Chapter 6

Summary of the thesis

In this thesis, we have undertaken a comprehensive exploration of various aspects of the ISM in two dwarf irregular galaxies within our local Universe, namely Ho II and LMC. Our analysis is based on the observational data acquired from different space-based telescopes, including *AstroSat* and *FUSE* for UV observations, as well as *Spitzer* and *Herschel* for IR observations. The goal is to develop a thorough understanding of the ISM characteristics in these galaxies. This thesis presents the first time high resolution UV observation of the galaxy Ho II, accomplished with *AstroSat*/UVIT. Simultaneously obtained X-ray observations of the galaxy are also incorporated to investigate potential correlations between X-ray and UV fluxes from the ULX source Ho II X-1. Furthermore, we delve into the properties of interstellar dust grains in Ho II, using UVIT data alongside complementary IR data from *Spitzer* and *Herschel*. This is achieved through a UV-IR correlation study and the modeling of diffuse FUV and IR emissions. Based on prior research by [97], we extend our investigation to model the diffuse FUV emission from 30 Doradus in LMC. This modeling is based on observations by [96] using the *FUSE* telescope, aiming to gain insights into the scattering geometry within the 30 Doradus region.

6.1 Key Outcomes

6.1.1 *AstroSat*/UVIT observation of Ho II

The substantial improvement in the observational capabilities achieved through the deployment of *AstroSat*/UVIT, particularly when compared to its precursor *GALEX* has been discussed in Chapter 2 of the thesis. While *GALEX* provided relatively poor resolution in its observations of Ho II (approximately $4.2''$ in FUV and $5.3''$ in NUV), *AstroSat*/UVIT has significantly enhanced this resolution by a factor of about 3. This enhancement has resulted in the most detailed UV observation of Ho II to date.

The improved resolution offered by *AstroSat*/UVIT is crucial as it allows for a comprehensive examination of both distinct point sources and diffuse UV emission. This is particularly beneficial for the clear identification and elimination of most point sources, enhancing the overall clarity of the observations. A visual comparison between UVIT and *GALEX* images, focusing on a specific region within the central star-forming arc of the galaxy, where it hosts the ULX point source Ho II X-1 is also shown. The visual comparison emphasizes the remarkable enhancement in resolution provided by UVIT, showcasing a significantly improved visibility of the ULX source when compared to the *GALEX* image. This detailed and enhanced observation with *AstroSat*/UVIT opens up new avenues for studying specific features and celestial objects within Ho II, contributing to a more detailed understanding of its astrophysical characteristics.

6.1.2 Nature of emission from the ULX source Ho II X-1

ULXs are distinct point-like sources located outside our galaxy, characterized by luminosities that surpass the Eddington limit typical for black holes within the Milky Way. According to current understanding, these sources are mostly considered to be binary systems, hosting either stellar-mass black holes or neutron stars that accrete material at rates exceeding the Eddington limit [123, 124]. These ULX sources demonstrate substantial variability in X-ray emissions and are also prominent emitters in the UV spectrum. Notably, the UV emissions arise from the reprocessing of X-ray photons, implying an expected correlation between UV and X-ray emissions.

AstroSat observed the ULX source hosted by Ho II viz. Ho II X-1 in ten epochs, with eight of them being simultaneous in both the X-ray and UV bands, from 2016 to early 2020. The *AstroSat* payload, comparable to *Swift* but with superior spatial resolution in UV/optical telescopes, enables the study of optical counterparts of X-ray sources even in crowded stellar fields. Despite Ho II X-1 being recognized as one of the most variable sources among confirmed ULXs, the observations captured it during a period of low variability. The variability factor observed was only 1.5 times in X-rays and approximately 25% (upper limit) in the UV band. This limited variability prevented the detection of a tight correlation between the X-ray and UV bands, as predicted by different models. Three heating models were considered: the heated thin disk, the wind, or the O-B supergiant donor star. However, the observed variability level was insufficient to reject any of these models. To distinguish between the models, an estimated X-ray variability of approximately 2.5 or higher is required.

A brief examination of recent *Swift* observations suggests that Ho II X-1 returned to a state of high variability since February 2021. This raises hope that further *AstroSat* observations will eventually detect the correlation, offering insights into the nature of Ho II X-1's UV-optical emission.

6.1.3 Interstellar dust properties

Dust grains play a crucial role in shaping our comprehension of the universe by obstructing starlight through the combined effects of scattering and absorption, collectively known as extinction. They scatter a notable portion of incident radiation, leading to diffuse emissions primarily observed in the FUV regime. The remaining fraction of radiation at shorter wavelengths (optical and UV) is absorbed and subsequently re-emitted at longer wavelengths, resulting in diffuse emissions in the IR and sub-millimeter wavelengths [11]. Therefore, correcting for the effects of extinction is highly crucial in determining the intrinsic properties of an astrophysical object [8]. The emergence of various space-based multi-wavelength observatories has facilitated the study of these diffuse emissions and the determination of the physical properties of dust grains. In Chapter 4 and Chapter 5, we have endeavored to determine the properties of dust grains based on the observed diffuse emissions in our two samples, namely, Ho II and LMC, respectively.

We employed UV observations from *AstroSat*/UVIT, complemented by IR observations from *Spitzer* and *Herschel* space telescopes, to probe the interstellar dust component of the ISM in Ho II. The investigation began with a correlation study between diffuse UV and IR emissions within the galaxy. Notably, we observed a stronger correlation between 70 μm IR emission and UV in regions with high HI density (N(HI) > 1×10^{21} cm $^{-2}$), suggesting the re-emission of UV photons absorbed by warm dust grains near hot, young stars. Voids (N(HI) < 1×10^{21} cm $^{-2}$) exhibited poor or weak negative UV - IR correlation, except for 160 μm, showing a reasonable correlation with NUV. We then focused on modeling diffuse FUV emission within the galaxy, with an aim to understand the role of dust scattering in contributing to diffuse UV emission. This study incorporates modeling techniques based on a well-established single scattering model [95], enabling the derivation of essential dust optical properties, specifically, the albedo (α) and asymmetry factor (g). Our model-derived dust optical parameters (α = 0.2, g = 0.5) exhibited reasonable agreement with theoretical predictions. This led us to conclude that the diffuse UV emission in regions with high HI density includes a component of dust scattering. Notably, we identified a low optical depth ($\tau \sim$ 0.02 - 0.12) for the scattering layer and a high g value, indicative of forward scattering by optically thin clouds. However, assessments based on low albedo values and optical depths from our model suggested that only a small portion of the total diffuse FUV emission could originate from dust scattering. Finally, we presented a first-time analysis of IR dust emission in Ho II, aiming to identify spatial variations in dust parameters across small scales of $\sim$ 82 pc. We modeled the IR spectra of the galaxy from different regions with a modified black body equation. Our analysis unveiled that the IR spectra cannot be represented by an isothermal dust population, rather requiring multiple dust populations, up to five, with different temperatures, in locations connected to physically distinct regions.

In the case of LMC, our specific focus was on the 30 Doradus H II region, commonly referred to as the Tarantula Nebula, recognized as the most active star-forming region in the Local Group. Building upon the diffuse FUV observations conducted across various regions in the LMC using the *FUSE* telescope by [96] and a prior UV - IR correlation study in the 30 Doradus region by [97], we proceeded to model the diffuse FUV emission from this region. Employing the same single scattering model utilized for modeling diffuse FUV emission in Ho II, we successfully replicated the observed diffuse FUV light within the 30 Doradus region. The outcomes unveiled a complex dust structure, predominantly an optically thick scattering medium, responsible for scattering FUV light. While a small fraction of FUV photons scattered off the thin outer dust layers, the majority interacted with dust grains and underwent thermal re-emission. To deepen our understanding of dust grain properties and the dust geometry in the 30 Doradus region, our future endeavors will include modeling the diffuse FUV emission alongside the thermally re-emitted MIR and FIR emissions using various multiple scattering models.

6.2 Future prospects

Several studies have explored the diffuse UV emission within our Milky Way, extensively discussing various possible origins for this phenomenon [120, 218–220]. Observations from *Voyager* focused on specific regions of the Milky Way ISM towards the North Galactic pole, revealing diffuse emission with a spectrum resembling that of a hot UV star [221], indicating starlight scattered by dust. [222] and [223] found a correlation between diffuse UV radiation and the IR sky background, reinforcing the role of dust in this emission. The term Diffuse Galactic Light (DGL) is used for the diffuse emission resulting from the scattering of FUV photons by dust around hot stars. Utilizing data from *GALEX*, [224] created an all-sky diffuse background map, showing emission following a cosecant distribution with galactic latitude and asymmetric intensities about the galactic plane. At high galactic latitudes, where much of the diffuse FUV emission is attributed to DGL, there may be additional components: *a*) diffuse background emission from other galaxies and the intergalactic medium, known as Extra-Galactic Background Light (EBL), and *b*) an unidentified component called the "Offset" component [225, 226]. Plausible origins for the offset component include two-photon decay continuum, FUV line emission from hot ionized medium, and emissions from the Earth's atmosphere. In the galactic poles, [226] found offsets of $230-290$ photons cm^{-2} s^{-1} sr^{-1} Å^{-1} in FUV, with approximately 120 photons cm^{-2} s^{-1} sr^{-1} Å^{-1} attributed to dust-scattered light, 110 photons cm^{-2} s^{-1} sr^{-1} Å^{-1} to extragalactic background, and another $120-180$ photons cm^{-2} s^{-1} sr^{-1} Å^{-1} to the unidentified background. At low galactic latitudes, scattered starlight from dust grains dominates the diffuse UV background [227]. Another potential contributor is H_2 fluorescence, as observed by [228] in the IC 63 nebula, containing embedded stars with non-negligible optical and UV depth. [218] suggested integrated light from spiral galaxies as a possible contributor to the extragalactic component, but its estimated contribution is deemed insignificant (about 1/10 of the minimum observed signal).

In the case of Ho II, regions with high N(HI) density exhibit diffuse FUV emission that can be attributed to the scattering of FUV photons by dust grains. However, the presence of faint FUV emission in regions with very low N(HI), such as the HI voids, poses a challenge in explaining its origin solely through dust scattering (see Table 4.1 in Chapter 4). For these regions, alternative sources contributing to diffuse FUV need consideration. In the context of Ho II, one plausible source could be the two-photon continuum emission from the warm ionized medium and low-velocity shocks. In the ISM of our galaxy, low-velocity shocks are prevalent. The Hα image of Ho II reveals numerous bubble-like structures (Figs. 1 and 2 in [108]), potentially originating from supernova remnants as high-velocity shocks that subsequently evolve into low-velocity shocks. These low-velocity shocks primarily cool through various mechanisms, including Lyα emission, two-photon continuum, and Hα emission. Lyα photons are absorbed by the dust grains, but the two-photon continuum emission, peaking at around 1400 Å (close to the mean wavelength of our FUV observation), emerges as a potential source for the observed diffuse FUV emission in void regions. For further discussions on the two-photon continuum, see [229].

Another interesting proposition regarding the origin of the diffuse FUV background comes from [230], building upon observations by [120] and [226, 231]. The author suggests that the diffuse FUV emission, not accounted for by dust scattering, might be associated with dark matter annihilation events within the Axion Quark Nugget (AQN) dark matter framework. In this scenario, as AQNs enters the ISM, the annihilation process begins, leading to an increase in the temperature of the nuggets. The spectral features of the emission from AQNs align with the characteristics of the observed diffuse FUV radiation. However, confirmation of the presence of this component requires more precise measurements of the diffuse UV radiation.

As a continuation of the work presented in this thesis, we aim to further investigate alternative components contributing to the diffuse UV emission in Ho II as well as other similar dwarf galaxies. The goal is to conclusively identify and quantify the individual contributions of various sources, such as two-photon continuum from warm ionized medium and low-velocity shocks, and potential dark matter annihilation events within the AQN framework. This comprehensive exploration will enhance our understanding of the intricate mechanisms shaping the diffuse UV background of the dwarf galaxies.