CHAPTER 4

Star-formation properties of distant BCDs

4.1 Motivation

XUV disk star formation serves as an excellent opportunity to probe low density and low metallicity star formation that prevailed in the Early Universe[326]. Study of such low-density environments also make us wonder about the viable processes that may lead to the cloud/cluster formation[398] because very outer reaches of galactic disks are mostly dominated by atomic H and it is very hard to convert HI to H_2 in these regions. At the same time a critical gas density was apparently seen in the study of inner disks of spirals [399] below which clouds do not form as per Toomre criterion[400]. It is quite interesting to have gas surface densities measured down to orders of 1 $M_{\odot}pc^{-2}$ [29] and below. H_2 gas density measurements reach as low as 0.35 $M_{\odot}pc^{-2}$ in the XUV disk of M63 and even in such low-density gas, star formation occurs; albeit with very low efficiencies[31]. The amount of gas present and how efficiently that gas can be converted into stars emerges as the famous Kennicutt-Schmidt relation[30, 401, 402]. But this relation doesn't seem to hold in such extreme environments (e.g. [31]). It subsequently makes one wonder if stars form in a similar manner as they do in the inner regions of galaxies or whether any variations in the stellar IMF may arise in such physically/chemically differing environments (e.g. [403]).

4.2 Data Analysis

4.2.1 Outer SFRD

To avoid the effect of the PSF, we estimate the inner and outer SFRD values using the intrinsic FUV disk profile. In that we integrate the intrinsic profile (Equation 2.9) within the inner (r = 0 to $R_{out,opt}$) as well as XUV region (R = $R_{out,opt}$ to $R_{out,FUV}$).

4.2.2 Rest-frame colours and SSP modelling

In order to obtain rest-frame colours of the BCDs, Spectral Energy Distributions (SED) modelling was performed using FAST[315]. We use Bruzual & Charlot (2003) models[404] with a Salpeter[370] IMF having metallicity Z = 0.008. We used an exponentially declining star formation history given by SFR $\sim$exp(-t/τ) and a Calzetti extinction curve[393] for the modelling. The e-folding time ranges from log τ = 7.5 to 9.3 in steps of 0.2. The age range from log age = 7.5 to 9.9 in steps of 0.2. The visual extinction A_V range from 0 to 3.0 in steps of 0.1 and a redshift range from 0.02 to 1.0 in steps of 0.05 has been used.

We use STARBURST99[32] stellar population models to estimate an average stellar population age in the XUV region based on the observed $FUV - NUV$ colours. For this, we make use of an instantaneous burst SFH and a continuous star-formation history (CSFH) with a Salpeter IMF[370] (1-100 $M_\odot$) with solar metallicity ($Z_\odot$) and 0.4$Z_\odot$. With that we used the Calzetti [393] extinction curve. We then obtain the model $FUV - NUV$ colours up to 1 Gyr by convolving the reddened (by using the $E(B - V)$ values) model spectra with the UVIT/F154W and N242W filters.

4.3 Results and Discussion

4.3.1 Low density star formation

The threshold surface brightness to classify Type 1 XUV disks is 27.25 mag arcsec^{-2}[18]. As used in Thilker et al. 2007[18], the equivalent star-formation rate surface density (SFRD) with a Salpeter IMF and solar metallicity ($Z_\odot$=0.02) (with the calibration of Kennicutt[30, 402]) is $SFRD_{th} = 3{\times}10^{-4}$ $M_\odot$ yr^{-1} kpc^{-2}. For the average intrinsic surface brightness in the XUV region of GS3 and GS6 (our representative BCDs), the SFRDs are $1.82 \pm 0.43 \times 10^{-5}$ $M_\odot$ yr^{-1} kpc^{-2}, and $2.25 \pm 0.48 \times 10^{-4}$ $M_\odot$ yr^{-1} kpc^{-2} respectively. At 0.4$Z_\odot$, these values would be $\sim$ 10% lower because the FUV emission of a 100 Myr old population is 1.1 times brighter[405]. Our SFRD estimates are comparable to previous measurements that reach $\sim$10^{-5}-10^{-6} $M_\odot$yr^{-1}kpc^{-2} in low-density, extreme environments, e.g., galaxy outskirts or stripped gas tails within galaxy clusters [29, 406]. The SFRD estimates are presented in Table 4.1.

BCD	FUV-NUV	$SFRD_{XUV}$
	mag	$M_\odot$yr^{-1}kpc^{-2}
GS1	-1.78±0.29	1.3±0.49 $\times10^{-4}$
GS2	0.00±0.18	2.4±0.49 $\times10^{-4}$
GS3	-0.37±0.21	1.8±0.43 $\times10^{-5}$
GS4	-0.42±0.33	8.7±2.30 $\times10^{-5}$
GS5	-0.92±1.45	1.1±8.58 $\times10^{-5}$
GS6	-0.44±0.24	2.3±0.48 $\times10^{-4}$
GS7	-0.29±0.22	1.8±0.83 $\times10^{-5}$
GS10	0.11±0.20	3.9±0.64 $\times10^{-4}$
GS11	0.14±0.13	6.4±1.10 $\times10^{-5}$
GS12	-0.56±0.20	5.8±0.13 $\times10^{-6}$
GS13	-1.15±0.28	2.7±0.74 $\times10^{-4}$
GS14	0.20±0.29	2.4±0.63 $\times10^{-5}$

Table 4.1: **SFRD and UV colour derived for the XUV disks of the BCDs. Column 2:** Observed FUV-NUV colour in the XUV region of the BCDs. **Column 3:** Intrinsic, profile-integrated SFRD values in the XUV region. The quoted uncertainties are 1σ.

If the FUV SFRD follows the Kennicutt relation [30], it would suggest star-formation at an average gas surface density of less than 1 $M_\odot$ pc^{-2} [31, 407]. For a steeper slope of the Kennicutt relation, as seen in the XUV region of M63[31], our SFRDs probe gas (HI+H_2) surface densities (independent of metallicity because the molecules are fully observed in M63) of $\sim$2.9 and $\sim$4.9

$M_{\odot}pc^{-2}$ for GS3 and GS6 respectively. The nature of star formation at such low density is largely unexplored.

4.3.2 UV-optical-NIR colours

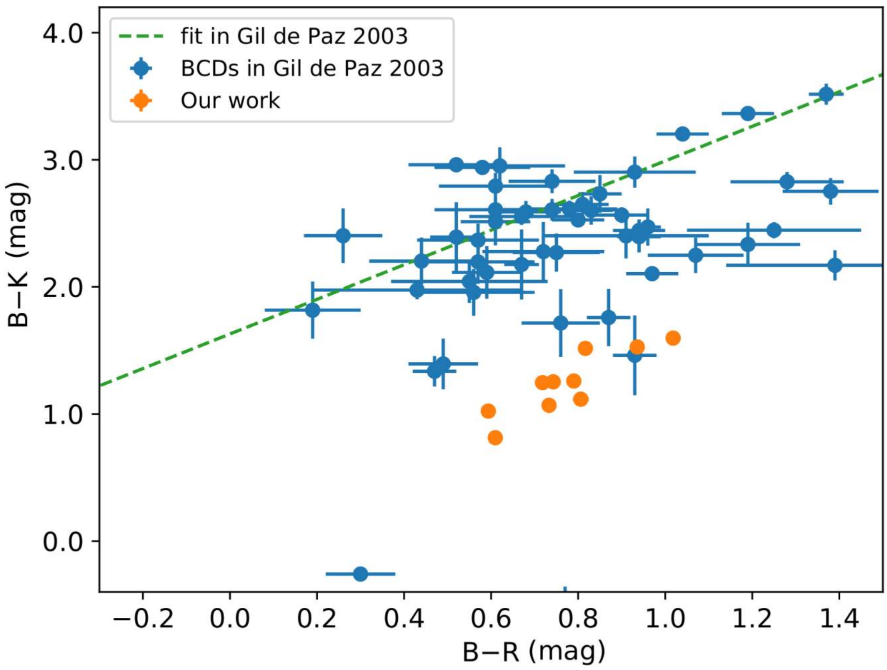

Figure 4.1: **Optical-NIR colours of z∼0.2 BCDs.** The B-K versus B-R colours of the distant BCDs are bluer as compared to the local BCDs in G03.

We compared the rest-frame B-K and B-R colours of our sample BCDs with that of local BCDs in Gil de Paz et al. 2003[3] (hereafter G03) as shown in Figure 4.1. The K band magnitudes of the local BCDs of G03 are obtained after cross-matching them with the 2MASS catalog[408]. The R band magnitudes are estimated from deep VIMOS R-band images of the *GOODS-South* field[409]. Here we see that our sample showed blue B-K colours as compared to the fit for G03 BCDs. This may be suggestive of a colour evolution with redshift some possible selection bias not understood here.

As presented in Figure 4.2, the B-R colour vs absolute magnitude, in the B-band (M_B), reveals that our sample of BCDs lie up quite well within the G03 BCD sample[3].

We further cross-matched the G03 sample with *GALEX* and 2MASS cata-

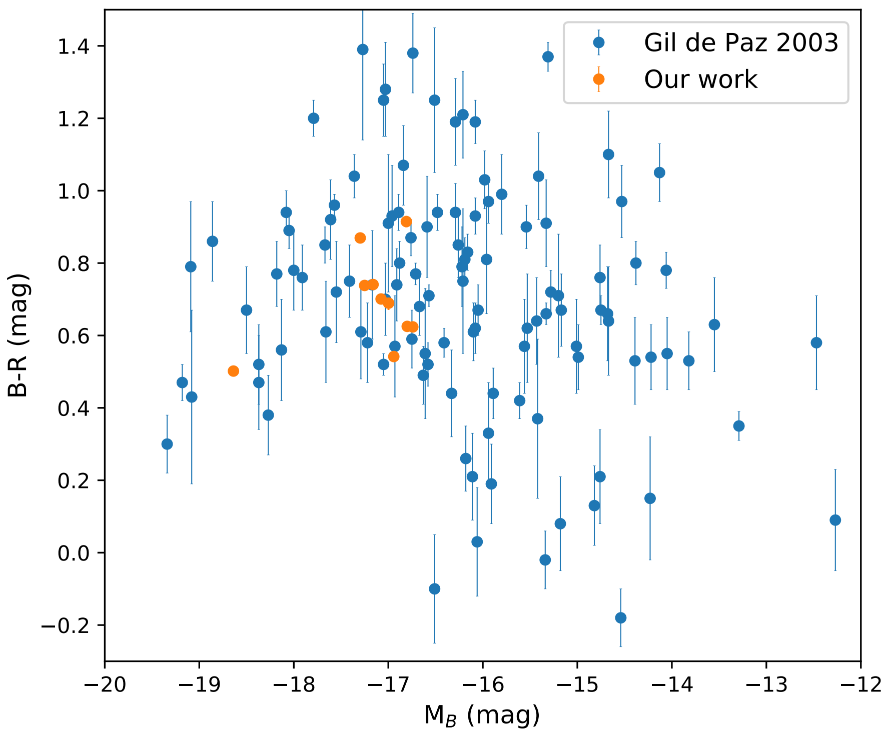

Figure 4.2: **Optical colours of z∼0.2 BCDs.** The distant BCDs are similar to the local BCDs in G03 in their optical colours and B band luminosities.

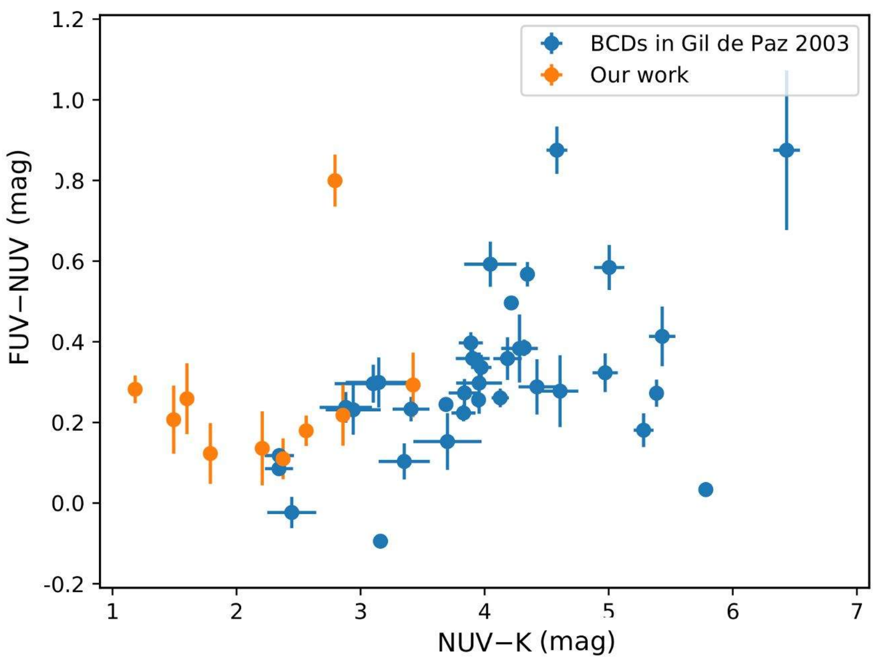

Figure 4.3: **UV-NIR colours of distant BCDs.** Figure shows the FUV-NUV versus NUV-K colour for our sample of BCDs and those of local BCDs from G03.

logs [408, 410] to obtain their FUV, NUV and K band magnitudes. A comparison of our BCD sample with that of G03 is shown in Figure 4.3. We find that our BCDs appear blue in NUV-K but almost half of them appear blue/red in FUV-NUV as compared to the G03 BCDs. The blue NUV-K colours indicate that our BCDs may be younger or are metal-poor compared to the local ones, suggestive of metallicity evolution in BCDs with redshift. The redder FUV-NUV colours indicate a possible suppression of star formation in these BCDs due to gas depletion or the extinction of FUV light due to the presence of dust. More analyses on a larger sample combined with multi-wavelength modelling of the galactic spectra will help us to provide a clearer picture in this context.

4.3.3 XUV disk properties

Figure 4.4 shows the SFRD versus $FUV - NUV$ colours, directly measured from the Galactic extinction corrected UVIT images, for 11 of our BCDs (excluding GS5). In young star-forming regions such as XUV disks, massive O and OB stars typically dominate the FUV emission. The FUV and NUV in such regions can detect star-formation in the past 100 to 200 Myr. Apart from this, evolved stars can also become bright in the FUV, but that normally occurs in the early-type galaxies; which is not the case here. Negative FUV-NUV values indicate very young portions of the galactic disk. Seven of our galaxies have $FUV - NUV < 0$ and four have $0 < FUV - NUV < 0.5$ in their XUV region. $FUV - NUV \sim 0.3$ and 0.2 for GS3 and GS6 respectively, within the observed optical extent. This is similar to local LITTLE THINGS dwarfs[411]. We calculate the stellar population ages of these XUV disks by comparing their observed $FUV - NUV$ colours with model colours obtained using the STARBURST99 code[32] as discussed above. In the case of an instantaneous burst at $Z_{\odot}$, the ages are 7.1 Myr and 12.3 Myr for GS3 and GS6 respectively, whereas for a CSFH, they are 106 Myr and 306 Myr old (the stellar populations are older by a factor of ~ 2 at 0.4 $Z_{\odot}$). The mean age of the stellar population for an instantaneous burst in the XUV disk of the BCDs is $\sim$ 26 Myr. In case of a CSFH, the mean stellar population can be $\sim$230 Myr old (excluding GS10 and GS11 where it would be $\geq$1 Gyr old). We also find that, in the case of lower metallicity, $Z = 0.4\ Z_{\odot}$, the XUV disks could be

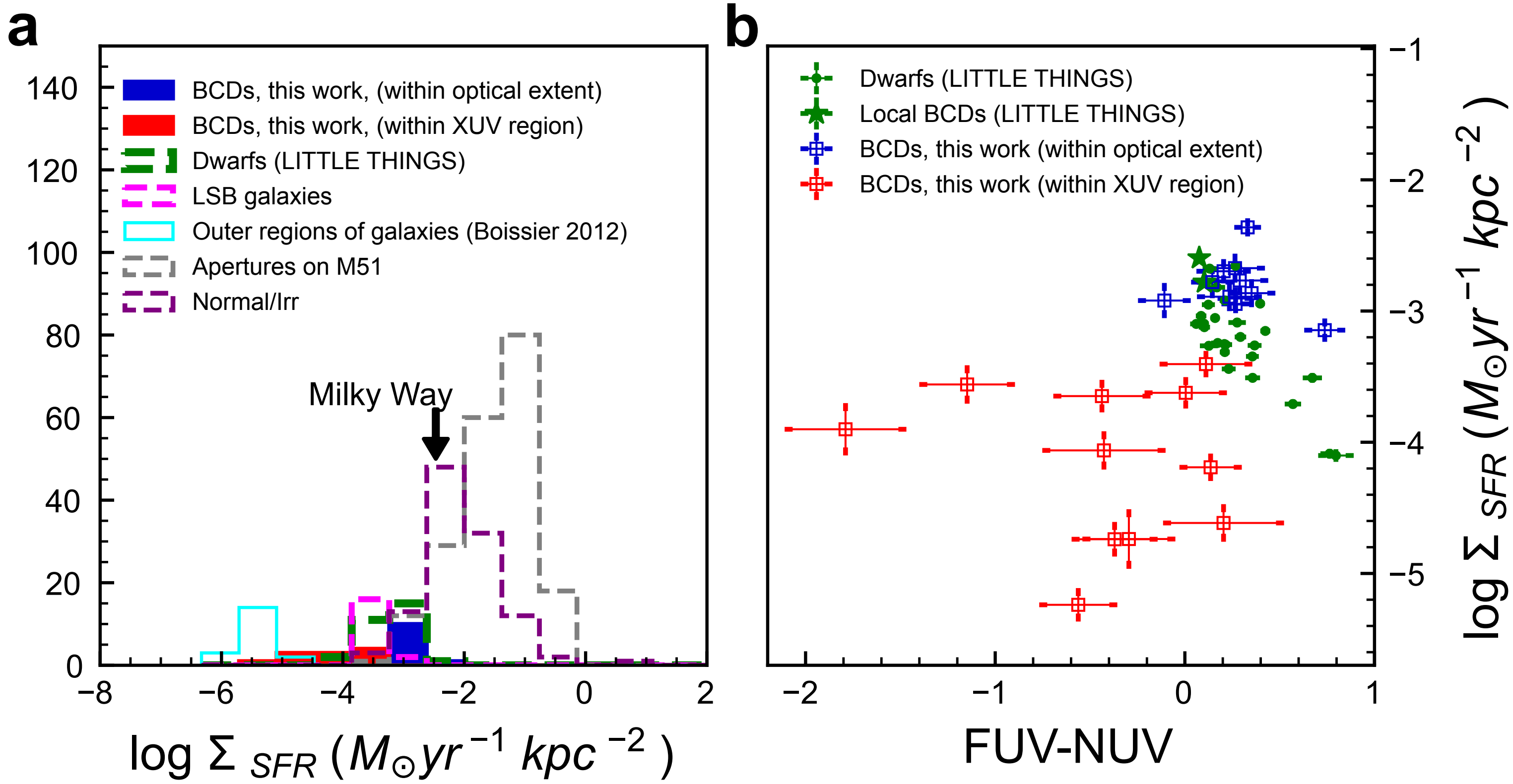

Figure 4.4: **Comparison of star-formation properties of our BCDs to local galaxies: a:** SFRD values of our sample BCDs (shown in filled blue and red), other local dwarfs (dashed-green – measured with *GALEX* within their Holmberg radii[411]), outer regions of galaxies[412] (solid-cyan), low surface brightness (LSB) galaxies, apertures on M51 and other Normal/Irr galaxies[30]. **b**: SFRD versus observed FUV-NUV colour of the current BCD sample (blue and red squares), local BCDs (green-stars) and other local dwarfs[411] (green points). The measurements for local BCDs and other dwarfs are within their Holmberg radii[411]. All our measurements are shown with 1σ error-bars[358].

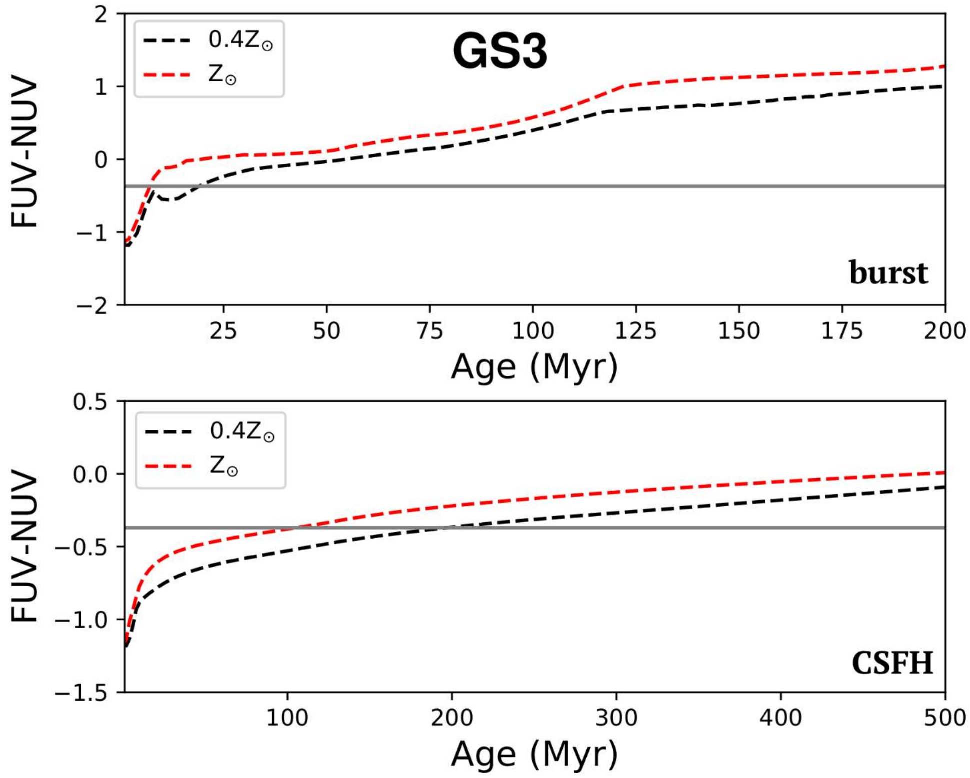

Figure 4.5: **Stellar population modelling of the XUV region of GS3 Top**: Single stellar population modelling for an instantaneous burst of star formation. **Bottom**: Single stellar population modelling for a continuous star formation history. In both cases the black and red dashed curves correspond to the metallicity (0.4Z⊙ and Z⊙ respectively) used during the modelling. The horizontal grey lines correspond to the FUV-NUV of the XUV region of the BCD - GS3.

∼42-324 Myr old. We tabulate the model ages for the XUV disks in Table 4.2 and show the colour modelling for GS3 in Figure 4.5.

4.4 Summary and Conclusions

In this chapter, we present the investigation of the star-formation properties of the distant XUV disk hosting BCDs, especially in their XUV region. The intrinsic SFRDs in these outer regions are a few factors of 10^{-6} $M_{\odot}yr^{-1}kpc^{-2}$ which would translate to gas surface densities of the order ∼1 $M_{\odot}pc^{-2}$ or less. The study of such low-density star formation is still open for further exploration which will require the study of the gas content and its distribution in these objects in the future. We obtain the rest-frame optical-NIR and UV-NIR colours of the BCDs with the help of SED modelling using FAST. This reveals that distant BCDs are bluer than their present-day counterparts.

	Ages (Myr)			
BCD	SF burst $Z_\odot$	continuous SF $Z_\odot$	SF burst 0.4 $Z_\odot$	continuous SF 0.4 $Z_\odot$
GS1	–	–	–	–
GS2	52.2	748.2	72.0	769.8
GS3	7.2	106.2	19.1	196.8
GS4	6.7	73.6	17.4	155.3
GS5	–	–	–	–
GS6	12.3	306.3	34.3	472.4
GS7	8.1	175.2	24.3	321
GS10	81.9	>1000	98.2	>1000
GS11	72.6	>1000	93.6	∼1000
GS12	7.0	99.5	18.8	190.0
GS13	1.8	2.6	3.0	4.7
GS14	12.3	327.5	37.5	482.1

Table 4.2: **XUV ages based on observed $FUV - NUV$ colour and stellar population synthesis. Column 2, 3:** Age estimates using an instantaneous burst and CSFH with $Z=Z_\odot$. **Column 4, 5:** Age estimates using a SF burst and continuous SF with 0.4 $Z_\odot$. We ignore GS1 due to extreme blue colour and GS5 due to being a marginal case.

Such overall blue colour, in addition to blue outer colours, indicates enhanced star formation in the outer disk and the presence of young stars. We then estimate the stellar ages of the XUV population using observed UV colours and STARBURST99[32] stellar population modelling. This reveals the average ages of the outer disk to be a few tens to hundreds of Myr as seen in nearby XUV disk galaxies.