CHAPTER 8

Summary and Future outlook

"Imagination is more important than knowledge. For knowledge is limited, whereas imagination encircles the world."

– Albert Einstein

Dust controls our view of the universe around us due to the fact that energy emitted by stars as shorter wavelength ultraviolet (UV) and optical radiation is attenuated by it and re-radiated in the infrared (IR) and longer wavelength bands [1]. In order to determine the intrinsic properties of an astrophysical object, it becomes highly crucial to correct the effects of such attenuation comprising of dust absorption and scattering, referred to collectively as extinction [17]. The extinction occurring due to dust is wavelength dependent which provides us with information about both the size and composition of the dust grains. Over the years, many models have been proposed to examine the dust in the diffuse interstellar medium (ISM) of galaxies based mainly on an analysis of extinction [23, 25, 45, 46, 57, 63, 68, 69, 242–247]. Nevertheless, the most accepted view is that interstellar dust grains consist of amorphous silicates and some form of carbonaceous material.

With the launch of space-based multi-wavelength observatories, a huge amount of dust scattering in the far-ultraviolet (FUV) and dust re-emission in the IR has been observed. In the mid-infrared (MIR), the emission is observed from Polycyclic Aromatic Hydrocarbon (PAH) molecules [248] and small grains [1] depending on their environment [78, 115] while the dust grain sizes gradually increase for the emission seen towards the far-infrared (FIR). The discovery of spectroscopic features complemented by laboratory study of materials for dust candidates has led to an increasing interest in the study of interstellar dust in the last decade. An overview of dust origins and properties, with recent dust grain models and multi-wavelength telescopes, is presented in **Chapter 1**.

Despite the importance of dust, determining the physical properties and amount of interstellar dust in other galaxies has been a very challenging task with much left to explore and understand. In this thesis, we have tried to interpret the interstellar dust characteristics at various locations in the local universe by studying their emission at different wavelength bands and subsequently modelling the dust grains starting with our own Milky Way (MW) galaxy and then expanding our sample of study to nearby regions including both the Magellanic clouds.

In order to understand the properties of a particular dust sample, we have first used archival space-based telescope data and carried out aperture photometry to determine the dust emission at individual locations for a particular wavelength. We have then made use of Spearman's rank correlation coefficient, which non-parametrically tells us about the monotonic relationship between two variables, to compare the emissions at multiple wavelengths and determine the nature of dust species present at the observed locations.

In **Chapter 2** of this thesis, we have studied the rank correlations in the Milky Way (MW) by comparing the FUV data observed by *Voyager* [107], *Far Ultraviolet Spectroscopic Explorer (FUSE)* [158, 159] and *Galaxy Evolution Explorer (GALEX)* [182] space telescopes with the archival MIR (8 μm, 24 μm) data observed by *Spitzer* [76, 77]. We have separated our observations into low and high latitude locations and found significantly better FUV-IR correlations for the lower latitudes indicating a decreasing abundance of PAHs and very small dust grains at high latitude locations. This has led us to propose an extragalactic origin of dust for the observed emission at high latitudes in the MW [100].

As we look outside our Galaxy, the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) have long served as ideal nearby laboratories to study dust properties and abundances in high-redshift galaxies owing to their nearly face-on orientation and closeness to the MW (LMC$\sim$50 kpc; SMC$\sim$60 kpc) [120, 139]. The difference in the properties of interstellar dust, as well as the gas-to-dust ratio, has been well documented by studying the variations in the FUV extinction curves of the MW, LMC and SMC [134, 135].

In **Chapter 3**, we have studied the rank correlations in the LMC between the FUV (1000–1157 Å) diffuse emissions observed by *FUSE* [158, 159] and the archival IR (8 μm, 15 μm, 24 μm, 90 μm) data observed by the *Spitzer* [76, 77] and *AKARI* [129] space telescopes. Our locations included two HII regions in the LMC, namely N11 and 30 Doradus and we observed better FUV-IR correlations for the former. We also found a higher FUV/IR(90 μm) intensity ratio for emissions in 30 Doradus due to the high unresolved star density at the observed LMC locations [101].

The SMC, in contrast to the LMC and MW, is a low-metallicity galaxy making it an ideal sample for studying the ISM of galaxies which are in the early stages of their chemical enrichment [140]. Now, the very conspicuous absence of the 2175 Å bump [21, 134] along most of the SMC has been attributed to the absence of carbonaceous content and PAHs [151]. In **Chapter 4**, we have attempted to explain the lack of this 2175 Å feature in the SMC using FUV-IR correlation studies by comparing the FUV (1000-1750 Å) data from *FUSE* [158, 159] and *International Ultraviolet Explorer (IUE)* [160–162] with archival *Spitzer*, *Wide-field Infrared Survey Explorer (WISE)* [164] and *AKARI* [129] data in the IR (8 μm, 22 μm, 24 μm, 65 μm, 90 μm). We find the larger sized dust grain emissions in the FIR to be better correlated to the FUV emissions as compared to the MIR data which indicates a lack or absence of PAHs at our observed locations. A comparison with the correlation trends observed in the LMC reveals that PAHs are shielded from destruction in high-metallicity galaxies as opposed to the low-metallicity SMC where we see a weak emission at 8 μm due to the possible destruction of PAHs by high energetic radiation fields in the vicinity [153, 165].

It is necessary to complement the inferences drawn from correlation studies with appropriate dust grain models in order to better understand the dust characteristics in a region. With this aim in mind, we have modified the dust FUV scattering model developed by Shalima et al. (2006) [89] to the study the diffuse radiation in the MW. In **Chapter 5**, we have used the Orion nebula (M42 or NGC 1976), which is our nearest site (∼420 pc) [249] of active star formation [171] and one of the brightest sources in the UV sky [172], as our sample of study to investigate the optical properties of dust in the region. We have first used photometric all-sky survey data observed by *GALEX* in the FUV and *AKARI* in the FIR to study the UV-IR correlations in a 10 degree radius around the Orion center. This revealed that the emissions at our observed locations were caused by larger dust grains belonging to colder environments with the smaller dust grains possibly getting destroyed or photo-evaporated by high radiation coming from the Trapezium star cluster [250] at the center of the nebula. We followed this by modelling the dust grains responsible for the FUV scattering in front of Orion's veil [173, 174] and obtained an albedo, α=0.7 and scattering phase function asymmetry factor, g=0.6 as the median values for dust at our observed locations. We also determined the distances to individual dust locations observed between us and the Orion central region in a 100-400 pc range, which allowed us to construct a 3D distribution of dust around Orion [102].

In addition to studying the optical properties of dust grains, an understanding of their chemical composition is essential to be able to explain the observed dust features at different wavelength bands. Since the polarization profile (peak wavelength, shape, and strength) of dust candidates is highly susceptible to the specific shape, composition as well as size of the dust grains [58, 251], we have studied the MIR (8–13 μm) linear polarization in a sample of young stars (MWC 1080A, MWC 297, HL Tau) in **Chapter 6**, to constrain the dust properties in their circumstellar environment [252]. We have generated Discrete Dipole Approximation (DDA) [96, 235] and Effective Medium Approximation (EMA) T-Matrix [92] based composite dust grain models [91] and then compared the simulated data with actual observations made in the MIR using CanariCam at the Gran Telescopio Canarias (GTC) [218]. We report the possible existence of silicon carbide (SiC) in the outer disk/envelope around one star in our sample which has been interpreted based on the shape, size, composition, and fraction of inclusions by volume in our composite dust grain models.

The key findings of each work have been presented together in **Chapter 7** and the thesis concludes with a brief summary and prospects for future work as presented here (**Chapter 8**).

Future work

As a follow-up to the work presented in this thesis work, we would like to probe the following issues in the near future:

- The data presented in Chapter 3 for diffuse dust observations in the Large Magellanic Cloud (LMC) is unique and we plan to model the dust grain emissions in both the HII regions (N11, 30 Doradus) theoretically by using suitable dust mixtures. For 30 Doradus one needs to use a special dust mixture and N11 can be modelled by using a Milky Way type of dust mixture. We hope to use the stellar/diffuse fraction which was presented by Pradhan et al. (2010) [130] and determine whether the stellar component of the FUV is indeed higher in 30 Doradus which has led to the observed correlation trends.

- Our findings on dust composition and properties around young stars as presented in Chapter 6 have been limited by the lack of polarimetric observations in the mid-infrared (MIR). We would like to look for better and more closely spaced MIR polarimetric data to add more credibility to our composite dust grain models. There is also a chance to explore the possible contribution of polycyclic aromatic hydrocarbon (PAH) molecules towards absorption/emission observed in the dusty envelopes surrounding young stars, with the availability of reliable MIR polarimetric observations.

- With the advent of new and upcoming space missions, a plethora of information and high level science products have/will become available for us to explore and analyse. *ASTROSAT UVIT* [253] has the ability to undertake interstellar extinction measurements [254] and it has a much better resolution as compared to *GALEX* which will highly benefit research to be carried out in the near future. The *James Webb Space Telescope (JWST)* to be launched in 2020 will make an enormous supply of IR data available for dust studies and it will very well complement the *ASTROSAT* X-ray and UV data for any kind of multi-wavelength studies to be carried out with high precision in the coming years.

In addition to the aforementioned prospects, there is a huge potential for studying the interstellar dust characteristics in both nearby and far-off galaxies, out of which we have examined only a tiny portion in this thesis work. Such studies will definitely go a long way towards understanding the nature and origins of dust in the universe around us.