THE ASTROPHYSICAL JOURNAL, 446:594–597, 1995 June 20

RADIO DETECTION OF A DOUBLE NUCLEUS IN THE MERGING GALAXY NGC 3256

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Received 1994 August 29; accepted 1994 December 16

ABSTRACT

NGC 3256 is a well-known merging galaxy with two prominent tidal tails. An extended and vigorous starburst makes it one of the nearest known luminous infrared galaxies. We have imaged the radio continuum using the Australia Telescope Compact Array and find clear indication of a double nucleus. Each of the two nuclei is compact but lies on an extended diffuse component, which may be related to the start of the two tidal tails. The existence of two nuclei implies that the galaxy is still in the process of merging, in contrast to earlier suggestions that the merger was almost complete. The radio continuum is predominantly nonthermal emission from remnants of supernovae which occur about one every 3 years in each nucleus. We find no evidence for a Seyfert nucleus.

Subject headings: galaxies: individual (NGC 3256) — galaxies: interactions — galaxies: nuclei — radio continuum: galaxies

1. INTRODUCTION

The nature of the relationship among merging galaxies, starburst, Seyfert, and luminous infrared galaxies is still far from clear, although the existence of a relationship is beyond doubt, since these different phenomena are frequently found in the same galaxy. Understanding this relationship will have important implications for the development of any unified theory of galaxy formation and evolution.

NGC 3256 is of particular interest as it belongs to at least three of these four categories of galaxy and is relatively nearby at a distance of 56.2 Mpc ($H_0 = 50$ km s^{-1} Mpc^{-1}). It is a southern example of a merger in progress. The galaxy possesses two tidal tails, indicative of the collision and subsequent merger of two equal-mass disk galaxies (Toomre & Toomre 1972). These tidal tails are particularly striking in neutral hydrogen where, in addition to the two main tails, a number of isolated fragments can also be seen (English et al. 1994, 1995). The collision has brought with it $\sim 10^{10}$ $M_\odot$ of molecular material which is extended beyond the nuclear region (Sargent, Sanders, & Phillips 1989). A spatially extended and vigorous starburst, coupled with dust throughout the galaxy, gives rise to an infrared luminosity of $\sim 5 \times 10^{11}$ $L_\odot$, which by some definitions places it in the class of ultraluminous infrared galaxies. The starburst may be powerful enough to drive a superwind from the nuclear region (Heckman, Armus, & Miley 1990).

Eventually NGC 3256 may resemble the merger-product ellipticals described by simulations (e.g., Barnes & Hernquist 1992), but its current evolutionary state is somewhat uncertain. The presence of only one nucleus at infrared wavelengths would suggest a well-evolved merger. Joseph & Wright (1985) examined the star formation properties for nine galaxies which they ordered into a crude "merger sequence" from recent to evolved systems. They included NGC 3256 as an example of a recent system and noted that this was the only galaxy in their sequence for which high-resolution radio measurements were not available. Previous radio observations by Wright (1974), using the Parkes telescope, had a resolution of 8′. More recently, Smith & Kassim (1993) imaged NGC 3256 (which they refer to as 1025−43) in a VLA snapshot survey with a resolution of 4″ at 6 cm and found a single nucleus at the resolution of their data. Here we present radio maps with arcsecond resolution at both 3 and 6 cm of the central region of NGC 3256. Our maps reveal two distinct nuclei, one of which is largely obscured at optical and infrared wavelengths.

2. OBSERVATIONS AND DATA REDUCTION

We observed NGC 3256 with the Australia Telescope Compact Array (ATCA) at 4.79 GHz (6 cm) and 8.64 GHz (3 cm) simultaneously. The observational parameters are given in Table 1. Our amplitude calibrator (1934−638) was observed at the beginning and the end of the run. The source and the phase calibrator (1104−445) were observed alternately for 12 hr. These data were edited, calibrated, and CLEANed using the AIPS software package. The final 3 cm map has a half-power beamwidth (HPBW) of 1″.25 × 0″.96 (p.a. = 1°), and rms noise of ∼62 μJy beam^{-1}. The 6 cm map has a HPBW of 2″.25 × 1″.59 (p.a. = 5°), and rms noise of ∼89 μJy beam^{-1}.

3. RESULTS

In Figures 1 and 2 we show contour maps of the 3 and 6 cm radio emission. The maps reveal two distinct, resolved (FWHM ∼ 1″.2) nuclei and some fainter diffuse radio emission extending east of the northern and west of the southern nucleus. This contrasts with the VLA observations by Smith & Kassim (1993), which showed only a single extended nucleus, but this can be attributed to their poorer resolution.

The radio emission is dominated by the two nuclei with the northern nucleus being ∼1.15 times brighter than the southern. The extensions of the diffuse emission are in the same directions as the tidal tails seen in H I and at optical wavelengths (English et al. 1994, 1995). The two nuclei have a similar spectral index of about −0.8 and are separated by about 5″ (1.4 kpc). The northern nucleus is coincident, within

TABLE 1

RADIO OBSERVATIONS

Parameter	Value
Telescope	Australia Telescope Compact Array
Date	1992 August 1
Configuration	6D
Shortest baseline	77 m
Longest baseline	5.9 km
Observing time	12 hr
Amplitude calibrator	1934−638
Flux density	6.35 Jy (6 cm), 2.59 Jy (3 cm)
Phase calibrator	1104−445

1″, with the optical/2.2 μm peak position estimated by Doyon, Joseph, & Wright (1994). Radio positions and measurements for the two nuclei and the galaxy as a whole are summarized in Table 2.

4. DISCUSSION

4.1. *Radio Morphology*

We have detected two distinct radio cores in the central region of NGC 3256. The similar size, brightness, and spectral index of these cores argue that they are the nuclei of the original progenitor galaxies. It is unlikely that either of the cores is an extranuclear starburst region, since both cores have very similar properties (apart from foreground extinction at optical and infrared wavelengths), and their presence is consistent with detailed simulations (English 1994) of the mergers. Furthermore, the supernova rate (discussed below) would be remarkably high for an extranuclear starburst. Both cores are accompanied by arms of diffuse continuum emission extending out toward the two giant tidal arms seen in H I. We therefore conclude that the two cores are indeed the nuclei of the progenitor galaxies.

The heavy dust extinction toward the southern nucleus (see Kotilainen et al. 1994) led Doyen et al. to refer to the northern nucleus as "the nucleus" and the southern nucleus as an additional infrared source called "5″ south." The southern nucleus is about 10% of the northern nucleus brightness at 2 μm (Moorwood & Oliva 1994). The radio emission from the two nuclei is of comparable intensity indicating that even 2 μm observations suffer from about 2.5 mag of extinction.

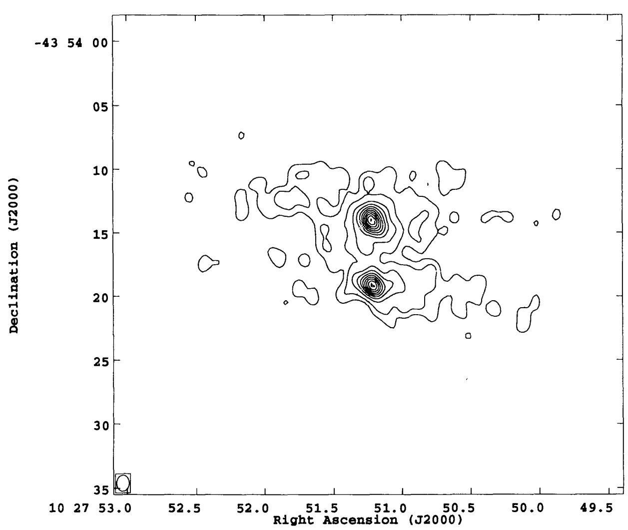

FIG. 1.—Contour map of the 3 cm radio emission. The beam size is shown in the lower left. Contour levels are 70 μJy × (−5, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100) mJy beam^{-1}, and the peak flux is 7.1 mJy beam^{-1}.

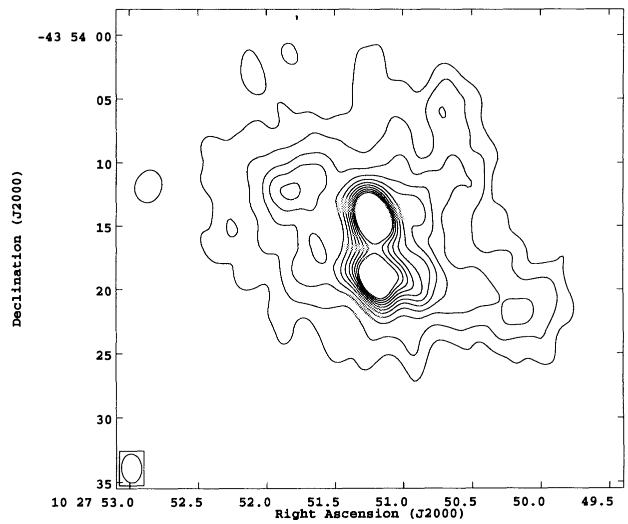

FIG. 2.—Contour map of the 6 cm radio emission. The beam size is shown in the lower left. Contour levels are 90 μJy × (−5, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100) mJy beam^{-1}, and the peak flux is 19.3 mJy beam^{-1}.

Doyon et al. also refer to an infrared source, or hot spot, located 5″ east of the northern nucleus. This feature corresponds to a local enhancement within the extended radio emission, which has a radio spectral index of −0.9 and is presumably an extranuclear starburst region. Optical images suggest that a weak 3 kpc ring surrounds the central region but is distorted by dust extinction in the south (Moorwood & Oliva 1994). Such rings are sometimes observed in radio continuum images (e.g., NGC 7552; Forbes et al. 1994), but in the case of NGC 3256 we see no evidence for such a ring.

The spectral indices for the two nuclei and the galaxy as a whole are quite steep ($\alpha \sim -0.9$). This indicates that the radio emission is dominated by nonthermal synchrotron processes and that the contribution to the radio emission from H II regions is negligible. Radio surveys of interacting/merging galaxies have been carried out by Sulentic (1976) and Smith & Kassim (1993). Sulentic found a bimodal distribution for the spectral indices with the main peak at ~ -0.95 and a secondary one at ~ -1.4. Smith & Kassim found a single, symmetric peak about an index of −0.89. Thus the radial spectral index for NGC 3256 is fairly typical for such galaxies.

In Table 2 we list the supernova rate inferred from the 6 cm radio emission in a 4″ diameter aperture on each nucleus and for the whole galaxy, using the method of Condon & Yin (1990). We find high supernova rates, of about one every 3 years for each nucleus, and as high as three per year for the galaxy as a whole. An alternative method for estimating the supernova rate is from the near-infrared [Fe II] line emission, which appears to be generated by the fast shocks associated with SNRs (Greenhouse et al. 1991; Forbes & Ward 1993). Moorwood & Oliva (1988) obtained an [Fe II] 1.64 μm line flux in a 6″ aperture centered on the northern nucleus of 6.8×10^{-14} ergs s^{-1} cm^{-2}. If we assume typical values for Galactic supernovae, namely an [Fe II] line luminosity per remnant of 2×10^{36} ergs s^{-1} (Moorwood & Oliva 1988) and a lifetime of 2×10^{4} yr (corresponding to the SNR adiabatic

TABLE 2

MEASURED PARAMETERS

Location	R.A. (J2000)	Decl. (J2000)	3 cm (mJy)	6 cm (mJy)	α	$L_{3\ cm}$ (10^{38} ergs s^{-1})	$L_{6\ cm}$ (10^{38} ergs s^{-1})	SN Rate (yr^{-1})
North Nucleus......	$10^h27^m51\overset{s}{.}21$	$-43°54'14\overset{''}{.}2$	21	34	−0.78	6.8	6.1	0.3
South Nucleus......	10 27 51.19	−43 54 19.1	18	31	−0.86	5.9	5.6	0.3
Total Galaxy	...	...	150	280	−1.0	48.8	50.5	3.8

NOTES.—Positions have estimated errors of $\pm0\overset{''}{.}3$. Nuclei measurements are for a 4" diameter aperture. The spectral index α is defined by $F \propto \nu^{\alpha}$.

phase), then the inferred supernova rate is 0.65 yr^{-1}. This estimate is uncertain by a factor of about 2. The measured 6 cm radio emission for the same region is 53 mJy, which corresponds to a supernova rate of 0.67 yr^{-1}. These two estimates are in very good agreement. This gives us confidence that the near-infrared [Fe II] line emission is a useful alternative for estimating the supernova rate *and* that the central radio emission in NGC 3256 is indeed mostly nonthermal emission from SNRs. The latter conclusion is also supported by the morphological similarity between the radio and [Fe II] 1.64 μm line emission presented by Kotilainen et al. (1994).

4.2. *The Evolutionary State of the Merger*

There is some disagreement in the literature concerning the evolutionary state of the NGC 3256 merger. The southern nucleus is largely obscured at infrared wavelengths by dust (Kotilainen et al. 1994), leaving the northern nucleus as the only obvious nucleus in the optical or infrared. We have clearly identified two distinct nuclei from the progenitor galaxies, which indicates that the merger is relatively recent.

Simulations suggest that the merger involved a prograde encounter (to explain the large tidal tails) of two disk galaxies (e.g., Barnes & Hernquist 1992; Mihos, Richstone, & Bothun 1992; English et al. 1995). Using these simulations to derive an age is complex because of different assumptions and initial conditions, but it appears that the first interaction occurred several hundred Myr ago, and the two nuclei are now orbiting each other pending the final merging of the nuclei. As they do so, episodic bursts of star formation are induced (Mihos & Hernquist 1994), and the starburst we observe is probably not the first to have occurred in this merger. Analysis of the near-infrared broadband colors (Glass & Moorwood 1985) and spectral lines (Doyon et al. 1994) indicate that the current starburst started only about 20 Myr ago.

Graham et al. (1984) argue that the *K*-band brightness profile is consistent with an $r^{1/4}$ law, suggesting that the system has had time to relax. However, the more extended profile presented by Moorwood & Oliva (1994) deviates strongly from a smooth $r^{1/4}$ profile, which suggests that the dominant stellar mass component is still somewhat chaotic and has yet to relax, implying a more recent merger. Any extinction present in the *K* band may complicate this interpretation. A recent merger is also supported by the conclusions of Schweizer (1986), on morphological grounds, and Sargent et al. (1989), based on the large quantity of molecular gas that still exists throughout the system.

4.3. *Do the Nuclei Contain Seyfert as Well as Starburst Activity?*

An intimate link between Seyfert and starburst activity is suggested by a variety of evidence, and it is also likely that Seyfert nuclei may be fuelled by an interaction. Therefore, we review the evidence for a Seyfert nucleus buried under many magnitudes of extinction in NGC 3256. Radio observations suggest that, although most starbursts classified by optical spectroscopy do not contain a Seyfert-like nucleus (Norris et al. 1990), there are a few cases, such as Arp 220 (Norris 1988) in which an AGN is buried beneath many magnitudes of extinction.

Seyferts (Norris, Allen, & Roche 1988; Wilson 1988) and radio-quiet quasars (Sopp & Alexander 1991) obey roughly the same correlation between the radio and far-infrared emission as normal, starburst, and ultraluminous galaxies (e.g., de Jong et al. 1985; Condon & Broderick 1986; Wunderlich, Klein, & Wielebinski 1987). It is believed that the correlation has its origins in star formation processes within galactic disks, and so this similarity implies that the radio luminosity of Seyfert galaxies and radio-quiet quasars is also dominated by star formation activity. This similarity also invalidates the argument of Smith & Kassim (1993), who, following Condon & Broderick (1991), used an infrared/radio index to argue that NGC 3256 is a starburst rather than an AGN. However, Condon & Broderick actually showed only that the infrared/radio index could be used to distinguish starbursts from radio-loud galaxies. Most Seyferts are radio-quiet and so the radio-infrared index cannot easily be used to distinguish between Seyferts and starbursts. A tight correlation between central radio emission and [Fe II] line emission has also been shown to exist for starburst and Seyfert galaxies alike (Forbes & Ward 1993). NGC 3256 lies at the high-luminosity end of both the radio versus [Fe II] and radio versus far-infrared relations that describe the starburst galaxies and Seyferts.

Given these similarities, it is natural to ask whether NGC 3256 might contain a buried Seyfert nucleus. Our radio data on NGC 3256 are consistent with the starburst generating all of the radio emission, although the general morphology (i.e., a compact source with extended linear emission) is similar to some of the Seyfert galaxies, described by Ulvestad & Wilson (1984). The two nonthermal nuclei could in principle contain a compact Seyfert nucleus, but high-resolution 2.3 GHz observations with a $0\overset{''}{.}1$ beam (R. P. Norris, unpublished data) place an upper limit of 8 mJy on any AGN radio cores in NGC 3256. However, this is still too high to exclude an AGN core with certainty. Near-infrared spectroscopy, for which the effects of dust extinction are significantly reduced, reveals no evidence for broad lines or high excitation coronal lines from an AGN (Moorwood & Oliva 1994). The soft X-ray luminosity of NGC 3256 is considerably higher than that of normal spiral galaxies but is comparable to those found for peculiar galaxies, once an extrapolation to softer X-ray energy is made (Fabbiano, Feigelson, & Zamorani 1982). The most likely sources for the X-ray emission in these galaxies are SNRs and binary stars.

We conclude that neither our radio observations nor the literature shows any evidence for a buried Seyfert nucleus in

NGC 3256. It is clear that the bolometric luminosity of NGC 3256 is dominated by starburst activity, although we are unable to rule out Seyfert activity completely.

5. CONCLUSIONS

Our high-resolution radio continuum maps at 3 and 6 cm of the merging galaxy NGC 3256 reveal, for the first time, two radio nuclei, along with extended radio emission which appears to be associated with extranuclear starburst activity. The presence of two distinct nuclei implies that the merging process has not fully proceeded, which may also explain the large spatial extent of the molecular material in this galaxy. We derive very high supernova rates for both nuclei, and find no evidence for a buried Seyfert nucleus.

We thank Chris Mihos and Jayanne English for helpful discussions, and Rafik Kandalian for his assistance with the observations. Partial financial support was provided by NSF grant 8809616.

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