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Bulge-Disk Evolution in Interacting Bulgeless Galaxies

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Abstract. Bulgeless galaxies are an extreme class of late type spiral galaxies that have practically no bulge and are nearly pure disk in morphology. Their lack of evolution is a puzzle for theories of galaxy formation and the secular evolution of galaxy disks. However, one of the processes by which these galaxies could evolve is through interactions with other galaxies. In this study we present radio (GMRT) observations of star formation in a sample of bulgeless galaxies. We did followup Hα imaging and optical spectroscopy of two galaxies, NGC 3445 and NGC 4027. Both galaxies have extended emission associated with their tidal interactions. Their nuclei show ongoing star formation but no signs of AGN activity. The R band images suggest that their centers have oval distortions or pseudobulges that may later evolve into larger bulges. Thus interactions are an important trigger for the formation of bulges in such disk dominated systems.

1. Introduction

Bulgeless galaxies are late type spirals that have practically no bulge and are nearly pure disk in morphology (Böker et al. 2002). Although they are not rare, their formation and lack of evolution remains a puzzle both for CDM theories of hierarchical galaxy formation, and the secular evolution theories of galaxy disks (Kautsch 2009). The former process leaves clear signatures of merger history in the disks and the latter leads to disky bulges; neither of these features are seen in most bulgeless galaxies. However, one of the processes by which these disks could evolve is through interactions with nearby companion galaxies. The main aim of this work is to search for signs of such evolution by mapping the star formation and nuclear activity in a sample of nearby bulgeless galaxies. We use radio observations to map the star formation; it has the advantage that it is not affected by dust obscuration and hence may be a better tracer of the star formation. We have followed up two interesting cases, NGC 3445 and NGC 4027, with optical spectroscopy and Hα imaging observations. In the following sections we present our observations, results and then discuss their implications.

2. Sample Galaxies and Observations

Our sample consists of twelve bulgeless spiral galaxies that have a range of disk morphologies from nearly pure disks to progressively more distinct bulges or pseudobulges

Table 1. Galaxy Parameters

Galaxy	Type	Distance (Mpc)	Velocity (km/s)	Optical Size	NVSS Radio Emission (mJy)[a]
ESO 418-8	SB(r)d	14.9	1195	1.2’	3.8
UGC 4499	SABdm	11.5	691	1.99’	2.0
NGC 3346	SB(rs)cd	22	1260	2.7’	13.8
NGC 3445	SAB(s)m	30.8	2069	1.6’	23.6
NGC 3782	SAB(s)cd	13.2	739	1.7’	4.6
NGC 3906	SB(s)d	16.1	961	1.9’	2.0
NGC 4027	SB(s)dm	27.9	1671	3.2’	91.0
NGC 4299	SAB(s)dm	7.79	232	1.7’	17.2
NGC 4540	SAB(rs)cd	22.1	1286	1.9’	3.1
NGC 4701	SA(s)cd	14.5	721	2.8’	18.5
NGC 5584	SAB(rs)cd	26	1638	2.45’	19.4
NGC 5668	SA(s)d	25	1582	3.3’	23.5

in their centers (Böker et al. 2003) (Table 1). They are all detected at some level in the VLA NVSS radio maps. However, the resolution of NVSS is poor (45$''$) and hence does not show the detailed radio morphology. We observed the galaxies in radio continuum at 1280 MHz using the Giant Meterwave Radio Telescope (GMRT) located near Pune, India. Observations were done during May, 2008. Nearby radio source were used for phase calibration. The data was analysed using AIPS. Bad data was iteratively edited and calibrated on a single channel until satifactory gain solutions were obtained using standard tasks in AIPS. Both natural and uniform weighted maps of the galaxies were made to obtain the extended structure and see if there is any compact emission associated with the nucleus.

We did Hα imaging and nuclear spectroscopy of the two galaxies, NGC 3445 and NGC 4027, that showed extended emission in the GMRT radio continuum maps. The observations were done with the 2m Himalayan Chandra Telescope (HCT) which is located at the Indian Astronomical Observatory (IAO) at Hanle. The spectrum of NGC 3445 was obtained on a cloudless night on 17 March 2010 and NGC 4027 was observed on a clear night on 19 January 2010. The spectra were obtained using a $11' \times 1''.92$ slit (#167l) in combination with a grism #7 (blue region) and grism #8 (red region) which cover the wavelength ranges 3700–7600 Å and 5500–9000 Å with dispersions of 1.46 Å pixel^{-1} and 1.26 Å pixel^{-1}, respectively. The slit was placed at the centre of the galaxy covering a central region of $\sim 2'' \times 5''$. The Hα images of NGC 3445 and NGC 4027 were obtained on 17 March 2010 from HCT. The Hα filter is centered at 6550 Å and has a bandwidth of 100 Å. Bessells *R* filter (centered around 6400 Åwith a BW of $\sim$ 1600 Å) was used for continuum subtraction. Each of the Hα frames was observed for 10 minutes. Sky subtracted *R* frame was scaled and subtracted out from the Hα; it was normalized with respect to exposure time.

3. Results

(i) Radio Emission : We have detected radio emission from five of the twelve galaxies in our sample, NGC 3445, NGC 3782, NGC 4027, NGC 4299 and NGC 5668. Our observations did not detect the extended, diffuse disk emission; instead we detected the

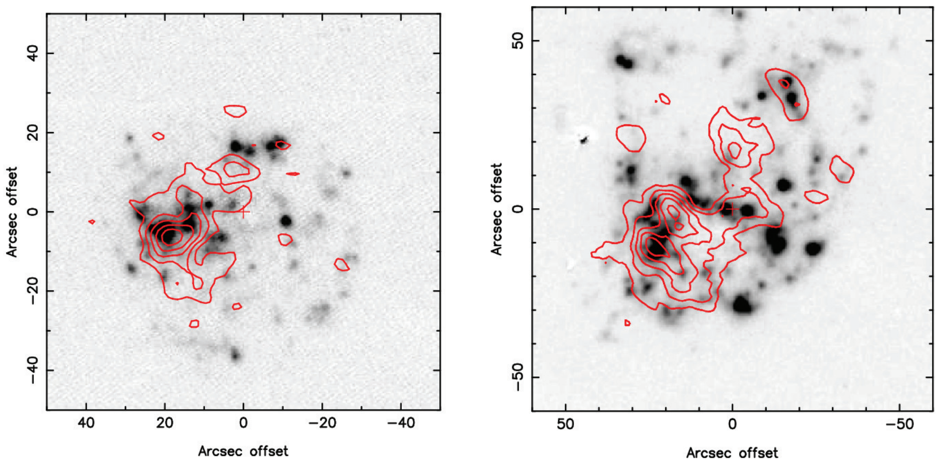

Figure 1. *Left:* Fig 1a : The figure shows the Hα image of NGC 3445 with the 1280 MHz radio continuum contours overalid in red. The peak radio flux is 2 $mJy\ beam^{-1}$ and the $beam \sim 8''$. The contours are 4, 6, 8, 10, 12 times the noise level which is 0.15 $mJy\ beam^{-1}$. The radio emission mainly traces the Hα emission and is more extened to the south. *Right:* Fig 1b : The figure shows the Hα image of NGC 4027 with the 1280 MHz radio continuum contours overalid in red. The peak radio flux is $\sim$ 3.5 $mJy\ beam^{-1}$ where $beam \sim 8''$; it is located in the disk and not the nucleus. The contours are 8, 10, 12, 14, 16, 18 times the noise level which is 0.21 $mJy\ beam^{-1}$.

more localized emission arising from localized star forming regions. For two galaxies NGC 3445 and NGC 4027, the emission is extended and the star formation rate relatively high. Interestingly, both these galaxies are also tidally interacting with nearby companion galaxies. The radio emission in NGC 3445 and NGC 4027 mainly follows the prominent southern spiral arm associated with the tidal interaction (Figure 1) and to some extent the less prominent northern arm. In NGC 4027 there is also some emission associated with the galaxy nucleus; it could be due to nuclear star formation or weak AGN activity.

(ii) Hα imaging and spectroscopy of NGC 3445 and NGC 4027 : The Hα emission (Figure 1) traces the star formation in these galaxies and is closely associated with the radio contours. Both NGC 3445 and NGC 4027 have knots of star formation along the southern spiral arms that are closer to the respective, nearby interacting galaxies. The maximum star formation rate in NGC 3445 derived from the Hα flux is 1.5 $M_{\odot}\ yr^{-1}$ (Kennicutt 1983); it is associated with the southern arm. For NGC 4027, the maximum star formation rate is 1.82 $M_{\odot}\ yr^{-1}$ and is also associated with a intense star forming region in the southern arm. The nuclear spectra of both galaxies suggest that there is ongoing nuclear star formation but no AGN activity. NGC 4027 suprisingly shows no [O] emission in its spectra.

(iii) Interaction induced bulge formation in NGC 3445 and NGC 4027 : The Hα subtracted R band images of both NGC 3445 and NGC 4027 were used to see if bulges were forming in these galaxies. We used the iraf task *ellipse* to fit ellipses to the central regions. NGC 4027 has an oval distortion of ellipticity approximately 0.6 and position angle 83°; its size is $\approx 15''$ or 0.65 kpc. The structure is disky and suggests that it may be a pseudobulge that has formed from the buckling of a much smaller bar and is in the process of growing into a bulge (Raha et al. 1991). The bulge-disk decomposition of NGC 4027 yields a bulge scale length of $r_e \sim 1''$ and disk $\mu_e \sim 16.2''$ (Baggett et al. 1998). The oval distortion in NGC 3445 is much smaller and is less than 0.5 kpc in size. It does not have the disky appearance of a pseudobulge and may be in a much earlier stage of bulge formation.

4. Implications

(i) Star formation in bulgeless galaxies : This study and others in the literature suggest that bulgeless galaxies have a relatively low rate of star formation, especially the low luminosity galaxies, unless they are closely interacting with companion galaxies. Thus in our study, only NGC 3445 and NGC 4027 show signifigant star formation as both are tidally interacting with nearby galaxies (Phookun et al. 1992). Both these galaxies may be more dark matter dominated than bright galaxies. The dark halo reduces the rate of disk instabilities which in turn lowers the star formation rate and gas infall rate in these galaxies. These factors lead to a slower rate of bulge evolution.
(ii) Bulge evolution triggered by tidal interactions : This study suggests that bulgeless galaxies can evolve bulges through tidal interactions with close companion galaxies. Such interactions lead to enhanced star formation and the formation of oval distortions in the galaxy centers. These ovals may represent pseudobulges that have formed due to the buckling of small bars in the galaxy centers; they may later evolve into larger bulges (Kormendy et al. 2010). Thus close tidal interactions rather than internal processes (i.e. secular evolution) may be important for bulge formation and disk evolution in such late type, disk dominated galaxies.
(iii) AGN-Bulge evolution in NGC 3445 and NGC 4027 : The well known black hole mass and bulge velocity relation suggests that AGN evolve with bulges. In our study neither NGC 3445 or NGC 4027 show optical emission lines characteristic of AGN. However, the AGN may develop later; in fact studies show that the nuclear black hole may begin to accrete and show AGN activity only after the initial starbursting phase is over (Cen 2011). This may be true for both these galaxies.

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