THE ASTROPHYSICAL JOURNAL, 428:233–236, 1994 June 10

VOYAGER OBSERVATIONS OF DUST SCATTERING NEAR THE COALSACK NEBULA

JAYANT MURTHY[1] AND R. C. HENRY[1]
Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218
AND
J. B. HOLBERG
Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721
Received 1993 August 2; accepted 1993 December 9

ABSTRACT

We present the results of four observations of the sky in the direction of the Coalsack nebula. These observations were made using the ultraviolet spectrometers aboard the two *Voyager* spacecraft in the spectral range between 912 and 1600 Å. Intense diffuse emission with a spectrum characteristic of an early B star was observed in all four targets, which we interpret as starlight forward scattered by interstellar dust in the foreground of the main mass of the Coalsack. While more detailed modeling is necessary to derive values for the optical constants of the dust grains, our data indicate that there is no decrease in the albedo toward shorter wavelengths, arguing that the far-ultraviolet rise in the interstellar extinction curve is due to an increasing number density of small particles rather than to a new population of low albedo grains.

Subject headings: dust, extinction — ISM: individual (Coalsack) — ultraviolet: ISM

1. INTRODUCTION

The albedo (a) and phase function (g) are among the most fundamental properties of the interstellar dust, yet they are poorly known over the entire spectral range. Not only is the determination of the optical constants crucial to understanding the nature and composition of interstellar dust but, as the dust plays a major role in the reprocessing of starlight, it is also necessary in modeling the energetics of the Galaxy. One of the best spectral regions to observe and interpret scattering by interstellar dust, and where the largest fraction of the incident energy is absorbed, is the ultraviolet, largely because of the lack of competing sources of diffuse emission. Technical difficulties have often limited the usefulness of such observations (Bowyer 1991; Henry 1991) and the derived optical constants have often been wildly divergent (see Table 2 in Bowyer 1991). While some of these variations may be due to actual differences in the properties of the grains in different environments, most probably reflect the difficulty of the observations and analysis.

We present here the results of three observations near the Coalsack nebula made with the ultraviolet spectrometers (UVSs) aboard the two *Voyager* spacecraft. While the planetary observations of the two *Voyager* spacecraft have been well documented, the UVSs have also carried on an active program of astronomical observations which ceased only early this year. The two spectrometers are almost identical, the primary difference being a factor of 2 in sensitivity in favor of the *Voyager 2* UVS. The spectral coverage is from about 500 Å to 1600 Å, although the sensitivity drops considerably at wavelengths greater than Lyα, with a resolution of 38 Å for diffuse sources ($\sim$18 Å for point sources), and a field of view of $0.^\circ8 \times 0.^\circ1$. A full description of the spacecraft and instrumentation is given by Holberg (1991).

The Coalsack nebula is one of the most prominent dark nebulae in the southern sky, easily visible to the naked eye as a dark patch against the rich star field of the Milky Way. Our observations of the Coalsack were part of a program to map the diffuse far-ultraviolet radiation field (Murthy, Henry, & Holberg 1991; Murthy et al. 1993). We had expected a moderate to low signal due to back scattering of the light from three nearby early B stars in front of the Coalsack—α Cru, β Cru, and β Cen—from dust in the nebula; instead we detected the brightest patch of scattered light (from the diffuse interstellar medium) yet observed in the UV. This emission, which reaches an intensity of about 30,000 photons cm^{-2} s^{-1} sr^{-1} Å^{-1} at 1100 Å, is primarily due to forward scattering of the light from the three stars above, which are three of the brightest FUV sources in the terrestrial sky, by a relatively small amount of dust in the foreground of the Coalsack, itself. While detailed modeling will be necessary to extract the actual values of the optical constants, we find no evidence for any change in the optical constants over the spectral range between 912 and 1400 Å.

2. OBSERVATIONS AND DATA ANALYSIS

Our observation log is in Table 1 with the locations of the targets plotted in Figure 1. Although the locations of targets A and B coincide, they were made using different spacecraft and hence had different orientations in the sky. The exact locations of the observations were chosen such that no stars of B9 or earlier were in the field of view; however, a post-observation search in the SKYMAP star catalog (Gottlieb 1978) and the SIMBAD database has revealed a faint B6 star in the field of view of target C. We will discuss the contributions of these stars to our observed signal below. Note that no star, regardless of its brightness, of spectral type later than A0 will contribute any flux shortward of 1200 Å.

The observations were made in the "Cruise 5A" mode consisting of individual 240 s integrations which we have summed over time. This integrated spectrum can be decomposed into three parts: an instrumental dark count, due to radiation from the spacecraft's radioisotope thermoelectric generator (RTG); emission lines from resonantly scattered solar radiation; and a residual containing any astrophysical signal. The shape of the dark count spectrum has been independently determined from observations of a shadowed region on the spacecraft (Holberg 1986) and the level in our data is

---

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

1994ApJ...428..233M

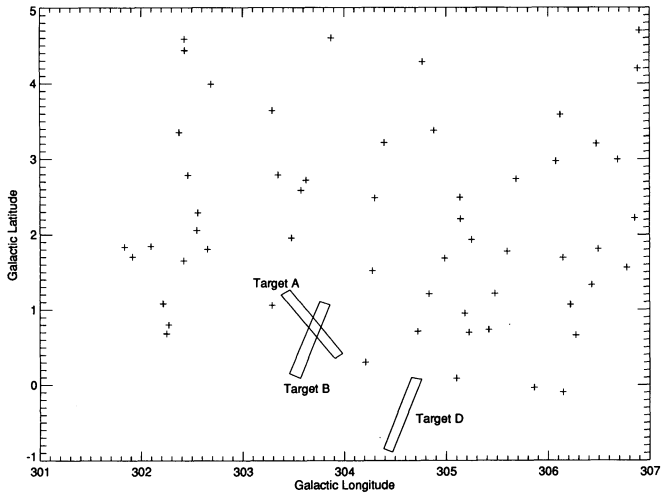

FIG. 1.—The positions of the UVS slits are shown for targets A, B, and D against those nearby stars nearer than 250 pc which were observed by Franco (1993). The two parallel slits are the *Voyager 2* observations while the other observation was made with *Voyager 1*. Target C is approximately 4° south of target D and is not in the field shown here. The star near the upper left hand corner of target A has an extinction (A_V) of 1 mag at a distance of 180 pc while the star to the lower right-hand corner has an extinction of 0.31 at a distance of 153 pc. The extinction is rather patchy over the whole field.

TABLE 1

OBSERVATION LOG

Target	l	b	Exposure Time (s)	Spacecraft
A.........	303.7	0.8	320,160	*Voyager 1*
B.........	303.7	0.8	135,662	*Voyager 2*
C.........	305.2	−5.7	62,494	*Voyager 2*
D.........	304.6	−0.4	31,230	*Voyager 2*

unambiguously set from the spectral region below the Lyman limit (912 Å), where the opacity of the interstellar medium (ISM) is so high that no astrophysical signal will be seen. Following the dark count subtraction, instrumental scattering is removed by applying a matrix operator determined from preflight calibrations. The resultant spectra, which still include the interplanetary lines of H I Lyα (1216 Å) and Lyβ (1026 Å), and He I (584 Å), are plotted in Figure 2.

Rather than attempt to subtract the interplanetary lines directly, we follow Murthy et al. (1993) in simultaneously fitting the data with a template for the interplanetary emission and a model for the diffuse radiation field. The template for the *Voyager 1* observation was constructed out of a long (10^6 s) exposure of the north Galactic pole in which no cosmic signal was detected (Holberg 1986). The corresponding template for

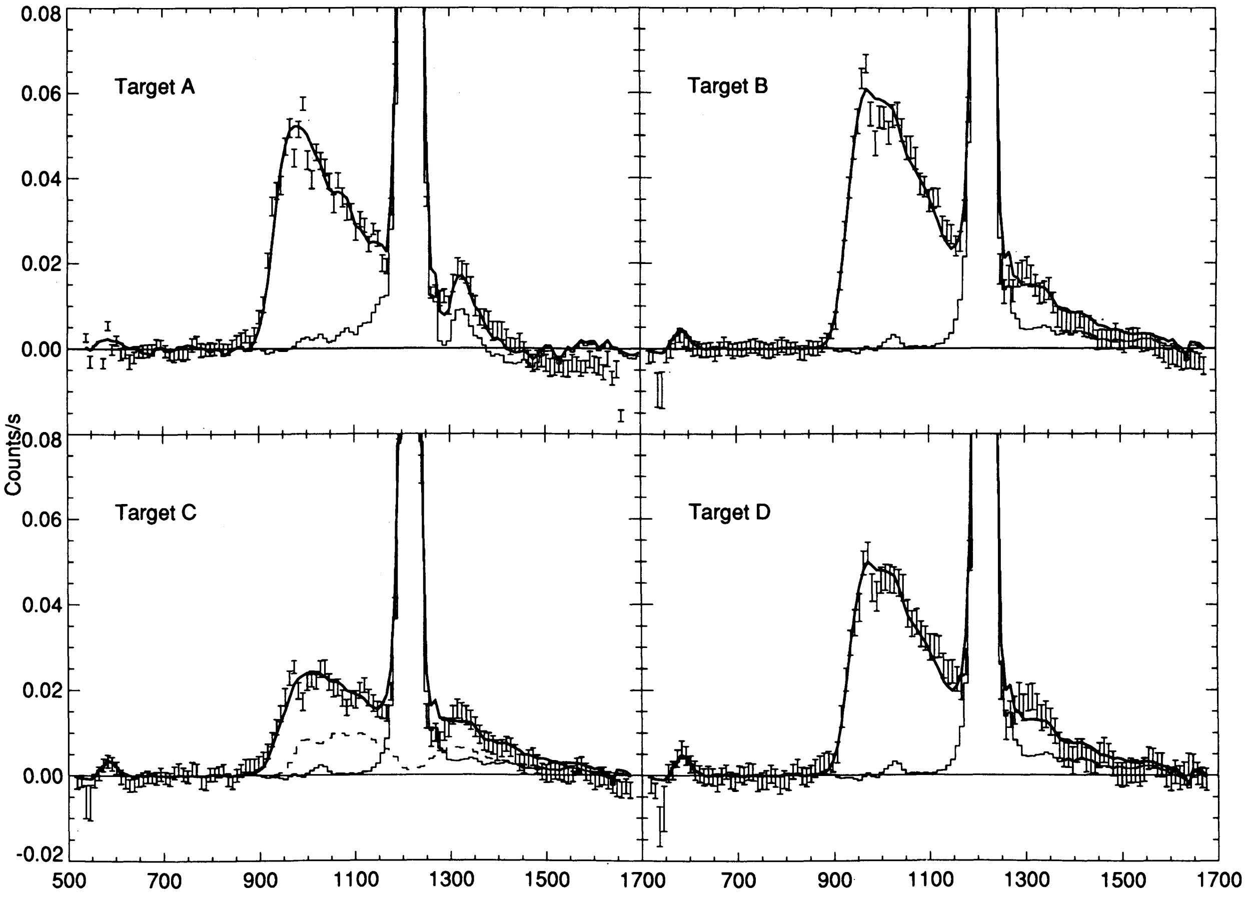

FIG. 2.—The observed data are plotted as ±1 σ error bars for each of the four targets. The dark line represents our best-fit model (which includes the interplanetary lines); the thin solid histogram is the scaled template; and the dashed line (in target C) represents the stellar contribution to the spectra, if any. Targets A, B, and D all have spectra representative of a B0 star; target C has been contaminated by a B6 star in the field of view.

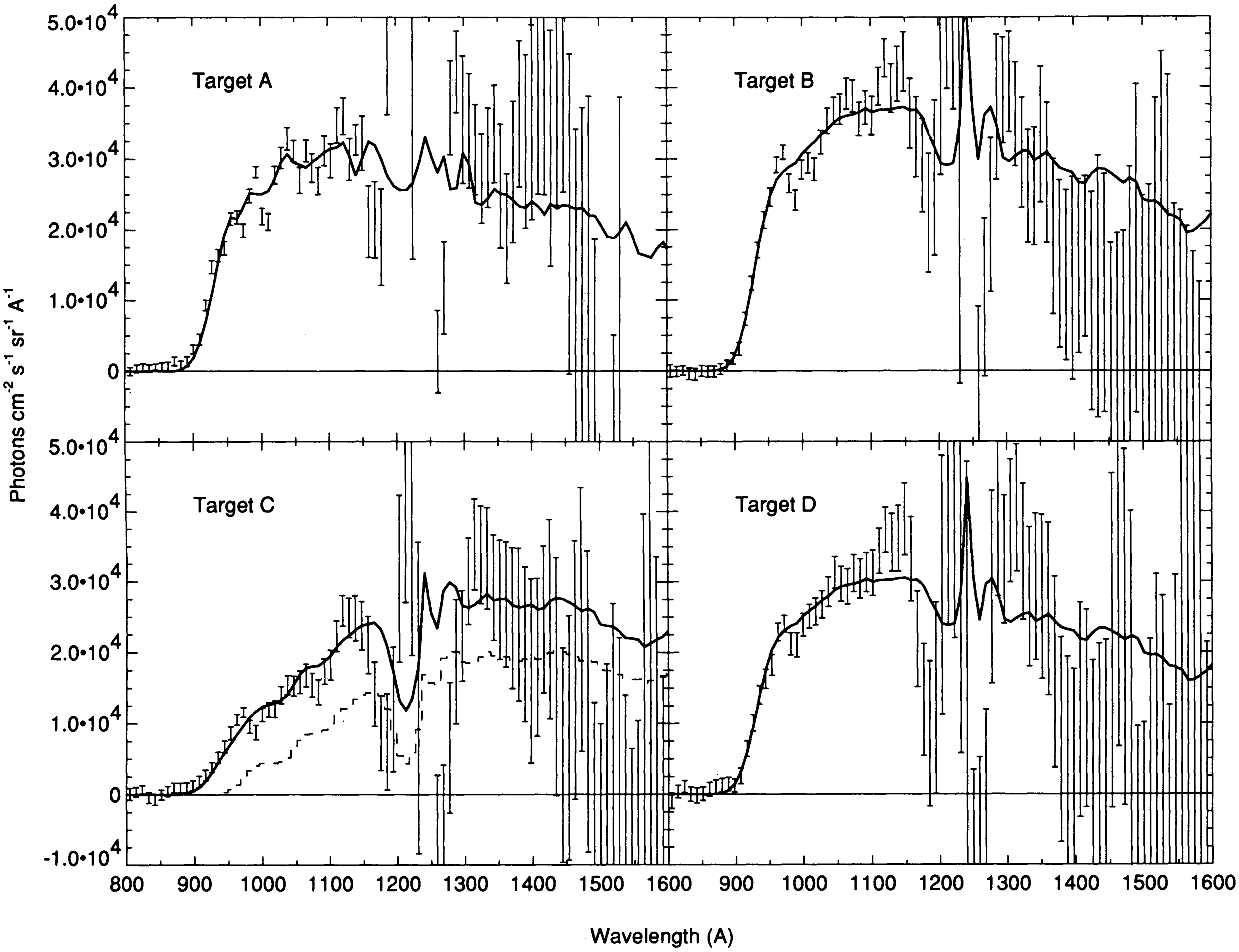

FIG. 3.—The calibrated intensities are plotted as ±1 σ error bars for each of the four targets after subtraction of the template. Note the low confidence of the data above 1500 Å.

the *Voyager 2* observations was constructed out of a weighted average of targets A, B, and D of Murthy et al. (1991) (their target C was rejected because of evidence for a weak cosmic signal) and a new observation of the high-latitude optical nebulosity first detected by Sandage (1976). In none of these observations was there any indication of a cosmic signal. We have checked the consistency of the template for *Voyager 2* by applying it to each of its components, finding no residuals. The two templates were scaled to the corresponding observations using a least squares method and subtracted with the resulting spectra plotted in Figure 3. In practice, our observed signals are so strong that only in the vicinity of the intense heliospheric Lyα line is the template subtraction important.

3. DISCUSSION

A detailed search of our fields of view using the SKYMAP star catalog and the SIMBAD database has found a B6 star [HD 115017; $V = 8.3$; $E(B-V) = 0.06$] in target C. We have modeled this star using Kurucz (1979) spectra of the appropriate temperatures and plotted its expected contribution to the observed signal in Figure 2*c*, where it provides almost half of the signal observed at wavelengths above 1000 Å. The star is too cool to emit significantly at shorter wavelengths and thus the continuum below 950 Å is entirely due to dust scattering. Because the instrumental response is not uniform across the aperture of the UVS, the signal due to a point source will vary with the attitude control motion of the spacecraft. Based on the lack of such variation in our data, we have set limits of about 20% on the contribution of any point sources to our diffuse signal in the other locations.

The dense mass of the Coalsack, at a distance of about 200 pc from the Sun, acts as a curtain blocking light from any star not in the foreground, especially in the FUV. In addition, three of the five brightest (as seen from the Earth) stars in the FUV are located at distances between 100 and 160 pc directly in front of the nebula (Table 2). Hence the radiation field at any point between the Sun and the Coalsack nebula is dominated by these three stars, all early B type, and can be well modeled by a B0 Kurucz (1979) spectrum. As mentioned above, we had originally expected to see only backscattered light from the dust in the nebula, which dominates the extinction in the line of sight. However, unless the scattering is predominantly backscattering ($g < 0$), the Coalsack itself can, under the most

TABLE 2

DOMINANT STARS

Star	Spectral Type	l	b	d (pc)	A_V (mag)
α Cru (HD 108248)	B0.5 IV	300.13	−0.36	114	0.09
β Cru (HD 111123)	B0.5 III	302.46	3.18	163	0.06
β Cen (HD 122451)	B1 III	311.77	1.25	90	0.09

favorable circumstances and assuming perfect reflectivity, produce no more than about 5000 photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \text{Å}^{-1}$. Detailed extinction studies (Franco 1989; Seidensticker 1989) show a significant amount of dust in the foreground; i.e., between the Coalsack and the Sun, and, in particular, between the three hot stars and the Sun, and it is this dust which contributes the largest fraction of the observed signal.

We have attempted to model the amount of scattered light using a variety of dust distributions; unfortunately, small variations in this distribution have a relatively large effect on the observed intensity. While we can easily reproduce the observed data with as little as 0.1 mag of reddening in the foreground or an albedo as low as 0.1, the uncertainties in the distribution are large enough that we cannot place useful limits on the derived optical constants. We should note parenthetically that molecular hydrogen fluorescence (e.g., Sternberg 1989) cannot account for more than about 1%–2% of the observed signal.

Independent of any model we can derive the simple relationship $I_o/I_* \propto a\sigma e^{-n\sigma}$—where I_o and I_* are the observed and incident intensities, respectively, a is the grain albedo, σ is the extinction cross section per H I atom (from Draine & Lee 1984) and n is the total H I column density along the line of sight—if the phase function g is constant over the spectral range involved and if every photon observed has been scattered once and once only. Using this formulation, a lower limit of 10^{20} cm^{-2} on the H I column density [corresponding to an A_V of 0.3 mag from Franco 1993 with $A_V/E(B-V) = 3.1$ and $n(\mathrm{H})/E(B-V) = 5.8 \times 10^{21}\ \mathrm{cm}^{-2}$; Bohlin, Savage, & Drake 1978), and arbitrarily fixing the albedo at 0.5 at 1400 Å, we can derive the spectral behavior of the albedo (Fig. 4). We have used only the spectrum from target B in this derivation; similar results are obtained if we use target D. If a new population of zero albedo small grains were responsible for the FUV rise in the extinction curve (cf. Witt et al. 1993), we would expect the albedo to drop significantly at short wavelengths. No such trend is seen in our data, perhaps implying an increase in the number density of the small grains rather than a dramatic change in their optical constants. It should be noted that the optical properties of the grains may be highly dependent on their environment and hence there should be no a priori expectation that the results derived here should match those elsewhere, particularly those obtained from a bright reflection nebula such as NGC 7023 (Witt et al. 1993), barring the aesthetics of minimizing the number of parameters involved.

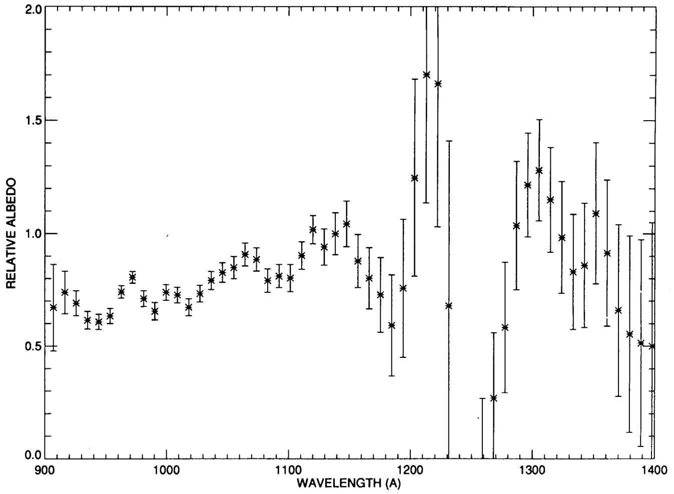

FIG. 4.—The relative spectral behavior of the albedo, fixed to be 0.5 at 1400 Å, is plotted as ±1 σ error bars (using photon statistics only). Only target B has been used in this analysis; similar results are obtained from target D. Targets A and C are of lower quality with target C being contaminated by a star in the slit. There is no significant decrease in the albedo toward short wavelengths suggesting that the FUV rise in the extinction curve is not due to a new population of low albedo particles. We have assumed an extinction (A_V) of 0.3 mag; higher extinctions will cause the relative albedo to be even higher at short wavelengths.

4. CONCLUSIONS

We have observed intense diffuse FUV radiation in several locations in the direction of the Coalsack nebula. This radiation is primarily due to the forward scattering of starlight from three bright early B stars by dust in the foreground of the Coalsack itself. While we cannot place useful constraints on the actual values of the optical constants, we find that, assuming no change with wavelength in g, the albedo does not change significantly over the spectral range from 912 to 1400 Å, arguing against the presence of a zero albedo population of small grains.

We plan to investigate this region further using more detailed models and, we hope, with new observations in different locations. Because the radiation field is precisely defined and the predominance of single scattering eases the modeling, this region provides one of the best opportunities to unambiguously deterime the scattering function of interstellar grains, if the observations can be chosen appropriately.

We have profited considerably through conversations with Dr. Gabriel Franco. Criticisms by an anonymous referee helped increase the readability of this work. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. We thank the National Space Science Data Center (NSSDC) for providing much of the ancillary data used in this work and the IDL Users Astronomy Library at NASA/GSFC for several IDL programs. This research has been supported at the Johns Hopkins University by NASA grant NAGW-1890 and at the University of Arizona by NASA grants NAGW-587 and NAGW-2648.

REFERENCES

Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Bowyer, S. 1991, ARA&A, 29, 59
Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89
Franco, G. A. P. 1989, A&A, 215, 119
———. 1993, in preparation
Gottlieb, D. M. 1978, ApJS, 38, 287
Henry, R. C. 1991, ARA&A, 29, 89
Holberg, J. B. 1986, ApJ, 311, 969
———. 1991, in IAU Colloq. 123, Observatories in Earth Orbit and Beyond, ed. Y. Kondo (Dordrecht: Reidel), 49
Kurucz, R. 1979, ApJS, 40, 1
Murthy, J., Henry, R. C., & Holberg, J. B. 1991, ApJ, 383, 198
Murthy, J., Im, M., Henry, R. C., & Holberg, J. B. 1993, ApJ, 419, 739
Sandage, A. 1976, AJ, 81, 954
Seidensticker, K. J. 1989, A&A, 220, 343
Sternberg, A. 1989, ApJ, 347, 863
Witt, A. N., Petersohn, J. K., Holberg, J. B., Murthy, J., Dring, A., & Henry, R. C. 1993, ApJ, 410, 714