Mon. Not. R. Astron. Soc. **352,** 1319–1322 (2004) doi:10.1111/j.1365-2966.2004.08022.x

Modelling of dust scattering toward the Coalsack

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Accepted 2004 May 11. Received 2004 May 11; in original form 2004 April 19

ABSTRACT

Murthy, Henry & Holberg discovered intense far-ultraviolet (FUV) ($\lambda\lambda$912–1600) emission from the direction of the Coalsack molecular cloud 10 years ago. We have used their results in conjunction with a Monte Carlo model for the scattering in the region to show that the scattering is from dust in the foreground of the Coalsack. The albedo of the grains is 0.4 ± 0.2. This is one of the few determinations of the albedo of dust in the diffuse interstellar medium in the FUV.

Key words: dust, extinction – ultraviolet: ISM.

1 INTRODUCTION

Although potentially useful for testing models of interstellar dust grains, measurements of two optical parameters – the albedo, a, and the phase function asymmetry factor, g, of the grains – have been too uncertain to have been of much utility (for a recent review see Draine 2003). There are two subjects of study that have been used for investigating the scattering properties of grains, both of which have been problematic for specific reasons: reflection nebulae, because an uncertain geometry can heavily influence the derived parameters (Mathis, Whitney & Wood 2002); and the diffuse background, because of its faintness and because there is often a tradeoff between a and g that allows neither to be tightly constrained (Draine 2003).

An excellent direction for the determination of the scattering properties of dust grains, particularly in the UV, is the line of sight towards the Coalsack molecular cloud, which was found to be one of the brightest sources of diffuse emission in the sky by Murthy et al. (1994). Without detailed modelling, they were unable to provide useful contraints on the optical constants of the grains but did suggest that most of the observed emission was due to forward scattering of photons from three of the brightest UV stars in the sky by foreground dust, rather than back-scattering from dust in the molecular cloud. We note that scattering from this region has also been observed in the visible by Mattila (1970), who, however, ascribed it to scattering from the Coalsack. In view of our results, we suggest that scattering by the foreground medium may be the major source of the visible emission also. In this paper, we have reinterpreted the *Voyager* observations of Murthy et al. (Table 1) using improved stellar distances, a detailed model for the interstellar dust distribution at the observed locations and a Monte Carlo model for the grain scattering. In agreement with Murthy et al., we find that the observed radiation is dominated by scattering from dust in the foreground cloud, rather than the Coalsack molecular cloud. The albedo of the grains is 0.4 ± 0.2 in the far ultraviolet (FUV).

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2 MODEL

We have developed a generalized Monte Carlo model to simulate the scattered emission from a star in an arbitrary scattering geometry. A schematic of our model is shown in Fig. 1. Each photon from the star is emitted in a random direction and continues in that direction until an interaction occurs, the probability of which depends on the local dust density at the point of interaction. The photon's effective weight is then reduced by a factor of a, the grain albedo, and a new direction is calculated using the Henyey–Greenstein (Henyey & Greenstein 1941) scattering phase function:

$$\phi(\theta) = \frac{(1 - g^2)}{4\pi[1 + g^2 - 2g\cos(\theta)]^{3/2}}. \quad (1)$$

In equation (1), g is the phase function asymmetry factor (defined as $\langle\cos(\theta)\rangle$) and θ is the angle of scattering. If g is close to zero, the scattering is nearly isotropic while a value of g near 1 implies strongly forward scattering grains.

We follow the photon through a sequence of interactions until it either leaves the area we are considering or its intensity drops to a negligible value. To save computational time, a part of the energy of every photon is redirected to the observer at each interaction. The model converges to a solution in a few million iterations, after which the results were scaled to the stellar output. Fortunately for us, only three early-type stars (Table 2) dominate the FUV radiation field in the Coalsack. The nebula itself blocks any light from more distant stars and the other foreground stars are all cool stars with negligible FUV emission. We have used data from the *Hipparcos* catalogue (Perryman et al. 1997) to specify the stellar spectral types, locations and distances. The flux from each star was calculated using a Kurucz (1979) model and scaled to the flux observed by the *International Ultraviolet Explorer* (*IUE*) at λ1500.[1]

The dust distribution, as usual, is more difficult to characterize and is the main source of uncertainty in our model. One of the major

[1] The *IUE* data were obtained from the *IUE* archive at http://archive.stsci.edu.

Table 1. Observed fluxes in the Coalsack.

Location	l (deg)	b (deg)	Intensity (observed)[a]	Ref.
1	303.7	0.8	$14\,000 \pm 2300^b$	Murthy et al. (1994)
2	303.7	0.8	$13\,800 \pm 2400^b$	Murthy et al. (1994)
3	305.2	−5.7	8000 ± 2000^b	Murthy et al. (1994)
4	304.6	−0.4	$11\,900 \pm 2400^b$	Murthy et al. (1994)
5	301.7	−1.7	$18\,900 \pm 400$	Murthy et al. (1999)

Notes. [a]photons cm^{-2} s^{-1} sr^{-1} Å^{-1}. [b]Fluxes have been reduced from the original paper due to an incorrect calibration used in that paper.

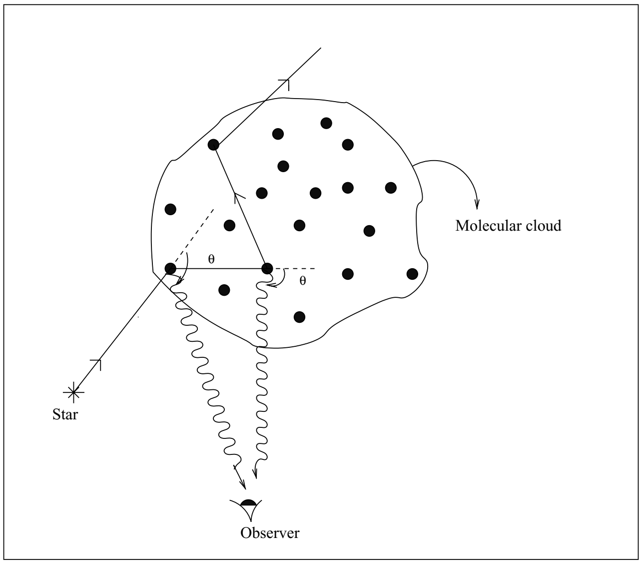

Figure 1. In our Monte Carlo model, photons are emitted by the star in a random direction and proceed until an interaction occurs. After each interaction, each photon is re-emitted in a new direction as determined by the scattering phase function. In order to save computational time, at each interaction a fraction of the energy of the photon depending on its scattering angle is redirected to the observer.

advantages of this direction is that the density and distribution of the medium in this region has been well studied. The molecular cloud comprising the Coalsack is clearly delimited by the CO contours of Dame, Hartmann & Thaddeus (2001), which we have converted into a total hydrogen column density using an $N_{\mathrm{H}_2}/W_{\mathrm{CO}}$ ratio of 2.8×10^{20} mol cm^{-2} K^{-1} km^{-1} s (Bloemen et al. 1986). The dark nebula is at a distance of 190 ± 10 pc from the Sun (Franco 1989), behind the hot stars listed in Table 2. As will be shown below, the contribution from the Coalsack is negligible compared with that from the foreground diffuse medium.

There is virtually no interstellar matter in this direction up to a distance of about 40 pc from the Sun, except for the Local Cloud, which has a column density of only about 5×10^{18} cm^{-2} (see Frisch 2002). The medium beyond 40 pc has been found to be in

Table 2. Properties of stars in our model.

Name	l (°)	b (°)	distance (pc)	Luminosity (λ1100) (photons s^{-1} Å^{-1})
α Cru	300.13	−0.36	98.3	8.46×10^{45}
β Cru	302.46	3.18	108.1	9.26×10^{45}
β Cen	311.77	1.25	161.3	2.42×10^{46}

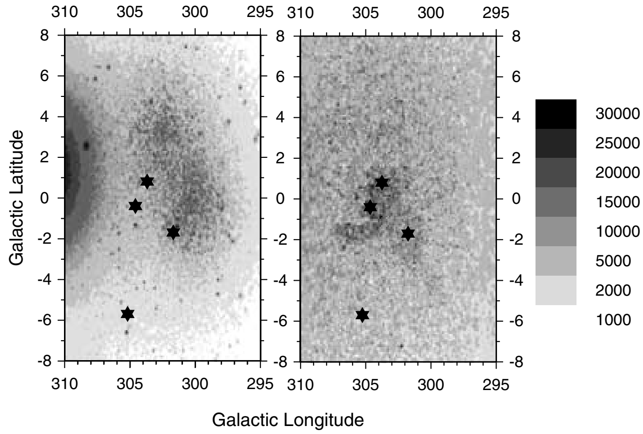

Figure 2. The emission predicted by our model with different values of a and g are shown here: $a = 0.4$; $g = 0.9$ on the left and $a = 0.4$; $g = 0.0$ on the right and the scale is shown on the right in units of photons cm^{-2} s^{-1} sr^{-1} Å^{-1}. The locations of the five *Voyager* observations are shown in the images as stars – note that one of the locations was observed with both *Voyager 1* and *Voyager 2*.

two extended sheet-like features (Corradi, Franco & Knude 1997, 2004), one at a distance of about 60 pc and the other at 120–150 pc from the Sun. Using the Na I column densities obtained by Corradi et al. and the $N_{\mathrm{NaI}}/N_{\mathrm{HI}}$ ratio of Ferlet, Vidal-Madjar & Gry (1985), we have obtained a neutral hydrogen column density of about 3×10^{19} cm^{-2} for the 60 pc feature and 3.7×10^{20}–2.6×10^{21} cm^{-2} for the 120–150 pc feature. We have used a column density of 10^{21} cm^{-2} and a distance of 135 pc for the denser sheet. We will address the effect of the uncertainty in the dust distribution in the next section.

We have run our model for various combinations of the optical constants and obtained the intensity over the entire $15^\circ \times 15^\circ$ field for each combination. The resulting intensity at the observed locations (marked by stars) is shown for two different g-values in Fig. 2. The two images clearly show the difference between the isotropic case ($g = 0.0$) where the Coalsack nebula can be seen in the centre of the image and the forward scattering case ($g = 0.9$) where scattering from β Cen – the brightest of the three hot stars mentioned in Table 2 – is visible towards the left of the image.

Apart from the uncertainties in the dust distribution, the use of the Henyey–Greenstein phase function may introduce additional errors in the modelled intensity, if it deviates from the actual phase function of the grains (Draine 2003). We have empirically accounted for these uncertainties by simply increasing the error bars associated with the data, such that the minimum $\chi^2 \equiv 1.0$.

3 RESULTS AND DISCUSSION

Five observations were made of four locations in the direction of the Coalsack by Murthy et al. (1994, 1999) using the *Voyager 1* and *Voyager 2* spacecraft (Table 1). By comparing our model runs with the observations, we find that the best-fit value for the albedo is 0.4 ± 0.2 for the assumed dust distribution (solid contour) as shown in Fig. 3.

We have explored other dust distributions within the limits quoted by Corradi et al. (2004) and the resulting contours corresponding to the maximum change in the albedo are also plotted in Fig. 3. The dashed contour corresponds to a column density of 1×10^{21} cm^{-2} and a distance of 150 pc for the denser sheet and the dotted contour represents the case where the column density is

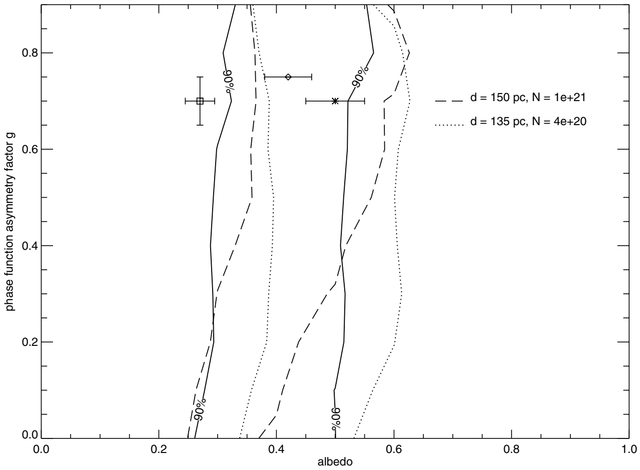

Figure 3. A 90 per cent confidence contour is plotted for g versus a. Although we can place few constraints on g, we can constrain a to 0.4 ± 0.2 (solid contour). The dashed abd dotted contours show the effects on the optical constants of changing the dust distribution within the limits specified by the Corradi et al. (2004) dust distribution. The values of the optical constants obtained by Draine (2003) (square), Murthy et al. (1993) (asterisk) and Witt et al. (1993) (diamond) are also plotted here. Note that Murthy et al. (1993) and Witt et al. (1993) simply assumed a g-value within the limits derived by Witt et al. (1992).

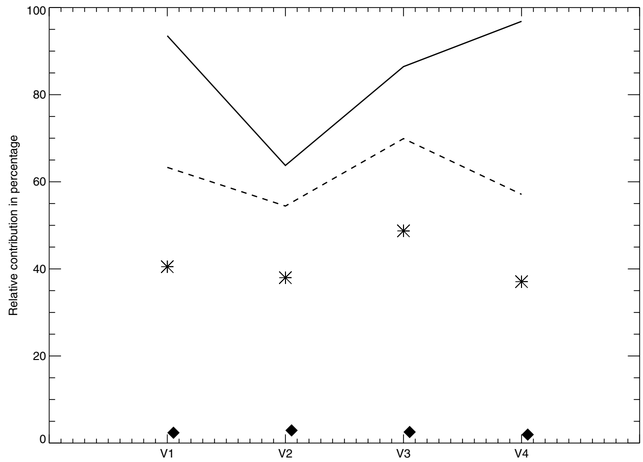

Figure 4. Relative contributions from two parts of the medium for the four *Voyager* locations. The solid line represents the contribution from the foreground medium for $g = 0.9$ and the dashed line denotes its contribution for $g = 0.0$. The contribution from the Coalsack for $g = 0.0$ and $g = 0.9$ is represented by the asterisks and the filled diamonds, respectively. The albedo used is 0.4 for all the four locations. Note that for location V2 we could not match the total observed flux with $a = 0.4$ and $g = 0.9$.

4×10^{20} cm^{-2} with a distance of 135 pc. They represent the lower and upper limits on the albedo of the grains allowed by uncertainties in the dust distribution.

We cannot similarly constrain g because, at the *Voyager* locations (shown as large stars in Fig. 2), the relative distribution of the medium and the stars is such that the total scattered intensity remains constant irrespective of the value of g. This can be understood by dividing the medium at these locations into two regions – the foreground medium ($d \leqslant 180$ pc) and the Coalsack molecular cloud ($d > 180$ pc), and separately calculating the scattered intensities from them. The relative contributions of these two media for two different g-values are given in Fig. 4. The solid line represents the contribution from the foreground medium for the case of $g = 0.9$ and the dashed line represents its contribution for $g = 0.0$. The contribution from the Coalsack molecular cloud is represented by the asterisks for $g = 0.0$ and by the filled diamonds for $g = 0.9$. In both cases the albedo is 0.4. From Fig. 4 we see that for $g = 0.0$, the Coalsack as well as the foreground medium contribute equally, whereas in the case of forward scattering all the contribution is made by the medium in front of the Coalsack. Coincidentally, for the four locations observed, the total intensity is almost the same regardless of the scattering medium. By the careful selection of targets we hope to remove this degeneracy in future observations.

4 CONCLUSIONS

Using our model we have found that the albedo of the grains is 0.4 ± 0.2. There are very few determinations of the optical constants of interstellar grains in the FUV (Draine 2003; Gordon 2004), and only one has been of grains in the diffuse ISM (Murthy, Henry & Holberg 1991). Our albedo limits are consistent with those of Witt et al. (1993) and Murthy et al. (1993) who used *Voyager 2* and the *Hopkins Ultraviolet Telescope* (*HUT*) observations (*HUT*), respectively, of NGC 7023 to derive an albedo of 0.4 – 0.5 by assuming the g-value derived by Witt et al. (1992). Using a dust model consisting of a mixture of carbonaceous grains and amorphous silicate grains, Draine (2003) has predicted a value of $a = 0.3$ at $\lambda 1100$, which is slightly different from the albedo derived here (Fig. 3).

In contrast to our result, Murthy et al. (1991) derived a very low albedo of $a < 0.1$ for grains in the diffuse ISM in the FUV using *Voyager 2* observations of four regions at different galactic latitudes and column densities. The main driver for this low albedo was that no diffuse radiation was observed at any of these locations, particularly one at a latitude of 11°.5. Because the column density of H I is very high at that one location, Murthy et al. (1991) expected that the scattered radiation would also be high and so used their null result to set the tight constraint on the albedo. It may be that an incomplete modelling of the interstellar scattering affected their results.

Our model predicts the intensities over the entire $15° \times 15°$ region towards Coalsack. In order to uniquely determine both a and g, we have selected locations where there is a variation in intensity with g and we will be obtaining new observations at these locations using the *Far Ultraviolet Spectroscopic Explorer (FUSE)* in the current observational cycle.

ACKNOWLEDGMENTS

We would like to thank the anonymous referee for useful comments and suggestions. This research has made use of the SIMBAD data base, operated at CDS, Strasbourg, France and NASA's Astrophysics Data System Bibliographic Services. Some of the data presented in this paper were obtained from the Multimission Archive at the Space Telescope Science Institute (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-*HST* data is provided by the NASA Office of Space Science via grant NAG5-7584 and by other grants and contracts.

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