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Probing the infrared counterparts of diffuse far-ultraviolet sources in the Galaxy

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ABSTRACT

Recent availability of high quality infrared (IR) data for diffuse regions in the Galaxy and external galaxies have added to our understanding of interstellar dust. A comparison of ultraviolet (UV) and IR observations may be used to estimate absorption, scattering and thermal emission from interstellar dust. In this paper, we report IR and UV observations for selective diffuse sources in the Galaxy. Using archival mid-infrared (MIR) and far-infrared (FIR) observations from *Spitzer Space Telescope*, we look for counterparts of diffuse far-ultraviolet (FUV) sources observed by the *Voyager*, *Far Ultraviolet Spectroscopic Explorer (FUSE)* and *Galaxy Evolution Explorer (GALEX)* telescopes in the Galaxy. IR emission features at 8 μm are generally attributed to Polycyclic Aromatic Hydrocarbon (PAH) molecules, while emission at 24 μm are attributed to Very Small Grains (VSGs). The data presented here is unique and our study tries to establish a relation between various dust populations. By studying the FUV-IR correlations separately at low and high latitude locations, we have identified the grain component responsible for the diffuse FUV emission.

1. Introduction

The discovery of scattering and absorption of incident radiation, known collectively as extinction, provided the first definitive proof of the existence of interstellar dust (Trumpler, 1930). Our study of the properties of dust such as grain size, composition, etc., is mainly based on the spectroscopic absorption or emission features and thermal emission from the dust. There are many models that have been proposed to examine the dust in the diffuse interstellar medium (ISM) (Witt, 2000) which are mainly based on an analysis of extinction (Mathis et al., 1977; Hong and Greenberg, 1980; Draine and Lee, 1984; Duley et al., 1989; Kim and Martin, 1994; Mathis, 1996; Li and Greenberg, 1997; Zubko, 1999; Weingartner and Draine, 2001). The importance of interstellar dust can be gauged from the fact that it not only affects how we see our own Galaxy, but also affects the appearance of other galaxies by attenuating the short wavelength radiation from stars, and by re-emitting in the infrared (IR), far-infrared (FIR), sub-millimeter, millimeter, and microwave wavelength bands (Draine, 2003). Inspite of the existence of multiple models, the most accepted view is that the interstellar dust grains consist of amorphous silicates and some form of carbonaceous materials.

In the mid-infrared (MIR), we observe emission from small Polycyclic Aromatic Hydrocarbon (PAH) molecules (Allamandola et al., 1985) and in the far-infrared (FIR) from solid grains which have sizes starting from a few tens of angstrom (Draine, 2003). These small grains are known as Very Small Grains (VSGs) and their emission is detected near 24 μm. PAH molecules are electronically excited by the background UV photons. The excited PAHs emit in the MIR through infrared fluorescence. A significant amount of emission is found near 8 μm (Wu et al., 2005).

There have been large scale observations of diffuse FUV dust scattering in the Galaxy with the advent of space based telescopes such as the IR-based *Spitzer Space Telescope* or the UV-based *Voyager*, *Far Ultraviolet Spectroscopic Explorer (FUSE)* and the more recent *Galaxy Evolution Explorer (GALEX)* telescope. According to Bendo et al. (2008), the stellar continuum-subtracted 8 μm gives PAH emission, 24 μm gives hot dust (VSG) emission and 160 μm gives cold dust emission. In particular, the (8 μm/24 μm) surface brightness ratio is observed to be high in the diffuse ISM and low in bright star-forming regions. By studying the correlations between the MIR/FIR and FUV observations for the same locations in the Galaxy, we hope to probe the dust properties in the region and give accurate explanations for the observed correlation trends.

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2. Observations and data analysis

We have looked for IR data corresponding to the FUV observations by *Voyager* (Murthy et al., 1994, 1999; Sujatha et al., 2007), *FUSE* (Murthy and Sahnow, 2004; Sujatha et al., 2007) and *GALEX* (Murthy, 2014) in our Galaxy. We found 48 MIR locations observed at 8 μm and 80 MIR locations observed at 24 μm in the *Spitzer Heritage Archive (SHA)*. The 8 μm observations have been taken with the *Infrared Array Camera (IRAC)* on-board the *Spitzer Space Telescope. IRAC* (Fazio et al., 2004) is a four-channel camera that provides simultaneous images at 3.6 μm, 4.5 μm, 5.8 μm, and 8 μm. Each of the four detector arrays in the camera is 256 × 256 pixels in size, with a pixel size of 1.2 × 1.2 arcsecs. The other 80 locations at 24 μm have been observed by the *Multiband Imaging Photometer for Spitzer (MIPS)*. The *MIPS* (Rieke et al., 2004) produced imaging and photometry in three broad spectral bands in the MIR and FIR: 128 × 128 pixels at 24 μm with a pixel size of 2.45 × 2.45″, 32 × 32 pixels at 70 μm with a pixel size of 4.0 × 4.0″, and 2 × 20 pixels at 160 μm with a pixel size of 8.0 × 8.0″. The FUV data and instruments have been well documented in the individual work (Murthy et al., 1994, 1999; Murthy and Sahnow, 2004; Sujatha et al., 2007; Murthy, 2014) that have been used as source for this work. Briefly, the *Voyager UVS* with a large field of view of $0.1° \times 0.87°$ observed diffuse radiation from 500 to 1600 Åwith a resolution of about 38 Å. It has long integration times resulting in a high sensitivity to diffuse radiation, viz. better than $100\ \text{photons cm}^{-2}\text{sr}^{-1}\text{s}^{-1}\text{Å}^{-1}$ (Sujatha et al., 2007). The *FUSE* telescope has the *LWRS* (30″ × 30″) aperture on-board and the four *FUSE* spectrographs having a resolution ($\lambda/\Delta\lambda$) of about 20,000 cover the wavelength range 850–1167 Å. It can detect background levels of $2000\ \text{photons cm}^{-2}\text{sr}^{-1}\text{s}^{-1}\text{Å}^{-1}$ (Sujatha et al., 2007). Murthy and Sahnow (2004) have described the method of extraction of diffuse surface brightness from FUSE spectra by analysis of the background observations. The spectra is collapsed into two wavelength bands per detector by treating the FUSE spectrum as a broadband photometric observation and excluding the terrestrial air glow lines (primarily Lyβ). The *GALEX* telescope instrument having spatial resolution of 5″ – 10″ has two detectors: FUV at 1344–1786 Åand NUV at 1771–2831 Å, which image a 0.6° radius field. It detects a diffuse signal of $100\ \text{photons cm}^{-2}\text{sr}^{-1}\text{s}^{-1}\text{Å}^{-1}$ in a typical *AIS* observation (Murthy, 2014).

We have used all the 48 locations with 8 μm data and all the 80 locations with 24 μm data. We have calculated the flux at these locations using aperture photometry technique and then converted them to intensities. The images have not been convolved. We have taken post basic calibrated data (pbcd) and treated the images at different wavelengths independently. After computing the IR intensities, we have calculated the Spearman's rank correlation coefficient (ρ) which is a non-parametric version of rank correlation. We have calculated the correlations among intensities and since the spatial resolution of all the telescopes are comparable, this should not affect the results. The Spearman's rank correlation is a simple and reliable method of testing both the strength and direction (positive or negative) of the monotonic relationship between two variables rather than the linear relationship between them. It does not assume any model, like a straight line fit, and hence it is non-parametric. We have used Spearman's rank correlation because monotonicity is ‘less restrictive’ than that of a linear relationship, i.e. we might get a pattern among our observed data that is monotonic, but not linear, and so it still tells us that they are related (Bevington and Robinson, 2003). The Spearman's rank correlation coefficient is calculated using the following relation:

$$\rho = 1 - \frac{6\Sigma d^2}{n^3 - n}$$

where, Σ = sum, d = difference between two ranks, n = no. of pairs of data.

The Spearman correlation coefficient, ρ, can take values inside the interval [−1, 1]. A value of +1 indicates a perfect association of ranks (as the value of one variable increases, so does the value of the other variable), zero indicates no association between ranks and −1 indicates a perfect negative association of ranks (as the value of one variable increases, the other variable value decreases). The closer ρ is to zero, the weaker the association between the ranks. Once we have calculated the rank correlation, we must test to see how likely it is that our calculation is not just the result of chance which is called significance testing. It considers our result in relation to how much data we have. The probability (δ) is a result of this significance testing which tells us the standard error in the calculation of the rank correlation coefficient. It is calculated as:

$$\delta = \frac{0.6325}{\sqrt{(n-1)}}$$

Lower the value of probability (δ), more is the reliability in the observed value of rank correlation coefficient.

Our locations include the *Coalsack* nebula, which is one of the prominent dark nebulae in the southern sky of the *Milky Way*. The emission from the nebula is mainly due to the forward scattering of light from the bright stars behind it as mentioned by Murthy et al. (1994). While *Infrared Spectrograph (IRS)* from *Spitzer* provides the most accurate way to study the dust features, it would be useful to use some combination of *IRAC* and *MIPS* images since having a photometric probe would allow for a larger range of objects and environments to be studied given that imaging is faster to acquire and can probe regions that are too faint for spectroscopy. The 8 μm band of the *IRAC* is

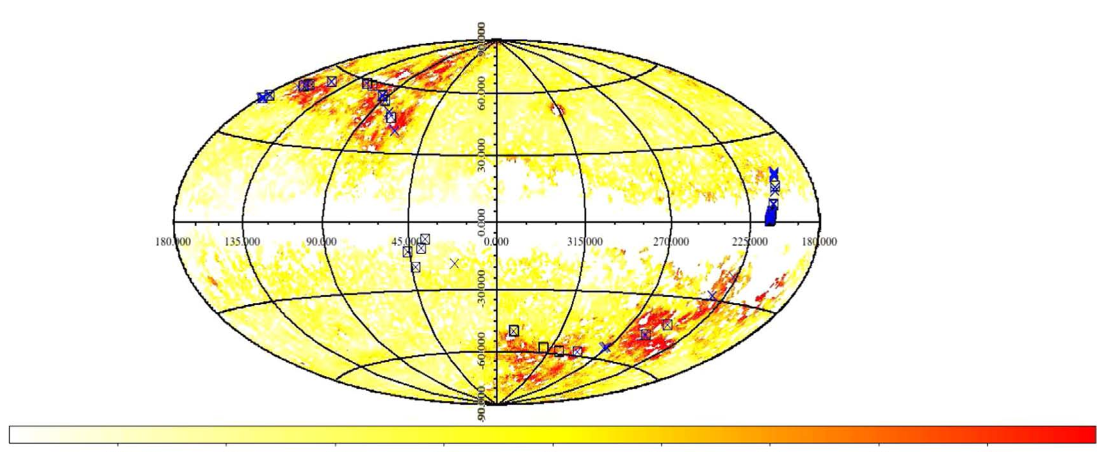

Fig. 1. Our locations plotted on an Aitoff with Galactic coordinates. The 8 μm locations are represented as squares and 24 μm locations as crosses. This is an all-sky map of the FUV diffuse sky from Murthy (2014).