Modelling the diffuse ultraviolet radiation observed by Dynamics Explorer 1

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ABSTRACT
The Dynamics Explorer spacecraft, DE-1, has undertaken two sky surveys in the far-ultraviolet regime, covering a wide variety of Galactic latitudes. We have used a single scattering dust model to probe into the optical constants and the distance of the interstellar dust clouds. We find that, in agreement with most other observations, the dust grains are strongly forward scattering with a relatively high albedo and, in addition, that the scattering is from dust sheets within 100 pc of the Sun.

Key words: dust, extinction – local interstellar matter – ultraviolet: ISM.

1 INTRODUCTION
The diffuse ultraviolet (UV) radiation field has traditionally been difficult to observe, primarily because of its faintness and competition with other sources, both instrumental and in the sky (reviewed recently by Murthy 2009). Despite much controversy in the early years of the field (reviewed by Bowyer 1991; Henry 1991) when the signal was near the detection limits of the instruments of the time, it is now accepted that most of the radiation at low- to mid-Galactic latitudes is due to starlight from hot stars scattered by interstellar dust. As such it is generally correlated with N(Hi) for relatively low optical depths (Haikala et al. 1995; Schiminovich et al. 2001) but with a strong dependence on the presence of nearby hot stars (Sujatha et al. 2005) in the line of sight.

Data from the Galaxy Evolution Explorer (GALEX) are now being used to probe the diffuse radiation in specific locations at high spatial resolution (∼1 arcmin) and are finding considerable small-scale variation (Sujatha et al., in preparation). However, there are a few large-scale observations where one can probe into the distribution of the diffuse background over much of the sky. In this context, we have re-examined the results of Fix, Craven & Frank (1989) who used data from the Dynamics Explorer 1 mission (DE-1). DE-1 observed two 0.32 wide strips of sky at 1450 Å, one in 1984 and another in 1987, yielding intensities along two great circles that cross the Galactic plane at longitudes of 100° (in the constellation of Carina) and 290° (in the constellation of Cepheus) (Fix et al. 1989).

Fix et al. (1989) found a strong dependence of the background on Galactic latitude and deduced that the radiation was due to highly forward scattering dust grains with a possible isotropic extragalactic component of about 500 photon units. There have been many improvements in the modelling of the diffuse radiation field since then and, in this paper, we present a re-interpretation of the DE-1 results based on current models. We confirm that the radiation is due to starlight scattered from highly reflective, forward scattering dust with the further constraint that the scattering originates within about 100 pc of the Sun.

2 OBSERVATIONS AND MODELLING
The DE-1 spacecraft was part of NASA’s DE-1 mission which consisted of two spacecrafts launched into polar orbits to study plasma in the Earth’s atmosphere (Frank et al. 1981). However, the UV imager – consisting of a telescope feeding a photomultiplier tube – was used to observe the diffuse sky background twice (1400–1900 Å); the first time in a strip of constant RA of about 10.4 h in 1984 and again in 1987.

After bright stars in the scan line were identified and their pixels removed, a total of 2613 locations remained (Fig. 1). The exposure time for each field was 3.4 ms for a single scan of the sky. The cumulative exposure time was 22 s pixel−1 in 1984 and 33 s pixel−1 in 1987, resulting in an effective signal-to-noise ratio of 3.5 for a sky brightness of 1000 photons cm−2 s−1 sr−1 Å−1 in the 1984 observations, dropping to 2.5 in the 1987 observations.

It is clear from Fig. 1 that there is a strong dependence of the observed diffuse radiation on the Galactic latitude suggesting that the radiation is primarily due to starlight scattered from forward scattering interstellar dust grains (Fix et al. 1989). Indeed, there are a few other possibilities at this wavelength (Leinert et al. 1998; Murthy 2009), the primary alternative being airglow. However, according to Fix et al. (1989) the lack of dependence on zenith angle shows that airglow contamination is not present in the DE data.

This leaves us with dust scattering and a possible extragalactic component. We had previously developed a 3D model to predict the

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Figure 1. Colour coded intensity plot of the Galactic coordinates observed in 1984 and 1987, with the intensities given in units of photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Å$^{-1}$.

### Table 1. Previous determinations of optical constants of interstellar dust.

<table>
<thead>
<tr>
<th>$a$</th>
<th>$g$</th>
<th>Wavelength (Å)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28 ± 0.04</td>
<td>0.61 ± 0.07</td>
<td>900–1200</td>
<td>Sujatha et al. (2007)</td>
</tr>
<tr>
<td>0.4 ± 0.1</td>
<td>0.55 ± 0.25</td>
<td>1100</td>
<td>Sujatha et al. (2005)</td>
</tr>
<tr>
<td>0.4 ± 0.2</td>
<td></td>
<td>1100</td>
<td>Shalima &amp; Murthy (2004)</td>
</tr>
<tr>
<td>0.45 ± 0.05</td>
<td>0.68 ± 0.1</td>
<td>1560</td>
<td>Witt, Friedmann &amp; Sasseen (1997)</td>
</tr>
<tr>
<td>0.45 ± 0.15</td>
<td></td>
<td>1200</td>
<td>Murty &amp; Henry (1995)</td>
</tr>
<tr>
<td>0.5</td>
<td>0.9</td>
<td>1500</td>
<td>Witt &amp; Peterson (1994)</td>
</tr>
<tr>
<td>0.42</td>
<td>0.44</td>
<td>1500</td>
<td>Wright (1992)</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>1550</td>
<td>Morgan, Nandy &amp; Thompson (1978)</td>
</tr>
<tr>
<td>0.6 ± 0.05</td>
<td>0.75 ± 0.15</td>
<td>1550</td>
<td>Lillie &amp; Witt (1976)</td>
</tr>
</tbody>
</table>

amount of dust-scattered diffuse radiation (Murthy & Henry 1995), an improved version of which was able to match the observed radiation to a reasonable degree in observations of the sky near M82 made by Sujatha et al. (2009). This model uses the known positions and spectral type of every bright UV star in the sky from the Hipparcos sky catalogue to predict the interstellar radiation field at any location in space (see Sujatha et al. 2004). This model of the stellar radiation field can be compared to that of Habing (1968) and Draine (1978) both of which do not include dust scattering. The integrated spectral energy density at 1400 Å for this model is 4.7 erg cm$^{-3}$ Å$^{-1}$ which is reasonably close to the values derived by Habing (1968) (4.2) and Draine (1978) (5.0) for this wavelength. This radiation is then convolved with the scattering function and number density of dust at the point of scattering to yield the surface brightness in that direction.

As has been the standard in studies of the dust-scattered radiation, we have used the two-parameter empirical formulation (Henyey & Greenstein 1941) with the albedo ($a$) and phase function asymmetry factor ($g = \langle \cos \theta \rangle$) as free parameters. Typical values (Table 1) centre around the theoretical predictions for a mixture of silicate and graphite grains of $a = 0.4$ and $g = 0.6$ (Draine 2003), i.e. moderately reflective, forward scattering dust grains. Our model explicitly assumes single scattering and moreover ignores clumping in the interstellar medium (ISM), both of which assumptions break down as the optical depth ($\tau$) nears unity. Although we have used multiple scattering Monte Carlo models for smaller fields with a restricted number of stars (Sujatha et al. 2007), this is computationally difficult for sky-survey data as we have here. We have therefore restricted our model to those fields that are more than $15^\circ$ away from the Galactic plane, thereby reducing the number of locations to 2275.

The primary uncertainty in this model is in the position of the scattering dust. Although the amount of scattering will be heavily dependent on the actual position of the star and the dust, for the purposes of this global study, we have assumed that the dust is in a single layer of thickness of 1 pc, at a distance of 100 pc from the Sun, more or less corresponding to the wall of neutral material found by Lallement et al. (2003) from Na I studies of nearby cool stars. The total hydrogen column density is converted to a dust density for each location. Some of this material is distributed as the Local Fluff material with a total hydrogen column density [N(H)] of $5 \times 10^{18}$ cm$^{-2}$ up to a distance of 20 pc from the Sun. Apart from this there is material in the local bubble with a negligible density of 0.0005 cm$^{-3}$. The rest is distributed in a 1 pc thick sheet at 100 pc. The results from this model are shown in Fig. 2 with a correlation coefficient of 0.68 and a minimum $\chi^2$ of 1.56. The best-fitting optical parameters are $a = 0.6$ and $g = 0.6$.

We find a much better fit to the data if we allow the distance of the scattering medium to vary between 20 and 150 pc, while keeping the optical constants of the dust fixed over the entire region. Another parameter that we have included is an offset intensity which can take values between 0 and 1000 photon units. The results are plotted in Fig. 3 with a correlation coefficient of 0.93 and a minimum $\chi^2$
Diffuse UV radiation observed by DE-1

Figure 2. Observed versus model intensities in units of photons cm$^{-2}$s$^{-1}$sr$^{-1}$Å$^{-1}$ for a dust distance of 100 pc.

Figure 3. Observed versus model intensities in units of photons cm$^{-2}$s$^{-1}$sr$^{-1}$Å$^{-1}$ for a dust sheet with varying distances.

Figure 4. Dust distances as a function of galactic longitude derived using our model (filled circles) and from Na I measurements (squares).

Figure 5. Variation of multiple scattering dust albedo with optical depth.

The corresponding $a$, $g$ and offset values are 0.6, 0.8 and 500 photon units, respectively. These results are in reasonable agreement with those derived by Witt & Peterson (1994) using the same data set. Wright (1992) has also used the DE-1 data and derived an albedo of 0.42 and a $g$ of 0.44, which has a very different $g$ value compared to ours. This difference is mainly because of their assumption of a plane-parallel geometry of dust grains. Our values are also reasonably close to those derived from other studies (Table 1).

One of the innovations of our method is that we treat the distance of the dust as a free parameter allowing us to simultaneously derive the location of the scattering layer. A smoothed plot of these distances is shown in Fig. 4 where we have plotted the best-fitting distances from our model along with derivations of the distance from the Na I measurements of Lallement et al. (2003). Although the ISM may vary on scales of less than 1 pc (Meyer & Blades 1996), we derive similar distances using the dust scattering to the gas absorption measurements of Lallement et al. (2003). In principle, our method will allow us to measure the distance of interstellar dust clouds even where there are no background stars. The regions where we see large differences in the two distance estimates correspond to high Galactic latitudes where there is no evidence for the presence of an absorbing medium up to 200 pc or more (Lallement et al. 2003). These are also the locations where there is the greatest deviation between our modelled and observed values, perhaps indicating an extragalactic contribution.

In order to get an approximate correction for multiple scattering we compared two sample programs, one using single scattering and the other which includes multiple scattering, each containing a single source and a dust distribution with a constant density at each point. We find that there is a ∼50 per cent decrease in the albedo in the multiple scattering case which reduces marginally with the optical depth. These reduced albedo values compared to our single scattering albedo of 0.6 have been plotted in Fig. 5. We find that our albedo values may therefore reduce to ∼0.3 which is in good agreement with the theoretical predictions as well with other results. However, this is just an approximation which can vary with the relative distribution of the stars and dust and in order to improve the accuracy of the results, we have to do an in-depth analysis for each location.

We have found an offset to the data of 500 photons cm$^{-2}$s$^{-1}$sr$^{-1}$Å$^{-1}$ which may comprise dark count, unresolved stars or a possible extragalactic background (see Murthy 2009 for a summary of contributors to the diffuse radiation field). In order to check for possible stellar contamination from O- and B-type stars fainter than 9th magnitude, we have used the Kharchenko catalogue (Kharchenko & Roeser 2009), which contains more than 2.5
million stars and is complete to a magnitude of 12–14, and checked for any such star within the field of view of each location. We find that all the locations are devoid of faint O and B stars, which eliminates this possible source of contamination. However, it is difficult to separate out the dust scattering from the offset without detailed multiple scattering models for every location, and hence we will leave the question of this offset until we develop better models in conjunction with our other work on the UV background.

3 CONCLUSIONS

We have used data from two scans of the sky made with the DE-1 satellite to study the global scattering of stellar radiation from interstellar dust at latitudes greater than 15° from the Galactic plane. We have implemented a single-scattering model which has fitted the scattered radiation well with an albedo of 0.6 and a phase function asymmetry factor \( g \) of 0.8, in reasonable agreement with other determinations of the optical constants of the interstellar dust grains.

We have also found that the scattering layer from whence the UV background originates is within 100 pc from the Sun in most directions but increasing near the plane. This provides a powerful new method to determine the distance of interstellar dust even in the absence of background stars.

The DE-1 data are one of the only sources of information on the diffuse background over the entire sky and have still to be fully utilized. We plan to develop a full Monte Carlo code to model these data at low Galactic latitudes where the optical depth increases beyond unity and both multiple scattering and clumping become important. These data complement our GALEX work at smaller scales where we probe the UV background at high spatial resolution and, together, will present a unified picture of interstellar dust scattering.

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