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Star formation in bulgeless late type spiral Galaxies

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Abstract. We present radio and follow-up optical observations of a sample of bulgeless late type spiral galaxies. We searched for signs of nuclear activity and disk star formation in the sample galaxies. Interaction induced star formation can often trigger bulge formation. We found significant radio emission associated with star formation in two sample galaxies, NGC3445 and NGC4027, both of which are tidally interacting with nearby companions. For the others, the star formation was either absent or limited to only localized regions in the disk. Both galaxies also have oval bars that are possibly pseudobulges that may later evolve into bulges. We did follow up optical Hα imaging and nuclear spectroscopy of NGC3445 and NGC4027 using the Himalayan Chandra Telescope (HCT). The Hα emission is mainly associated with strong spiral arms that have been triggered by the tidal interact1ions. The nuclear spectra of both galaxies indicate ongoing nuclear star formation but do not show signs of AGN activity. We thus conclude that star formation in bulgeless galaxies is generally low but is enhanced when the galaxies interact with nearby companions; this activity may ultimately lead to the formation of bulges in these galaxies.

Keywords : galaxies: active – galaxies: bulges – galaxies: spiral – galaxies: interactions – radio continuum: galaxies

1. Introduction

Bulgeless galaxies are an extreme class of late type spiral galaxiess (Scd to Sm) that have practically no bulge and are nearly pure disk in morphology (Boker, Laine, van

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der Marel et al. 2002). Although these galaxies 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 (Kormendy & Kennicutt 2004). The former process will leave clear signatures of merger history in the disks and the latter would lead to the presence of oval distortions or 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.

Bulgeless galaxies show a wide variation in disk morphologies, ranging from the irregular dwarf galaxies to the nearly pure disk galaxies such as NGC 6503. However, we focus only on low luminosity bulgeless galaxies that may or may not have a bar, but do not have a prominent bulge. The large scale spiral arms and bars that signify strong disk instabilities are not seen in these galaxies. This suggests that these galaxies have dominant dark matter halos that stabilise their disks against disk instabilities. Only nearby interactions can trigger disk instabilities that can lead to bulge formation. Apart from the challenge of forming such pure disk galaxies, there is also the question of how they form nuclear black holes and active galactic nuclei (AGN) as galaxy bulges and AGN are thought to co-evolve in galaxies. However, AGN have been detected in the nuclei of bulgeless galaxies and have been found to be associated with IMBHs (Satyapal et al. 2007; Peterson et al. 2005). It is not clear where these galaxies lie on the $M-\sigma$ correlation as they barely have a bulge; or how to explain their AGN activity which should be correlated with the formation of a bulge. Recent studies indicate that the SMBHs do not correlate with the disks or pseudobulges in galaxies (Kormendy et al. 2011), hence the disk is not directly correlated with the growth of nuclear black holes in bulgeless galaxies.

In this paper we investigate how star formation and nuclear activity can influence disk evolution in bulgeless galaxies. We use radio continuum observations to map the star formation and search for compact nuclear emission which may be associated with AGN activity. Radio emission has the advantage that it is not affected by dust obscuration and hence is a better tracer of the star formation. We have followed up two interesting cases with optical spectroscopy and Hα imaging observations. In the following sections we discuss our sample, the observations and our results.

2. Galaxy sample and observations

Our sample consists of twelve late type spiral galaxies that appear to be bulgeless or have a minimal bulge in their HST WFPC2 images (table 1). The galaxies have a range of disk morphologies; some have nearly pure disks and some have progressively more distinct bulges or pseudobulges. They all have compact stellar nuclei as indicated by their HST I band light profiles and are 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 contin-

Table 1. Galaxy sample and parameters.

Galaxy	Distance (Mpc)	Position (RA, Dec)	Optical size
ESO 418-8	14.9	03h31m30.6s, -30d12m48s	1.2′
UGC 4499	11.5	08h37m41.5s, +51d39m09s	1.99′
NGC 3346	22	10h43m38.9s, +14d52m19	2.7′
NGC 3445	30.8	10h54m35.5s, +56d59m26s	1.6′
NGC 3782	13.2	11h39m20.7s, +46d30m50s	1.7′
NGC 3906	16.1	11h49m40.5s, +48d25m33s	1.9′
NGC 4027	27.9	11h59m30.2s -19d15m55s	3.2′
NGC 4299	7.79	12h21m40.9s, +11d30m12s	1.7′
NGC 4540	22.1	12h34m50.8s, +15d33m05s	1.9′
NGC 4701	14.5	12h49m11.6s, +03d23m19s	2.8′
NGC 5584	26	14h22m23.8s, -00d23m16s	2.45′
NGC 5668	25	14h33m24.3s +04d27m02s	3.3′

uum at 1280 MHz using the Giant Meterwave Radio Telescope (GMRT) located near Pune. Observations were done during May, 2008. Nearby radio source were used for phase calibration. The data was obtained in the native "lta" format, converted to FITS format and then analysed using 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 optical spectroscopy of two galaxies in the sample that showed extended emission in the GMRT radio continuum maps, NGC 3445 and NGC 4027, using the 2m Himalayan Chandra Telescope (HCT). The HCT is part of the Indian Astronomical Observatory (IAO) and is remotely controlled from the Center for Research and Education in Science and Technology (CREST) which is part of the Indian Institute of Astrophyiscs (IIA) in Bangalore. 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). These cover the wavelength ranges of 3700–7200 Å and 5500–9000 Å͘The spectral resolution is around $\sim$ 8.7 Å (398 km s^{-1} FWHM or σ = 169 km s^{-1} at Hα) for grism #7 and $\sim$ 7 Å (σ = 136 and 103 km s^{-1} at Hα and Ca triplet respectively) for grism #8. Imaging and spectroscopic data were both reduced using the standard tasks available in IRAF which includes bias subtraction, extraction of one dimensional spectra, wavelength calibration using the ferrous argon lamp for grism #7 and ferrous neon lamp for grism #8. The wavelength calibrated spectra were flux calibrated using one of the spectroscopic standards observed on the same night and then corrected for the redshifts of the galaxies.

3. Results

1. We have detected radio emission from five of the twelve galaxies in our sample. Although all twelve galaxies have radio emission in their NVSS images, only five

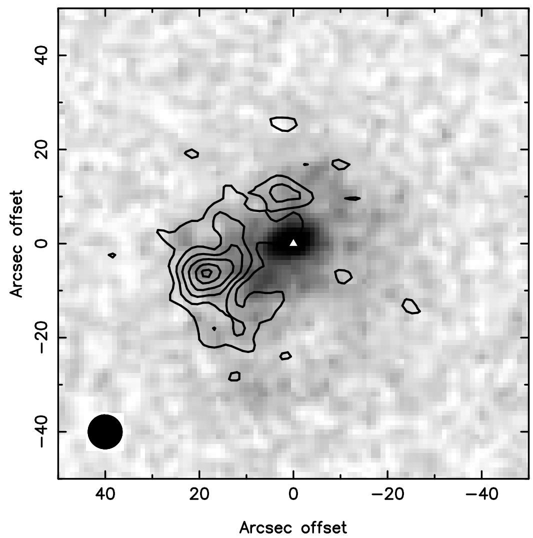

Figure 1. The contours of the natural weighted GMRT 1280 MHz radio continuum map of NGC 3445 superimposed on the 2MASS near-IR image of the galaxy is shown. The peak radio flux is 2 mJy beam^{-1} and the beam$\sim 8''$. The contours are 4, 6, 8, 10, 12 times the noise level which is 0.15 mJy beam^{-1}. The galaxy center is marked with a filled triangle. Note that the emission is offset from the center of the galaxy and lies mainly east of the nucleus.

were detected in our study, possibly because the NVSS beam ($45''$) is much larger than that of our GMRT observations ($\approx 8''$). Hence, although our observations could not detect the diffuse, widespread radio emission from the galaxies we did detect the localized emission arising from star forming regions. We determined the infrared to radio luminosity ratios (q) of the five detected galaxies using the IRAS 60 and 100 μm fluxes and the NVSS 1.4 GHz flux. We found that q was larger than two for all galaxies, which indicates that the radio emission is associated with star formation and not AGN in these galaxies (Condon et al. 2001). Of the five detected galaxies, three show only patchy radio emission associated with the disk. Two galaxies, NGC 3445 and NGC 4027, have extended radio continuum associated with disk star formation. Both these galaxies are also tidally interacting with neighbouring galaxies.

2. The followup Hα imaging and optical spectroscopic observations show that the radio emission closely follows the Hα emission arising from star forming regions in the tidally interacting arms. For NGC 4027 the Hα emission is much higher compared to NGC 3445; this is not suprising as the star formation rate is also higher and tidal interaction much stronger. The Hα emission shows knots of star formation along the tidal arms for both galaxies. NGC 4027 also shows some nuclear emission that could be associated with nuclear cluster star formation or weak AGN activity. However, the narrow Hα lines in the optical spectra of both galaxies suggests star formation rather than AGN activity. In NGC 3445, the [O III] and Hβ ratio and the NII and Hα ratios when plotted on the BPT diagram confirm the presence of nuclear star formation. In

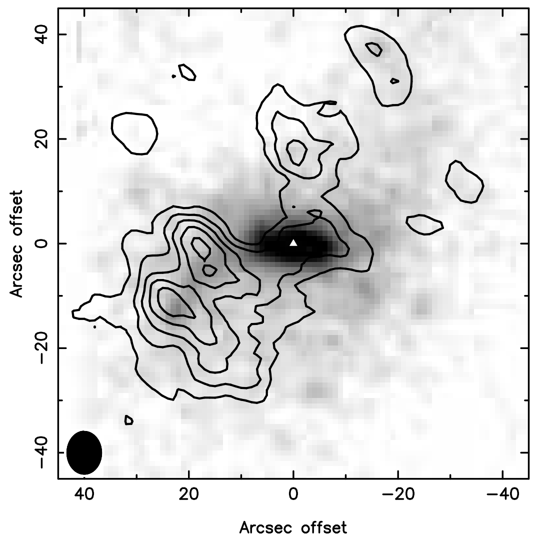

Figure 2. The contours of the natural weighted GMRT 1280 MHz radio continuum map of NGC 4027 superimposed on the 2MASS near-IR image of the galaxy is shown. The peak radio flux is ∼ 3.5 mJy beam^{-1} where beam∼ 8″; it is located in the disk and not the nucleus. The contours are 8, 10, 12, 14, 16, 18 times the noise level which is 0.21 mJy beam^{-1}. The galaxy center is marked with a filled triangle. The radio emission is mostly associated with the spiral arms and the southern arm is more prominent.

NGC 4027, the spectrum does not show either [O III] or [O II] and hence an AGN is probably not present in this galaxy either.

3. The main result of this work is that we have found two cases of ongoing bulge formation in the low luminosity bulgeless galaxies NGC 3445 and NGC 4027. The bulge formation has been triggered by close tidal encounters with nearby galaxies. Both galaxies are clearly dark matter dominated systems since they are late type spirals and have low luminosity disks (Salucci & Persic 1997). Such systems are not easily perturbed to form bars and spiral arms. Thus, close tidal encounters are an important mechanism for the evolution of halo dominated systems, such as low luminosity bulgeless galaxies, into bulge dominated disk galaxies.

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