Chapter 2

Ultraviolet observation of the dwarf galaxy Holmberg II with UVIT instrument onboard *AstroSat*

2.1 Holmberg II: A general introduction

Holmberg II (Ho II hereafter) is an irregular Im-type dwarf galaxy, residing within the M81-NGC 2403 galaxy group at a distance of 3.39 Mpc [98]. Ho II exhibits a low metallicity, estimated to be either 0.1 $Z_{\odot}$ or 0.3 $Z_{\odot}$ [99], owing to its low oxygen abundance [100]. The galaxy's relatively modest inclination angle ($\approx 27°$[101]) renders Ho II an exceptionally informative subject for studying the distribution of gas and dust within interstellar discs. This galaxy has been extensively surveyed across a broad range of electromagnetic spectrum through surveys like SINGS [102], KINGFISH [103], THINGS [104] etc. Ho II exhibits several striking features, including a central star-forming arc that radiates brightly in the UV and Hα, housing massive O-type stars within giant star clusters. The ISM of Ho II is primarily comprised of abundant HI [105]. It possesses numerous shells and cavities within its HI distribution, with sizes ranging from a few hundred parsecs to over a kpc [106]. [107] identified 82 H II regions in the galaxy, forming chain-like structures and constituting the "central arc" of the galaxy [108]. These connected complexes of ongoing star formation show clear indications of being triggered by HI supershell collisions [108]. The HI cavities within Ho II were formed by stars that have been born throughout the galaxy's evolution [106, 109]. In addition, this galaxy contains one of the brightest ULX source Ho II X-1 with X-ray luminosity $L_X > 10^{40}$ ergs/s.

Table 2.1 Some general properties of Ho II

Properties	Value
Name[a]	Holmberg II, Ho II, DDO 50, UGC 4305
Central position[b]	
RA (J2000.0)	$08^h19^m03^s.7$
Dec (J2000.0)	$70°43'23''.6$
Morphology[a]	Im
Distance[c]	3.39 ± 0.20 Mpc
M_B magnitude[c]	-16.71 ± 0.16
Color $B-V$[c]	0.11 ± 0.05
Gas mass[b]	1.3×10^9 $M_\odot$
Inclination	49°[b]
	38°[d]
	27°[e]
Position angle[b]	176°
Rotation velocity[b]	35.7 km/s

[a] NED, NASA/IPAC Extragalactic Database (https://ned.ipac.caltech.edu/)
[b] [110]
[c] [98]
[d] [111]
[e] [101]

2.2 *AstroSat*/UVIT observation of Ho II

2.2.1 *AstroSat*

AstroSat is India's maiden multi-wavelength space observatory, launched on September 28, 2015, from the Satish Dhawan Space Centre in Sriharikota. Placed into orbit at an altitude of 650 kilometers with a 6° inclination to the equator, this observatory was originally designed for a mission life of five years. Remarkably, it continues to operate effectively. One of *AstroSat*'s most distinguishing attributes lies in its capacity to conduct simultaneous multi-wavelength observations of celestial objects from FUV to γ-rays. Its scientific ensemble comprises five payloads: Ultra Violet Imaging Telescope (UVIT), Large Area X-ray Proportional Counter (LAXPC), Cadmium Zinc Telluride Imager (CZTI), Soft X-ray Telescope (SXT) and Scanning Sky Monitor (SSM). In the context of this chapter, our focus centers on the UVIT payload. UVIT is equipped with two co-aligned Ritchey-Chretien telescopes, each with an aperture of 375 mm. One of these telescopes feeds the FUV detector, spanning

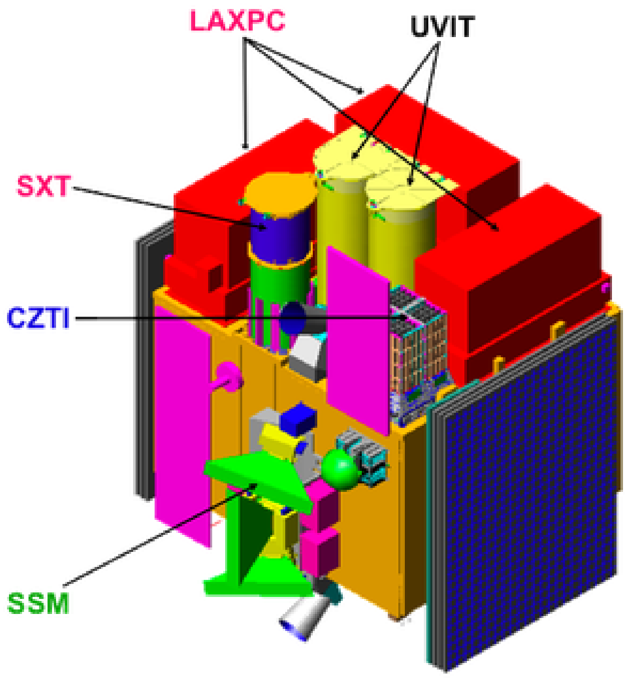


Fig. 2.1 The different payloads onboard *AstroSat* (Image credit: ISRO)

the wavelength range of 1300 – 1800 Å while the other telescope feeds two detectors: the Near UV (NUV) covering wavelength range of 1800 – 3000 Å and the Visible (VIS) with wavelength range of 3200 – 5500 Å via a dichroic filter, providing a field of view of 28 $'$ with a pixel scale of 0.41$''$. Each channel is equipped with a 512×512 CMOS detector, which can detect photons either in photon counting mode or integration mode. In photon counting mode, the detector can capture frames at a rate of 29 frames per second, with a 35 ms exposure time per frame [112]. The VIS channel is used only for the correction of spacecraft motion, which always works in the integration mode. At present, UVIT holds the distinction of being the highest angular resolution UV telescope in operation in space, offering an achievable resolution of 1.2$''$-1.6$''$ [113]. Apart from UVIT, it's noteworthy to mention that LAXPC has the highest collecting area among X-ray detectors to date. Furthermore, CZTI exhibits the remarkable capability to measure X-ray polarization and also serves as an open detector beyond 100 keV.

2.2.2 UV observations

The UV observation of Ho II was carried out with the help of the UVIT instrument onboard *AstroSat*. The galaxy was observed from 2016 till 2020 in 8 epochs: 3 epochs in 2016, 2 epochs in 2019 and 3 epochs in 2020 [114]. The details of these observations are provided in Table 2.2. The properties of different filters used in our UV observations are listed in Table 2.3.

Table 2.2 Details of *AstroSat*/UVIT observations of Ho II

Sl No.	Obs ID	Obs date	Channel & Filter	t_{exp} (ks)
1	G05_204T01_9000000688	30-09-2016	FUV F1 (F148W)	11.2
			NUV N6 (N279N)	10.6
2	A02_046T01_9000000814	21-11-2016	FUV F2 (F154W)	9.0
			NUV N3 (N245M)	8.2
3	A02_046T01_9000000864	09-12-2016	FUV F2 (F154W)	9.1
			NUV N3 (N245M)	8.7
4	A07_054T01_9000003370	17-12-2019	FUV F1 (F148W)	17.4
5	A07_054T01_9000003378	21-12-2019	FUV F1 (F148W)	17.2
6	A07_054T01_9000003406	02-01-2020	FUV F1 (F148W)	16.8
7	A07_054T01_9000003486	08-02-2020	FUV F1 (F148W)	16.6
8	A07_054T01_9000003504	16-02-2020	FUV F1 (F148W)	17.1

2.2.3 UVIT image processing

The raw UV data, denoted as Level 1 data, were obtained from the Indian Space Science Data Center (ISSDC) and are provided in the form of a single zipped archive for each observation. Within each archive, the files are systematically organized into subdirectories based on orbit number and file type, all residing under a unified top-level directory. All data files within these archives are formatted as FITS binary tables. Upon extraction from the archive, four distinct sets of files are obtained:

1. Level 1 data files for VIS ("uvtV"): Exclusively used for spacecraft correction purposes.
2. Level 1 data files for FUV ("uvtF") and/or NUV ("uvtN"): It is mandatory for at least one file from this set to be present.

Table 2.3 Properties of different UVIT filters used in our observation

Channel	Slot	Filter	Name	Mean wavelength λ_{mean} (Å)	Bandwidth $\Delta\lambda$ (Å)
FUV	1	F148W	CaF2-1	1481	500
	2	F154W	BaF2	1541	380
NUV	3	N245M	NUVB13	2447	280
	6	N279N	NUVN2	2792	90

3. Housekeeping files ("*.lbt"): Frames lacking housekeeping information are disregarded.

4. Attitude files ("*.att"): These are essential for an initial estimation of pointing accuracy.

These Level 1 data are in photon counting mode and had to undergo processing to transform them into images suitable for various scientific analyses, known as Level 2 data. This conversion from Level 1 to Level 2 is essential due to the spacecraft's oscillatory movements. The spacecraft is commanded to oscillate around the target point, with a few arcminutes of amplitude and a velocity of a few arcseconds per second. This is designed to protect the detectors from the bright stars and to mitigate image artifacts caused by bad pixels. The consequence of this spacecraft oscillation is that the positions of stars change over time. To produce scientifically valuable images, it's necessary to correct for this motion, ensuring that each photon is accurately placed in the final image. Various data processing pipelines have been developed for UVIT, and for this work, we utilized one called JUDE[1] (Jayant's UVIT Data Explorer), developed by Prof. Jayant Murthy from the Indian Institute of Astrophysics, Bengaluru, India. JUDE is an alternative data processing pipeline for UVIT, comprising a set of GNU Data Language (GDL) routines [117]. JUDE operates in two modes: automatic and manual. Initially, we processed the Level 1 data in automatic mode. This involved reading the Level 1 data, extracting photon events from each frame, correcting for spacecraft motion (image registration), and creating an image.

- VIS files processing: Observations in the VIS channel are conducted in integration mode, where the CMOS detector is read once per second. The *jude_read_vis.pro* routine within JUDE is employed to read each VIS frame. The x and y positions of stars in the field are then extracted using the library routine *find.pro* (based on DAOPHOT [118]). The spacecraft motion, calculated as the shift between successive frames, is determined and recorded into a text file using *jude_vis_shifts.pro*.

- Housekeeping and attitude files: The housekeeping files encompass extensive data regarding the health and environmental status of UVIT, with a significant portion of information that is not directly applicable to scientific analysis. Simultaneously, the attitude files document the spacecraft boresight position, determined by the star sensor every 16 seconds. To read both the housekeeping and attitude files, we employed the *jude_read_hk.pro* routine.

[1]Released under the Apache License 2.0, and archived at the Astrophysics Source Code Library [115]. The latest version is available at https://github.com/jaymurthy/JUDE. JUDE Manual is published in [116].

- UV data processing: At the initial stage, each individual photon impinges on the photocathode of the detector, triggering the ejection of electrons. These electrons undergo acceleration through a microchannel plate before reaching a phosphor screen, producing flashes of green light. Each such flash signifies a single photon hit and is duly recorded on the CMOS sensor. Subsequently, the onboard software transforms these flashes into discrete photon events, achieving a remarkable resolution of 1/8 of a pixel. This information is then transmitted to the ground. The ISSDC undertakes the separation of data based on instrument and channel, presenting it to the observer as Level 1 data. Each frame comprises a maximum of 336 events, with additional events leading to the creation of a new frame. The reading of each frame and extraction of photon events are executed using *jude_get_xy.pro* routine. The conclusive step in the Level 2 data production involves the elimination of duplicate frames and the merging of files that might be disrupted in the midst of an exposure.

The output of the above processes creates time tagged photon event lists and are stored in FITS binary tables, constituting the primary Level 2 data. These individual photon lists can be added to produce an image of the sky using *jude_add_frames.pro*. However, the quality of the image depends on the image registration. In the automatic mode, the image registration might not always meet the desired standards. To enhance the accuracy of image registration, we reprocessed the Level 2 data in manual mode. Achieving a spatial resolution of approximately $1.2'' - 1.6''$ in the UV bands is possible with precise image registration [113]. Each sub-observation, the uninterrupted segment between the spacecraft's passages through the South Atlantic Anomaly, was individually processed. After processing, these segments were calibrated astrometrically, aligned to a common reference frame, and subsequently co-added. This co-added image can be used for different scientific analyses. A more detailed description of the algorithm of the image production can be found in [119]. A list of the different JUDE modules and their purposes are given in Table 2.4. For the FUV data, we achieved a spatial resolution of about $1.4'' - 1.8''$, which varies from one observation to another. In the case of NUV data, a slightly better resolution of $1.2'' - 1.4''$ was obtained [114]. It's worth noting that NUV data was obtained only for the 3 epochs in 2016, as the NUV channel stopped functioning on March 20, 2018, while the FUV channel remains operational to the present day. Consequently, for subsequent epochs, only FUV data was obtained.

Table 2.4 JUDE modules and their purposes

Module	Purpose
jude_get_files	Returns names of data files
jude_params	Sets operating parameters
jude_err_process	Error handler
jude_read_vis	Reads the visible data
jude_create_uvit_hdr	Creates FITS data header for Level 2 data files.
jude_read_hk_files	Reads housekeeping files
jude_set_dqi	Sets instrumental parameters
jude_get_xy	Extracts individual events from Level 1 data
jude_cnvt_att_xy	calculates X and Y shifts from boresight
jude_check_bod	Check and reject bright object detection (BOD)
jude_register_data	Corrects for spacecraft motion
jude_add_frames	Combines individual frames into image
jude_vis_shifts	Calculates spacecraft motion from the visible data
jude_add_vis	Adds visible frames together
jude_obs_log	Creates observation log from Level 2 files
jude_merge_files	Combines files with overlapping data
jude_match_vis_offsets	Matches the visible offsets to the UV channels
jude_apply_cal	Applies photometric calibration to data
jude_centroid	Tracks spacecraft motion through centroids of stars
jude_uv_cleanup	Post processimg of Level 2 data
jude_interactive	Interactive exploration of Level 2 data

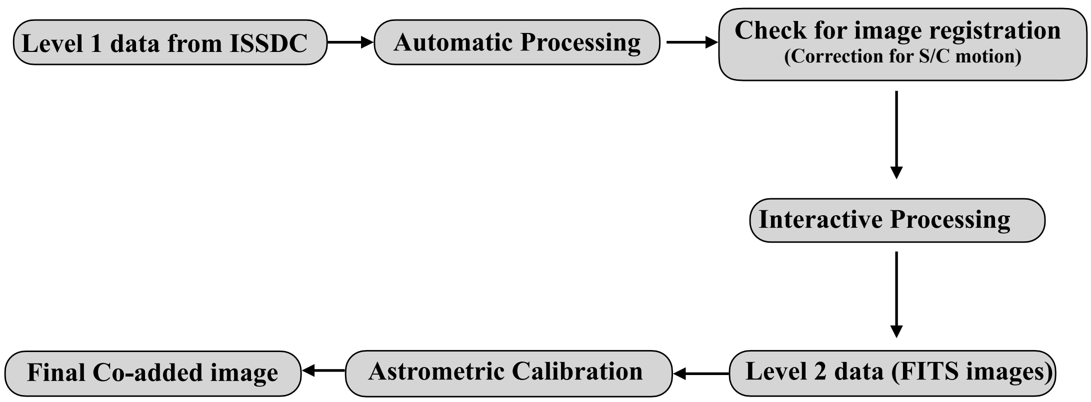


Fig. 2.2 An schematic diagram showing the different processes involved in the processing of UVIT data with JUDE

2.2.4 UVIT images of Ho II

Fig. 2.3 and Fig. 2.4 present the FUV and NUV co-added images of Ho II obtained with the UVIT instrument, after processing through JUDE. It is evident from the images that the distribution of UV emission in Ho II is quite patchy in nature, the highest intensities of UV emission being concentrated near the UV emitting stars or star forming central arc. Such distribution of UV emission has also been observed in our galaxy by [120].

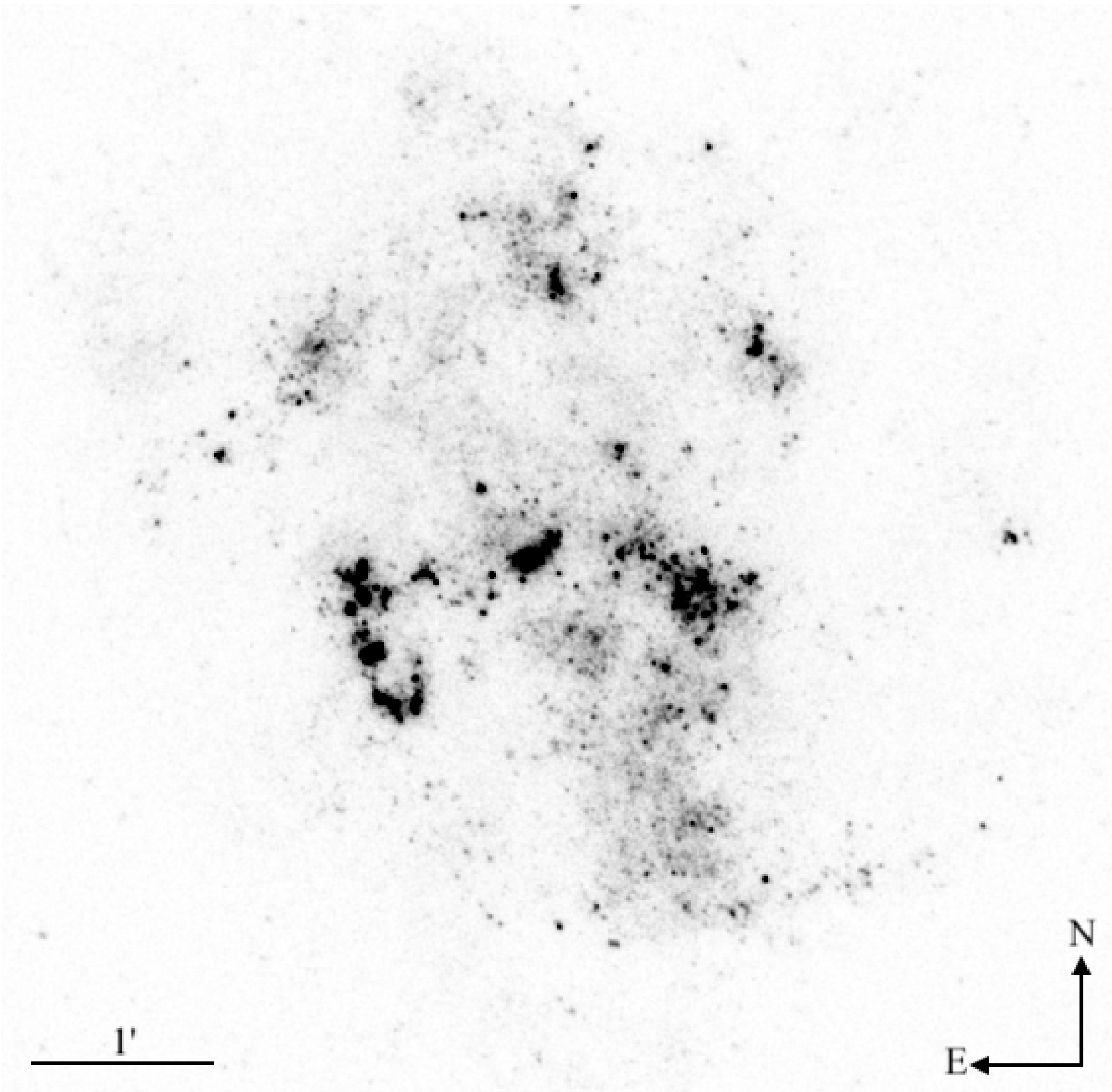


Fig. 2.3 UVIT - FUV co-added image of Ho II (Observation date: December 9, 2016, Filter: F154W)

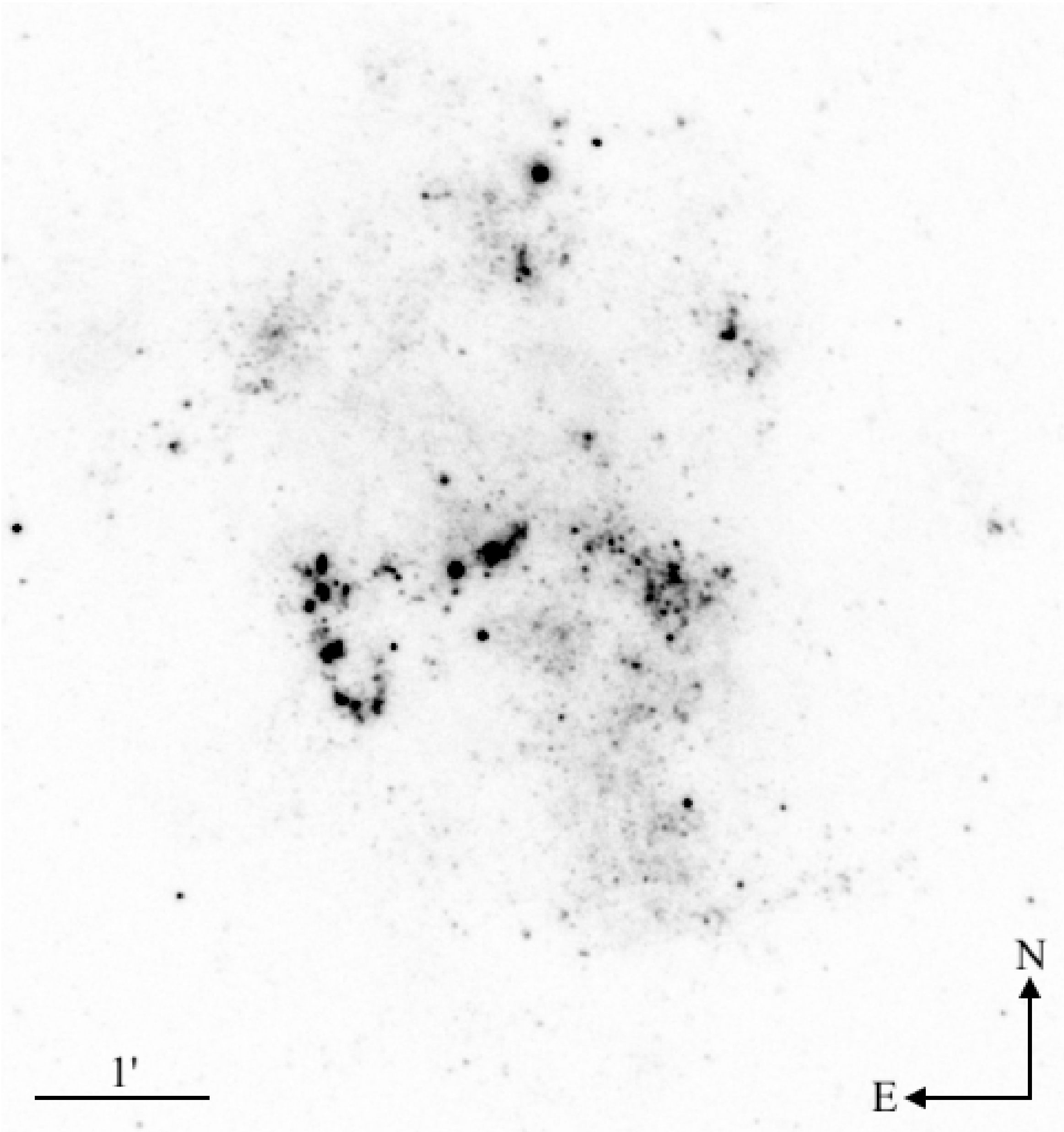
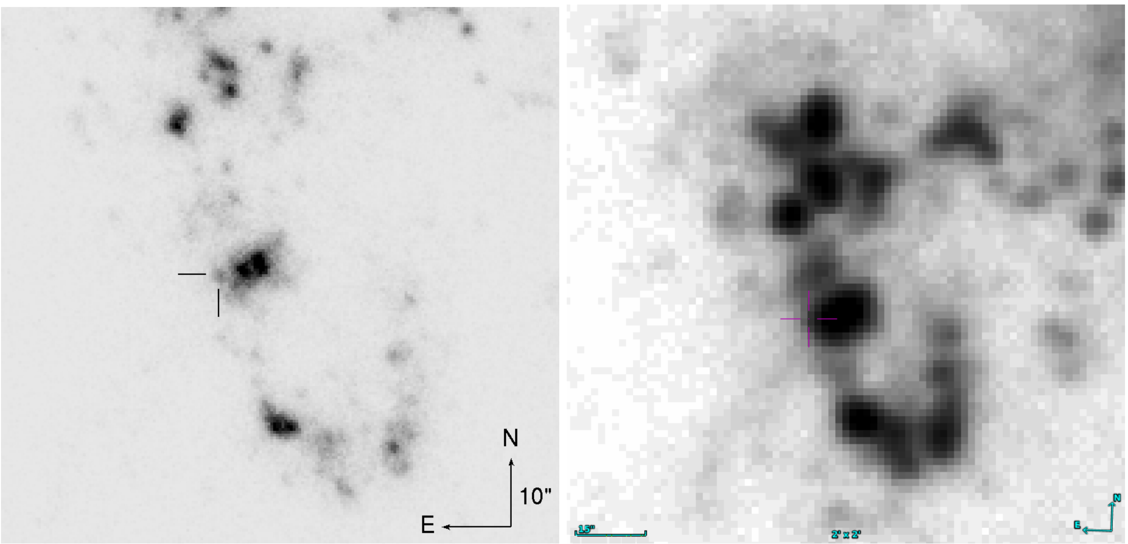


Fig. 2.4 UVIT - NUV co-added image of Ho II (Observation date: December 9, 2016, Filter: N245M)

2.3 Conclusions

Ho II has been observed by other UV telescopes such as the *Ultraviolet Imaging Telescope (UIT)* on the ASTRO-2 mission [121], *HST*/UVIS [122], and *GALEX* before the *AstroSat*/UVIT observations. While *HST*/UVIS offers better angular resolution (around $0.09''$), it has a smaller field of view (approximately $2.5'$). The *UIT*, although having a larger field of view (40′) than UVIT, has lower angular resolution (2″). *GALEX* boasts a very large field of view (1.2°) but has relatively poor resolution (around 4.2″ in FUV and 5.3″ in NUV), which limits its ability to resolve distinct point sources. Therefore, considering both angular resolution and field of view, *AstroSat*/UVIT emerges as a better choice compared to the other UV telescopes. The substantial enhancement in resolution (by a factor of ∼ 3) achieved with *AstroSat*/UVIT comapred to *GALEX* (by a factor of ∼ 3) has provided us with a detailed UV observation of Ho II. This improved resolution in UVIT images enables comprehensive examination of the point sources as well as diffuse UV emission, as it allows for clear identification and elimination of most point sources. Fig. 2.5 presents a comparison between UVIT and *GALEX*[2] (observation ID: GI3_050003_HolmbergII_0001, observation date: 31 March, 2007) FUV images of a section within the central star-forming arc of the galaxy. This specific region harbors the ULX source Ho II X-1, indicated by the reticle on both images. The images clearly illustrate the remarkable enhancement in resolution in the UVIT images, significantly improving the visibility of the ULX source compared to the *GALEX* image.



(a) *AstroSat*/UVIT (b) *GALEX*

Fig. 2.5 (a) *AstroSat*/UVIT image of the star forming region harboring the ULX Ho II X-1, (b) *GALEX* image of the same region. The location of the ULX is shown with the reticle. The two images clearly highlight the significant improvement of the resolution of UVIT compared to *GALEX*

[2]For access to the GALEX image, kindly visit https://galex.stsci.edu/GR6/?page=downloadlist&tilenum=23043&type=coaddI