the albedo below 1100 Å using the Ultraviolet System (UVS) spectrometers on *Voyager 2*. This is strong evidence that the nature of the dust grains is heavily affected by the environment, although uncertainties in the models of scattering in either the reflection nebula or the diffuse Galactic light may seriously compromise this conclusion.

The uncertainty in the exact pointing is immaterial in this analysis because we use the HUT spectrum only to scale the integrated nebular flux obtained at 1440 Å by Witt et al. (1992). There is an implicit assumption in this procedure that the ratio of the nebular flux to the stellar flux at any point in the nebula reflects the ratio of the integrated nebular flux to that of the star, an assumption borne out by *Voyager* observations of the entire nebula (Witt et al. 1993). By the same rationale, a uniform correction to the nebular flux of 0.1% of the stellar flux, to account for instrumental scattering, does not affect the analysis: we expect that instrumental scattering adds about 10% to the error bars derived above.

It is also interesting to calculate σ_s ($=a\tau$) and σ_a [$=(1-a)\tau$], the cross sections for scattering and absorption, respectively, and these are plotted in Figure 4. It is apparent that σ_s remains essentially constant over the entire wavelength region, while there is a significant increase in σ_a, implying that much of the far-ultraviolet (FUV) rise in the extinction curve (Fitzpatrick & Massa 1988) must be due to absorption rather than scattering. As the albedo drops with the rise in σ_a, this would suggest that the scattering is done primarily by large grains with a constant albedo throughout the entire spectral region and that a new low-albedo component, presumably small grains, becomes increasingly important to the scattering below about 1400 Å. We have performed similar calculations for other geometries in the cloud, finding that if we can associate more of the total reddening with the nebula, we can obtain a constant low albedo with an increase in σ_s at shorter wavelengths, consistent with an increase in the number density of the grains at smaller sizes.

5. CONCLUSIONS

We have found that the ratio of the nebular flux to the stellar flux (F_N/F_*) is relatively constant between 1100 and 1860 Å. The albedo derived from this result is heavily dependent on the actual amount of dust present in the nebula. However, if we use a spherical nebula with the column density in the cloud constrained by the IR emission of the cloud, we find an albedo of 0.5 at 1100 Å rising to 0.7 at 1800 Å. This is much higher than

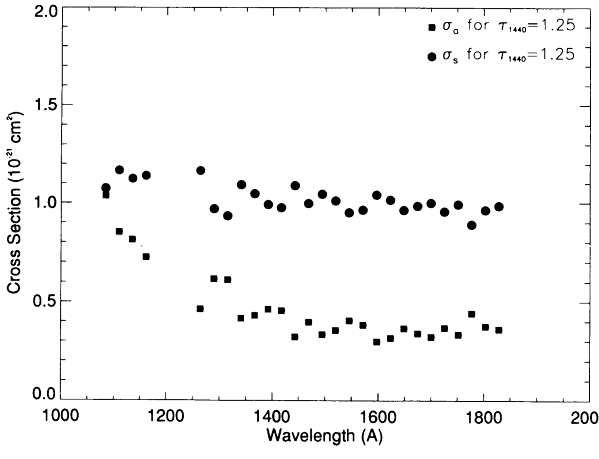

FIG. 4.—Cross sections for absorption (σ_a) and scattering (σ_s) are plotted for $E(B-V) = 0.14$; σ_a shows a sharp increase toward shorter wavelengths, implying that much of the FUV rise in the extinction curve must be due to an increase in absorption.

recent determinations of the albedo from observations of the diffuse UV radiation field (Murthy et al. 1991; Hurwitz et al. 1991), implying either that the environment of the grains strongly affects their characteristics or that there are difficulties with one or the other model. The rise in the extinction curve in the FUV is due to an increase primarily in σ_a (the absorption cross section). Again assuming the spherical model, this is evidence for a new population of low-albedo small grains.

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