The Ultraviolet Deep Imaging Survey of Galaxies in the Boote Void. I. Catalog, Color–Magnitude Relations, and Star Formation

Divya Pandey¹, Kanak Saha², and Ananta C. Pradhan¹

¹ Department of Physics and Astronomy, National Institute of Technology, Rourkela 769 008, India; divyaパンディ@gmail.com
² Inter-University Centre for Astronomy & Astrophysics, Postbag 4, Ganeshkhind, Pune 411 007, India

Received October 21, 2020; revised June 24, 2021; accepted June 27, 2021; published September 29

Abstract

We present a deep far and near-ultraviolet (FUV and NUV) wide-field imaging survey of galaxies in the Boote void using the Ultraviolet Imaging Telescope on board AstroSat. Our data reach $5\sigma$ limiting magnitudes for point sources at 23.0 and 24.0 AB mag in the FUV and NUV, respectively. We report a total of six star-forming galaxies residing in the Boote void alongside the full catalog, and of these, three are newly detected in our FUV observation. Our void galaxy sample spans a range of UV colors ($-0.35$ mag $\leq$ FUV–NUV $\leq$ 0.68 mag) and absolute magnitudes ($-14.16$ mag $\leq M_{\text{NUV}} \leq -18.65$ mag). In addition, Sloan Digital Sky Survey and Two Micron All Sky Survey archival data are being used to study UV, optical, and infrared color–magnitude relations for our galaxies in the void. We investigate the nature of bimodal color distribution, morphologies, and star formation of the void galaxies. Most of the galaxies in our sample are fainter and less massive than L galaxies, with $M_B > -20$ mag. Our analysis reveals a dominant fraction of bluer galaxies over the red ones in the void region probed. The internal and Galactic extinction corrected FUV star formation rates (SFRs) in our void galaxy catalog varies in a large range of 0.05–51.01 $M_{\odot}$ yr$^{-1}$, with a median of 3.96 $M_{\odot}$ yr$^{-1}$. We find a weak effect of the environment on the SFRs of galaxies. Implications of our findings are discussed.

Unified Astronomy Thesaurus concepts: Star formation (1569); Ultraviolet surveys (1742); Catalogs (205); Voids (1779); Galaxy properties (615)

1. Introduction

Cosmic web, largely composed of voids, filaments, and wall-like structures, is observed to be inhomogeneous at the megaparsec scale. The large-scale structures that we see in our present day universe are a manifestation of the primordial gravitational density fluctuations (Schaefer & Shafi 1993). The cosmic voids occupy $\sim$77% of the cosmic volume and they represent $\sim$15% of the total halo mass content implying that the average density of the void is around 20% of the average cosmic density (Cautun et al. 2014). The formation and evolution of the voids depend on two processes, i.e., small voids merge to shape into a larger underdensity and due to collapse of overdensities around a region in space (Sheth & van de Weygaert 2004; van de Weygaert 2016). They usually tend to exist within the cosmic web (Libeskind et al. 2018) in a spherical foam-like structure. Such voids can be populated by substructures such as mini-sheets and filaments that run through the voids. As these voids grow older they become progressively empty and possess less substructures within them (Sahni et al. 1994).

The typical size of a large-scale void ranges from $20–50$ h$^{-1}$ Mpc, but its depth remains unclear with an under-density of $\delta_v = \frac{\rho_v}{\rho_m} - 1 \approx -0.8$. The voids were first discovered in observation by Gregory & Thompson (1978); Jöeveer et al. (1978). Later Kirshner et al. (1981, 1987) discovered the Boote Void, one of the largest void present in the northern hemisphere. More recently, Sloan Digital Sky Survey (SDSS) provided a detailed structure of cosmic voids using large-scale structure galaxy catalog from the Baryon Oscillation Spectroscopic Survey (Mao et al. 2017).

Voids are thought to provide a pristine environment for understanding the secular evolution and dynamics of galaxies (van de Weygaert & Platen 2011) as they are devoid of phenomena typically active in a denser medium like groups and clusters, e.g., ram pressure stripping (Gunn et al. 1972) and gas strangulation (Peng et al. 2015) (galaxy nurture). As a result, the evolution of void galaxies is thought to be slower than those in denser medium leading to an abundance of young galaxies at primitive stages of evolution; thus, studying void galaxies may unearth key features of the early stages of galaxy formation scenario. In fact, a number of objective prism surveys (Moody et al. 1987), imaging, and spectroscopic observations (Weistrop et al. 1995; Szomoru et al. 1996; Cruzen et al. 2002) of the Boote void show remarkable similarity in the overall void galaxy properties. The galaxies present in voids tend to be bluer than wall and field galaxies with large specific star formation rates (sSFRs; Moorman et al. 2016). Voids are mainly populated with late-type galaxies, although the presence of active galactic nuclei (AGNs) and early-type galaxies have also been reported recently (Begy et al. 2017). Not only that, void galaxies have also shown evidences of recent merger interaction (Grogin & Geller 2000; Kreckel et al. 2012). Some of these galaxies show unusual morphological features such as knots, asymmetries, apparent one-spiral arm, and offset nucleus (Cruzen et al. 1997). Based on these recent reports, one would expect to find a complete spectrum of galaxy morphology at different evolutionary phases in a void environment.

It has been shown that the global properties, such as morphology, color, and star formation rates (SFRs), of galaxies depend predominantly on their local environment and internally driven mechanism rather than their global environment (Szomoru et al. 1996; Tinker & Conroy 2009; Penny et al. 2015). Based on a comparative analysis of the emission line galaxies (ELGs) situated in sparse and dense environments, it has been suggested that the local environment density around a galaxy may have no effect on its chemical evolution.
of the void region. SDSS has already done a great job in this aspect. Deep imaging observation of the void in the far- and near-ultraviolet (FUV and NUV) bands with SDSS-like spatial resolution is, however, missing since Galaxy Evolution Explorer (GALEX; Martin et al. 2005) did shallow surveys (~205 s) of the void region (e.g., of the Bootes Void in the northern hemisphere).

In this work, we present a deep imaging survey of about a 615 arcmin² region of the Bootes Void in FUV and NUV filters of the Ultraviolet Imaging Telescope (UVIT) onboard AstroSat Satellite (Tandon et al. 2017). Since the galaxies in voids show a bluer color and are star forming, the stellar population would contain a significant fraction of young stars (O, B type) of intermediate masses (2–5 M☉, which actively emit in the FUV and NUV (Grogin & Geller 1999; Rojas et al. 2005, 2004). The FUV emission in a galaxy arises from the photosphere of massive O- and B-type stars, and therefore, it traces star formation going on in a galaxy over a timescale of ~10⁸ yr (Calzetti 2013, pp. 419–458; Lee et al. 2009). Using our UV deep imaging survey, we produce a catalog of void galaxies with fluxes from FUV to near-infrared (NIR) and study their morphology, UV-optical, and NIR color–magnitude relations (Baldry et al. 2004; Gil de Paz et al. 2007; Wyder et al. 2007), their star formation properties and compare them with non-void galaxies.

This work is organized as follows: In Section 2, we describe our data used for analysis, and in Section 3, we explain the procedure adopted for data reduction and analysis. We briefly discuss our methodology for catalog preparation and photometric redshift calculation in Section 4, whereas in Section 5, we deduce the reliability of our UVIT detection followed by Sections 6–8, where we discuss the internal dust obscuration, stellar masses, and quantify UV emission of galaxies. In Section 9, we discuss the properties of void galaxies detected in the analysis of the basis of various color–magnitude diagrams (CMDs). Finally, in Section 10, we conclude our findings and examine the future prospects of our research. A standard Λ cold dark matter cosmology with ΩM = 0.3, Ωλ = 0.7, and H₀ = 70 km s⁻¹ Mpc⁻¹ is assumed in this work. The AB magnitude system (Oke 1974) has been followed throughout the work. We have converted Two Micron All Sky Survey (2MASS) Vega magnitudes to AB using conversions given in Blanton et al. (2005) to maintain uniformity of the magnitude scale.

2. AstroSat Observation and Other Archival Data

The AstroSat is India’s first dedicated multiwavelength space satellite launched by the Indian Space Research Organization (ISRO) in 2015 September. UVIT onboard AstroSat satellite observes primarily in three channels: FUV (λ = 1300–1800 Å), NUV (λ = 2000–3000 Å), and visible (λ = 3200–5500 Å) wavelength bands. The field of view (FoV) of each channel is about 28′ in diameter with a pixel size of ~0.417″ and spatial resolution of <1.8″ in the FUV and NUV channels (Tandon et al. 2017). The angular resolution of UVIT is 3–4 times higher as compared to the previously launched UV space telescope GALEX.

We proposed to explore an area of 615 arcmin² in the Bootes Void to observe with UVIT. The aforementioned area is centered at α = 212.115°/14°08′27.8″ and δ = 48.932°/48°55′56.6″. Observations were taken in the BaF2 (λeff = 1541 Å) and Silica-1 (λeff = 2418 Å) filters of UVIT. The total on-source exposure time assigned to BaF2 (F154W) and Silica-1 (N242W) filters ~10,000 s each (PI: Kanak Saha). Figure 1 shows the field of observation of a recent KPNO International Spectroscopic Survey (KISS) of ELGs in the direction of the Bootes Void (Wegner et al. 2019) and our UVIT FoV. The top panel of Figure 2 shows the FUV/NUV FoV observed by UVIT; in the bottom panel, we have shown the color composite images of five peculiar galaxies detected in our FoV. The images are color coded as follows: red: SDSS r filter, green: UVIT NUV, and blue: UVIT FUV. Two of the five galaxies (third and fourth images) in the figure are void members, while the others lie outside the void.

To extend this survey further into the optical and infrared parts of the electromagnetic spectrum, we have included SDSS and 2MASS observations. SDSS has five filters u, g, r, i, z having mean wavelengths of 3560, 4680, 6180, 7500, and 8870 Å, respectively, spanning over the optical and infrared bands of the electromagnetic spectrum (York et al. 2000). We have used well-calibrated archival imaging data from the SDSS Data Release 12 (DR12; Alam et al. 2015) for the same patch of sky in the Bootes Void as observed by UVIT. Similarly, imaging archival data from 2MASS have also been taken up, which observes in the NIR wavelength filters J, H, and K with mean wavelengths 1.24, 1.66, and 2.16 μm, respectively (Skrutskie et al. 2006).

3. Data Reduction and Analysis

The FUV and NUV observations were carried out by AstroSat/UVIT in the photon counting mode with a frame rate of ~30 frames per second. This would accumulate about ~45,000–50,000 frames in a typical good dump orbit. The orbit-wise dataset was processed using the official L2 pipeline in which we removed frames that are affected by the cosmic-ray shower and these were not included in the final science-ready
images and the subsequent calculation of the photometry. This results in an average loss of ~20% data to science-ready images. The final science-ready image had a total exposure time of $t_{\text{exp}} = 8600$ s in the FUV and $t_{\text{exp}} = 7513$ s NUV bands.

Astrometric correction was performed using the GALEX FUV/NUV tiles and SDSS $r$-band images as references. We have used an IDL program that takes an input set of matched xpixel/ypixel (from UVIT images) and R.A./decl. (from GALEX FUV/NUV and SDSS $r$ band image) and perform a TANGENT-Plane astrometric plate solution similar to the ccmath task of IRAF (Tody 1993). The astrometric accuracy in the NUV was found to be $\sim 0.2^\prime$ while for the FUV, the rms was found to be $\sim 0.24^\prime$, approximately half a pixel size. The photometric calibration was performed with a white dwarf star Hz4; the photometric zero-point for the F154W band is 17.78 mag. The photometric calibration and astrometric correction are success-
vally applied, we run the Source Extractor (SExtractor) software (Bertin & Arnouts 1996) on the science-ready images to extract sources and estimate the background. We use following extraction parameters to detect sources in FUV and NUV images: DETECT_THRESH = 3− and 5$\sigma$ and DETECT_MINAREA = 16/9 pixels for FUV/NUV filters depending on their angular resolution (see, Section 3.1).

### 3.1. Point-spread Function (PSF) and Background Estimation

We perform a robust calculation of FWHM measurements of the PSF on the UVIT NUV and FUV science-ready images. We start with stacking a few unsaturated, isolated point sources of varying magnitudes to get an unbiased profile of a point source with a high signal-to-noise ratio (S/N; see inset image in Figure 3). The isolated sources were selected from our UVIT FUV/NUV 3$\sigma$ catalog with the additional criteria of CLASS_STAR (discussed in Section 4) $\geq 0.9$. Also, we visually examine the sources to check their symmetry around its centroid. In this work, we have adopted two methods: First, isophotal ellipse fitting is performed on the stacked images using IRAF STSDAS package. We fit the one-dimensional circular Moffat function over the surface brightness distribution $I(r)$ as a function of radius to obtain the parameters required for calculating the FWHM (Moffat 1969). The Moffat function used to model the PSF is given by the following equation:

$$
I(r) = I_0 \left[ 1 + \left( \frac{r}{\alpha} \right)^2 \right]^{-\beta},
$$

with an FWHM = $2\alpha \sqrt{2^\beta - 1}$. Here, $I_0$ is the central surface brightness and $\beta$ and $\alpha$ are the free parameters. $\beta$ is the seeing parameter that determines the spread of Moffat function. We have used the Moffat function here as a Gaussian distribution alone, which does not accurately fit the wings of a stellar profile (Trujillo et al. 2001) but see Saha et al. 2021 for the wing modelling in F154W band. The Gaussian function is a limiting case of Moffat function ($\beta \to \infty$). The second method for determining the PSF involves creating an encircled energy (EE) curve as a function of radius for the same stacked source. As per our calculation, the radius corresponding to a circular area enclosing 80% of the total normalized energy of the stacked stellar profile came out to be close to the PSF FWHM obtained using the first method. The results from both methods are in a
good agreement as shown in Figure 3. The resulting values of the PSF FWHM for F154W and N242W filters from the fitting are 3.83 pixels (1.59") and 2.58 pixels (1.08"), respectively.

We perform the background subtraction over the science-ready images in both filters for accurate flux estimation from the sources. For this, we run SExtractor (Bertin & Arnouts 1996) with a detection threshold = $2\sigma$ on both images. Subsequently, we mask all sources at and above $2\sigma$ from the entire FUV and NUV images. Thereafter, we measure integrated flux due to background by randomly placing multiple square boxes ($\approx$1000) over various parts of the masked image avoiding the source locations. The size of boxes (5 × 5 pixels for NUV/7 × 7 pixels for FUV) were chosen such that the area enclosed within the boxes were close to the area bounded by a PSF-size point source. Figure 4 shows the background flux histograms for the FUV and NUV images. These histograms are fitted with a Gaussian function with a mean ($\mu$) and standard deviation ($\sigma$). From the fitting, we

Figure 3. Top panels: surface brightness distribution of the PSF is fitted with a circular Moffat function (see Equation 1) in FUV and NUV filters. FWHM refers to the full width at half maxima for the Moffat function. Inset images show the stacked PSF. Bottom panels: encircled energy curve for FUV (left) and NUV (right). Vertical dashed lines in either case denote the radii containing 80% encircled energy. One pixel = 0.417".

Figure 4. The figure comprises background flux histograms for the UVIT FUV/NUV filters. Background flux per pixel is calculated by fitting a single peak Gaussian function over the integrated flux distribution of 1000 boxes spread across the entire image.
obtain a sky surface brightness of 27.99 and 27.55 mag arcsec$^{-2}$ in the FUV and NUV observations, respectively, and measured mean background flux per pixel was subtracted prior to photometry. We follow the Kron photometric technique (Kron 1980) in this work. The Kron apertures are elliptical or circular depending on the intensity distribution of the source, and the apertures capture 80%–90% of the total flux radiated by a source. We calculate the point-source detection limit using the estimated background noise ($\sigma_{\text{sky}}$), number of pixels in a circular aperture ($r$), and desired detection threshold. The detection limits are calculated at the 3$\sigma$ and 5$\sigma$ thresholds considering aperture radius $r = 4$ pixels ($\sim 1.6''$) and 3 pixels ($\sim 1.2''$) for the FUV and NUV images, respectively. We use $\sigma_{\text{sky}}$ corresponding to our FUV/NUV sky histograms (Figure 4) $\approx 8.4 \times 10^{-6} / 3.23 \times 10^{-5}$ count s$^{-1}$ (cps). Note that these values are about a factor of $\approx 3$ times lowered than their counterparts obtained using the SExtractor (FUV/NUV $\approx 2.2 \times 10^{-5}$ cps/9.5 $\times 10^{-5}$ cps). Nevertheless, the mean background obtained from both the methods are in good agreement. Using our $\sigma_{\text{sky}}$ from the histograms, the 3$\sigma$ point-source detection limit for the FUV/NUV observations are found to be 25.02/26.22 mag. Similarly, our FUV/NUV survey reaches a detection limit of 24.46/25.66 mag at 5$\sigma$. Although we realize that the actual 3$\sigma$ and 5$\sigma$ detection limits depend on aperture size or the number of pixels within; shape of the object (point-like or extended), we consider this to be a good approximation of the actual UVIT detection limits. Figure 5 shows a magnitude histogram for all the extracted sources from FUV/NUV observation. From the magnitude histogram, the limiting magnitude for FUV/NUV observations is at and above 3$\sigma$ $\approx 24.0 / 25.0$ mag. Whereas for the 5$\sigma$ threshold, the limiting magnitude for FUV/NUV $\approx 23.0 / 24.0$ mag. Typical uncertainty in FUV/NUV magnitudes within the limit magnitudes is 0.3/0.2 mag.

UV fluxes are highly susceptible to both internal and Galactic dust attenuation. The Schlegel et al. (1998) full-sky 100 $\mu$m map gives us Galactic dust reddening $E(B-V)$ along a given line of sight. The values of extinction parameter $A_{\text{F154W}}/E(B-V) = 8.104$, $A_{\text{N242W}}/E(B-V) = 7.746$ were calculated using the Cardelli et al. (1989) extinction law. We correct SDSS $u, g, r, i, z$ and 2MASS $J, H, K$-band fluxes for Galactic extinction in a similar manner. We use the method given by Chilingarian & Zolotukhin (2012) for redshift K-correction ($K_\lambda$) of the catalog fluxes to $z = 0$. Consequently, we calculate the absolute magnitude ($M_\lambda$) of a galaxy at luminosity distance $D_L$ in a given passband (denoted by its wavelength $\lambda$) using the following equation:

$$M_\lambda = m_\lambda - 5(\log D_L - 1.0) - A_\lambda - K_\lambda.$$  

The crossmatching of sources over several observational surveys is a nontrivial task as morphologies and resolution may change over various wavelengths and filters used. Particularly, in our case, the PSF FWHM for UVIT, SDSS, and the 2MASS survey are $\approx 1.5''$, $1.3''$, and $2.8''$, respectively. The minimum crossmatching radius that we use for matching UVIT to SDSS catalogs $\approx 1.5''$, whereas to 2MASS catalog $\approx 2.8''$. Such values for crossmatching radius were selected as our field is a void field and to a large extent non-crowded. We find no multiple matches for any source present in our UVIT 3$\sigma$ catalog on crossmatching with other catalogs from different surveys. We employ topcat$^4$ software for the purpose. While we did the crossmatching, we also visually examined the sources in the UVIT FoV.

4. Catalog Construction and Source Classification

The total number of sources extracted at 3$\sigma$ depth from FUV/NUV images are 709/4,931 and at 5$\sigma$ depth, 146/2,050$^5$. As we are probing void galaxies in our FoV, we segregate the extended objects from the rest of the sources. At a rudimentary level, we use CLASS_STAR (hereafter, CS) parameter given by SExtractor. The parameter gives a probabilistic value between 0 (=GALAXY) to 1 (=STAR). In the current work, the CS corresponding to the SDSS r-band image is considered for the analysis where an object with CS $\leq 0.1$ is regarded as an extended source. As a result, we identify 184 and 74 extended sources with 3$\sigma$ and 5$\sigma$ detections, respectively. For all these extended sources, we have FUV and NUV observations. We are exclusively interested in sources with measured redshifts (spectroscopic/photometric). Therefore, on matching sources in the UVIT FoV.

$^4$ http://www.starlink.ac.uk/topcat/

$^5$ The UVIT 3$\sigma$ and 5$\sigma$ source catalog can be made available with an online request. These catalogs are going to be published online soon.

Figure 5. The magnitude histograms for 3$\sigma$ and 5$\sigma$ FUV/NUV sources extracted by SExtractor (Bertin & Arnouts 1996) and are not extinction corrected. Typical foreground dust extinction values for this FoV are $A_{\text{F154W}} = 0.24$ mag and $A_{\text{N242W}} = 0.22$ mag.
the extended sources (CS \leq 0.1) present in the UVIT FUV/NUV combined 3\sigma catalog with the SDSS spectroscopic/photometric catalog taken from SDSS DR12, we split the 184 extended sources into the following categories:

1. Objects with photo-z only = 159
2. Objects with spec-z = 8
3. Objects absent in either of the catalogs (spectroscopic/photometric) = 17

Visual examination of the sources that were not a part of any of the two catalogs reveals that some of them are bright and saturated stars, part of an extended source, or faint sources (u \sim 23 mag). Hence, we reject the objects in this category for any further analysis. All eight extended sources with spec-z were already classified as a galaxy by SDSS. In addition, we find a pea-shaped/compact object having spec-z in our FoV with CS > 0.1, classified as a galaxy by SDSS. The 159 extended sources present in the UVIT 3\sigma catalog with photo-z are subjected to a rigorous classification methodology.

For the identification of 159 objects as galaxies, we use the color–color diagrams described in Bianchi et al. (2007) that classify photometrically selected sources into various categories of astrophysical origin. This method involves broadband photometric data combining seven passbands from GALEX (FUV/NUV) to SDSS (u, g, r, i, z). We use NUV–g versus g–i and FUV–NUV versus g–r color–color diagrams as extended sources (mostly galaxies) are well separated from point-like (star/QSO) sources on these color–color planes (Figure 6). For this purpose, we curate a catalog of point sources combining archival GALEX All-sky Imaging Survey (AIS) observations with the archival SDSS DR12 spectroscopic catalog. The point sources present in the catalog are spectroscopically classified as a star by SDSS. On the other hand, the extended source catalog comprising galaxies are taken from GALEX-SDSS-WISE (Wide-field Infrared Survey Explorer) Legacy catalog (Salim et al. 2016, hereafter, Salim Catalog). We plot our 159 objects along with the sources present in the point source and extended catalogs on the color–color diagrams to observe that our UVIT sources mostly overlap the region corresponding to extended sources in both color–color diagrams, and therefore, we consider these objects as extended sources (or galaxies) for further analysis in the work.

On matching SDSS spectroscopic catalog with our UVIT 3\sigma catalog, we confirm two galaxy members of the Bootes Void. The photometric redshifts given by SDSS (z^\prime) have comparable (of the same order) errors (\sigma_{z^\prime}) associated with them. Hitherto, z^\prime for none of the galaxies fall within the redshift of the Bootes Void, i.e., 0.04 \leq z \leq 0.06 (Kirshner et al. 1987, 1981). However, nine galaxies are identified out of 159 photometrically selected extended sources such that z^\prime \pm \sigma_{z^\prime} falls within the void’s redshift range. In the following section, we determine our own set of photometric redshifts for galaxies with z^\prime by modeling their broadband spectral energy distribution (SED) to select the void galaxy candidates with increased certainty.

4.1. Determination of Photometric Redshifts and Assigning Candidature to the Bootes Void

We determine the photometric redshifts of all 159 photometrically selected galaxies using the photo-z code EAZY (Brammer et al. 2008). In the process, the photometric fluxes of seven broadband filters were utilized, namely, UVIT (FUV, NUV) and SDSS (u, g, r, i, z). EAZY provides us \chi^2 minimized redshift for the best-fit linear combination of all galaxy templates. We use six standard galaxy templates in our calculations and derive photometric redshifts (z^\text{phot}) for all galaxies. The procedure is inclusive of the wavelength dependent template error function.

In order to find the quality of our fit, we deduce photometric redshifts for the two void galaxies with z^\text{spec} in a similar manner with an equal number of broadband filter magnitudes and calculate \Delta z = (z^\text{phot} - z^\text{spec})/(1 + z^\text{spec}). The quantity \Delta z for the two void galaxies averages to \approx 0.01 wherein conventionally one discards z^\text{phot} with \Delta z > 0.1 (Skelton et al. 2014). The result indicates fair agreement between the EAZY photo-z and SDSS spectroscopic redshifts. EAZY also provides us with 1\sigma, 2\sigma, and 3\sigma confidence intervals computed from posterior probability distribution for each galaxy. The mean redshift (\mu_z) and sigma (\sigma_z) for the probability distributions were calculated post assuming these distributions as a single peak Gaussian function. Nearly, all z^\text{phot} fall within 1\sigma confidence limits of the
with probability distribution function $P(z)$ as a function of redshift color coded for four void galaxies with $z_{\text{phot}}$ based on our EAZY redshift estimation with $P(z) \geq 0.5$. Redshift extent of the Bootes Void marked with black dotted lines. The galaxies are numbered according to Table 1. Right panel: EAZY best-fit SEDs with observed fluxes for the four void galaxies. The galaxies are color coded and numbered the same as the left panel.

Table 1

| G No. | R.A. (1) | Decl. (2) | FUVGALEX (3) | NUVGALEX (4) | FUVUVIT (5) | NUVUVIT (6) | $z'$ (7) | $z$ (8) | $n$ (9) | $P(z)$ (10) |
|-------|---------|----------|-------------|-------------|-------------|-------------|---------|-------|-------|-------------|
| G1    | 14:07:25.63 | 48:50:43.4 | 20.32 ± 0.14 | 19.94 ± 0.09 | 20.29 ± 0.05 | 19.80 ± 0.01 | 0.029 ± 0.23 | 0.055 ± 0.012 | 1 | 0.54 |
| G2    | 14:07:39.55 | 48:57:33.1 | ...         | 23.31 ± 0.22 | 23.07 ± 0.07 | 0.449 ± 0.154 | 0.057 ± 0.064 | 2 | 0.12 |
| G3    | 14:08:43.44 | 48:54:10.8 | 22.55 ± 0.41 | 22.27 ± 0.14 | 22.47 ± 0.05 | 0.102 ± 0.047 | 0.043 ± 0.011 | 1 | 0.56 |
| G4    | 14:07:53.33 | 49:01:13.1 | 21.70 ± 0.32 | 21.74 ± 0.25 | 21.52 ± 0.09 | 21.91 ± 0.03 | 0.177 ± 0.094 | 0.057 ± 0.003 | 1 | 0.77 |
| G5    | 14:09:09.34 | 49:08:49.2 | ...         | 21.97 ± 0.28 | 22.20 ± 0.13 | 22.05 ± 0.04 | 0.253 ± 0.182 | 0.053 ± 0.055 | 2 | 0.14 |
| G6    | 14:07:40.08 | 49:05:10.5 | 21.10 ± 0.19 | 20.73 ± 0.14 | 20.87 ± 0.07 | 20.58 ± 0.02 | 0.078 ± 0.023 | 0.055 ± 0.014 | 1 | 0.50 |

Notes. Column ID: (1) Galaxy No., (2) R.A. J2000, (3) decl. J2000, (4) GALEX FUV mag, (5) GALEX NUV mag, (6) UVIT FUV mag, (7) UVIT NUV mag, (8) photometric redshift given by SDSS, (9) photometric redshift calculated using EAZY, (10) $n = \frac{|z - z_{\text{red}}|}{0.04}$, and (11) cumulative probability of the galaxy at redshift $z$. Magnitudes in the table are not corrected for Galactic extinction.

posterior probability distribution (see $n$ in Table 1) and the uncertainty in $z_{\text{phot}}$ were given by $\sqrt{z_{\text{phot}}^2 - \mu_z^2}$.

EAZY photometric redshift of six galaxies lie in the redshift range of the Bootes Void. The cumulative probabilities for all six galaxies to exist inside the void corresponding to their EAZY redshift ($P(0.04 \leq z \leq 0.06)$) and the output redshifts are given in Table 1. Evidently, $P(z)$ gives a clear depiction of the void candidate among the six galaxies. With a cut of $P(z) \geq 0.5$, we further narrow down our potential void candidates sample to four galaxies (G1, G3, G4, and G6) with $z_{\text{phot}}$ which we intend to study further in the work. Furthermore, the probability distribution function $P(z)$ as a function of $z$, and the model SEDs and observed fluxes for the four galaxies are shown in the left and right panels of Figure 7, respectively.

With this work, we report four newly detected void galaxies with $z_{\text{phot}}$ (G1, G3, G4, and G6) along with two previously identified void galaxies with $z_{\text{spec}}$. Figure 8 shows the redshift distribution of galaxies in the direction of the Bootes Void. The void is roughly considered as spherical in shape. The red circle marks a radius of $\sim 46$ Mpc from the center and roughly denotes the boundary of the void. As described in Kirshner et al. (1983), we assume the center of the void at $\alpha = 14^h 48^m$, $\delta = +47^d$ and mean redshift of $\sim 0.05$. Most of our UVIT detected void galaxies lie close to the boundary of the void. A follow-up spectroscopic survey would be required to confirm void membership of the four galaxies with $z_{\text{phot}}$.

5. UVIT Detections

Prior to UVIT, GALEX has observed our FoV in both FUV and NUV passbands as part of its AIS. We compare the S/Ns of the void galaxies with $z_{\text{phot}}$ in GALEX and UVIT FUV observations to showcase the enhanced sensitivity of the UVIT deep imaging survey. We use the following equation for our calculations of S/Ns: (Saha et al. 2020):

$$\frac{S}{N} = \frac{F_g t e}{\sqrt{F_g t e + f_b n_{\text{pix}} t e}},$$

where $f_b$ denotes the background noise per pixel (estimated from the final science-ready images) and $t$ is the exposure time for the UVIT FUV observation as mentioned in Section 3. $F_g$ denotes the total number of detected photons from the source alone within a given aperture containing $n_{\text{pix}}$ pixels measured from the science-ready images. In other words, $F_g$ denotes the total number of detected photons minus the number of background photons from the same aperture. For comparison with GALEX observation, we consider a circular aperture of $r \approx 2.5''$ at a fixed position corresponding to the R.A./decl. of...
three new void galaxies in our FUV observation, i.e., G3, G4, and G6.

In addition, we refer to GALEX merged catalog for procuring FUV/NUV magnitudes with errors and for the size of Kron apertures used for photometry for all six void galaxy candidates (Bianchi et al. 2017). Table 1 lists GALEX and UVIT FUV/NUV magnitudes for all void galaxy candidates. Of these, three galaxies fainter than 22 mag in the UVIT FUV observation are not detected in the GALEX catalog (G2, G3, and G5). It is worth mentioning here that GALEX AIS reaches a typical 5σ depth of ~20 AB mag in the FUV (Bianchi et al. 2017). Moreover, on overlaying GALEX FUV Kron apertures on SDSS cutouts, we find a few nearby sources within the apertures in case of G1 and G4 making them unfit in the subsequent analysis.

Figure 8 shows a color composite image of a portion of our FoV using SDSS i, g and UVIT NUV filters. We highlight all four void galaxies discussed earlier in this section. The result underlines the importance of using the UVIT deep observations over GALEX AIS data for this analysis.

### 6. Extinction in the UV Continuum

Internal dust present within a galaxy scatters and/or absorbs UV photons, which makes it challenging to estimate the absolute UV flux emitted from a galaxy. Several factors, such as the geometry of a galaxy, amount of dust and its components, affect the intensity of UV flux attenuation in a galaxy. There are various dust attenuation laws available for local and high redshift star-forming galaxies (Calzetti et al. 1994, 2000; Reddy et al. 2015). Different methods could be used to solve for dust obscuration of UV photons, which are based on two principles: using slope (β) of a power-law function (f_λ = λ^β) followed by UV continuum emission of galaxies over the wavelength range 1300–2600 Å (Calzetti et al. 1994). The other method is based on total energy budget of a galaxy and it represents a combination of FUV and IR luminosities (Hao et al. 2011).

The UV β slope works efficiently as a diagnostic for internal dust attenuation (Meurer et al. 1999; Wilkins et al. 2013) and far-IR luminosities are unavailable for our entire sample of void galaxies. Therefore, we use a method based on the UV spectral slope β. The values of β are calculated using the following relation (Nordon et al. 2012):

\[
\beta = -\frac{m(\lambda_1) - m(\lambda_2)}{2.5\log\left(\frac{\lambda_1}{\lambda_2}\right)} - 2. 
\]

Here, \(\lambda_1\) and \(\lambda_2\) are the effective wavelengths corresponding to UVIT FUV and UVIT NUV filters. The slope, thus, calculated can be used to find color excess \(E(B-V)\) using the following relation (Reddy et al. 2018):

\[
\beta = -2.616 + 4.684E(B-V). 
\]

The relation is derived using the Calzetti + 00 dust curve (Calzetti et al. 2000) on the Binary Population and Spectral Synthesis galaxy model (Reddy et al. 2018). The dust attenuation law established by Calzetti et al. (2000) is used to find the value of \(k(\lambda)\) for F154W filter of UVIT. The extinction relation, \(A_\lambda = k(\lambda)E(B-V)\) (where \(k(1541) Å = 10.18\)) gives us total extinction in the FUV filter. The resultant \(A_{FUV}\) versus β curve obtained by the above discussed method is less steeper than the Meurer et al. (1999) curve. Slope β provides us rough
estimates of the ongoing star formation and internal dust obscuration of a galaxy (Reddy et al. 2018). Lesser negative values of \( \beta \) symbolizes either the abundance of old stellar type or high internal dust concentration within a galaxy. \( \beta \) for our sample ranges from \(-2.72\) to \(-0.60\) with median \(\approx-1.35\) indicating active ongoing star formation with low to moderate internal dust obscuration (Yamanaka & Yamada 2019).

Henceforth, the intrinsic FUV luminosities of galaxies are used to calculate the FUV SFRs as described in Section 8. In the following part of the work, unless mentioned otherwise, all colors and absolute magnitudes are corrected for Galactic extinction only, while the SFRs reported are corrected also for internal extinction.

### 7. Stellar Mass Estimation

Stellar masses (\(M_\star\)) of galaxies are widely considered as one of the fundamental parameters that drive galaxy evolution over cosmic time. Not only galaxy evolution, unbiased, robust estimate of stellar masses can play a crucial role to constrain models of galaxy formation as well (Salmon et al. 2015). We estimate stellar masses of the void galaxies and the remaining non-void galaxies up to \(z \leq 0.1\) present in the FoV using two methods.

In our first method, we perform broadband (from AstroSat/UVIT far-UV to SDSS \(z\)-band) spectral energy distribution (SED) modeling using the Code Investigating GALaxy Emission (CIGALE; Boquien et al. 2019), similar to previous Section 4.1. Our SED modeling proceeds with standard assumptions for the star formation histories (SFHs), initial mass function (IMF), dust attenuation, etc.

We adopt a double exponential function for the SFH with \(\text{SFR}(t) \propto \exp(-t/\tau)\) forming the bulk of the stellar mass and another exponential function to accommodate the recent burst of star formation. In the previous expression, \(t\) is the time since onset of star formation and \(\tau\) is e-folding timescale. The young and old stellar populations are separated by 10 Myr. The

![Figure 9](image-url)

**Figure 9.** The figure shows the cutout images of four void galaxies with \(z_{\text{phot}}\) in three filters (top row: SDSS \(r\), middle row: UVIT FUV, and bottom row: GALEX FUV). The blue colored numbers in the top row are assigned to the galaxies according to Table 1. The radius of each circle shown in the figure is 2.5″. The S/Ns for all sources estimated from UVIT and GALEX FUV observations are written beneath the middle and bottom rows, respectively.

![Figure 10](image-url)

**Figure 10.** The color composite image (red: SDSS \(i\) filter, green: SDSS \(g\) filter, blue: UVIT NUV filter) highlights the four void galaxies out of which three (G3, G4, and G6 in Figure 9) are undetected in the GALEX FUV observation. The serial numbers given to the galaxies are in reference to Table 1. The figure illustrates the importance of using deep imaging data provided by UVIT.
intrinsic stellar population in the galaxy is modeled with a Bruzual & Charlot (2003) stellar population library. We choose the Salpeter (1955) IMF with a range of masses varying from 0.1–100 $M_\odot$ for determining the intrinsic population. The metallicity for each galaxy was given as a free parameter which is based on $\delta$ from an array of values [0.0004, 0.004, 0.008, and 0.02] in the fitting. For the dust attenuation, we adopt the module, dustatt_modifed_starbust based on the Calzetti et al. (2000) starburst attenuation curve. The input parameters for color excess or reddening of stellar continuum and nebular lines are provided in accordance with our dust attenuation calculation in Section 6. We fix the power-law slope ($\delta$) of the dust attenuation curve to $-0.5$ which is steeper than the Calzetti et al. (2000) curve ($\delta = 0$) and the UV bump amplitude to 1.0, respectively. In addition, we use the Dale et al. (2014) module to model polycyclic aromatic hydrocarbon emission. Under this module, we consider no AGN contribution and the IR power-law slope is set to 2.0. The above-mentioned modules and input parameters remain unchanged throughout the process.

In the second method, color-based stellar masses ($M_{\text{color}}$) for individual galaxies are obtained from the relation between the $g-r$ color and stellar mass-to-light ratio corresponding to optical luminosity ($L_g$) using the result from Bell et al. (2003), which is based on diet Salpeter IMF. Later we multiply $M_{\text{color}}$ by a factor of 0.7 to scale it to normal Salpeter IMF for appropriate comparison with SED-based stellar masses ($M_{\text{SED}}$). Figure 11 shows a one-to-one relation between $M_{\text{SED}}$ and $M_{\text{color}}$. Both set of stellar masses are in close agreement with each other. Henceforth, we use $M_{\text{SED}}$ throughout the work for analysis. Void galaxies with $z_{\text{phot}}$ reported in the work are low-mass systems ($M_\odot \lesssim 10^9 M_\odot$) and evidently, $M_\odot$ for most the void galaxies lies below the stellar mass of a L$^*$ galaxy, i.e., $3 \times 10^9 M_\odot$.

8. FUV SFR

The SFR provides a key insight into the assembly history of a galaxy’s stellar mass. FUV fluxes emitted by young, massive stars (typically O, B type) amounts to the instantaneous star formation in a galaxy. In other words, FUV fluxes (if internal extinction corrected) can provide one of the best estimates of the recent star formation (over $\sim 100$ Myr) in a galaxy. The FUV emission and the associated SFR have been estimated in galaxies with different Hubble types, ranging from late types to early types (Yi et al. 2005; Calzetti 2013, pp. 419–458). We have calculated the FUV SFR (in units of solar mass per year) using the following relation given by Kennicutt (1998):

$$\text{SFR}_{\text{FUV}} = 1.4 \times 10^{-28}L_{\text{FUV}} \text{ erg s}^{-1} \text{ Hz}^{-1},$$

where $L_{\text{FUV}}$ is the intrinsic FUV luminosity of a galaxy. The FUV SFRs are calibrated assuming that the SFH of a galaxy is constant for the last $\sim 100$ Myr. In Table 2, we show the SFR along with UV magnitudes (FUV/NUV), stellar masses, absolute magnitudes ($M_\odot$), optical color $g-r$, and UV–optical color NUV$-r$ for our sample of void galaxies. The FUV SFRs for the void galaxies detected in the FoV spans a wide range from 0.05–51.01 $M_\odot$ yr$^{-1}$ with a median SFR$_{\text{FUV}} \sim 3.96 M_\odot$ yr$^{-1}$. The FUV SFRs for most of our sample galaxies are comparable to that of a normal spiral galaxy within the local volume and are higher than that of a low-mass, star-forming dwarf galaxy.

In Figure 12, we show the distribution of void and non-void galaxies on the sSFR–$M_\odot$ plane. The Salim Catalog comprises background galaxies with $z \lesssim 0.1$. We compute the internal dust corrected FUV SFRs and color-based stellar masses for the background sample using the same recipe as described in the preceding sections. The background galaxies from the Salim Catalog are well distributed over the sSFR–$M_\odot$ plane. However, as Figure 12 shows, most of the void galaxies with photo-$z$ lie on the low-mass end of the distribution and they are basically vigorously star-forming galaxies with log(sSFR) ranging from $-9.5$ to $-7.7$ yr$^{-1}$ with a median $\approx 9.09$ yr$^{-1}$. These values signify that all the void galaxies

| S No. | R.A. J2000 | Decl. J2000 | FUV$_{\text{spec}}$ | NUV$_{\text{spec}}$ | $z$ | SFR$_{\text{FUV}}$ | $M_\odot$ | $M_\odot$ | g$-r$ | NUV$-r$ |
|-------|------------|------------|------------------|------------------|----|----------------|----------|----------|------|---------|
| G1    | 14:07:25.63| 48:50:34.4 | 20.29 ± 0.05     | 19.80 ± 0.01     | 0.055 ± 0.012 | 8.874 | 0.044        | ~18.47   | 0.13    | 1.13  |
| G3    | 14:08:43.44| 48:54:10.8 | 22.27 ± 0.14     | 22.47 ± 0.05     | 0.043 ± 0.011 | 0.053 | 0.011        | ~16.00   | 0.35    | 1.84  |
| G4    | 14:07:33.33| 49:01:31.1 | 21.52 ± 0.10     | 21.91 ± 0.04     | 0.057 ± 0.004 | 0.088 | 0.029        | ~16.74   | 0.26    | 1.44  |
| G6    | 14:07:40.08| 49:05:10.5 | 20.88 ± 0.07     | 20.58 ± 0.02     | 0.055 ± 0.014 | 2.253 | 0.093        | ~18.44   | 0.34    | 1.91  |
| S1    | 14:08:13.59| 48:51:44.7 | 19.06 ± 0.03     | 18.40 ± 0.01     | 0.0518 ± 0.0001 | 51.010 | 7.009       | ~22.08   | 0.60    | 3.35  |
| S2    | 14:08:11.40| 48:53:44.4 | 19.36 ± 0.04     | 19.15 ± 0.01     | 0.0511 ± 0.0002 | 5.668  | 0.631       | ~20.16   | 0.39    | 2.30  |

Note. Colors and absolute magnitudes are K-corrected and extinction corrected. SFR$_{\text{FUV}}$ are also corrected for internal extinction. G1-, G3-, G4-, and G6-void galaxies with $z_{\text{phot}}$; S1- and S2-void galaxies with $z_{\text{spec}}$.

Figure 11. Comparison between SED-derived and color-derived stellar masses for void and non-void galaxies ($z \lesssim 0.1$) in our FoV. Dashed line represents one-to-one relation, while the dotted lines represent 1σ scatter.
detected in our work are star-forming in nature. Even the most massive galaxy in our sample belongs to the star-forming cloud. Interestingly, the sSFR for the non-void galaxies detected in our FoV are comparable to those of void galaxies.

9. CMDs

In this section, we summarize the results from the UV/optical/NIR CMDs to study the properties of our sample void galaxies. Our void galaxies are divided in two categories, i.e., with \( z_{\text{spec}} \) and \( z_{\text{photo}} \) based on the means of their redshift determination. The galaxies detected outside the Bootes void having either redshifts (photometric/spectroscopic) are termed as non-void galaxies with \( z \leq 0.1 \) in the subsequent CMDs.

9.1. UV CMD

The FUV – NUV color for a large sample galaxies varies across \( \sim 2 \) mag (see Figure 13). In general, star-forming galaxies are found to have an average FUV – NUV color \( \approx 0.4 \) mag and the color peaks at 0.9 mag where the transition from late (young) to early (old) type galaxies takes place (Gil de Paz et al. 2007). In Figure 13, we have shown UV CMD distribution for all galaxies detected in our FoV up to \( z \leq 0.1 \) wherein the side color bar represents their internal dust corrected FUV SFRs. The FUV – NUV color of the void galaxies (with \( z_{\text{spec}} \) or \( z_{\text{photo}} \)) are inclined toward the bluer end of the color scale with an average value of \( \approx 0.2 \) mag indicating recent star formation in these systems along with late-type or irregular morphological features. Based on the FUV – NUV colors and FUV SFRs, it is apparent that void galaxies comprise a significant amount of young stellar population. However, we do not observe any strong correlation between FUV SFRs and FUV – NUV color for our entire sample of galaxies, which is in agreement with Hunter et al. (2010).

Wyder et al. (2005) derived UV luminosity function for local galaxies (\( z \leq 0.1 \)) for which the characteristic NUV magnitude (\( M_{\text{NUV}} \)) came out to be \( -18.23 \) mag, whereas \( M_{\text{NUV}} \in [-14.16, -18.65] \) mag for our sample of void galaxies, implying that the distribution of our void sample traverses both the galaxy population type. Figure 13 shows no major difference in FUV SFRs of the void and non-void galaxies. Previously reported work such as Wegner et al. (2019), Beygu et al. (2016), and Cooper et al. (2008) deduce similar results where impact of the environment on the SFRs of galaxies were found to be insignificant. However, the total fraction of blue/red galaxies is strongly dependent on the environment at a given stellar mass range (De Propris et al. 2004; Baldry et al. 2006).

9.2. UV–NIR CMD

In Figure 14, the background galaxies are from the Salim Catalog (\( z \leq 0.1 \)). We refer to the 2MASS all-sky Extended Source Catalog (XSC) (Jarrett et al. 2000) for procuring \( K \)-band magnitudes for all galaxies present in the Salim Catalog.
The 2MASS XSC magnitudes are converted to AB magnitude system using the relation given in Blanton et al. (2005). On the NUV—$K$ color—magnitude plane, the distribution of galaxies is bivariate as can be seen in Figure 14. The NUV—$K$ color provides a range of $\approx 8$ mag which can be used efficiently to distinguish between galaxies based on their morphologies and stellar population type (early/late). Also, $K$—band luminosity is a tracer for total stellar mass of a galaxy (Bell et al. 2003).

As most of our photometrically verified void galaxies are absent in the NIR observations, therefore, we only study properties of void galaxies with spectroscopic observations using this CMD (see Figure 14). We scale (NUV—$K$)$_{AB}$—Vega color from Gil de Paz et al. (2007) to an (NUV—$K$)$_{AB}$—AB magnitude system following prescriptions given by Blanton et al. (2005) and find that the blue sequence comprising of spirals and irregular galaxies peak at 3.55 mag. The two void galaxies belong to the blue sequence as seen in Figure 14. Here, the absolute magnitudes, $M_K$, of these galaxies show a striking difference of two magnitude, implying a significant variation in their total stellar masses.

9.3. Galaxy Bimodality Using Optical Colors

Optical colors have been quite successful in classifying galaxies in the local universe (Strateva et al. 2001). Galaxies present in the local universe can be broadly classified into two categories, i.e., star formation quenched galaxies, which are dominated with elliptical and S0s, likely to be found in denser environments and actively star-forming galaxies with spiral, disk-like, and irregular morphologies mostly residing in a sparse environment (Kauffmann et al. 2004). These galaxies tend to separate themselves into two groups based on UV—optical, optical—optical, and UV—NIR colors up to $z \sim 1$ (Baldry et al. 2004; Yi et al. 2005; Wyder et al. 2007). In Figure 15, we show $g - r$ vs. $M_r$ CMD that is circumscribed around two modes: blue cloud peaking at $g - r = 0.5$ mag and red sequence peaks at $g - r = 0.9$ mag. Galaxies that fall in between the two groups are said to be green valley galaxies (Salim 2014).

Figure 15 show optical CMD of UVIT identified void and non-void galaxies present in our FoV. In the background, we use a magnitude limited sample of 116,010 galaxies brighter than $r < 17.77$ mag from SDSS up to $z \lesssim 0.1$ to construct the color—magnitude contours. Nearly all our UVIT detected void galaxies belong to the blue cloud population, which fits the conventional understanding of galaxy formation and evolution. Thereby, the red counterpart of the bimodal distribution is unseen in our void sample. The two spectroscopically verified void galaxies belong to two different population types, i.e., the blue cloud (image labeled as (d) in Figure 2) and the green valley (image labeled as (c) in Figure 2). The remaining void galaxies with $z_{\text{phot}}$ are blue in color with late-type morphologies. In totality, our sample follows a similar trend on the given optical CMD as shown by the galaxies present in Void Galaxy Survey (VGS; Kreckel et al. 2012) (see Figure 15). The absolute magnitudes, $M_r$, for most of our sample and the VGS is fainter than $\approx 20$ mag. A few of the galaxies from VGS are the members of the red sequence as seen in Figure 15. However, we find none such galaxies for our sample. We observe that the non-void galaxies detected in our FoV belong to both population types, spanning a wide range of optical color and luminosity while void galaxies primarily confined to the bluer and fainter end of the optical CMD.

9.4. UV—Optical CMD

We have shown NUV—$r$ vs. $M_r$ CMD for galaxies observed in our FoV in the left panel of Figure 16. The background sample comprises galaxies in the Salim Catalog ($z \lesssim 0.1$). The bivariate distribution of galaxies as a function of NUV—optical color and optical absolute magnitude is clearly visible. We fit the following relation to the peak color as a function of the absolute magnitude in the red sequence (Equation (7)) and blue sequence (Equation (8)), respectively (Wyder et al. 2007):

\[
\text{(NUV } - r \text{)} = 1.897 - 0.175M_r \tag{7}
\]

\[
\text{(NUV } - r \text{)} = 2.39 + 0.075(M_r + 20) - 0.808 \tanh \frac{M_r + 20.32}{1.81}. \tag{8}
\]

The UV—optical CMD has been extensively used in the literature to follow the evolution of galaxies from the blue sequence to the red sequence, to study the evolution of early-type galaxies, and to deduce the mechanism responsible for star formation quenching (Wyder et al. 2007; Mazzei et al. 2014; Kaviraj et al. 2007). The NUV—$r$ color is a tracer of minimal amounts ($\sim 1\%$ mass fraction) of recent star formation (RSF) ($\lesssim 1$ Gyr) (Schawinski et al. 2007). Kaviraj et al. (2007) suggest that galaxies with NUV—$r < 5.5$ mag are likely to have undergone RSF confirming episodes of RSF for our void galaxies. The non-void galaxies in our FoV are distributed among both population types, but we do not observe such a bimodality within the UVIT identified void galaxies.

The NUV—$r$ color histogram in the right panel of Figure 16 shows the color distribution for our sample and for galaxies present in the Salim Catalog. The galaxies from the Salim Catalog show a clear bivariate distribution, which fits well with a double peaked Gaussian function. The mean NUV—$r$ colors for the blue and red sequences are $\mu_{\text{blue}}^{\text{Salim}} = 3.02$ mag and $\mu_{\text{red}}^{\text{Salim}} = 5.36$ mag, respectively, whereas the mean $\mu_{\text{UVIT}}^{\text{VG}}$ for
our sample calculated by fitting a single component Gaussian profile equals 1.99 mag. The spread in the NUV−r color for our UVIT detected void galaxies is unimodal, and centered below μ_blue. Moreover, we perform Kolmogorov–Smirnov (K-S) and Anderson–Darling (AD) tests on the NUV−r color distribution of our void galaxies and the blue sequence of the Salim Catalog (NUV−r ≤ 4) to find whether the distribution of NUV−r color for the void galaxies are a subset of a larger sample of local galaxies. With a p-value = 0.007, high K-S statistic (=0.64), and AD statistic (=0.60), we reject null hypothesis at a significance level = 0.05 and infer that both sets of color belong to different parent populations. We acknowledge that our sample size for void galaxies is not significant enough for a strong statistical inference. The blueward shift in the NUV−r color of our void galaxies could be seen as a consequence of their low-density environment.

Intriguingly, we detect a few older (red) galaxies (NUV−r > 4) outside the Bootes void using UVIT observation; however, none of the void galaxies is seen to be passive, red, and dead. Based on various CMDs studied in this work, we show that the star-forming void galaxies in our sample are fainter than their counterparts present in the field/dense environment. Our sample of void galaxies lacks faint early-type galaxies such as dwarf ellipticals. Perhaps one needs to have a dedicated, high-sensitivity infrared survey of galaxies in these sparse environments.

10. Discussion and Conclusions

This work primarily focuses on the photometric properties of the void galaxies detected in the Bootes void, for which we have an ongoing survey covering a larger fraction of void using UVIT/AstroSat. The science-ready images are created first by processing the Level 1 data provided by ISRO using the official L2 pipeline. The end product of this pipeline is an L2 image, which is further corrected for astrometry. We use the appropriate GALEX tiles and SDSS r-band images to correct for the astrometry in the L2 image (both in the FUV and NUV). The difference in morphological features of a galaxy in various wave bands may have induced a slight offset (~0.2′–0.3′) in the centroid (R.A./decl.) of sources in the final UVIT images (but see the color composite in Figure 10).

Most of the void galaxies reported by us lack spectroscopic observations. SDSS spectroscopic target selection criteria depend on the r-band apparent magnitude, and mean surface brightness (Strauss et al. 2002), along with several other parameters. Our analysis and previous reports on void or isolated galaxies suggest that these systems have low optical luminosities and surface brightness (Kreckel et al. 2012; Hoyle et al. 2005; Galaz et al. 2011). Therefore, one must reset the desired observational limits while surveying a void field. We encounter a few false detections and discrepancies in star/galaxy classification in an archival SDSS photometric catalog. Hence, we perform star/galaxy classification of our detected sources using UV–optical color–color diagrams. We work with SDSS photometric redshifts due to the absence of spectroscopic observation for all objects detected in our FoV. The error associated with SDSS photometric redshifts was significant enough to be included in our analysis. Thereafter, we use EAZY for determining photo-z with better precision to assign void membership to the galaxies. Most of the galaxies with $z_{\text{phot}}$ were either absent in 2MASS images or detected with poor S/N ($\lesssim 3$). In the process, we only use photometric fluxes of seven wave bands. Hence, the lack of IR fluxes may induce slight inaccuracy in our photo-z calculations. Spectroscopic observations of the final sample of four void galaxies with $z_{\text{phot}}$ would confirm their candidature in the Bootes void. In a similar manner, we exclude IR fluxes in the SED fitting process for determining $M_{\text{SED}}$ that may incur certain discrepancies in our calculations, although, we verify our results with $M_{\text{color}}$ and find good correspondence between the two stellar masses in most of the cases.

UV emission from galaxies is subjected to extensive internal dust extinction. We calculate $A_{\text{FUV}}$ with the help of two extreme UV broadband fluxes. This method tends to be erroneous as the UV continuum may get altered by some spectral features, and by the presence of an old population (Pilo 2013). Other techniques to calculate $A_{\text{FUV}}$ require Balmer series line ratios—the classic Balmer decrement method (Groves et al., 2012), or total IR imaging observations (Hao et al., 2011), which are not available for our entire sample.

This work discusses the effect of the global environment on the FUV SFRs and sSFRs of galaxies. The local effects such as galaxy interactions are not taken into account in our analysis. We argue that the global environment weakly impacts the
ongoing star formation in galaxies, which is supported by similar studies done previously. We stress the fact that our sample size is small to provide conclusive evidence for our findings. Quantities such as SFRs and dispersion in sSFRs distribution depend on the stellar mass range of the galaxies under consideration (Huang et al. 2012; Kreckel et al. 2012). We further plan to investigate the problem with a large and diverse sample in terms of stellar mass for a concrete understanding of the environmental effects. The following are the primary scientific outcomes from our multiwavelength analysis of star-forming galaxies present the Bootes void:

1. We present a total of six void galaxies having FUV observations based on the deep UV imaging survey carried out by AstroSat/UVIT. Of these, three are new detections within the UVIT FoV.

2. Our sample spans quite a range of stellar masses, even though, it is predominated by low-mass systems as most of them have stellar masses below L* galaxies.

3. The SFRs are corrected for the internal dust extinction using the UV spectral slope β. The resultant values of β suggest low to moderate dust obscuration in the void galaxies.

4. The median SFR_{FUV} for the reported void galaxy sample is 3.96 M_solar yr^{-1}. The FUV SFRs of void galaxies are comparable to non-void low-mass, star-forming galaxies present in our sample. The ongoing moderate-to-high SFRs indicate the abundance of young massive O, B-type stars. Void galaxies show high values of sSFRs with median log(sSFR) ≈ −9.09 yr^{-1} signifying ongoing star formation at rapid timescales.

5. The UV, optical, and NIR CMDs show that our void galaxies are bluer in color and possess disk-like, irregular morphologies, in some cases with spiral features. The most of our void galaxies have optical and UV luminosities less than L* galaxies.

6. The color distribution of our void sample is confined to the blue sequence as seen in all the CMDs. In particular, we find a distinct shift in the NUV−r color distribution (Figure 16) in our sample when compared to the blue sequence of a larger sample of local galaxies. This implies that galaxies present in voids are bluer than their counterpart present in the field or denser environment.

7. Galaxies belonging to the red sequence are missing from our sample. Perhaps, a deeper infrared observation of the void region is needed to reach a firm conclusion. It could also be possible that a handful of galaxies in the low-density environment are recently formed and are not matured yet. This remains to be investigated.

We thank the referee for providing constructive suggestions/comments. The authors, D.P. and A.C.P. thank the Inter University Center for Astronomy and Astrophysics (IUCAA), Pune, India, for providing facilities to carry out this work. This publication uses the data from the AstroSat mission of the Indian Space Research Organisation (ISRO), archived at the Indian Space Science Data Center (ISSDC). The UVIT data used here was processed by the Payload Operations Centre at IIA. The UVIT was built in collaboration between IIA, IUCAA, TIFR, ISRO, and CSA.

Software: Astropy (Astropy Collaboration et al. 2013), IRAF (Tody 1993), Extractor (Bertin & Arnouts 1996), EAZY (Brammer et al. 2008), CIGALE (Boquien et al. 2019).

References

Alam, S., Albareti, F. D., Allende Prieto, C., et al., 2015, ApJS, 219, 12
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al., 2013, A&A, 558, A33
Baldry, I. K., Balogh, M. L., Bower, R. G., et al., 2006, MNRAS, 373, 469
Baldry, I. K., Glazebrook, K., Brinkmann, J., et al., 2004, ApJ, 600, 681
Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, ApJS, 149, 289
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Beygu, B., Kreckel, K., van der Hulst, J. M., et al., 2016, MNRAS, 458, 394
Beygu, B., Peletier, R. F., van der Hulst, J. M., et al., 2017, MNRAS, 464, 666
Bianchi, L., Rodríguez-Merino, L., Viton, M., et al., 2007, ApJ, 173, 659
Bianchi, L., Shiao, B., & Thilker, D. 2017, ApJS, 230, 24
Blanton, M. R., Schlegel, D. J., Strauss, M. A., et al., 2005, ApJ, 129, 2562
Boquien, M., Burgarella, D., Roehlly, E., et al., 2019, A&A, 622, A103
Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, ApJ, 686, 1503
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D. 2013, in in Secular Evolution of Galaxies, ed. J. Falcón-Barroso & H. J. Knapen (Cambridge: Cambridge University Press), 419
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Cautun, M., van de Weygaert, R., Jones, B. J. T., & Frenk, C. S. 2014, MNRAS, 441, 2923
Chilingarian, I. V., & Zolotukhin, I. Y. 2012, MNRAS, 419, 1727
Cooper, M. C., Newman, J. A., Weinr, B. J., et al., 2008, MNRAS, 383, 1058
Cruzen, S., Wehr, T., Weistrop, D., Angione, R. J., & Hoopes, C. 2002, AJ, 123, 142
Dale, D. A., Helou, G., Magdis, G. E., et al., 2014, ApJ, 784, 83
De Propris, R., Colless, M., Peacock, J. A., et al. 2004, MNRAS, 351, 125
Galaz, G., Herrera-Camus, R., Garcia-Lambas, D., & Padilla, N. 2011, ApJ, 728, 74
Gil de Paz, A., Boissier, S., Madore, B. F., et al. 2007, ApJS, 173, 185
Gregory, S. A., & Thompson, L. A. 1978, ApJ, 222, 784
Groves, B., Brinchmann, J., & Walcher, C. J. 2012, MNRAS, 419, 1402
Gunn, J. E., Gott, J., & Richard, I. 1972, ApJ, 176, 1
Hao, C.-N., Kennicutt, R. C., Johnson, B. D., et al. 2011, ApJ, 741, 124
Hoyle, F., Rojas, R. R., Vogeley, M. S., & Brinkmann, J. 2005, ApJ, 620, 618
Huang, S., Haynes, M. P., Giovannelli, R., & Brinchmann, J. 2012, ApJ, 756, 113
Hunter, D. A., Elmegreen, B. G., & Ludka, B. C. 2010, AJ, 139, 447
Jarrett, T. H., Chester, T., Cutri, R., et al. 2000, ApJ, 119, 2498
Jöevers, M., Ënast, J., & Tago, E. 1978, MNRAS, 353, 375
Kaufman, G., White, D. M., Heckman, T. M., et al. 2004, MNRAS, 353, 713
Kaviraj, S., Schawinski, K., Devriendt, J. E. G., et al. 2007, ApJS, 173, 619
Kennicutt, R. C. J. 1998, ARA&A, 36, 189
Kirshner, R. P., Oemler, A. J., Schechter, P. M., & Shectman, S. A. 1983, in Early Evolution of the Universe and its Present Structure, ed. G. O. Abell & G. Chincarini (Berlin: Springer)
Kirshner, R. P., Oemler, A. J., Schechter, P. L., & Shectman, S. A. 1981, ApJL, 248, L57
Kirshner, R. P., Oemler, A. J., Schechter, P. L., & Shectman, S. A. 1987, ApJ, 314, 493
Kreckel, K., Platen, E., Aragón-Calvo, M. A., et al. 2012, ApJ, 144, 16
Kron, R. G. 1980, ApJS, 43, 305
Lee, J. C., Gil de Paz, A., Tremonti, C., et al. 2009, ApJ, 706, 599
Libeskind, N. I., van de Weygaert, R., & Cautun, M. 2018, MNRAS, 473, 1195
Mao, Q., Berlind, A. A., Scherrer, R. J., et al. 2017, ApJ, 835, 161
Martin, D. C., Fanson, J., Schiminovich, D., et al. 2005, ApJL, 619, L1
Mazzei, P., Marino, A., & Rampazzo, R. 2014, ApJ, 782, 53
Meurer, G. R., Heckman, T. M., & Calzetti, D. 1999, ApJL, 521, 64
 Moffat, A. F. J. 1969, A&A, 3, 455
Moody, J. W., Kirshner, R. P., MacAlpine, G. M., & Gregory, S. A. 1987, ApJL, 314, L33
Moorman, C. M., Moreno, J., White, A., et al. 2016, ApJ, 831, 118
