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# Far-ultraviolet scattering by dust in Orion

P. Shalima,[1★] N. V. Sujatha,[1★] Jayant Murthy,[1★] Richard Conn Henry[2★] and David J. Sahnow[2★]

[1]*Indian Institute of Astrophysics, Bangalore 560034, India*
[2]*Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA*

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**ABSTRACT**

We have modelled diffuse far-ultraviolet (FUV) spectrum observed by the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) near M42 as the scattering of the starlight from the Trapezium stars by dust in front of the nebula. The dust grains are known to be anomalous in Orion with $R_V = 5.5$ and these are the first measurements of the FUV optical properties of the grains outside of 'normal' Milky Way dust. We find an albedo varying from 0.3 ± 0.1 at 912 Å to 0.5 ± 0.2 at 1020 Å which is consistent with theoretical predictions.

**Key words:** dust, extinction – ultraviolet: ISM.

## 1 INTRODUCTION

The Orion Nebula (M42) was first observed as one of the brightest diffuse sources in the ultraviolet (UV) sky by Carruthers & Opal (1977). They identified this light to be due to the radiation from the bright Orion stars scattered by dust in the Orion Molecular Cloud. Further observations allowed Wen & O'Dell (1995) to suggest a model for the M42 region in which M42, itself, is a thin blister of ionized gas in front of the Orion Molecular Cloud. The scattering arises in a neutral sheet in front of the Nebula known as the Veil (O'Dell, Walter & Dufour 1992) where there is a deficiency of small grains compared to the diffuse interstellar medium (Baade & Minkowski 1937; Costero & Peimbert 1970; Cardelli & Clayton 1988).

The first observations of far-ultraviolet (FUV: 905–1187 Å) emission in this region were made by Murthy, Sahnow & Henry (2005) who used serendipitous pointings of the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) to find intensities as high as $3 \times 10^5$ ph cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Å$^{-1}$. In this work, we have modelled these observations in order to determine the optical properties of the dust grains in the FUV. We find that the albedo of these grains varies from 0.3 ± 0.1 at 912 Å to 0.5 ± 0.2 at 1020 Å which is consistent with the theoretical predictions of Draine (2003).

## 2 OBSERVATIONS AND MODEL

As part of the *FUSE* S405/505 programme, regions of nominally blank sky were observed to allow the instrument to thermalize before realignment of the spectrograph mirrors. Murthy & Sahnow (2004) found diffuse radiation in many of these locations with the brightest being the two in the vicinity of M42 (Murthy et al. 2005). The locations and brightnesses of these two observations are listed in Table 1 and the Digital Sky Survey (DSS) map of M42 and the surrounding region is shown in Fig. 1 with the location of the *FUSE* observation superimposed (square).

The spectrum of the diffuse light is shown in Fig. 2. Although only 1.5 arcmin from HD 36981, Murthy et al. (2005) have shown that the observed emission could not be scattered radiation from that star because the broad photospheric Lyman $\beta$ (Ly$\beta$) absorption line in the stellar spectrum is not reflected in the diffuse spectrum and suggested that the radiation was instead due to scattering of the light from the Trapezium cluster of stars. Indeed, 65 per cent of the radiation at the scattering location is provided by $\theta^1$ Ori C alone and 99 per cent by the four Trapezium stars in Table 2.

The amount of light scattered by the dust depends on the scattering properties of the interstellar dust grains (albedo, cross-section and scattering phase function), their number density and distribution, and the relative geometry of the stars and dust. We have used the Henyey–Greenstein function (Henyey & Greenstein 1941) for the scattering phase function. Although this is a purely empirical function which may not represent the true scattering, particularly for strongly forward scattering grains (Draine 2003), it is the most prevalent in the literature.

We have used the overall morphology of M42 and the surrounding medium described in O'Dell (2001) to derive the scattering geometry (Fig. 3) for our location. Light from the Trapezium stars passes behind the foreground H I sheet (Orion's Veil) and is scattered by dust in the edges of the H I sheet at point A, about 3 ± 1 pc from $\theta^1$ Ori C. Assuming that the Veil is always parallel to the molecular cloud, this distance corresponds to the distance of the Veil (Abel et al. 2004) at point A.

The strong interstellar absorption line at Ly$\beta$ indicates a total column density of $N$(H I) = $(6.3 \pm 0.1) \times 10^{20}$ cm$^{-2}$ (using

★E-mail: shalima@iiap.res.in (PS); sujaskm@yahoo.co.in (NVS); jmurthy@yahoo.com (JM); henry@jhu.edu (RCH); sahnow@pha.jhu.edu (DJS)

**Table 1.** *FUSE* observations.

| Data set | l (°) | b (°) | Time (s) | Intensity (1100 Å) ($\times 10^5$ ph cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Å$^{-1}$) |
|---|---|---|---|---|
| S4054601 | 208.8 | −19.3 | 10 565 | 2.93 ± 0.03 |
| S4054602 | 208.8 | −19.3 | 5696 | 2.95 ± 0.04 |

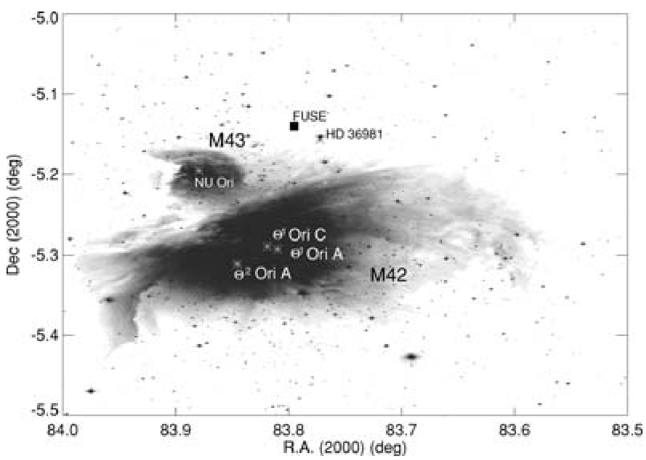


**Figure 1.** DSS map of the region with the brightest stars (asterisks) and the *FUSE* location (filled square) overplotted.

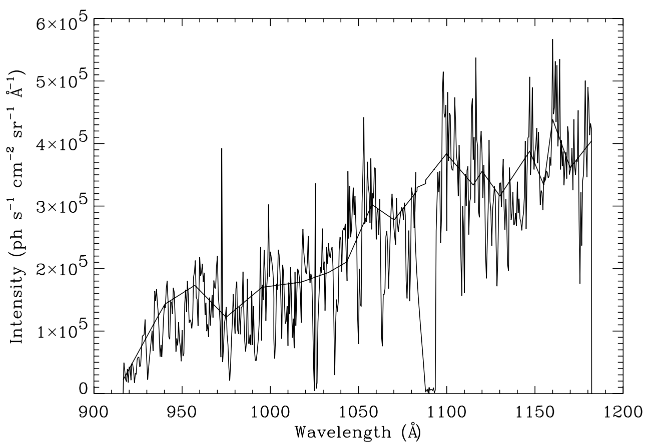


**Figure 2.** Observed diffuse spectrum from Murthy et al. (2005). The assumed dust scattering continuum is overplotted as a dark line.

the 'H2OOLS' package of McCandliss 2003), but 21-cm observations (Condon et al. 1998) show a much smaller column density of $4.5 \times 10^{19}$ cm$^{-2}$ ($\tau_{912-1020\,\text{Å}} \sim 0.029$–$0.033$) at Point A.[1] Most of the absorption therefore arises in the medium between the Trapezium cluster of stars and the scattering location. Interestingly, the column density along the direct line of sight to the Trapezium stars [$N(\text{H}) = 3.9 \times 10^{21}$ cm$^{-2}$; Shuping & Snow 1997] is much higher than that seen in our scattered light observation, indicating that we are actually observing light from $\theta^1$ Ori C reflected around the foreground clouds.

In order to convert the H I column densities into effective dust densities, we have used the dust cross-sections per hydrogen atom

[1] The 21-cm intensities have been converted to H I column densities using the ratio of van der Werf & Goss (1989) for the material in the envelope of the molecular cloud.

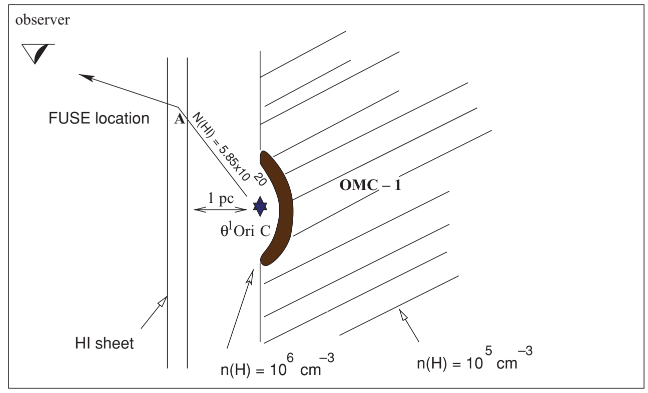


**Figure 3.** Schematic representation of the distribution of dust at the location showing the path (arrow) taken by the observed photons from the Trapezium stars towards the observer. The figure is not to scale.

tabulated by Draine (2003) for an $R_V$ [$=A_V/E(B-V)$] of 5.5, characteristic of the interstellar dust in Orion (Cardelli, Clayton & Mathis 1989; Fitzpatrick 1999). We note that Draine's cross-sections assume the standard gas-to-dust ratio of Bohlin, Savage & Drake (1978); however, this is 2.06 times higher than the ratio observed in Orion (Shuping & Snow 1997). We have therefore reduced the dust cross-sections per hydrogen atom by this factor.

In summary, we have assumed that the observed emission is due to the scattering of the light from the Trapezium stars by a scattering layer of thickness $4.5 \times 10^{19}$ cm$^{-2}$ at a distance of approximately 3 pc from $\theta^1$ Ori C. The radiation from the Trapezium stars has been attenuated by a column density of $6.3 \times 10^{20}$ cm$^{-2}$, using an extinction curve corresponding to $R_V = 5.5$.

The observed spectrum (Fig. 2) includes many lines, both absorption and emission, of molecular hydrogen (France & McCandliss 2005) as well as the H I Lyman series of absorption lines. In order to deduce the level of the dust scattered emission, we masked out these features and applied a 50-point median filter to the data (dark line in Fig. 2). We then calculated the dust scattered radiation as a function of the optical constants $a$ and $g$ using single scattering (since $\tau < 1$) and compared the intensities with the observations to constrain the values of the parameters. Beyond 1020 Å the observed radiation is contaminated by fluorescent emission of $H_2$ because of which we were unable to derive the optical constants.

## 3 RESULTS AND DISCUSSION

We have plotted our derived albedos as circles in Fig. 4 corresponding to $g = 0.55$. Because we only have observations at a single location, where the scattering angle is about 48°, it was not possible for us to constrain $g$ and we assumed the value, $g = 0.55 \pm 0.25$ derived by Sujatha et al. (2005) for locations in Ophiuchus. The error bars on the albedos for each value of $g$, include the observational errors as well as the uncertainties in the exact location of the scattering cloud. Within the assumed range of $g$, the albedo varies from $0.3 \pm 0.1$ at 912 Å to $0.5 \pm 0.2$ at 1020 Å. The maximum allowed albedo corresponds to $g = 0.8$, while the minimum corresponds to $g = 0.4$.

As mentioned above, the dust grains are anomalous in Orion with a depleted population of small grains with respect to the general interstellar medium, perhaps due to the destruction and selective acceleration of the small grains by the stellar radiation combined with their coagulation into large grains (Cardelli & Clayton 1988). However, the measured albedo is really a weighted average over all the different dust sizes and hence is only mildly dependent

**Table 2.** Properties of stars near target.

| HD number | Name | $l$ (°) | $b$ (°) | Angular distance (arcmin) | Spectral type[a] | $d$[b] (pc) | Flux at location (1100 Å) ($\times 10^5$ ph cm$^{-2}$ s$^{-1}$ Å$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 37022 | $\theta^1$ Ori C | 209.01 | −19.38 | 12.7 | O6pe | 450 | 1500 |
| 37041 | $\theta^2$ Ori A | 209.05 | −19.37 | 14.8 | O9.5V | 450 | 370 |
| 37020 | $\theta^1$ Ori A | 209.01 | −19.39 | 12.9 | B0.5V | 450 | 150 |
| 37023 | $\theta^1$ Ori D | 209.01 | −19.38 | 12.7 | B0.5Vp | 450 | 250 |

[a]Obtained from the SIMBAD astronomical data base.
[b]Hipparcos catalogue.

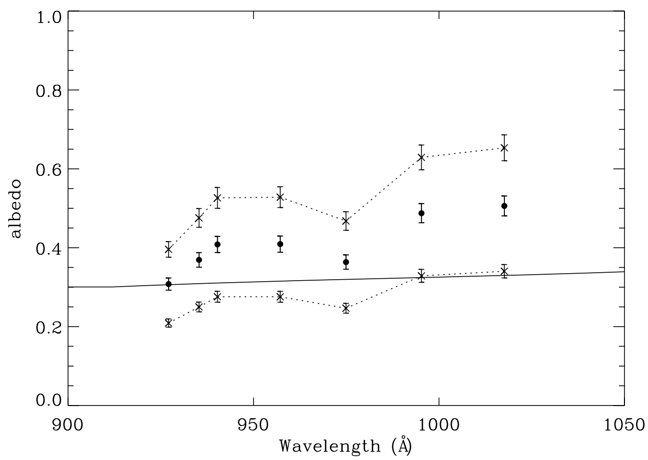


**Figure 4.** Allowed values of $a$ (circles) corresponding to $g = 0.55$, as a function of wavelength for dust cross-sections reduced by a factor of 2 compared to the $R_V = 5.5$ model. The minimum and maximum values corresponding to $g = 0.4$ and $g = 0.8$, respectively, are marked as '×'. The solid line represents the theoretical values of Draine (2003).

on $R_V$ in the FUV. In fact, we do find that our derived albedo is comparable to other determinations in the same wavelength region (Table 3).

Calzetti et al. (1995) have derived the albedo and $g$ for IC 435 in Orion using the data from the *International Ultraviolet Explorer* (*IUE*). They obtained a high albedo of 0.8 corresponding to $g = 0.75$ at 1200 Å for dust with an $R_V$ of 5.3. However, as suggested by Burgh, McCandliss & Feldman (2002), if this is due to the low optical depths used by them, using the correct optical depths would result in low albedos similar to those obtained for other regions, despite the difference in $R_V$.

## 4 CONCLUSIONS

We have modelled the intense diffuse light observed near M42 by Murthy et al. (2005) as the starlight from the Trapezium stars scattered by interstellar dust in Orion's Veil, a sheet of neutral hydrogen in front of the Orion Nebula. Most of the absorption seen in the spectrum is due to the material between the Trapezium and the scattering location and is much less than the absorption along the direct line of sight to the Trapezium.

**Table 3.** Previous determinations.

| Location | Wavelength (Å) | Albedo | $g$ | Reference |
|---|---|---|---|---|
| NGC 7023 | 1000 | 0.42 ± 0.04 | 0.75 | Witt et al. (1993) |
| NGC 2023 | 1100 | 0.35 ± 0.05 | 0.85 | Burgh et al. (2002) |
| Ophiuchus | 1100 | 0.40± 0.10 | 0.55 ± 0.25 | Sujatha et al. (2005) |

If we fix $g$ at 0.55, the albedo of the interstellar grains increases from a value of 0.3 ± 0.02 at 912 Å to 0.5 ± 0.03 at 1020 Å, close to previously observed values but with a different $R_V$. On the other hand, if we assume a $g$ of 0.85, as observed by Burgh et al. (2002), the albedo increases from 0.40 ± 0.02 to 0.68 ± 0.03. We have restricted our analysis up to 1020 Å since molecular hydrogen fluorescence contaminates the spectrum longward of 1020 Å. These observations are the first of dust grains with an $R_V$ significantly different from the Galactic norm in the FUV; however, we do not find a significant difference in the optical properties.

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