Tracing Young Star-forming Clumps in the Nearby Flocculent Spiral Galaxy NGC 7793 with UVIT Imaging

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Abstract

Star formation in galaxies is a hierarchical process with a wide range of scales, from smaller clusters to larger stellar complexes. Here, we present an ultra-violet imaging study of the nearby flocculent spiral galaxy NGC 7793, observed using the Ultra-Violet Imaging Telescope (UVIT). We find that the disk scale length estimated in Far-UV (2.64 ± 0.16 kpc) is larger than that in Near-UV (2.21 ± 0.21 Kpc) and optical (1.08 Kpc), which supports the inside-out growth scenario of the galaxy disk. The star-forming UV disk is also found to be contained within the extent of H1 gas, with a column density greater than $10^{21}$ cm$^{-2}$. With the spatial resolution of UVIT (1 pixel ~ 6.8 pc), we identified 2046 young star-forming clumps in the galaxy with radii between ~12 and 70 pc, which matches well with the size of giant molecular clouds (GMCs) detected in the galaxy. Around 61% of the regions identified in our study are younger than 20 Myr, which points to a recent enhancement in star formation across the galaxy. We also note that the youngest star-forming regions, with an age of <10 Myr, distinctly trace the flocculent arms of the galaxy. The estimated mass of the clumps covers a range between $10^3$ and $10^6 M_\odot$. We notice a gradient in the mass distribution of identified clumps along the spiral arms. We also study the nuclear star cluster of the galaxy, finding that the stellar populations in the cluster outskirts are younger than the inner part.

Unified Astronomy Thesaurus concepts: Spiral galaxies (1560); Star formation (1569); Star-forming regions (1565); Ultraviolet astronomy (1736)

1. Introduction

Galaxies of different morphologies exhibit distinct characteristics in terms of ongoing star formation. The massive elliptical, systems that have exhausted their molecular gas, show no signs of star formation, whereas gas-rich spiral and irregular galaxies are found to be more active in nature. Star formation in spiral galaxies is observed mainly in their disks, which contain the spiral arms (Blanton & Moustakas 2009). Depending on the nature of the arms, Elmegreen (1981) classified spirals into two categories: Galaxies having long and continuous well-defined arms with two-armed axial symmetry are referred to as grand design spirals, whereas flocculent spirals are characterised by their patchy, fragmented, short wispy spiral structures. Understanding the formation and evolution of these different spiral features is important in the context of galaxy evolution.

The observed morphology of spiral features is found to show variations in different wave bands, as stars formed in the density waves begin moving out gradually with increasing age (Pour-Imani et al. 2016). The role of density waves in triggering star formation along the spiral arms has been studied via both simulations and observations. Roberts (1969) proposed that spiral density waves can induce gravitational collapse of the gas clouds, triggering star formation along the arms. However, the efficiency of star formation locally depends on several factors, such as gas density, gravitational potential, and shear, as well as Coriolis forces due to disk rotation, ambient pressure, and the metallicity of the ISM (Leroy et al. 2008). Elmegreen & Elmegreen (1986) reported only a small difference between the average star formation rate (SFR) in grand design and flocculent spiral galaxies. This implies that spiral density waves do not have a strong impact on triggering star formation in galaxies. Several observational studies (for example, Seigar & James (2002)) have supported the idea of Roberts (1969) regarding triggered star formation in spirals. Observation in FUV or 8 μm, which traces the location of the youngest stars, or the ongoing star formation in a galaxy, delineates the current morphology of spiral arms, whereas optical and near-infrared bands pick up relatively older stars that have moved out from the density waves (Pour-Imani et al. 2016).

Spiral galaxies mostly follow the inside-out growth scenario, whereby the inner part of the disk forms earlier than the outer part (White & Frenk 1991; Mo et al. 1998; Brook et al. 2006). Several studies examining the star formation history of many nearby spirals across their disks, have found evidence of inside-out formation (Muñoz-Mateos et al. 2007; Gogarten et al. 2010). Muñoz-Mateos et al. (2007) studied 161 nearby spiral galaxies, utilizing the Galaxy Evolution Explorer (GALEX) and 2MASS observations, and found the signature of moderate inside-out disk growth in the majority of their samples. Several studies have also reported the radial migration of stars as one of the reasons for the observed flattening of metallicity, or age of stellar populations, in the outer disk of spiral galaxies (Roškar et al. 2008; Vlačić et al. 2009, 2011).

NGC 7793 is an SA(s)d-type flocculent spiral galaxy of the nearby sculptor group (de Vaucouleurs et al. 1991). It is located at a distance of 3.4 Mpc, and has two nearby dwarf companions (Zgirski et al. 2017; Koribalski et al. 2018). The galaxy has an absolute B band magnitude of $-18.31$, and a stellar mass of $3.2 \times 10^9 M_\odot$ with a sub-solar metallicity (Carignan 1985;...
Bothwell et al. 2009; Van Dyk et al. 2012). The optical radius \((R_{25})\) of the galaxy is around 4.67 (~4.62 Kpc) (de Vaucouleurs et al. 1991). The properties of the galaxy are listed in Table 1. Elmegreen & Elmegreen (1984) identified NGC 7793 as an extreme flocculent galaxy, reporting that the galaxy does not show specific structures in its older disk, whereas images in the bluer band show structures that may be ascribed to star formation or weak stellar density ripples. The galaxy is reported to have a very small bulge, and a nuclear star cluster at the center (Dicaire et al. 2008; Kacharov et al. 2018).

Several observational studies have explored the disk properties of NGC 7793 in various wave bands. Carignan (1985) studied the H I disk of the galaxy, and reported that it extended up to 1.5 times the optical diameter of the galaxy. They also observed the galaxy rotation curve to be declining in nature in its outer part. A recent H I study by Koribalski et al. (2018) traced the H I disk even further out, along with a significant warp in the outer disk. The properties of the CO molecular gas of the galaxy were also studied by Muraoaka et al. (2016). Hermanowicz et al. (2013) used GALEX FUV data to identify several star-forming regions in the galaxy, comparing their FUV flux to that of Hα. Dicaire et al. (2008) identified the signature of Hα emission up to the extent of the H I disk, which points to ongoing star formation across the galaxy. Several studies have also been conducted using Hubble Space Telescope (HST) observations in order to understand the star formation history, the hierarchy of star-forming regions, and the interplay between young star clusters and giant molecular clouds in this galaxy (Elmegreen et al. 2014; Radburn-Smith et al. 2012; Grasha et al. 2018; Sacchi et al. 2019). These observations cover a wide wavelength range, from near-UV to infrared. The results conclude that the disk of the galaxy supports an inside-out growth scenario, with a considerable amount of stars formed in recent times. Radburn-Smith et al. (2012) reported that the outer disk of the galaxy beyond ~3 Kpc is mostly populated with younger populations, with a break at a radius of ~5 Kpc.

The young stellar populations of a galaxy emit most of their radiation in the ultra-violet (UV) band (Kennicutt & Evans 2012). As such, imaging a galaxy in FUV and Near-UV (NUV) will help to locate the regions with active star formation, and to delineate the overall disk structure, as traced by the younger population. In this study, we explore the nature of the UV disk, and the properties of young star-forming regions of galaxy NGC 7793, utilizing FUV and NUV broadband observations from the Ultra-Violet Imaging Telescope (UVIT). The primary aim is to explore recent star-forming activity in this flocculent spiral system, which offers a unique platform from which to investigate the characteristics of density waves. With the large field of view of UVIT, we are able to cover the entire galaxy disk, well beyond its optical radius. This provides us with the scope to understand the overall disk structure in UV, and also to pick up young star-forming clumps across the disk, including the outskirts. Although the disk of the galaxy has been explored in different wave bands, a detailed study has not yet been undertaken to combine the data from both the FUV and NUV band at the same time. Our study provides a comprehensive view of the young star-forming regions in the galaxy, resolved up to length scales of ~25 pc. We have analyzed the overall UV disk profile, and correlated it with the H I column density map of the galaxy. Deep and high-resolution UV images are utilized to identify star-forming clumps, and to estimate their age and mass using simple stellar population (SSP) models. Our study reveals the spatial distribution of young stellar clumps as a function of their age and mass across the entire disk. We have also analyzed the nuclear star cluster of the galaxy using the UVIT data. The paper is arranged as follows: the observations and data are presented in Section 2, theoretical models in Section 3, extinction in UV in Section 4, and analysis in Section 5, followed by results and discussions, and a summary, in Sections 6 and 7, respectively.

### 2. Observations and Data

The galaxy NGC 7793 was imaged in UV by the Ultra-Violet Imaging Telescope (UVIT), located on board the AstroSat satellite (Kumar et al. 2012) (Figure 1). UVIT has the capacity to observe simultaneously in FUV, NUV, and visible bands. Each of the FUV and NUV channels of the telescope is equipped with multiple filters. The visible channel is used to track the drift of the satellite during the course of observations. Along with multi-band imaging in UV, the telescope also offers a superior spatial resolution of ~1.7", which altogether makes the instrument unique in terms of UV imaging. NGC 7793 was observed in two UVIT broadband filters: F148W (FUV), and N242W (NUV). The complete observation was performed over 8 satellite orbits on 2016, November 10. We used CCDLAB software (Postma & Leahy 2017) to correct the drift for all the images. Each image is flat-fielded, and further corrected for distortion and fixed pattern noise using the calibration files (Postma et al. 2011; Girish et al. 2017). The corrected images are co-aligned and combined, with the help of the same software, to produce the final deep images. The final images have dimensions of 4096 × 4096 pixels, where 1 pixel corresponds to ~0.4" (~6.8 pc at the distance of NGC 7793). The exposure times obtained for the images in F148W and N242W band are ~6.5 ks and 9 ks, respectively. The zero-point magnitude and the unit conversion factors (see Table 2) for the filters used here are adopted from Tandon et al. (2017). We also used the H I column density map of the galaxy from The H I Nearby Galaxy Survey (THINGS) (Walter et al. 2008).

### 3. Theoretical Models

In order to characterize the star-forming regions in NGC 7793, we used the Starburst99 SSP model (Leitherer et al. 1999). This model offers integrated spectra of young star clusters for a set of chosen parameters. These spectra can then be used to produce diagnostic diagrams for tracing the evolutionary stages of an unresolved star cluster in a given

| Property          | Value          | Reference               |
|-------------------|----------------|-------------------------|
| Morphological type| SA(s)d         | de Vaucouleurs et al. (1991) |
| R.A.              | 23 57 49.7     | Skrutskie et al. (2006)  |
| Decl.             | −32 35 27.6    | Skrutskie et al. (2006)  |
| Distance          | 3.4 Mpc        | Zgierski et al. (2017)   |
| Metallicity (Z)   | 0.6Z           | Van Dyk et al. (2012)    |
| Inclination       | 53°            | Carignan (1985)          |
| PA of major axis  | 279°3          | Carignan (1985)          |
| Stellar mass      | $3.2 \times 10^9 M_\odot$ | Bothwell et al. (2009)   |
galaxy. We have exploited the Starburst99 model data in order to produce Figure 2, to estimate the age and mass of star-forming clumps in the galaxy. We assumed instantaneous star formation law and kroupa stellar initial mass function (Kroupa 2001) for the stellar mass limit of 0.1–120 M\(_\odot\) (Table 3). We considered 19 spectra between the age range 1–900 Myr, and metallicity \(Z = 0.008\). This metallicity is adopted from the available model values as the closest to that of NGC 7793, as reported by Van Dyk et al. (2012). We convolved the UVIT filter effective area with these spectra, and estimated the expected magnitudes in the F148W and N242W bands for four different cluster masses \((10^6 M_\odot, 10^5 M_\odot, 10^4 M_\odot, 10^3 M_\odot)\) at the distance of the galaxy. The spectra we considered in our study include flux from both stellar and nebular emission. The simulated plot (Figure 2) signifies that the (F148W–N242W) color of a cluster changes only with its age, whereas a fixed age F148W magnitude becomes brighter with increasing mass, and vice versa. Therefore, the magnitude axis of Figure 2 traces the mass of a cluster, and the age can be estimated from the observed color value.

4. Extinction in UV

One of the important factors requiring to be considered when studying an external galaxy in UV is the effect of extinction. This is due to the higher value of the extinction coefficient in UV, as well as to the characteristic variations in extinction law in different galaxies. In order to estimate the extinction value via the UVIT filters, we adopted the value of \(E(B - V) = 0.179\) for NGC 7793, based on the study by Bibby & Crowther (2010). Moreover, as the metallicity of this galaxy is similar to that of the Large Magellanic Cloud (LMC), we have assumed the extinction law to be of the average LMC type, as modeled by Gordon et al. (2003). We used the extinction law calculator of McCall (2004), provided by the NASA/IPAC Extra-galactic Database (NED), to estimate the value of extinction coefficients \((R_\lambda)\) in the F148W and N242W bands. The values of \(R_{\text{F148W}}\) and \(R_{\text{N242W}}\) are found to be 9.78 and 8.12, respectively. Using the value of \(R_\lambda\) and \(E(B - V)\) in Equation (1), we estimated the value of extinctions in both bands. The values of \(A_{\text{F148W}}\) and \(A_{\text{N242W}}\) are found to be 1.75 mag and 1.45 mag, respectively. We used these values to correct the observed flux of the identified objects in our study, as follows:

\[
A_\lambda = R_\lambda E(B - V).
\]

5. Analysis

5.1. UV Disk Profile of NGC 7793

The FUV and NUV emission in a galaxy primarily trace the stellar population for ages up to 100 and 200 Myr, respectively (Kennicutt & Evans 2012). In order to understand the characteristics of UV emission in the galaxy, we produced radial luminosity density profiles in both FUV and NUV. The
nature of these profiles is expected to highlight the distribution of younger star-forming regions across the galaxy. We assumed the distance, galaxy center, inclination, and positional angle of the galaxy based on Table 1, and used the equation given in Section 2 of van der Marel & Cioni (2001) to estimate galactocentric distance in kpc for each image pixel. Starting from the galaxy center, we considered concentric annuli of width 0.5 Kpc, and estimated the value of luminosity density (erg s⁻¹ pc⁻²) in each annulus, based on the measured flux. We normalized the measured luminosity values with respect to the maximum of the respective curve, and plotted the profiles for both FUV and NUV, as shown in Figure 3. Both profiles exhibit an exponential nature.

In order to estimate the disk parameters, we fitted exponential curves to these observed profiles, and estimated the values of disk scale length ($R_d$) in FUV and NUV. The values of $R_d$ are found to be $2.64 \pm 0.16$ Kpc, and $2.21 \pm 0.21$ Kpc, respectively, in FUV and NUV. The optical disk scale length of the galaxy was reported to be 1.08 Kpc by Carignan (1985). As such, the disk of the galaxy is more extended toward shorter wavelengths. We note that both of the observed profiles in Figure 3 follow each other, up to a radius of 3 Kpc. Beyond that, the profile of FUV luminosity becomes flatter than that of NUV in the outer disk. Together, these observations signify that the stellar populations detected in UV in the outer disk beyond 3 Kpc are generally younger. Our results satisfy the inferences projected by Radburn-Smith et al. (2012). Using HST observations, Radburn-Smith et al. (2012) identified stars of different ages, finding that the radial number density profile of younger stars between 3 and 5 Kpc is flatter in comparison to that of older stars. We further note that the observed FUV luminosity density profile has a break at a radius of around 5 Kpc, which is also noted in Figure 6 of Radburn-Smith et al. (2012) with regard to younger populations.

5.2. Correlation with H I Column Density

The H I column density is known to have a threshold value of $\sim 10^{21}$ cm⁻² in order for star formation to occur in galaxies (Skillman 1987; Clark & Glover 2014). Carignan & Puche (1990) observed NGC 7793 via the VLA, tracing H I gas with a column density of $5 \times 10^{19}$ cm⁻² up to the $1.5R_{25}$ radius of the galaxy. Given that the FUV and NUV disk emission profiles trace the distribution of young star-forming regions, we compare these with the H I gas density profile in order to understand the relationship between gas and star formation. Figure 4 shows a moment 0 H I map of the galaxy, observed via the VLA by Walter et al. (2008). To compare the emission profiles in FUV, NUV, and H I, we plotted contours as displayed in Figure 4. The yellow contour signifies the extent of the H I disk with a column density greater than $10^{21}$ cm⁻². To trace the extent of the disk in FUV and NUV, we adopted a threshold of five times the average background flux for each respective band, and created contours. The contours are shown in blue and red, respectively, for FUV and NUV in the figure. The extent of the disk emission in both FUV and NUV is found to be quite similar for the adopted thresholds. In addition, the H I disk with a column density greater than $10^{21}$ cm⁻² closely matches both of the UV profiles. In some regions along the eastern and western part, we observed that the H I contours were a little more extended than those of the UV. In the northern part, we found that part of the UV contours extended outside the H I contour. The overall good spatial correlation

Table 3

| Parameter                  | Value                           |
|----------------------------|---------------------------------|
| Star formation             | Instantaneous                   |
| Stellar IMF                | Kroupa (1.3, 2.3)               |
| Stellar mass limit         | $0.1, 0.5, 120 M_\odot$        |
| Total cluster mass         | $10^4 M_\odot$ – $10^5 M_\odot$ |
| Stellar evolution track    | Geneva (high mass loss)         |
| Metallicity                | $Z = 0.008$                     |
| Age range                  | 1–900 Myr                       |

Figure 2. F148W vs. (F148W –N242W) color–magnitude diagram, simulated using the Starburst99 SSP model. The different curves (continuous line) signify four different total cluster masses ($10^4 M_\odot$, $10^5 M_\odot$, $10^4 M_\odot$, $10^3 M_\odot$). The points shown in each curve are for different ages, from 1 to 900 Myr (increasing along the color axis) with age intervals of 10 Myr for the 1–100 Myr range, and 100 Myr for the 100–900 Myr range. The dashed lines are plotted by adding extinction and reddening, as applicable in galaxy NGC 7793 (Section 4), to the model curves. The values of the model’s input parameters are listed in Table 3.

Figure 3. FUV and NUV radial luminosity density profiles of the galaxy are respectively indicated by solid blue and red lines. Each profile is normalized with respect to the maximum of the respective curve. The dashed lines are the exponential fits for each of the observed profiles. The values of the estimated disk scale lengths in FUV and NUV are $2.64 \pm 0.16$ Kpc, and $2.21 \pm 0.21$ Kpc, respectively.
between the UV and H I profiles signifies that star formation is happening in the galaxy, to the extent where H I column density is greater than the threshold value of $10^{21}$ cm$^{-2}$.

5.3. Identification of Young Star-forming Clumps

As the FUV emission is predominantly contributed by massive young OB stars, imaging in FUV will eventually trace the young star-forming regions hosting massive stars in a galaxy. To identify young star-forming clumps in NGC 7793, we utilized the UVIT FUV observation. We used the astrodendro Python package to locate bright star-forming clumps in the FUV image. The code helps to identify clumps in an intensity map for a given value of threshold flux, and a minimum number of pixels. It locates both parent and child structures, and builds a dendrogram. We fixed the minimum pixel number value at 10, meaning that structures formed with less than 10 pixels are not considered. The area covered by 10 pixels is equivalent to a circle of radius $\sim 1.8$ pixel ($\sim 12$ pc at the distance of the galaxy). This value is chosen such that the size of the smallest detectable clump ($\sim 3.6$ pixel) matches the FWHM of the PSF, which is $\sim 3.5$ pixel in the observed field.

To fix the threshold flux, we started with a value five times the average FUV background flux $\log(\text{flux} \text{(erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1})) = -18.40$, and increased it by 0.2 intervals in a logarithmic scale, up to $\log(\text{flux}) = -16.20$. For each threshold, we counted the number of identified parent and child structures, as plotted in Figure 5. The individual structures with no internal sub-structure are counted as both parent and child structures in astrodendro. The ratio of child and parent structures, represented by the black line, shows an increasing trend with decreasing threshold flux, and becomes nearly constant after the value $\log(\text{flux}) = -17.80$. This flux value also corresponds to the flux of a B5 spectral type star at the distance of NGC 7793. As stars with spectral types cooler than the B type do not contribute much FUV flux, we fixed this value $\log(\text{flux} \text{(erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}) = -17.80$ to be

Figure 4. H I moment 0 map of the galaxy. The grayscale is given by Jy/B"{M}/S. The yellow contours show regions with H I column density greater than $10^{21}$ cm$^{-2}$. Blue and red contours, respectively, represent FUV and NUV emission profiles. These are generated for a threshold flux of five times the average measured background value for each respective band. The black dashed ellipse shows the $R_{25}$ boundary of the galaxy.

Figure 5. The number of identified parent and child structures are shown as a function of varying threshold flux. The black line shows the ratio of the number of child and parent structures. The vertical green dashed line represents the threshold flux $\log(\text{flux}) = -17.80$ selected for our analysis.

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5 http://www.dendrograms.org/
the threshold flux. For this threshold, the number of identified parent and child structures is found to be 835 and 3266, respectively, within a galactocentric radius of 7 Kpc. We considered 7 Kpc as the outer boundary, as this value is equivalent to $\sim 1.5 R_{25}$, up to which region Carignan & Puche (1990) traced the H I disk. Again, as per the study of Radburn-Smith et al. (2012), the signature of the younger population has been traced up to this radius using HST observations. In Figure 6, we provide an example of parent and child structures, identified at a particular star-forming region of the galaxy for the chosen threshold flux.

As the larger parent structures contain multiple unresolved clumps, we considered the child structures, identified as individual star-forming clumps in the UVIT image, for further analysis. The output of astrodendro provides position, area, and flux for each of the identified clumps. We considered the area of these irregular shaped clumps, and equated it to the area of a circle so as to estimate the equivalent radius, which shows a range between $\sim 12$ and 70 pc. A histogram of the size is shown in Figure 7. This matches well with the size of the GMCs detected in the galaxy (Grasha et al. 2018). The error bars shown in the histogram are measured from the square root of the numbers in each bin. We used the position and area equivalent radius of these identified clumps as measured in the FUV image, and estimated FUV and NUV fluxes from each of the respective images for the same calculated aperture size. This provides both the FUV and NUV magnitudes of the clumps. We corrected these magnitudes for background and extinction. The average background in each individual image is estimated by considering four circular regions, each of radius $1'$, in the observed field, located away from the galaxy. The extinction correction is performed as explained in Section 4. Several other studies have also explored the maximum size of the star-forming region over which star formation is physically correlated (e.g., Grasha et al. 2017). Sánchez et al. (2010), Grasha et al. (2017), and Jimena Rodríguez et al. (2020) used the detected stars and clusters in selected nearby galaxies, reporting a length scale of between 200 and 1000 pc for the largest hierarchical structures. In this study, we have used the FUV flux map to identify individual clumps or large structures in the observed image. Using the adopted threshold flux (i.e., $\log(\text{flux} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}) = -17.80$), we found the largest structure formed by the star-forming clumps has a size of $\sim 3$ Kpc in the NGC 7793 galaxy. This size is estimated based on the area of the largest parent structure, as identified by astrodendro.

In order to avoid clumps with relatively larger photometric errors ($\geq 0.1$ mag), we considered only those clumps with a corrected FUV magnitude brighter than 21 mag in our analysis. This results in a total of 2046 individual star-forming clumps. A histogram of the (F148W–N242W) color of these clumps is provided in the top panel of Figure 8. The distribution shows a Gaussian nature, with a peak around (F148W–N242W) = 0.25. We also estimated the galactocentric distance for each clump by adopting the method explained in Section 5.1. The (F148W–N242W) colors of the clumps are plotted as a function of galactocentric distance in the bottom panel of Figure 8. The distribution shows a flat aspect to the inner 3 Kpc radius of the galaxy, whereas the clumps identified in the outer part beyond 3 Kpc display a slightly bluer trend than the inner part. This signifies that the outer part of the galaxy primarily contains younger sources, whereas the inner part shows a more uniform distribution.

5.4. Age Estimation

As discussed in Section 3, the age of an unresolved star cluster can be estimated based on its observed (F148W–N242W) color. The child structures identified in the FUV image are likely to be the unresolved FUV bright star-forming clumps of the NGC 7793 galaxy. Of these, the smaller clumps are primarily comprise a single entity, whereas the larger ones may be stellar associations, or a combination of multiple clumps, which could not be resolved further with UVIT. In order to apply the SSP model to these clumps, we assumed each of them to be single entities. We estimated the background and extinction-corrected F148W magnitude, and the (F148W–N242W) color of these identified clumps, as shown in Figure 9 (gray points), along with the model curves given in Figure 2. Only a few of the observed points lie outside the model color range on the bluer side. This may be due to an
overestimation of the extinction value, or to a large photometric error. We have excluded these points from our analysis. We considered the \( (F148W-N242W) \) color for the remaining clumps, and performed linear interpolation along the color axis to estimate the age of each clump. A histogram of the estimated ages is shown in Figure 10. We noted a richness of younger clumps with an age below 20 Myr. This suggests that the stellar populations identified in the FUV image are mostly younger, and that the galaxy has undergone an enhanced phase of star formation in the last 20 Myr.

5.5. Age Distribution

The spatial distribution of star-forming clumps as a function of age conveys the star formation history across a galaxy. As star formation in a galaxy can be triggered by multiple mechanisms, a spatial age map of the young star-forming clumps is important when drawing conclusions about the impact of the local environment, as well as possible triggering activities. This will also shed light on the nature of disk growth in the NGC 7793 galaxy. To visualize the spatial distribution of the identified star-forming clumps as a function of age in NGC 7793, we divided them into four different groups, with an age range of between 1 and 400 Myr. The age ranges of the groups are 1–10 Myr, 10–20 Myr, 20–50 Myr, and 50–400 Myr. The bin size of the groups is chosen on the basis of the age histogram shown in Figure 10. We fixed the interval to be smaller where there is a greater number of clumps, and to be wider where there are fewer clumps. In addition, for each selected bin, the value of the mean error in the estimated ages is lower, as compared to the bin size.

The locations of the clumps identified in each age group are shown in the galaxy image in Figure 11. The youngest star-forming clumps (age group: 1–10 Myr) are found to be predominantly located along the flocculent arms in the outer part of the galaxy. The distribution of these clumps is also more compact in nature. In the case of clumps with ages between 10 and 20 Myr, we noticed a similar pattern, with a predominant distribution along the arms. We find an overall scattered distribution of clumps in the age range from 20–50 Myr across the galaxy. These tend to be found away from the arms. Beyond the age 50 Myr, the clumps are observed to be more prevalent in the inner part of the galaxy. The regions between two arms are mostly populated by clumps older than 20 Myr. The overall picture thus suggests that star formation in the last 20 Myr has taken place primarily along the flocculent arms of the galaxy. The star-forming regions located in the far outer region in the eastern direction are found to be populated by clumps younger than 20 Myr.

5.6. Mass Estimation

We also estimated the mass of each clump based on its observed F148W magnitude. On the basis of the known value of \( (F148W-N242W) \) color for each clump, we used the F148W-band’s observed magnitude, and performed a linear
interpolation along the magnitude axis of Figure 9 to estimate mass. A histogram for the estimated mass is shown in Figure 12. It shows that the identified clumps have a mass range between $3 \times 10^2 M_\odot$ and $10^6 M_\odot$ with a peak around $10^4 M_\odot$. The GMCs identified in this galaxy also share a similar mass range (Grasha et al. 2018). The estimation of masses below $10^3 M_\odot$ is not accurate, due to the lower limit of the model’s mass range. The majority of the clumps are found to have an intermediate mass between $10^3 M_\odot$ and $10^4 M_\odot$. The number of clumps with a mass greater than $10^5 M_\odot$ is relatively small in number. This might indicate that the galaxy has not formed many massive complexes in recent times.

5.7. Mass Distribution

The mass of a star-forming clump depends on the mass of the parent molecular cloud in which it has formed. The massive clumps generally form from giant molecular clouds, whereas low-mass clumps can be produced from molecular clouds of relatively smaller mass. It is thus important to know the mass distribution of clumps in order to explore the star-forming environment across a galaxy. In order to understand the mass distribution of identified clumps across the galaxy, we identified four groups based on different mass ranges. The mass ranges of the groups are $\log(M/M_\odot) < 3.5$, $3.5 < \log(M/M_\odot) < 4.0$, $4.0 < \log(M/M_\odot) < 4.5$, and $4.5 < \log(M/M_\odot)$. The figures show the spatial distribution of clumps as a function of their estimated age, in a range between 1 and 400 Myr. The figures represent four different age groups, as discussed in the text. The age range of each group is given in the corresponding panel. The background image shows the F148W-band flux map of the galaxy.
log($M/M_\odot$) < 6.0. The bins are fixed by following the same steps as discussed in Section 5.5. In Figure 13, we show the position of these clumps, superimposed on the FUV image of the NGC 7793 galaxy. We observe a hierarchical distribution of star-forming clumps as a function of mass. The low-mass clumps (log($M/M_\odot$) < 3.5) are mainly distributed along the flocculent arms. The central region of the galaxy has a few of these low-mass clumps. Those clumps with a mass in the range 3.5 < log($M/M_\odot$) < 4.0 show similar distribution, and are relatively fewer in number. These clumps tend to be located in the inner part of the arms, rather than their outer part. The distribution of more massive clumps, with mass between 4.0 < log($M/M_\odot$) < 4.5, gradually shrinks toward the inner part. These are also to be found between the arms. The most massive clumps (4.5 < log($M/M_\odot$) < 6.0) in the galaxy tend to be distributed in the central part of the galaxy. The overall scenario indicates that the inner part of the flocculent arms contains both low- and high-mass clumps, whereas the outer part of these arms is populated with more low-mass clumps, with a mass of log($M/M_\odot$) < 3.5. This highlights the hierarchical distribution of star-forming clumps along the spiral arms.

5.8. Nuclear Star Cluster

A nuclear star cluster is known to be a dense stellar system, generally observed in the dynamical center of disk galaxies (Neumayer et al. 2020; Seth et al. 2019). The sizes of these objects are similar to those of globular clusters. It has been found that more than 75% of nearby late-type spiral galaxies have a nuclear star cluster at their center (Böker et al. 2002). NGC 7793 is also reported to have a nuclear star cluster (Walcher et al. 2006; Carson et al. 2015; Kacharov et al. 2018). The cluster has an effective radius of 12.45 pc, measured in the HST F275W band (Carson et al. 2015). Carson et al. (2015) studied the cluster using multi-band HST data, and reported that the size of the cluster is bigger in the U band than in the optical band. The SFH of the cluster reveals a complex nature. The Very Large Telescope (VLT) spectroscopic observations by Kacharov et al. (2018) found that the cluster contains a stellar population of four different age ranges. The majority of the cluster’s populations are older than 10 Gyr, whereas some have an age of around 2 Gyr, some are between 200 and 600 Myr in age, and some are very young, with an age of ~10 Myr.

In this study, we have used UVIT FUV and NUV observations to characterize the nuclear cluster. To examine its properties in UV, we considered both FUV and NUV images, and defined multiple apertures, centered on the reported cluster position. The radius of the smallest aperture is considered to be 1.5 pixel (~0.′6, i.e., diameter of the aperture ~FWHM of PSF), and is further increased in increments of 3 pixels to define four more apertures (see Figure 14(a)). We measured fluxes in both F148W and N242W bands for each of these defined annuli. The measured fluxes are corrected for extinction and background to estimate the (F148W−N242W) color, depicted in Figure 14(b) as a function of aperture radius. The (F148W−N242W) color gradually becomes bluer with increasing radius, and flattens beyond a radius of 10 pixels. This signifies that the stellar populations present in the outskirts of the nuclear cluster are younger than those in the inner part, which indirectly supports the earlier conclusion of circum-nuclear star formation proposed by Carson et al. (2015). This can also happen due to the accretion of the younger population from nearby stellar groups to the nuclear cluster. The variation in (F148W−N242W) color in the nuclear region may not be genuine if there is a significant variation in extinction. The study by Kahre et al. (2018) showed that extinction in the central region of the galaxy is relatively high, however, and it has a nearly constant value. This rules out the possibility of color variation due to variations in extinction.

We also identified this cluster as a single star-forming clump via the method discussed in Section 5.3. The estimated values of cluster age and mass are found to be 19.1 ± 0.8 Myr, and 2.3 × 10^5 M_\odot, respectively. As FUV emission traces the younger populations, these age and mass values therefore constitute a sample of the properties of the youngest among the four different types of stellar population, as observed by Kacharov et al. (2018).

6. Results and Discussion

The primary aims of this study are to understand the UV disk structure of NGC 7793, and to identify young star-forming clumps in the galaxy estimating their age and mass. To do that, we used FUV and NUV imaging data of the galaxy, observed via the F148W and N242W filters of UVIT. The spatial resolution of UVIT has helped to identify clumps with radii up to ~12 pc. The fluxes measured in the FUV and NUV bands are compared with the model values to estimate the ages and masses of the clumps.

We used Starburst99 model data to simulate the diagnostic plot, which helped us to estimate the age and mass of the clumps, based on their observed F148W magnitude and (F148W−N242W) color. Therefore, errors in the measurements of magnitude and color will be reflected in the estimated values of age and mass. The degree of photometric error in both F148W and N242W bands lie within a range between ~0.01 and 0.1 mag. The corresponding error in age has a range between ~1 and 80 Myr. The younger clumps have fewer errors in terms of age, whereas the older clumps show relatively larger errors. The mean error value for each of the four age groups defined in our study is smaller than the bin size. For example, the group containing clumps with ages between 1 and 10 Myr has a mean error of ~3 Myr. Similarly, the error in F148W magnitudes results in ~1%–15% error in the estimated mass values. Another parameter that may change the measured age and mass values of the clumps is the adopted value of E (B − V). The extinction and reddening inside a galaxy can
exhibit spatial variation, which will affect the observed flux differently in different locations. Therefore, our assumption of a fixed reddening value across the galaxy may have added a degree of uncertainty in the estimated values of age and mass. A larger reddening will make the clumps younger and more massive, and vice versa. We selected the extinction law to be an average LMC type for dealing with the interstellar extinction in NGC 7793. A change in extinction law will also affect the estimated age and mass values accordingly. The identified star-forming regions of the galaxy may also have different metallicity, which can further affect the derived parameters, as color changes with varying metallicity for a fixed age.

Several studies have been conducted, using observations in different bands, to investigate the disk properties of NGC 7793. Vlajić et al. (2011) observed two fields in the extended outer part of the galaxy with the Gemini Multi Object Spectrograph, and reported that the galaxy disk beyond ∼5 Kpc is mostly populated with older red giant branch stars. Their study was able to trace the stellar disk up to ∼10 Kpc. Utilizing HST observations, Radburn-Smith et al. (2012) studied a part of the galaxy disk on the eastern side, finding that the surface density of the older population in the outer disk between 3 and 5 Kpc decreases gradually, while it remains almost constant in the case of the younger population. They also noticed a break in

Figure 13. Spatial distribution of clumps (red points) as a function of their estimated mass in the range between $3 \times 10^2$ and $10^6 M_\odot$. The figures represent four different mass groups, as discussed above. The mass range of each group is given in the corresponding panel. The background image shows the the F148W-band flux map of the NGC 7793 galaxy.
Radburn-Smith et al. (2012) studied a limited part of the disk, whereas our study covers the entire galaxy disk from the center to the edge. The radial nature of the disk, derived from a limited region in the eastern side by the HST, was found to remain similar when averaged over the entire disk. Hence the enhancement in recent star formation between radius 3 and 5 Kpc can generally be said to have happened along all azimuthal directions. Sacchi et al. (2019) performed a more comprehensive study by almost covering the entire disk via HST observations, in order to understand the radial star formation history in the NGC 7793 galaxy. They studied the distribution of stars in an age range from a few Myr to \(~\)10 Gyr, and reported an inside-out growth for the galaxy disk. The SFR in the outer part of the galaxy has been enhanced in more recent times, while the inner part is dominated by populations older than 1 Gyr. We measured the values of disk scale length in FUV and NUV to be $2.64 \pm 0.16$ Kpc, and $2.21 \pm 0.21$ Kpc, respectively. The optical scale length of the galaxy has been reported as 1.08 Kpc by Carignan (1985). These together signify that the disk becomes extended in shorter wavelengths. This, in other words, means that the older populations are more centrally concentrated, which indicates an inside-out growth scenario for the disk of NGC 7793. The HST observations presented by Grasha et al. (2018) and Sacchi et al. (2019) have not covered the outskirts of the galaxy disk. We detected star-forming clumps younger than 20 Myr in such regions, which signifies recent star-forming activity in the disk outskirts. The larger star-forming knot located in the eastern outskirts (an area not covered by the HST) can be seen to have undergone recent star formation. This further strengthens the proposition of an inside-out disk formation in this galaxy.

The H$_1$ disk of the galaxy also exhibits some notable characteristics. Carignan & Puche (1990) noticed non-circular motion in the northern part of the galaxy, and speculated on the possibility of past interactions with a nearby companion of the sculptor group. Along the north and north-eastern regions, we noted that some parts of the star-forming UV disk extended beyond the extent of an H$_1$ gas density greater than $10^{21}$ cm$^{-2}$. These features could be the result of a recent interaction, resulting in an enhancement in star formation in the outer part of the galaxy.

There is ample evidence of recent star-forming activity in NGC 7793. An HST study by Grasha et al. (2018) covered almost the entire galaxy disk, up to a radius of around 5 Kpc, and identified 293 young star clusters, with 65% of these being younger than 10 Myr. Bibby & Crowther (2010) identified 74 emission-line regions across the galaxy disk, using imaging observation from the VLT/FOcal Reducer and Spectrograph (FORS1). Dicaire et al. (2008) detected H$_\alpha$ emission up to the edge of the H$_1$ gas disk of the galaxy, and speculated that massive stars were the source of this emission. Taken altogether, these studies indicate an enhancement in recent star formation across the NGC 7793 galaxy. In our study, we found around 61% of the 2046 FUV identified clumps to be younger than 20 Myr, which signifies enhanced star-forming activity in the galaxy during the last 20 Myr.

Elmegreen et al. (2014) studied the galaxy as part of the HST Legacy UV survey, and reported a hierarchical distribution of star-forming regions, ranging in size between \(~\)1 and 70 pc. The star-forming clumps identified in our study were found to have radii in the range 12–70 pc. Those clumps with radii smaller than 12 pc could not be resolved in our study, due to

The distribution of younger stars at a radius of 5 Kpc. The luminosity density profiles presented in our study support these earlier results. The FUV luminosity profile, derived from UVIT observation, also shows a break at a radius of 5 Kpc. We further noted that the FUV profile to overtook NUV at a 3 Kpc radius, and becomes more flat up to a 5 Kpc radius. We also found that the clumps identified between radii 3 and 5 Kpc are generally bluer. This signifies that the stellar populations identified in UV in the outer disk between 3 and 5 Kpc are mostly younger. It is also possible that the outer disk of the galaxy has relatively lower reddening than the adopted value. A decrease in the $(E(B-V))$ value will make the clumps redder, which will make the color distribution of clumps in the outer disk, between radii 3 and 5 Kpc, flatter.

The drop in the FUV luminosity beyond 5 Kpc conveys that the disk outside this radius has a smaller younger and/or massive population. Works by both Vlajić et al. (2011) and
the resolution limit of UVIT. It is also possible that the larger clumps identified by UVIT are actually a combination of multiple smaller clumps, which appear as a single clump in the UVIT images. Grasha et al. (2018) reported a similar range for the radius of GMCs identified in the galaxy. They further concluded that the younger clusters are more closely associated with GMCs, while the older ones are found to be more dispersed away from the natal cloud. This, along with the similarity in sizes, further strengthens the connection between star-forming clumps and molecular clouds in the galaxy. We also searched for the largest star-forming parent structure identified by astrodendro for the adopted threshold flux, and found that it has a size of $\sim 3$ Kpc. This length scale, which is sensitive to the value of threshold flux, will become smaller with increasing threshold, and vice versa.

Our study found that the distribution of the youngest star-forming clumps (i.e., with an age of $< 10$ Myr) is compact in nature, and that they trace the flocculent arms of the galaxy. This signifies that the enhancement of star formation during the last 10 Myr has specifically occurred along the arms. A recent study by Sacchi et al. (2019) found that the presence of a spiral density wave is not clearly seen in the distribution of stellar populations older than 1 Gyr in the galaxy, whereas younger populations were mostly seen along the flocculent arms. Based on this view, they inferred the possible lack of spiral density waves in the galaxy. In this study, using UV data, we traced only those young star-forming clumps up to an age of $\sim 400$ Myr observing the youngest stellar clumps to distinctly trace the flocculent arms of the galaxy. The role of density waves in triggering star formation in disk galaxies is still a subject of debate. Therefore, these results offer a scenario in which to explore whether the arm structures observed in our study are due only to the distribution of star-forming regions, or if these are formed due to the impact of spiral density waves, which trigger star formation along the flocculent arms.

Our study also reveals that the central region of the galaxy has not shown much star formation during the last 10 Myr. This correlates well with the fact that the central 1 Kpc region of the galaxy has a much lower molecular gas concentration ($n_{\text{H}_2} \sim 10^{2.3} \text{ cm}^{-3}$) than the global average, as reported by Muraoka et al. (2016). On the other hand, the molecular gas density is found to be relatively higher away from the center, specifically along two arms in the east and west directions. We identified several star-forming clumps younger than 10 Myr in these locations, which points to active star formation in regions with dense molecular gas.

The star-forming clumps identified in our study mostly cover a mass range between $10^3$ and $10^5 M_\odot$. We observed only a few clumps more massive than $10^5 M_\odot$. This scenario correlates with the mass of GMCs identified in the galaxy (Grasha et al. 2018). The clumps with relatively more mass (4 $< \log(M/M_\odot) < 6$) are mostly seen in the inner part of the galaxy disk. This may be the result of an artifact due to crowding. The inner part of a disk galaxy has a more crowded environment than the outer part; therefore, it is possible that some of the massive clumps identified in the inner disk are actually a group of multiple clumps that could not be resolved by UVIT. The other interesting result is the distribution of clumps along the flocculent arms. We noted that the ends of the arms are populated with more low-mass clumps ($\log(M/M_\odot) < 3.5$), whereas the inner part of arms exhibit low as well as more massive clumps. This portrays a gradient in the mass distribution from the inner to the outer part along the arms.

We have also characterized the nuclear star cluster of the galaxy via UV observations. Carson et al. (2015) reported that the nuclear cluster of NGC 7793 has a decreasing effective radius with increasing wavelength, which signifies a recent circum-nuclear star formation. Walcher et al. (2006) found a stellar population younger than 100 Myr in the nucleus of the galaxy. Kacharov et al. (2018) reported a complex star formation history for this cluster. They noted a stellar population of different ages, from $\sim 10$ Myr to $> 10$ Gyr within the cluster. They concluded that merging of multiple clusters with different ages could give rise to the observed properties of the nuclear cluster. The (F148W–N242W) color profile of the cluster, derived in our study, was shown to become bluer with increasing aperture size. This supports the possibility of circum-nuclear star formation, or the accretion of a young stellar population from nearby stellar groups to the nuclear cluster. The effective radius of the cluster is reported to be 12.45 pc in the HST F275W band, according to Carson et al. (2015). Considering the limit of UVIT resolution, the smallest aperture we could define is around this value. Therefore, apertures larger than the effective radius (i.e., the annuli in Figure 14) of the cluster basically trace stellar population in the cluster outskirts, or those which are in the process of being accreted by the nuclear cluster. We estimated the age and mass of the cluster as 19.1 $\pm 0.8$ Myr, and $2.3 \times 10^5 M_\odot$, respectively. As FUV and NUV emission primarily trace stellar populations with ages up to a few hundred Myr, the estimated age of the cluster, reported to have stellar populations across a wide age range, characterizes the younger populations. Similarly, the estimated mass of the cluster signifies the amount of mass contributed by younger populations present in the cluster.

7. Summary

The main results of this study are summarized below.

1. We used UVIT FUV and NUV observations to investigate the UV disk emission profile, and to identify young star-forming clumps in the NGC 7793 galaxy.
2. The value of the galaxy disk’s scale length ($R_d$) is found to increase toward shorter wavelengths, from optical to FUV. We estimated the value of $R_d$ to be $2.64 \pm 0.16$ Kpc, and $2.21 \pm 0.21$ Kpc in FUV and NUV, respectively.
3. Relative to the inner part, we observed FUV emission to be more dominant than the NUV emission in the outer part of the galaxy (between radius 3 and 5 Kpc).
4. We identified 2046 young star-forming clumps in the galaxy, with radii ranging between $\sim 12$ and 70 pc.
5. The majority of the clumps were found to have an age younger than 20 Myr, which signifies an enhancement in recent star formation across the galaxy.
6. The youngest clumps (age $< 10$ Myr) are specifically found along the flocculent arms of the galaxy.
7. The identified clumps cover a mass range between $10^3 M_\odot$ and $10^6 M_\odot$.
8. We noticed a hierarchical mass distribution of the clumps along the flocculent arms. The end of the flocculent arms contains more low-mass clumps, whereas the inner part...
of those arms contains low-mass as well as higher-mass clumps.

9. The extent of the star-forming UV disk of the galaxy closely matches with the extent of an H I disk with a column density greater than $10^{21}$ cm$^{-2}$.

10. The stellar population in the outskirts of the nuclear star cluster is found to be younger compared to the inner part. This indicates the possibility of circum-nuclear star formation, or accretion of the younger stellar population from nearby stellar groups to the nuclear cluster.

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