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VOYAGER 2 OBSERVATIONS OF NGC 7023: DUST SCATTERING SHORTWARD OF 1600 Å

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ABSTRACT

We report the first observational determination of the nebular-to-stellar flux ratio out to wavelengths as short as 1000 Å for the reflection nebula NGC 7023, using a combination of spectroscopic data from *Voyager 2* and from the Hopkins Ultraviolet Telescope (HUT) on the Astro 1 mission. After accounting for contributions by H_2 fluorescence to the nebular flux, the wavelength variation of the ratio of the residual dust scattered flux to that observable from the embedded star is consistent with a reduction of the dust albedo by 25% over the wavelength interval 1300–1000 Å. This is most easily interpreted, if the particles responsible for the far-UV rise in the extinction curve are low-albedo, not necessarily zero-albedo, grains. The direct proportionality between the nebular surface brightness, measured at 22″ offset by HUT, and the nebular flux suggests that the phase function of scattering does not vary in the 2000–1000 Å range.

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

1. INTRODUCTION

Reflection nebulae are well-suited for the study of *relative* variations of the albedo and the scattering phase function of dust with wavelength, provided a number of conditions are met: (1) the wavelength dependence of the optical depth is known, (2) the nebular surface brightness distribution has been measured at several well-separated wavelengths, (3) the ratio of nebular to stellar flux is observed at several wavelengths. Such data exist for the bright reflection nebula NGC 7023 for a wide range of wavelengths from the near-IR to the far-UV (Sellgren, Werner, & Dinerstein, 1992; Grygar 1959; Roshkovskii 1965; Witt & Cottrell 1980; Witt et al. 1982; Witt et al. 1992; Murthy et al. 1993).

In this paper we report on observations of NGC 7023 and its illuminating star, HD 200775, with the ultraviolet spectrometer on *Voyager 2* (Broadfoot et al. 1977). When combined with the separate observation of HD 200775 alone, by the Hopkins Ultraviolet Telescope (HUT) on Astro 1, these data provide the first opportunity for extending the measurement of the ratio of nebular to stellar flux for this object to wavelengths as short as 1000 Å. Hence, new information can be derived about the variation of the dust albedo in that region of the far-UV spectrum, which is characterized by a steep rise in the extinction efficiency at $\lambda < 1500$ Å.

Recently, the scattering in NGC 7023 was explored with UV-filter images from the Ultraviolet Imaging Telescope (UIT) on Astro 1 (Stecher et al. 1992), covering the spectral range 1440–2800 Å (Witt et al. 1992). These data provided evidence for a relatively high dust albedo both longward and shortward of the 2175 Å extinction band, for the pure absorption nature of this band, and for an increasingly forward-directed phase function with decreasing wavelength. The present study relies upon the fact that the wide entrance slit of the *Voyager 2* spectrometer (FOV:0°.1 × 0°.87) admits almost the entire flux from NGC 7023, together with that from the centrally embedded star, HD 200775. The nebular flux may be determined separately by subtracting from the combined *Voyager 2* signal the flux of HD 200775, obtained by a separate observation with HUT (Murthy et al. 1993) during the Astro 1 mission. Thus, the ratio of nebular to stellar flux can be uniquely obtained. This quantity is principally dependent upon the dust albedo and the nebular optical depth in front of the star (Witt et al. 1992). We will show that regardless of the value chosen for the latter quantity, the dust albedo declines with decreasing wavelength shortward of 1500 Å, demonstrating that the rise in extinction at these wavelengths is caused by mainly absorbing particles.

We describe the observational data and their treatment in § 2 and discuss our analysis approach in § 3 of this paper. A discussion of the results and a summary are contained in §§ 4 and 5, respectively.

2. OBSERVATIONS

2.1. *Voyager 2 Data*

The *Voyager 2* ultraviolet spectrometer (UVS) is an objective grating instrument covering the wavelength range 500–1700 Å, with a spectral resolution of approximately 18 Å for a point source and 30 Å for a diffuse source. Use of this instrument for astronomical observations is described in Holberg (1990).

NGC 7023 was observed by *Voyager 2* on 1991 September 20, for a period of 7 days. During this time, approximately 120,000 spectra were returned. Near the end of this period, NGC 7023 had begun to drift out of the field of view. The best

[1] Guest Observer with the *Voyager* Ultraviolet Spectrometers.

data, covering the period September 20 to September 24, are presented here.

The attitude control motion of the spacecraft caused the field of view to slowly oscillate with respect to the position of NGC 7023. This motion, which had a peak-to-peak amplitude of 0°.16 on the sky, allowed spatial coverage of virtually the entire nebula. Although a relatively faint source for *Voyager*, NGC 7023 was easily located when the data were spatially binned. Spectra were extracted using standard techniques which averaged all spectra lying within $\pm 0°.035$ of the center of the nebula. This resulted in an effective integration time of 151,255 s. The slit orientation during this exposure was at position angle 98°.6, i.e., almost east–west.

In the region of wavelength overlap with previous observational programs, the *Voyager 2* fluxes are in excellent agreement with the observation of NGC 7023 and HD 200775 with *TD-1* by Viotti (1976), and the sum of the nebular flux observed with UIT (Witt et al. 1992) and stellar flux observed with *IUE* (Witt et al. 1982). This provides assurance that the relative changes of the scattering properties to be derived for wavelengths less than 1300 Å will indeed be consistent with previous work.

The *Voyager 2* spectrum of NGC 7023 plus HD 200775 is shown as the uppermost dashed curve in Figure 1.

2.2. *HUT Data for HD 200775*

HD 200775 was observed with the HUT spectrograph through an 18″ aperture on 1990 December 5, and again on 1990 December 9, with respective exposure times of 660 s and 2622 s, and we used only the second spectrum. The resolution of the original spectrum which covered the range from 830 to 1860 Å in first order, was approximately 3 Å. The HUT spectrum of HD 200775 is shown in Figure 1, where we have degraded the resolution to match that of the *Voyager 2* spectrometer. We have reproduced only those sections of the spectrum which correspond to the usable portions of the *Voyager 2* spectrum. A complete reproduction and discussion of the HUT spectrum of HD 200775 is provided by Murthy et al. (1993).

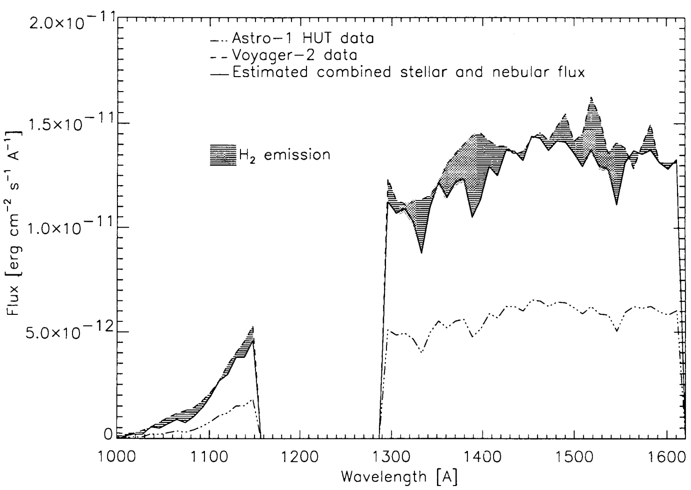

FIG. 1.—The combined spectrum of NGC 7023 and HD 200775 as observed by the ultraviolet spectrometer on *Voyager 2* is shown over its usable wavelength region. A separate spectrum of HD 200775, obtained by HUT and degraded to the *Voyager 2* resolution, is plotted for the same wavelength region on the identical scale. The procedure for determining the combined stellar and nebular flux, corrected for H_2 emission, is described in the text.

Again, in the wavelength region of overlap between the HUT spectrum of HD 200775 and earlier *IUE* data of the same star (Witt et al. 1982), the agreement is better than within 10%.

3. ANALYSIS

3.1. *Separation of Scattered Nebular Light and* H_2 *Fluorescence*

The usable portions of the *Voyager 2* spectrum of NGC 7023 and HD 200775 (Fig. 1, *top curve*) extend in wavelength from 1000 to 1150 Å and from 1290 to 1620 Å. The gap between 1150 and 1290 Å is contaminated by backscattered solar Lyα radiation, arising from interstellar H I which has penetrated the heliospheric cavity; these data have been eliminated.

The signal in the *Voyager 2* spectrum arises from three principal sources: the flux from the central star, dust-scattered starlight from the surrounding nebula NGC 7023, and H_2 fluorescence emission originating in photodissociation regions within NGC 7023 (e.g., Chokshi et al. 1988).

In contrast to the UIT data (Witt et al. 1992), the *Voyager 2* observation of NGC 7023 provides no spatially resolved surface brightness measurements. Our analysis must therefore be based on a determination of the ratio of total dust-scattered nebular flux to observed stellar flux as a function of wavelength. This requires a separation of the nebular flux into components due to dust scattering and due to H_2 fluorescence. We utilize the fact that the H_2 fluorescence spectrum reaches very low relative intensities longward of 1600 Å and in a 50 Å band around 1320 Å (Witt et al. 1989; Sternberg 1989), and we interpret the level of the *Voyager 2* spectrum there as due to the sum of stellar and dust-scattered nebular flux alone.

The dust-scattered light should have a spectral distribution similar to that of the illuminating source. For the 1620–1290 Å range we find that scaling the flux of HD 200775 by a factor of 2.20 nearly matches the *Voyager 2* spectrum at both end points; in order to achieve zero H_2 flux at 1320 Å, scaling by a factor 2.33 would be required. This nearly constant scaling factor is consistent with the HUT measurement of the ratio of nebular surface brightness to stellar flux of NGC 7023 at an offset of 22″, which is also found to be constant over this range (Murthy et al. 1993). The excess above the HUT spectrum scaled by 2.20 is interpreted as H_2 fluorescence, as shown in Figure 1 as a cross-hatched area. We estimate that the H_2 fluorescence component contributes about 15% to the total nebular flux in the 1300–1600 Å range.

The H_2 fluorescence contribution shortward of 1150 Å is more difficult to estimate. Predictions of the relative intensity of this emission in the 1000–1150 Å range compared to the 1300–1600 Å range (Sternberg 1989) suggest an increase by factors of 2–3, depending on prevailing conditions. However, the internal opacity of the nebula due to dust extinction and H_2 absorption in this range is also substantially greater. If we assume that H_2 emission in the 1000–1150 Å range contributes 15% to the total nebular flux, probably a lower limit, we find for the resulting ratio of scattered nebular to stellar flux the value 1.70.

If, as appears more likely, the H_2 contribution is about 25% of the nebular flux, the ratio of dust-scattered light to stellar light reduces to 1.50. This value is consistent with the small increase in nebular surface brightness at 22″ offset found by HUT (Murthy et al.) for the 1000–1150 Å range compared with the 1300–1600 Å range, when normalized to the stellar flux. The HUT observation of NGC 7023 at 22″ offset shows no measurable spectral feature of H_2 fluorescence and may therefore be used to first order as an indicator of the nebular brightness due to dust scattering.

3.2. *Corrections for Beam Efficiency*

While the *Voyager 2* spectrometer entrance slit is long and wide enough to accept most of the image of NGC 7023, the response perpendicular to the slit is not uniform for off-axis rays. Given the known orientation of the slit and the known slit response function, we convolved the latter with the two-dimensional brightness distribution of NGC 7023, based on the deepest UIT-B1 image (Witt et al. 1992). The result is that about 82% of the nebular flux contained within a radius of 300" from HD 200775 is accepted by the spectrometer when HD 200775 is on-axis. As a result, the addition of H_2 fluorescence to the nebular flux and the reduction of the detected flux due to beam limitations approximately cancel in the case of NGC 7023.

3.3. *Comparisons with Radiative Transfer Models*

We employed the Monte Carlo radiative transfer model of Witt et al. (1982, 1992) to compute predicted values for the ratio of nebular to stellar flux. For a completely embedded star, this ratio is independent of distance, only marginally dependent on the phase function and the nebular density distribution, but strongly dependent on the albedo and the nebular optical thickness. Model results for a spherical nebula with a centrally embedded star and a phase function asymmetry $g = 0.75$ are given in Figure 2 for a range of albedos $0.2 \leq a \leq 0.8$ and for optical depth radii $\tau \leq 5$.

Before a comparison between observational results and predictions is possible, one needs to determine the optical depth in front of the star, which can be assigned to the nebula proper as compared to the total optical depth arising from dust along the entire line of sight.

NGC 7023 is located at galactic latitude $b = +14\overset{\circ}{.}2$, embedded in the isolated dark cloud L1174. The extent of this dark cloud has been mapped with CO observations by Elmegreen & Elmegreen (1978), and by Watt et al. (1986). A typical radius of NGC 7023 on the deepest optical and UV images is about 40% of the typical radial scale of L1174. Even if one assumes that there is no dust along the line of sight except for that in L1174, one may then attribute 40% of the reddening observed in HD 200775 to the nebula proper. The color excess $E(B-V)$ for HD 200775, corrected for intrinsic reddening typical for Be stars, has been determined as 0.44 or 0.45 (Witt & Cottrell 1980; Pfau, Pirola, & Reimann 1987); and the separation of the observed linear polarization into intrinsic and interstellar components suggests a normal dust size distribution, i.e., $R_v \simeq 3.1$. On this basis, Witt et al. (1982, 1992) adopted $\tau = 0.54$ as the optical depth radius for NGC 7023 at V as a measure of the average dust column density within 1 pc radius of HD 200775.

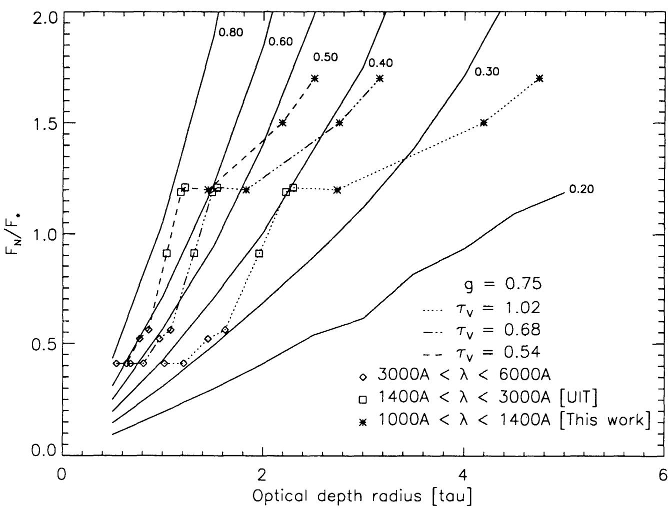

FIG. 2.—The observed ratios of nebular-to-stellar flux, including data from ground-based studies and UIT observations (Table 1), are compared with theoretically predicted ratios of this quantity (*solid lines*). The numbers appearing to the right of each solid line are the corresponding constant albedo values. The optical depth radius τ is the optical depth of the cloud surrounding HD 200775 out to a radius of 1 pc. Three cases of the observed set of F_N/F_* values, attributing respectively, 75% ($\tau_v = 1.02$), 50% ($\tau_v = 0.68$), and 40% ($\tau_v = 0.54$) of the total line-of-sight optical depth to HD 200775 to the nebula within 1 pc of the star, are represented. Deviations of the lines connecting corresponding observed points from the solid lines are indicative of a wavelength-dependent albedo.

The scaling of the optical depth radius into the UV to $1/\lambda = 8[\mu^{-1}]$ was done with the observed extinction curve for HD 200775 by Walker et al. (1980). An extension of this curve to shorter wavelengths was possible with studies of the far-UV extinction approaching the Lyman limit by York et al. (1973), Snow, Allen, & Polidan (1990), and Green et al. (1992).

In Table 1 we list the adopted optical depth radii for NGC 7023 for the wavelengths at which the flux ratio has been determined. In addition to the case of $\tau_v = 0.54$, which has been the basis of past studies of NGC 7023, we also include cases in which we attribute 50% and 75% of the total line-of-sight optical depth to NGC 7023, corresponding to $\tau_v = 0.68$ and $\tau_v = 1.02$, respectively.

TABLE 1

NGC 7023: OBSERVATIONAL DATA AND MODEL PARAMETERS

			OPTICAL DEPTH RADIUS OF NGC 7023			
BANDPASS	λ[Å]	$(F_N/F_*)_{0-300''}$	$\tau_v = 0.54$	$\tau_v = 0.68$	$\tau_v = 1.02$	SOURCE
y or *V*	5515	0.41	0.54	0.68	1.02	1
b	4733	0.43	0.64	0.81	1.21	1
v	4093	0.54	0.77	0.97	1.45	1
u	3470	0.56	0.86	1.08	1.62	1
UIT-A1	2763	0.91	1.04	1.31	1.96	2
UIT-B5	1518	1.19	1.18	1.49	2.23	2
UIT-B1	1443	1.21	1.25	1.58	2.36	2
Voyager-UV1	1300	1.20	1.45	1.83	2.74	This work
Voyager-UV2	1111	1.50	2.19	2.76	4.14	This work
Voyager-UV3	1000	1.70	2.51	3.16	4.74	This work

REFERENCES.—(1) Witt et al. 1982; (2) Witt et al. 1992.

We overplotted the theoretical predictions for constant albedos ($0.2 \le a \le 0.8$) shown in Figure 2 with the observations for the three model cases. Regardless of which particular set is chosen, the slopes defined by the *Voyager 2* data in the far-UV are substantially and consistently less than those for the model curves for constant albedo falling into the same region of the diagram. As the optical depth increases with decreasing wavelength, the albedo declines in NGC 7023. Independent of the particular optical depth assumptions, the decline of the albedo amounts to about 25% in the wavelength range from 1300 to 1000 Å. Accepting the optical depths $\tau_v = 0.54$ and $\tau_v = 0.68$ as the most likely range for NGC 7023, we derive $a(1000\ \text{Å}) = 0.42 \pm 0.04$.

4. DISCUSSION

4.1. *Impact on Dust Models*

The present result of a decline in the dust albedo at decreasing wavelengths shortward of 1500 Å provides an important constraint for current dust models. In most such models (see Mathis [1990] for recent review), the region of the far-UV rise in the extinction curve shortward of 1500 Å is attributed to a population of very small grains or organic molecules. Underlying the extinction caused by this population is the still present scattering and absorption by larger grains, which are also responsible for interstellar reddening in the visible and near-IR regions. It is not certain how the extinction contributions of these two populations add at far-UV wavelength; if one assumes that the larger grains saturate at 1500 Å and all further increase in extinction at shorter wavelengths is due to the small-grain component, our results indicate that the small grains have a low but nonzero albedo; i.e., the overall decrease of the albedo below the level found at 1500 Å is smaller than the relative increase in extinction above the level at 1500 Å. The actual value of the albedo of the small grains at 1000 Å is model-dependent and ranges from 0.3 for $\tau_v = 0.54$ to 0.1 for $\tau_v = 1.02$. A zero albedo for the far-UV absorbers, characteristic of molecules, could be accommodated by our results only if a significant fraction of the far-UV rise is contributed by the larger grains, i.e., the extinction to the larger grains would not saturate at 1500 Å. In particular, if the large grains would retain their albedo measured at 1500 Å, only about 37% of the total extinction at 1000 Å could be attributed to small-grain zero-albedo absorbers, instead of 50% in the previously assumed case of small low-albedo grains.

It is well documented that the wavelength dependence of galactic interstellar extinction is spatially variable, mainly in the UV (e.g., Witt, Bohlin, & Stecher 1984). If this variability is due to differences in the contribution made by different grain components to the total extinction, we expect, on the basis of our result, that the far-UV albedo of dust in different clouds will differ as well. We predict that the albedo will be higher, the less steep the far-UV extinction curve. For example, the decline of the albedo shortward of 1300 Å found in NGC 7023 should be essentially absent in the Orion Nebula, which is characterized by a mostly flat far-UV extinction curve.

4.2. *The Phase Function Asymmetry*

The conclusions drawn by Murthy et al. (1993) regarding the dust albedo in NGC 7023 is in fundamental agreement with our present result. The agreement is based on the fact that the surface brightness of NGC 7023 at 22″ offset, the quantity measured by HUT, is directly proportional to the entire nebular flux, the quantity modeled by Murthy et al., over the wavelength region under consideration. Given that the surface brightness at small offsets is determined mainly by single scattering (Witt & Oshel 1977), this proportionality really implies that the phase function of scattering is unchanged over the same spectral range. We conclude therefore, that the far-UV range of declining dust albedo is characterized by the same phase-function asymmetry that determines the scattering at longer wavelengths. The analysis of UIT images of NGC 7023 had led to a result for the asymmetry factor of $g = 0.75$ for $\lambda < 2000$ Å (Witt et al. 1992). This result is easily understood theoretically if the larger grains in NGC 7023 dominate the scattering even in the UV. The minor scattering contribution from the small low-albedo grains, probably isotropic in nature, has little chance of affecting the overall scattering pattern in a geometry with a centrally embedded star, such as NGC 7023.

5. CONCLUSIONS

The present results, as well as the comparison of these results with those of Murthy et al. (1993) lead us to two conclusions, which are independent of any particular model for NGC 7023:

1. The dust albedo in the far-UV declines as the extinction increases steeply. The decline amounts to about 25% between 1300 and 1000 Å. This behavior is understood most easily if one assumes that the increasing extinction in the far-UV is produced by an additional grain component which is highly absorbing.

2. The phase function asymmetry of scattering in the 1600–1000 Å range is approximately constant.

When specific reference is made to the model of Witt et al. (1982, 1992), which has yielded a consistent interpretation of observations of NGC 7023 from the visible into the UV, we can further conclude:

3. A likely dust albedo value is $a = 0.42 \pm 0.04$ at $\lambda = 1000$ Å for NGC 7023.

4. The phase function asymmetry is constant near $g = 0.75$ in the far-UV, slightly larger than it is found to be in the visible.

A general prediction made very likely by our results is the following:

5. The far-UV albedo is likely to be spatially variable, with consistently higher albedo associated with clouds characterized by flat UV extinction curves.

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