Modelling the diffuse dust emission around Orion

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Accepted 2018 February 23. Received 2018 February 13; in original form 2018 January 26

ABSTRACT
We have studied the diffuse radiation in the surroundings of M42 using photometric data from the Galaxy Evolution Explorer (GALEX) in the far-ultraviolet (FUV) and infrared observations of the AKARI space telescope. The main source of the FUV diffuse emission is the starlight from the Trapezium stars scattered by dust in front of the nebula. We initially compare the diffuse FUV with the far-infrared (FIR) observations at the same locations. The FUV–IR correlations enable us to determine the type of dust contributing to this emission. We then use an existing model for studying the FUV dust scattering in Orion to check if it can be extended to regions away from the centre in a 10 deg radius. We obtain an albedo, \( \alpha = 0.7 \) and scattering phase function asymmetry factor, \( g = 0.6 \) as the median values for our dust locations on different sides of the central Orion region. We find a uniform value of optical parameters across our sample of locations with the dust properties varying significantly from those at the centre of the nebula.

Key words: dust, extinction – infrared: diffuse background – ultraviolet: ISM.

1 INTRODUCTION

The Orion nebula (M42 or NGC 1976) is one of the most studied and nearest sites of active star formation (Bally 2008) from the Milky Way (MW). It spans more than 700 deg\(^2\) in the sky (Beitia-Antero & Gómez de Castro 2017) with emissions at different wavelengths. M42 is one of the brightest sources in the ultraviolet (UV) sky (Carruthers & Opal 1977) and is one of the first objects targeted with new instruments for calibration purposes. The dust properties in Orion are known to be different from average MW dust with the presence of much larger dust grains (Draine 2003). The brightness in Orion is attributed to the light from the Trapezium cluster of stars being forward scattered by the thin sheet of neutral hydrogen (H\(_i\)), known as Orion’s veil (Lockhart & Goss 1978; O’Dell et al. 1993), located \( \sim 1 \) pc in front of the nebula. Abel et al. (2004) state that the veil subtends an angle of at least 10 arcmin in the plane of the sky, which amounts to 1.5 pc at 500 pc. O’Dell (2001) has presented an extensive review of Orion nebula and related observations.

Murthy & Sahnow (2004) reported the first far-ultraviolet (FUV) diffuse observations in this region with data from the Far Ultraviolet Spectroscopic Explorer (FUSE) telescope. Shalima et al. (2006) continued this work by modelling these observations to study the dust properties in the FUV and found that the albedo of these grains varies from 0.3 ± 0.1 at 912 Å to 0.5 ± 0.2 at 1020 Å. The results of their proposed model were consistent with those of Draine (2003).

In the recent past, a lot of work has been done to study the dust properties in the central region of Orion, mainly concentrating on the \( \sim 5 \) arcmin diameter optically bright region referred to as the Huygens region (Huygens 1659) centred on the Trapezium stars, and the veil (Scandariato et al. 2011; van der Werf, Goss & O’Dell 2013; Schlafly et al. 2015; Weibacher et al. 2015; Beitia-Antero & Gómez de Castro 2017), but studies on the surroundings of Orion have been limited.

In this work, we present the findings after applying the dust model used successfully by Shalima et al. (2006) at the Orion centre, to the surroundings of Orion in an unprecedented 10 deg radius. We have used archival data from the Galaxy Evolution Explorer (GALEX) (Martin et al. 2005) at FUV 1539 Å and from the AKARI space telescope (Murakami et al. 2007) in the far-ultraviolet (FUV) and the AKARI infrared (IR) observations. We then proceed to model the dust scattered FUV light in the Orion surroundings, which will tell us about the scattering properties of the dust grains (albedo, cross-section, and scattering phase function), and the nature of dust species as we move away from the centre of the nebula. We finally compare our results with previous work done for the Orion region and present our conclusions.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 The data

We have taken the location observed by Shalima et al. (2006), i.e. \( l = 208.8, b = -19.3 \) as centre and looked for

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observations in a 10 deg radius. The GALEX mission performed surveys of the UV sky in two wavelength bands: FUV ($\lambda_{\text{eff}} \sim 1528 \text{ Å}$, 1344–1786 Å) and NUV ($\lambda_{\text{eff}} \sim 2310 \text{ Å}$, 1771–2831 Å) with different depth and coverage (Morrissey et al. 2007; Bianchi 2009). GALEX had a field of view $\approx 1.2^\circ$ diameter, with a spatial resolution of $\approx 4.2$ arcsec (FUV) and $\approx 5.3$ arcsec (NUV) (Morrissey et al. 2007). The two detectors provided simultaneous observations of the same field in two bands owing to the presence of a dichroic beam splitter (Bianchi, Conti & Shiao 2014). The GALEX all-sky imaging survey (AIS) was completed in 2007 covering $\sim 26,000 \text{ deg}^2$ (Beitia-Antero & Gómez de Castro 2017).

Since Orion is very bright in the UV, GALEX did not observe the central region of the nebula due to instrumental constraints and the observations start from an angular distance of 6.96 deg, which works to our advantage. We have an opportunity to apply a model working at the central region towards the outskirts of the nebula. We have taken 42 locations observed by GALEX in the FUV (1539 Å) from the final data release of the spacecraft (GR6/GR7). We have 40 observations from GALEX AIS and 2 observations from GALEX Guest Investigator (GI) programme. Using aperture photometry technique, we have calculated the flux at these locations and then converted them to intensities without convolving the images. The observed intensities have been corrected for airglow and background emission as described by Murthy (2014). Our locations with respect to the Orion centre are shown in Fig. 1. The GALEX FUV details along with observed intensities are shown in Table 4.

We have looked for IR data at the same 42 locations in the AKARI legacy archive at four wavelength bands: 65, 90, 140, and 160 μm. These four wavelength bands were observed by the AKARI Far-Infrared Surveyor (FIS) (Kawada et al. 2007), which was the instrument chiefly intended to make an all-sky survey at FIR wavelengths (Doi et al. 2015; Takita et al. 2015). The observation bands were named as: N60 (50–80 μm), WIDE-S (60–110 μm), WIDE-L (110–180 μm), and N160 (140–180 μm). The IR intensities $I_{65 \mu m}$, $I_{90 \mu m}$, $I_{140 \mu m}$, and $I_{160 \mu m}$ (with the subscript representing the wavelength in microns) observed by AKARI at our locations (calculated using aperture photometry) are shown in Table 5.

### 2.2 Correlation studies

We have calculated the Spearman’s rank correlations among the FUV (1539 Å = 0.15 μm) and the four FIR wavelengths for which we have collected the archival data. The correlation value tells us both the strength and direction (positive or negative) of the monotonic relationship between two variables. It is non-parametric in the sense that it does not assume any model, like a straight line fit (Bevington & Robinson 2003). The Spearman’s rank correlation coefficient is calculated using the following relation:

$$p = 1 - \frac{6\Sigma d^2}{n(n^2 - 1)}$$

where $\Sigma = \text{sum}$, $d = \text{difference between two ranks}$, $n = \text{no. of pairs of data}$.

The observed correlations between the GALEX FUV data (Table 4) and the AKARI FIR data (Table 5) are shown in Table 1 and the corresponding graphs are shown in Fig. 2. The probability or $p$-value is also shown which tells us how likely it is for the calculation to be a result of chance. A lower $p$-value signifies more reliability in the observed value of rank correlation coefficient.

### 2.3 The FUV model

We have used the model by Shalima et al. (2006) and hence we try to constrain the albedo and the asymmetry factor of the dust grains in the region surrounding Orion. The model uses the Henyey–Greenstein scattering phase function (Henyey & Greenstein 1941):

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

where ‘$g$’ is the phase function asymmetry factor and $\theta$ is the scattering angle. A value of ‘$g$’ close to zero implies that the scattering is nearly isotropic while a value of $g$ near 1 implies strongly forward scattering grains.

**Figure 1.** Our 42 locations around the Orion centre. We have distributed the locations into four groups based on their position with respect to the centre. The reference stars are used to get an estimate of the extinction and hydrogen column density near our dust locations with changing distance.

**Table 1.** The rank correlation values among the FUV–FIR intensities for our 42 locations.

| FUV–FIR          | Rank correlation ($\rho$) | $p$-value |
|------------------|--------------------------|-----------|
| $I_{65 \mu m} \sim I_{65 \mu m}$ | 0.221                    | 0.1642    |
| $I_{90 \mu m} \sim I_{90 \mu m}$ | 0.545                    | 0.0002    |
| $I_{140 \mu m} \sim I_{140 \mu m}$ | 0.505                    | 0.0007    |
| $I_{160 \mu m} \sim I_{160 \mu m}$ | 0.401                    | 0.0092    |
The Trapezium cluster of stars in Orion are the brightest source of radiation from the nebula as mentioned by Shalima et al. (2006). But since our region under consideration is much further away from the centre of M42, we have taken into account the 14 brightest stars, in addition to the Trapezium stars as contributors of radiation at our locations as shown in Table 2. The stellar luminosities shown in Table 2 have been calculated using data from the International Ultraviolet Explorer (IUE) archives at 1539 Å. We have first used the all-sky 100 \( \mu \)m dust emission maps by Schlegel, Finkbeiner & Davis (1998) to extract the \( E(B-V) \) for our stars. We have then used the dust cross-section per hydrogen atom from Draine (2003) and an extinction \( R_V = 5.5 \) for Orion to calculate the total extinction \( A(V) \) and \( N(H) \) for each location:

\[
\frac{A(V)}{E(B-V)} = R_V = 5.5,
\]

\[
N(H) = 1.8 \times 10^{21} \text{ atoms cm}^{-2} \text{ mag}^{-1} / A(V).
\]

Since we do have much idea about the dust properties at our 42 locations, we have selected a set of reference stars as shown in

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Table 2. Properties of the 14 contributing central stars. The spectral type has been obtained from the SIMBAD astronomical data base. The distance has been taken from the Hipparcos catalogue.

| HD number | \( l \) (°) | \( b \) (°) | Spectral type | Distance (pc) | Luminosity (1539 Å) \( \text{ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Å}^{-1} \) | \( N(H) \) (cm\(^{-2}\)) |
|-----------|-------------|-------------|---------------|--------------|---------------------------------------------------|-------------------|
| 037043    | 209.5221    | -19.5835    | O9III         | 406.5041     | 0.453 \times 10^9                                  | 11.870 \times 10^{21} |
| 037022    | 209.0107    | -19.3840    | O7V           | 450.4504     | 7.244 \times 10^9                                  | 342.245 \times 10^{21} |
| 036512    | 210.4356    | -20.9830    | O9.7V         | 473.9337     | 9.443 \times 10^8                                  | 1.906 \times 10^{21} |
| 037017    | 208.1770    | -18.9571    | B1.5V         | 373.1343     | 9.086 \times 10^7                                  | 6.508 \times 10^{21} |
| 037481    | 210.5290    | -19.1698    | B2IV/V        | 480.7692     | 8.111 \times 10^8                                  | 8.952 \times 10^{21} |
| 037303    | 209.7887    | -19.1469    | B2V           | 416.6667     | 1.282 \times 10^8                                  | 4.414 \times 10^{21} |
| 037061    | 208.9248    | -19.2736    | O9V           | 361.0108     | 2.298 \times 10^8                                  | 230.939 \times 10^{21} |
| 037018    | 208.5036    | -19.1092    | B1V           | 240.9639     | 2.352 \times 10^9                                  | 35.432 \times 10^{21} |
| 037356    | 208.7804    | -18.5426    | B3V           | 343.6426     | 2.753 \times 10^7                                  | 0.791 \times 10^{21} |
| 037526    | 209.2749    | -18.4597    | B5V           | 332.2259     | 6.272 \times 10^6                                  | 1.715 \times 10^{21} |
| 036487    | 210.1646    | -20.9242    | B6IV          | 377.3585     | 4.621 \times 10^6                                  | 1.328 \times 10^{21} |
| 037468    | 206.8163    | -17.3360    | O9.5V         | 352.1127     | 1.212 \times 10^6                                  | 2.317 \times 10^{21} |
| 037056    | 207.1087    | -18.3495    | B8/9V         | 446.4286     | 5.391 \times 10^6                                  | 2.883 \times 10^{21} |
| 036120    | 208.6580    | -20.9250    | B8V           | 390.6250     | 9.85 \times 10^6                                  | 0.527 \times 10^{21} |
3 RESULTS AND DISCUSSION

We see from our correlation studies in Table 1 and Fig. 2 that the FUV–FIR rank correlation is almost similar for emission at 90 and 140 μm with a slightly weaker correlation coefficient at 140 μm. The correlation is better than what is seen at 65 μm for all longer wavelengths. This shows that the dust species which shows emission at both wavelength bands around 100 μm is from similar cold environments (Seon et al. 2011a, b; Hamden, Schiminovich & Seibert 2013). The emission beyond 100 μm is from colder and larger grains and hence the weaker correlation as we move to longer wavelengths. Now, emission at 65 μm is associated with...
star-forming regions (Onaka & Okada 2003). Therefore, the dust
gains are prone to destruction in the presence of high UV radi-
ation fields (Madden 2000; Galliano et al. 2005) and hence the
observed low value of correlation coefficient. The overall cor-
relation trend indicates that the dust contributing to the scatter-
ing in our locations away from the centre of the Orion nebula
is associated with colder environments as compared to the cen-
tre which has the Trapezium star cluster. This is in agreement
with the previous work done by Shalima et al. (2006) where it
is seen that dust in the neutral H I sheet is responsible for the scatter-
ing and not dust in the H II region. So this thin sheet of dust
may be extending even for our locations but at a slightly different
distance.

Our model gives the outputs separately for each combination of
\( \alpha \), \( \beta \), and distance of dust cloud. We have done our calculations for
a dust sheet 0.1 pc thick with input parameters as discussed in
Section 2.3. We compare our model results with the observed
GaLEX FUV values from Table 4 by placing the dust at various
distances ranging from 100 to 450 pc. We get the best-fitting \( \alpha \), \( \beta \), and distance values for the different dust locations from our model and as shown in Table 3. We see higher deviation between the model and observed values as we move the dust farther away towards 450 pc from the distances specified in Table 3. Since the dust gains are forward scattering, it is expected that the dust responsible for the scattering should be in front of the stars which is evident from our distance calculations as shown in Fig. 3. In order to check this argument, we have removed all the dust behind the stars to see the contribution from foreground dust. We find that the change in output varies from 0.4 to 16% per which means that at least 84% of the light scattering is from foreground dust. So, we can say that the background dust contribution is negligible.

We have tried to check the results by grouping our locations intoour regions according to their position in Fig. 1. Group 1: single
location on top of the 14 stars at the centre, Group 2: 15 locations
to the left, Group 3: four locations to the bottom, and Group 4: 22
locations to the right of the central region. We see that there

\[ \begin{array}{cccccc}
\text{Survey} & l & b & \text{Angular distance} & \text{Exp. time} & \text{FUV intensity (1539 Å)} \\
\hline
\text{AIS} & 215.9858 & -21.03678 & 6.96443 & 216 & 13,192.089 \\
\text{AIS} & 216.3477 & -20.05170 & 7.14608 & 247 & 11,670.878 \\
\text{AIS} & 216.6843 & -21.82404 & 7.80018 & 104 & 10,691.843 \\
\text{AIS} & 216.3610 & -22.73478 & 7.84751 & 213 & 9540.414 \\
\text{AIS} & 217.0416 & -20.85384 & 7.89419 & 390.15 & 10,889.231 \\
\text{AIS} & 217.3502 & -19.92822 & 8.07774 & 198 & 9935.189 \\
\text{AIS} & 217.6604 & -18.98852 & 8.37539 & 190 & 9244.332 \\
\text{GI} & 203.7195 & -26.30023 & 8.41982 & 1654.15 & 7533.637 \\
\text{AIS} & 217.4199 & -22.61161 & 8.70799 & 186 & 9441.720 \\
\text{AIS} & 217.7529 & -21.67958 & 8.71578 & 211.05 & 10,264.169 \\
\text{AIS} & 217.9658 & -18.02852 & 8.77530 & 199 & 10,691.843 \\
\text{AIS} & 217.0605 & -23.54354 & 8.78004 & 191.1 & 10,428.659 \\
\text{AIS} & 218.0538 & -20.73285 & 8.81077 & 199 & 11,514.293 \\
\text{AIS} & 203.1845 & -26.43342 & 8.81313 & 169 & 6448.004 \\
\text{AIS} & 218.3820 & -19.80989 & 9.04263 & 136 & 10,264.169 \\
\text{AIS} & 200.9855 & -24.76113 & 9.06785 & 176 & 10,922.129 \\
\text{AIS} & 199.4499 & -22.13578 & 9.19124 & 112 & 10,527.353 \\
\text{AIS} & 199.0548 & -19.42800 & 9.19351 & 181.05 & 13,257.885 \\
\text{AIS} & 201.5206 & -25.63027 & 9.23280 & 188 & 8158.699 \\
\text{AIS} & 218.2467 & -17.08630 & 9.24187 & 194 & 10,461.557 \\
\text{AIS} & 218.6914 & -18.85640 & 9.35742 & 217 & 10,090.985 \\
\text{AIS} & 198.9741 & -21.24889 & 9.41884 & 110 & 10,922.129 \\
\text{AIS} & 209.4986 & -28.72108 & 9.44258 & 283 & 9507.516 \\
\text{AIS} & 210.6291 & -28.62830 & 9.47636 & 168 & 9672.006 \\
\text{AIS} & 202.0663 & -26.48617 & 9.48874 & 184.05 & 5329.472 \\
\text{AIS} & 218.4705 & -22.45449 & 9.56769 & 265 & 8356.086 \\
\text{AIS} & 218.1448 & -23.38423 & 9.61104 & 204.05 & 8520.576 \\
\text{AIS} & 217.7865 & -24.31932 & 9.73240 & 201.05 & 8685.066 \\
\text{AIS} & 218.9770 & -17.90198 & 9.74467 & 213.1 & 10,264.169 \\
\text{AIS} & 218.5336 & -16.11330 & 9.80239 & 197 & 10,264.169 \\
\text{AIS} & 202.6347 & -27.34658 & 9.83424 & 189 & 6119.024 \\
\text{AIS} & 199.3837 & -23.90570 & 9.88809 & 174 & 10,362.863 \\
\text{AIS} & 199.8962 & -24.77457 & 9.89899 & 184.05 & 12,468.334 \\
\text{AIS} & 219.4075 & -19.65953 & 10.00526 & 220 & 9704.904 \\
\text{AIS} & 200.4167 & -25.65025 & 10.01125 & 185 & 5921.636 \\
\text{GI} & 203.5377 & -10.56900 & 10.10194 & 2446.25 & 17008.255 \\
\text{AIS} & 198.0511 & -19.49966 & 10.13952 & 192 & 14,244.825 \\
\text{AIS} & 219.2478 & -16.95318 & 10.13073 & 273 & 11,185.313 \\
\text{AIS} & 200.9614 & -26.51945 & 10.20460 & 187 & 5822.942 \\
\text{AIS} & 209.0111 & -29.63168 & 10.33346 & 288.05 & 10,033.883 \\
\text{AIS} & 207.8586 & -29.71661 & 10.45161 & 296 & 6119.024 \\
\text{AIS} & 201.5159 & -27.37775 & 10.48114 & 188 & 5066.288 
\end{array} \]
is a consistency for all the groups irrespective of the distance and location and although individual locations have varying $\alpha$ and $g$ with distance (Table 3), each group has the same median values for these parameters, i.e. $\alpha = 0.7$, $g = 0.6$ at 1539 Å. This is an increase in the value of the albedo from those observed by Shalima et al. (2006) at lower wavelengths for their sample. This is also an increase in the value of the albedo from those observed by Shalima et al. (2006) at lower wavelengths indicating the origin of the emission to be from larger dust grains. This is in agreement to the findings of a lack of small dust particles by Beitia-Antero & Gómez de Castro (2017) as confirmed by the decrease in the strength of the 2175 Å feature. The reason might be due to possible destruction of polycyclic aromatic hydrocarbons (PAHs) or photo evaporation of the small dust grains in sites of heavy irradiation as evident from the low correlation values seen at shorter wavelengths (Table 1).

(ii) The FUV light scattering observed by us is predominantly from the foreground dust that provides for at least 84 percent of the scattered radiation. Schlafly et al. (2015) have found a 14° circular ring of dust engulfing the star-forming regions as well as dust clouds in Orion and they have estimated all the material to be lying between 400 and 550 pc giving a 150 pc depth and 100–400 pc width to the ring. Almost all of our dust locations lie within the 100–400 pc range (Table 3) and hence we are less concerned with the predictions of Draine (2003) model.

4 CONCLUSIONS

(i) We find the dust grains contributing to the extinction in our locations to be associated with colder environments as compared to the central Orion region (with the Trapezium star cluster) which agrees with the observations made by Shalima et al. (2006), where Orion’s veil is seen to be responsible for the scattering and not the H II region dust. We also see better correlation values at longer wavelengths indicating the origin of the emission to be from larger sized dust grains. This is in agreement to the findings of a lack of small dust particles by Beitia-Antero & Gómez de Castro (2017) as confirmed by the decrease in the strength of the 2175 Å feature. The reason might be due to possible destruction of polycyclic aromatic hydrocarbons (PAHs) or photo evaporation of the small dust grains in sites of heavy irradiation as evident from the low correlation values seen at shorter wavelengths (Table 1).
with the negligible background dust contaminating our observed results.

(iii) We find the median values for our model parameters to be $\alpha = 0.7$, $g = 0.6$, which are same for all the four groups in Fig. 1 irrespective of distance or location. Although these values are higher than those predicted by Draine (2003), we do find consistency in results of few individual locations (Table 3). This might be attributed to the presence of larger sized dust grains (as seen from the correlation studies) at our locations leading to high extinction values.

(iv) From our obtained $\alpha$ and $g$ values, we can conclude that the dust grain properties at our observed locations are significantly different from those close to the centre which was expected. This is supported by observations made by Scandariato et al. (2011) showing that the central Orion molecular complex, towards the direction of the Trapezium cluster, accounts for the largest amount of extinction with a decrease in the extinction towards the edge of the nebula. This indicates that the thin layer of neutral H I does not extend as far as our observed locations.

ACKNOWLEDGEMENTS

We thank an anonymous referee for useful comments and suggestions which have helped in improving this paper. This work is based on observations with AKARI, a JAXA project with the participation of ESA. Some of the data presented in this paper was obtained from the Mikulski Archive for Space Telescopes (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 NNX09AF08G and by other grants and contracts. This research has made use of the SIMBAD data base, operated at CDS, Strasbourg, France. RG would like to thank the IUCAA associateship programme for their support and hospitality.

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