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BUBBLES AND BRAIDED JETS IN GALAXIES WITH COMPACT RADIO NUCLEI

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ABSTRACT

We present narrow-band Hα CCD images showing ionized gas in organized kiloparsec-scale structures in three galaxies with low-level active nuclei. The edge-on spiral NGC 3079 contains an apparent loop structure which corresponds to previously reported nonthermal radio emission along the minor axis. The optical emission probably results from interaction between the ejected plasma and the ISM in the disk and halo. The S0 galaxy NGC 3998 exhibits an S-shaped structure centered on the nucleus, with no other evidence for spiral structure. In the spiral galaxy NGC 4258 we confirm the presence of continuum-free emission-line arms which coincide with the nonthermal radio arms. The morphology of the arms suggests the presence of two double-sided jets which braid or wrap around one another and which bifurcate on both sides. We conclude that the optical and radio emission in NGC 3079 and in NGC 4258 are related and suggest that both are powered by a plasma which flows from the active nucleus and dissipates kinetic energy in the surrounding ISM.

Subject headings: galaxies: individual — galaxies: jets — galaxies: nuclei

I. INTRODUCTION

Little is known about the nature and occurrence of large-scale, extranuclear emission in active galaxies, and the possible causal relationship between such large-scale structure and nuclear activity. In particular the relative importance of photoionization by the nucleus (Fillipenko 1985) versus shock-induced ionization by plasma ejection is not clear, especially in those active nuclei with a weak or undetectable ionizing continuum. If low-luminosity radio nuclei produce small-scale jets which are analogous to the powerful classical radio triples, then dissipation of the jets' mechanical energy in the interstellar medium (ISM) could provide the link between extended optical emission and nuclear activity. Extended radio structures which are either bent (Wilson and Ulvestad 1982) or are limb brightened by compression and shocks (Clarke, Burns, and Feigelson 1986) provide strong evidence for interaction of a jet with the ISM. Further evidence is provided when optical emission is found, coinciding with the radio structure. The best examples of this process in Seyfert and LINER galaxies are M51 (Ford *et al.* 1985), NGC 1068 (Wilson and Ulvestad 1983; Atherton, Reay, and Taylor 1985), and NGC 5929 (Keel 1985; Whittle *et al.* 1986).

The presence of weak jets in Seyferts and LINERs, and the detection of optical emission in giant double radio lobes (van Breugel 1986 and references therein) suggest that in broad outline there is a continuity in properties from the most powerful radio triples to galaxies with barely detectable nuclear activity. This supports the idea that all nuclear activity originates through a common mechanism such as activity around a black hole. The characteristics of this activity are then determined by the properties of the black hole, the fueling rate (Norman and Silk 1983), and the galactic environment (Norman and Miley 1984).

If these ideas are correct, we expect large-scale emission to be relatively common in galaxies with active nuclei. We are testing this hypothesis by surveying active galaxies for extended emission, and by using the large-scale structures to study the interstellar medium in early-type galaxies, the frequency of jets originating in low-luminosity nuclei, and the confinement of jets. We selected galaxies from the complete sample of galactic nuclei of Heckman, Balick, and Crane (1980) with spectroscopic and VLA observations. We observed those galaxies which were designated as LINERs and/or had a compact radio core (Heckman 1980). In this *Letter* we

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present interesting results on three galaxies which justify publication before further detailed spectroscopic and radio observations.

II. OBSERVATIONS

The optical, radio, and X-ray properties of the three galaxies discussed in this *Letter* are given in Table 1. The fluxes and line widths in Hα are weighted averages from Heckman, Balick, and Crane (1980), Dahari (1985), Keel (1983), and from Stauffer (1982). The latter two authors observed with higher resolution and higher signal-to-noise ratio (S/N), so double weights were given to their results. We observed the galaxies with the Kitt Peak National Observatory (KPNO) RCA CCD (No. 3) camera at the f/7.5 focus of the No. 1 0.9 m telescope, which gives a scale of 0."86 per 30 μm pixel. We used 75 Å-wide redshifted Hα + [N II] interference filters, a KPNO *B* filter, and either a 6204/149 or a 6194/347 continuum ("off-band") filter. Typical exposure times were 30, 5, and 10 minutes, respectively. De-biasing and flat-fielding were performed in the manner described by the KPNO user's manual (Schoening 1983). After registration, the scaled off-band image was subtracted from the Hα image to create a "difference image" in which the underlying smooth stellar continuum is reduced to zero. The off-band, Hα, and difference images are displayed in Figures 1–3 (Plates L2–L4).

III. RESULTS

a) NGC 3079

The optical nucleus of this nearly edge-on late-type spiral galaxy is heavily reddened (Heckman 1980; Lawrence *et al.* 1985), as can be seen in Figure 1. Although Heckman (1980) classified NGC 3079 as a LINER, the reddening-corrected line ratios and the suspected broad component of Hα (Stauffer 1982) suggest that the galaxy has a heavily obscured Seyfert nucleus. A compact radio source (de Bruyn 1977), an unresolved X-ray source (Fabbiano, Feigelson, and Zamorani 1982), and a warm infrared spectrum (Lawrence *et al.* 1985) are further evidence for nuclear activity.

De Bruyn (1977) and Hummel, van Gorkom, and Kotanyi (1983) noted an unusual radio emission feature, which was later studied in detail by Duric *et al.* (1983, hereafter DSCBD) and by Duric and Seaquist (1986). The radio emission is clearly extended along the minor axis of the galaxy, and was described by DSCBD as two lobes symmetrically located on both sides of the nucleus and connected to the nucleus by curving bridges. There is no stellar counterpart to the radio emission.

Figure 1 shows a prominent Hα loop or ring east of the nucleus which is absent in the off-band image. Although the ring is not uniformly bright, it is probably complete at low intensity levels. (A similar loop was found in the S0 galaxy NGC 2655 [Dahari *et al.* 1986].) The circular symmetry of the loop strongly suggests that it lies out of the galaxy's plane, like the radio feature (DSCBD). There is no corresponding Hα emission west of the nucleus except for a weak feature at p.a. 240°, ~ 15" away, which may be H II regions in the western spiral arm.

In order to overlay the radio map with our optical images we compared the superpositions published by de Bruyn (1977) and by Hummel, van Gorkom, and Kotanyi (1983), finding ~ 10" difference between their registrations. Consequently, we used the Space Telescope's Guide Star Selection System Schmidt plates to measure the astrometric position of the three stars marked a, b, c, in Figure 1. These coordinates were used to locate de Bruyn's (1977) radio position in our optical image (marked by a cross), and to overlay DSCBD's VLA radio map accordingly. The optical/radio alignment in Figure 1 is within ~ 1" of de Bruyn's registration.

The NE radio lobe extends away from the Hα ring and is tangent to its lowest surface brightness segment. The Hα loop roughly coincides with the much fainter, incomplete inner radio loop seen in Duric and Seaquist's (1986) map. Comparison of DSCBD's radio polarization map with Figure 1 shows that polarization at 6 cm is detected only outside the Hα ring. This suggests that the Hα ring is in reality a shell or bubble of ionized gas which envelopes the inner radio plasma and thus reduces its polarization. The lack of optical emission and of depolarization in the outer radio lobe suggest that the relativistic plasma has escaped from the disk's ISM through the top of the Hα shell into the halo where its interaction with the low-density corona produces little or no Hα emission.

On the SW side of the nucleus the *inner* side of the radio extension is polarized while its outer part is not. We believe that this polarized radio emission originates in the *disk* of the galaxy because it extends in a N-S direction and apparently coincides with the H II regions in the galaxy's spiral arms. The galaxy's west side is the near side (de Bruyn 1977); consequently, the emission from the SW lobe is depolarized by the disk. The absence of Hα associated with the SW radio lobe is then explained by obscuration.

The angle of the radio lobes subtended by the nucleus (assuming small projection effects) is larger than Bridle and Perley's (1984) criterion for the maximum opening angle of radio jets. Consequently, Duric and Seaquist (1986) proposed

TABLE 1

OPTICAL, RADIO, AND X-RAY PROPERTIES OF THE GALAXIES' NUCLEI

Property	NGC 3079	NGC 3998	NGC 4258
Type[a]	Sc pec	$S0_1(3)$	Sb(a)II
M_B[a]	−21.64	−20.43	−22.04
D[a](Mpc, $H_0 = 50$)	24.5	24.3	10.4
$F(\mathrm{H}\alpha)$[b] (ergs cm^{-2} s^{-1})	6.87×10^{-14}	3.08×10^{-13}	1.18×10^{-13}
FWHM (km s^{-1})	570[b]	600[c]	400[b]
S(6 cm, mJy)	85[c]	77[d]	< 2[c]
S(20 cm, mJy)	150[c]	104[c]	~ 3[e]
α[d]	0.31	0.17	...
f_X(0.5–3 keV, ergs cm^{-2} s^{-1})	3.7[f] $\times 10^{-13}$	4.0[g] $\times 10^{-12}$	...

[a]Sandage and Tamman 1981.
[b]Average (see text).
[c]Heckman, Balick, and Crane 1980.
[d]Hummel, van der Hulst, and Dickey 1984.
[e]van Albada and van der Hulst 1982.
[f]Fabbiano, Feigelson, and Zamorani 1982.
[g]Dressel and Wilson 1985.

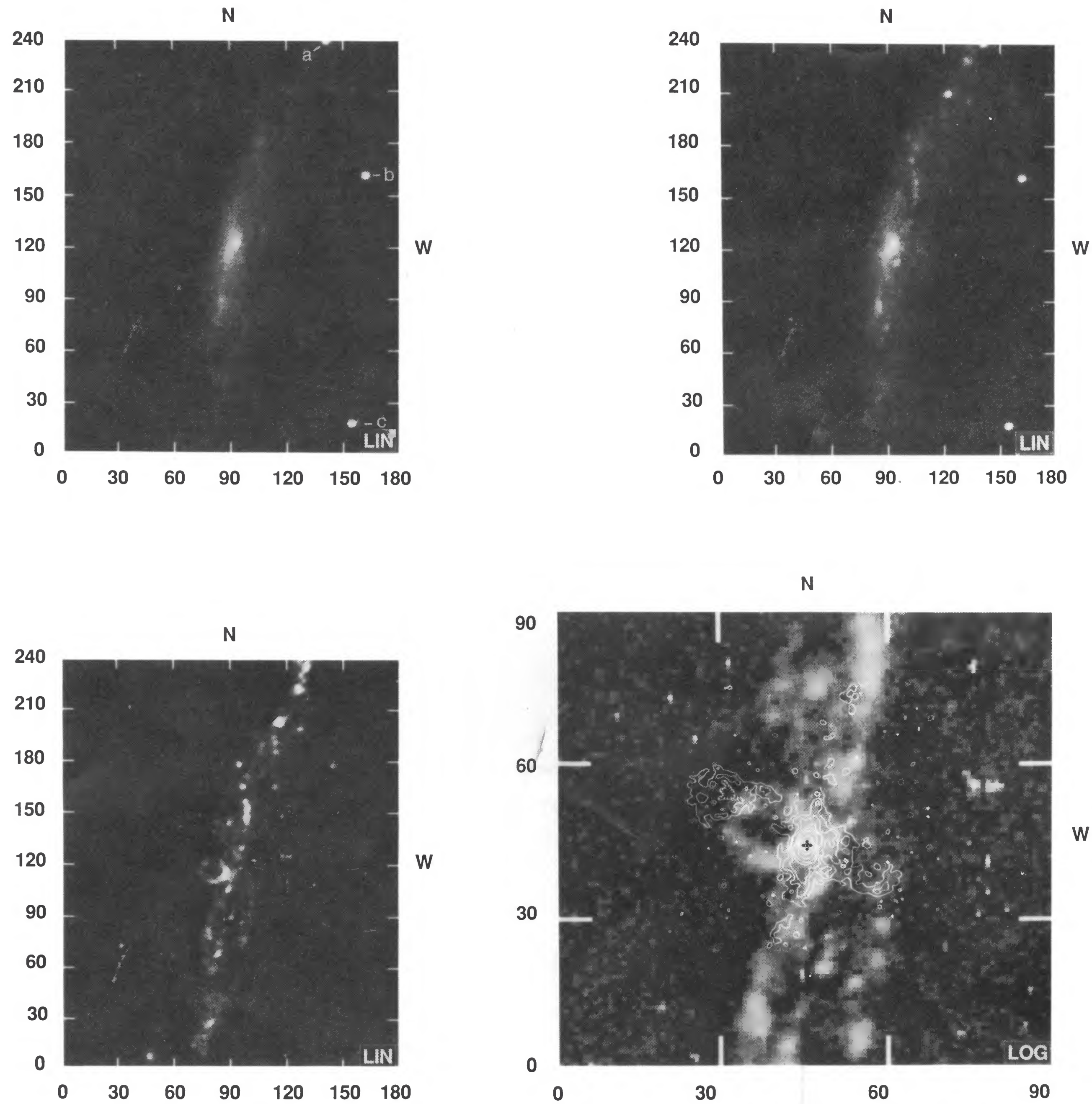

FIG. 1.—NGC 3079. Gray-scale prints of the continuum (*top left*), Hα + [N II] (*top right*) and difference (*bottom left*) images are displayed. On bottom right, the radio continuum map from Fig. 1 of Duric *et al.* (1983, courtesy of N. Duric and *The Astrophysical Journal*, published by the University of Chicago Press; © The American Astronomical Society) is overlayed on the central region of the difference image. The stars marked a, b, c were used to register the radio map and optical image. The cross marks the position of the unresolved radio source (de Bruyn 1977). In Figs. 1–3, the abbreviation LOG or LIN are printed on logarithmic or linear intensity prints respectively, and the spatial scale is given in arc seconds.

FORD *et al.* (*see* page L8)

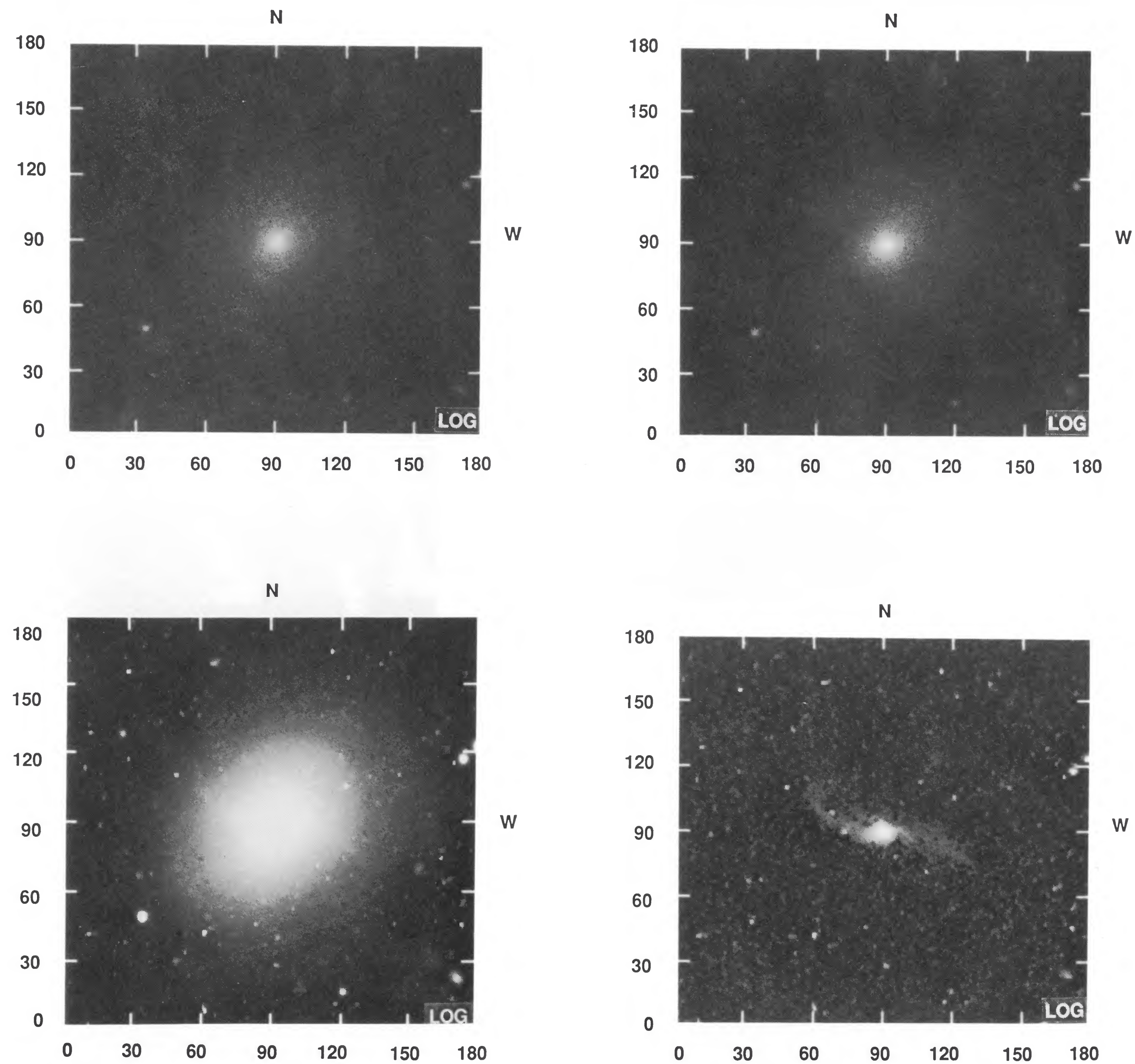

FIG. 2.—NGC 3998. Top prints are similar to Fig. 1. The bottom left print is the same image as top right, but the nucleus is overexposed to emphasize the faint emission arms. On bottom right is the difference image, where the emission structure is clearly visible.

FORD *et al.* (*see* page L8)

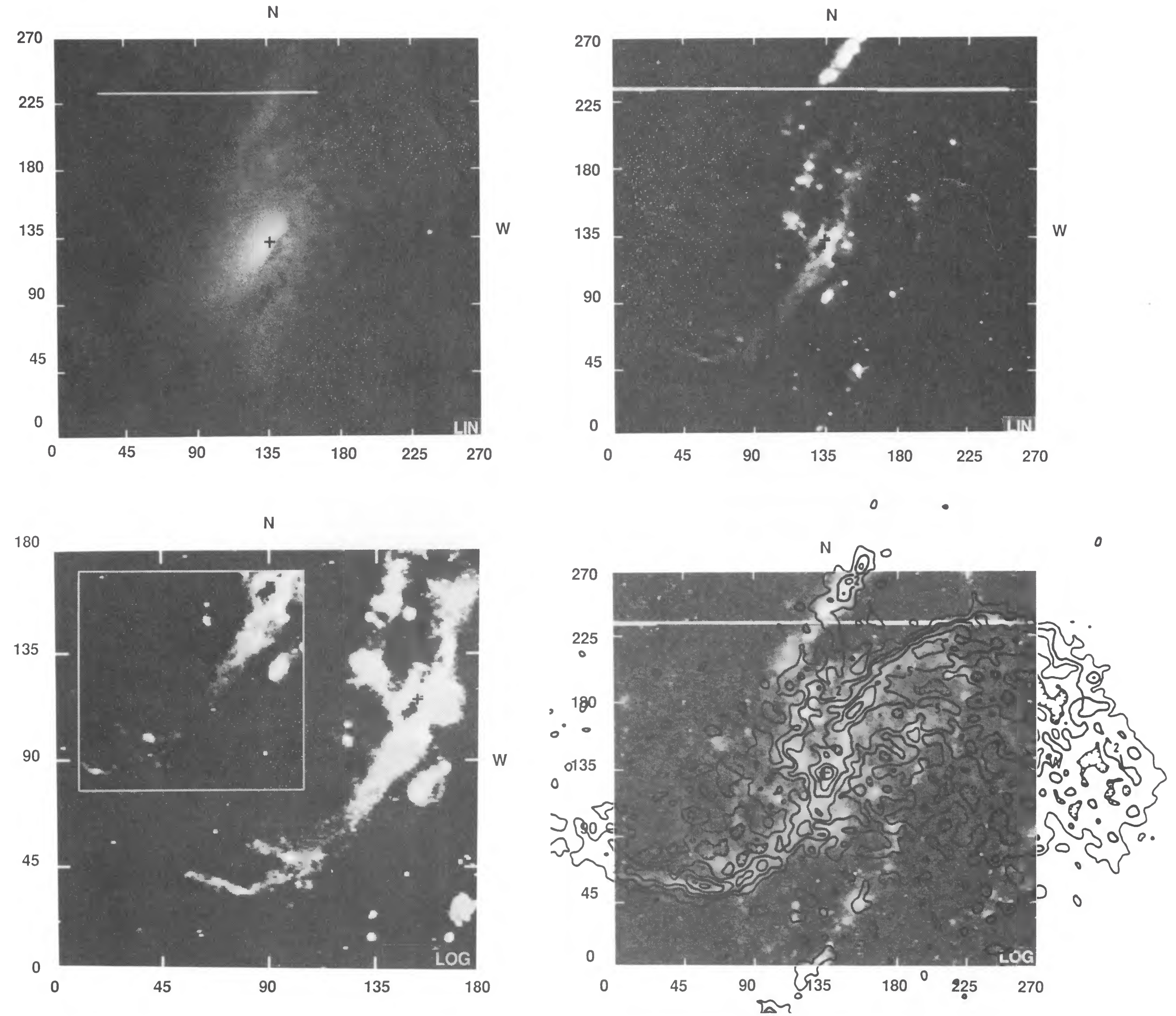

FIG. 3.—NGC 4258. Continuum and difference images are displayed on the top left and top right, respectively. Crosses mark the approximate position of the optical nucleus. The "anomalous" arms are seen in the difference image (NW and SE of the nucleus), but not in the continuum. On the bottom left, the SE arms are enlarged and printed with two different intensity-level limits to illustrate the braiding structure. On the bottom right the radio-continuum map from Fig. 1 of van Albada and van der Hulst (1982, courtesy of G. van Albada and *Astronomy and Astrophysics*, © Springer-Verlag New York) is overlayed on the difference image. It was registered assuming the radio and optical peak intensities are overlapping. The horizontal lines in the upper part of the images are caused by a nonlinear column in the CCD detector.

FORD *et al.* (*see* page L8)

a wind model wherein the ISM is blown outward in a cone perpendicular to the galactic disk by the hot plasma in the active nucleus. However, the apparent "figure 8" in their radio map is brightest on the diametrically opposed sides at a position angle of $\sim 40°$. This could result from a narrow precessing jet which presently projects at that position angle. An even higher resolution radio map is needed near the nucleus in order to distinguish a jet from a wind.

b) *NGC 3998*

Although NGC 3998 is an E/S0 galaxy with an unremarkable optical appearance, it has many anomalous characteristics. The galaxy harbors a compact flat-spectrum nuclear radio source (Hummel 1980), hosts a strong unresolved X-ray source (Dressel and Wilson 1985), and has a LINER optical spectrum (Heckman 1980; Keel 1983) with a broad Hα (Filippenko and Sargent 1985). Wrobel and Heeschen (1984) found evidence for extended radio continuum emission, and Blackman, Wilson, and Ward (1983) discovered extended ionized gas with velocities which they suggested arose from a combination of rotation and expansion. The amount of H I found in NGC 3998 is comparable to other E galaxies, but small for an S0 (Knapp, van Driel, and van Woerden 1985). The position angle of the galaxy's major axis, the lines of nodes for the H I rotation, and the rotation of the stars and ionized gas are at position angles 140°, 50°, and 90° respectively.

The extended Hα emission (Fig. 2) has an S shape with a total extent of at least 1′ ($\sim$ 7 kpc at 24.5 Mpc). The Hα surface brightness decreases with increasing distance from the nucleus and is smooth with no distinct H II regions which characterize spiral arms. The NE arm is sharper on the outer edge and has higher curvature than the SW arm.

The S shape of the "arms" and the brightening on the outer edge of the NE arm might be explained by a stationary two-sided jet interacting with the rotating H I disk and being swept forward by ram pressure (see model by Wilson and Ulvestad 1982). However, the presence of weak rather than strong extended radio emission outside the nucleus (Wrobel and Heeschen 1984) poses difficulties for the jet hypothesis. Furthermore, the radio emission extends only toward the SW (starting at p.a. $\sim 200°$ and extending to $\sim 3'$) and curves in the opposite direction from the SW Hα arm.

The gas possibly could be photoionized by a nuclear source. However, the projected dimensions of the H I disk (Knapp, van Driel and van Woerden 1985) are much larger than the Hα feature, and it is difficult to understand how a central source ionizes only a selected part of the H I disk. Alternatively, we note that the companion S0 galaxy NGC 3990 may interact with NGC 3998 (Dahari 1985), and thus the H I and ionized gas might have originated in a recent interaction. If this is true, the S shape of the ionized gas can be explained by wrapping of the rotation plane of the gas as it spirals into the nucleus (see van Albada, Kotanyi, and Schwarzschild 1982; Steiman-Cameron and Durison 1984). This is consistent with the position angles of the H I disk and the rotation axis (see above). High S/N spectrophotometry along the arms as well as radio maps with higher resolution and dynamic range are needed to explain the origin of the emission.

c) *NGC 4258*

Courtes and Cruvellier (1961) provided the first evidence for unusual morphology in NGC 4258 by Hα pictures which showed a "four-branched jet" (two branches on each side), emanating from diametrically opposed points in the optical disk. Their observations were confirmed by Deharveng and Pellet (1970). Both groups noted the absence of blue continuum in the filaments and concluded that the excitation is not by O–B stars. Spectra of these "anomalous arms" (van der Kruit 1974) show emission lines, and the radial velocities suggest prograde rotation which lags the disk rotational velocities by 100–150 km s^{-1}.

Van der Kruit, Oort, and Mathewson's (1972) radio continuum observations revealed two bright, trailing, nonthermal arms coincident with the optical emission and originating in the weak radio nucleus. To explain the trailing geometry of the arms, they suggested bidirectional, ballistic ejection of clouds into the disk. Higher resolution VLA observations by de Bruyn (1977), van Albada (1980), and van Albada and van der Hulst (1982) showed that the NW radio arm bifurcates, with a brightening before the split, and that the leading edges of the radio arms are slightly steeper than the trailing edges. Van Albada and van der Hulst (1982) found that the onset of high ($\sim$ 50%) polarization near the ends of the anomalous arms. The lack of polarization closer in can be explained if the arms are in (or behind) the galactic disk.

NGC 4258's nuclear Hα and radio luminosities are relatively low (cf. Table 1), showing that its nucleus is not extraordinarily active. The galaxy was not detected in the single short *Einstein Observatory* X-ray exposure (G. Fabbiano, private communication). The optical spectrum was classified by Heckman (1980) as a transition between LINER and H II–region, while Stauffer (1982) found that the line ratios fall between models of shock-excitation and power-law photoionization. A very weak broad component of Hα, suspected by Stauffer, was confirmed by Filippenko and Sargent (1985).

The bidirectional arms are well defined in our difference images (Fig. 3), with no counterpart in either the off-band or *B* images, thus confirming earlier work. The SE arm is resolved into two arms which appear to braid or wrap around one another. The NW arm is less well defined but also forks $\sim 90''$ from the nucleus. Since the NW and SE arms fork at approximately the same radial distance, we conclude that the NW arm probably is *two* unresolved arms.

The radio map and our difference image (Fig. 3) show a high degree of correspondence. On both sides of the nucleus the optical separations occur at bright spots in the radio maps. The radio resolution and dynamic range are not sufficient to determine if the radio arms separate at the optical bifurcations. The NW radio arm does appear to split, but at a position closer to the nucleus than the fork in the optical arm.

Based on the presence of strong nonthermal radio emission and the absence of any stellar continuum in the arms, we suggest that the emission is caused by two pairs of powerful bidirectional jets which originate in the nucleus and are directed into the surrounding disk. The jets bore through the disk for $\sim 90''$ on each side, and then separate and bend sharply, most likely breaking out of the disk (as suggested by the radio polarization). The optical emission occurs along the edges of the plasma channels where the relativistic fluid shocks and excites the confining ISM through viscous coupling. Accordingly, we expect to find shock-excited emission lines along the jet, and broad, low-intensity wings on the emission lines which result from turbulence at the boundary of the plasma channel.

A stationary jet would be bent in the opposite direction of the spiral arms (Wilson and Ulvestad 1982). Apart from the inner part of the NW jet (which curves in agreement with this model), the jets bend in the same direction as the spiral arms. A jet model thus requires that the source of the jets rotate in the same direction as the stars (this would explain the weak radio emission on the trailing sides of the jets). Alternatively, the observed curvature of the jets is reversed by projection, which then requires that they are in a plane tilted with respect to the disk. Unlike the radio emission, the Hα surface brightness of the NW jet is lower than that of the SE jet, which may indicate that the NW jet is behind the disk.

How do we account for *two* double-sided jets? One possibility is that the central engine both precesses and flip-flops. There is convincing evidence for precession in other radio sources (Miley 1980), and many authors have suggested that one-sided jets are caused by flip-flops (Bridle and Perley 1984, and references therein). There is no *a priori* reason why both phenomena could not occur in the same engine. However, this being the case we would expect to see a modulation of the intensity along the jets on both sides. A more natural explanation is the possible presence of two nuclei. We are aware of only one other radio source with double nuclei and double two-sided jets—3C 75 in Abell 400 (Owen *et al.* 1985). It is not clear, however, if Abell 400 is a double nucleus elliptical galaxy, or a superposition of two galaxies (Hoessel, Borne, and Schneider 1985; Tonry 1985). The Maypole morphology of the jets in 3C 75 suggests bending by the orbital motion of the nuclei (Yokosawa and Inoue 1985) and thus may indicate a merging process. Another interesting galaxy is 3C 159 (Tytler and Browne 1985). It has double-peaked optical emission lines in the nucleus, and two clearly separated emission regions on one radio lobe with parallel connections to the nucleus, which indicate the possible presence of two parallel jets. Our data for NGC 4258 does not resolve the nucleus, however, and higher resolution radio and optical (e.g., Space Telescope) observations are needed in order to definitively establish the presence of two sources and two jets.

Close examination of the SE arms' morphology suggests that the two jets are twisted or braided around one another, similar to, but tighter than the jets in 3C 75. This structure is definitely unique, and introduces a new theoretical challenge. Does the wrapping result from hydrodynamic confinement of two originally parallel jets or from large-scale electromagnetic forces? If the initial wrapping is caused by the orbital motion of two nuclei, it may be possible to combine an estimate of the jets' velocities through the disk with the observed wavelengths of the braids to estimate the precession or orbital period. Spatial resolution of the two sources could then lead to an estimate of the masses.

IV. SUMMARY

We have presented three galaxies with LINER or near-LINER nuclei and compact radio sources which exhibit extranuclear optical emission. The morphology of that emission is very different in each galaxy. In NGC 3079 and NGC 4258 the extended optical emission corresponds to the morphology of the nonthermal radio emission. We have argued that this and other evidence suggests that the optical and radio emission are related, and that both are caused by the interaction of plasma ejected from the active nucleus with the ISM. The very different morphologies clearly demonstrate that the structure of the resulting emission depends strongly on the orientation and characteristics of the jets (or winds), and on the spatial distribution and density of the ISM.

These results and similar phenomena observed in other active galaxies (see § I) provide low luminosity analogs of the powerful classical radio triples. Like high-luminosity triples, the radio luminosities of the nuclei of M51 and NGC 4258 are considerably lower than the luminosity of the "lobes"; thus, the sources are relatively efficient in powering jets. The mechanical energy in the jets is then dissipated and made visible at both radio and optical wavelengths through interactions with a confining ISM. These arguments lend support to the assumption that the same basic physical processes are working in both the high luminosity and low luminosity sources.

The galaxies M51, NGC 1068, NGC 4151, and NGC 4258 show that the "engines" can be misaligned by as much as 90° with respect to the rotation axis of the galaxy (see also Tohline and Osterbrock 1982). This misalignment poses considerable problems for the collimation model of Blandford and Rees (1974, 1978). We note that when observing face-on spiral galaxies our optical selection technique strongly discriminates in favor of finding tipped jets which are dissipating energy in the disk. Optical evidence for jets which are approximately aligned with the galaxy's rotational axis (such as NGC 3079) will be harder to find, since the pressure of the ISM outside the disk may be too low to cause shocks around the plasma jets. Consequently, jets may be much more common in spirals with active nuclei than previously thought.

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