THE ASTROPHYSICAL JOURNAL, 299:L77–L81, 1985 December 15

© 1985. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THE 1 PARSEC RADIO CORE AND POSSIBLE NUCLEAR EJECTION IN NGC 253

J. L. TURNER AND P. T. P. HO[1]
Harvard-Smithsonian Center for Astrophysics

Received 1985 August 20; accepted 1985 September 24

ABSTRACT

We present a high-resolution (0″.2 × 0″.1) 2 cm VLA continuum map of the nuclear region of the spiral galaxy NGC 253. The central radio source is barely resolved (0″.05 × 0″.04): the implied brightness temperature of $\gtrsim 9 \times 10^4$ K indicates nonthermal nuclear activity. The central source in NGC 253 is surrounded by compact knots ($\lesssim$ 0″.1), with relatively flat spectral indices ($\alpha \approx -0.3$) and brightness temperatures of at least a few thousand degrees. These knots lie in the plane of the galaxy, and may represent emission associated with starforming regions or they may be related to ejection from the nuclear source. The latter possibility is suggested because the knots are highly collimated over the central 9″ (~ 100 pc) to within 1° in projection. The alignment is at an apparent position angle 44° ± 1°, or 19° ± 5° deprojected onto the plane of the sky. The radio structure is oriented perpendicular to the bar seen in the optical and near-infrared. If the knots were formed by a single mechanism, as implied by their alignment, the propagation time across the structure requires a supersonic disturbance across the region. The orientation of the nuclear structure perpendicular to the bar suggests that the bar is in some way linked to the nuclear activity.

Subject headings: galaxies: individual — galaxies: jets — galaxies: nuclei — interferometry — radio sources: galaxies

I. INTRODUCTION

Nuclear activity is a common occurrence in galaxies, from quasars to normal spirals, perhaps differing only in magnitude. In normal spiral galaxies, the observed nuclear emission at radio frequencies is a mixture of thermal bremsstrahlung from H II regions, compact synchrotron cores, and extended synchrotron emission. With the high-resolution and beam-matching capabilities of the Very Large Array, these different phenomena can be distinguished in nearby galaxies.

NGC 253 is an excellent candidate for the study of nuclear activity in spirals. It is close (~ 2.5 Mpc) and has been extensively observed in radio, infrared, and molecular line emission. From optical morphology, NGC 253 is classified as a normal SBc/Sc galaxy. However, infrared measurements indicate vigorous nuclear star formation (Wynn-Williams *et al.* 1979; Rieke *et al.* 1980; Beck and Beckwith 1984), accompanied by nonthermal processes in optical line (Keel 1984), radio continuum (Condon *et al.* 1982; Turner and Ho 1983), and X-ray (Fabbiano and Trinchieri 1984) emission. These data have prompted classifications of NGC 253 either as "normal" or "starburst" or "active."

This project was designed to examine the nuclear radio emission of NGC 253, on scales of 1 to 30 pc, and complements the recent studies of the extended structure by Klein *et al.* (1983) and Hummel *et al.* (1984). The relatively flat spectral index of the central source at 1″ resolution (Turner and Ho 1983) suggests either an H II region or a compact synchrotron source. The high resolution and sensitivity of this experiment allow us to resolve a small nuclear source whose brightness temperature is substantially greater than 10^4 K, thus eliminating a thermal origin for the radio emission.

II. OBSERVATIONS

The observations were made with the Very Large Array of the National Radio Astronomy Observatory[2] in 1983 October. A beam size of 0″.21 × 0″.10 was obtained, using the A configuration. Approximately 35 minutes were spent on-source, distributed over three cuts. Phases were calibrated with respect to 0202 − 172. Absolute positions are limited by the positional uncertainty of 0202 − 172, which is ~ 0″.1. Fluxes were calibrated assuming 1.9 Jy for the calibrator 2021 + 614 (R. Sramek, private communication) and are accurate to 5%. The maps were CLEANed and self-calibrated. The rms noise level achieved approaches the theoretical value, at 0.13 mJy per beam with natural weighting.

III. RESULTS

In Figure 1, the 2 cm map of NGC 253 with 0″.2 resolution is presented as an enlargement of the central core region of a 6 cm map with 1″ resolution (Turner and Ho 1983). A number of compact condensations are found. These knots are suggested in the lower resolution map but are clearly evident under higher resolution. Because the shortest baseline is 3 km, the interferometer is insensitive to structures greater than ~ 3″; however, for the purpose of identifying high brightness

---

[1] Alfred P. Sloan Foundation Fellow.

[2] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...299L..77T

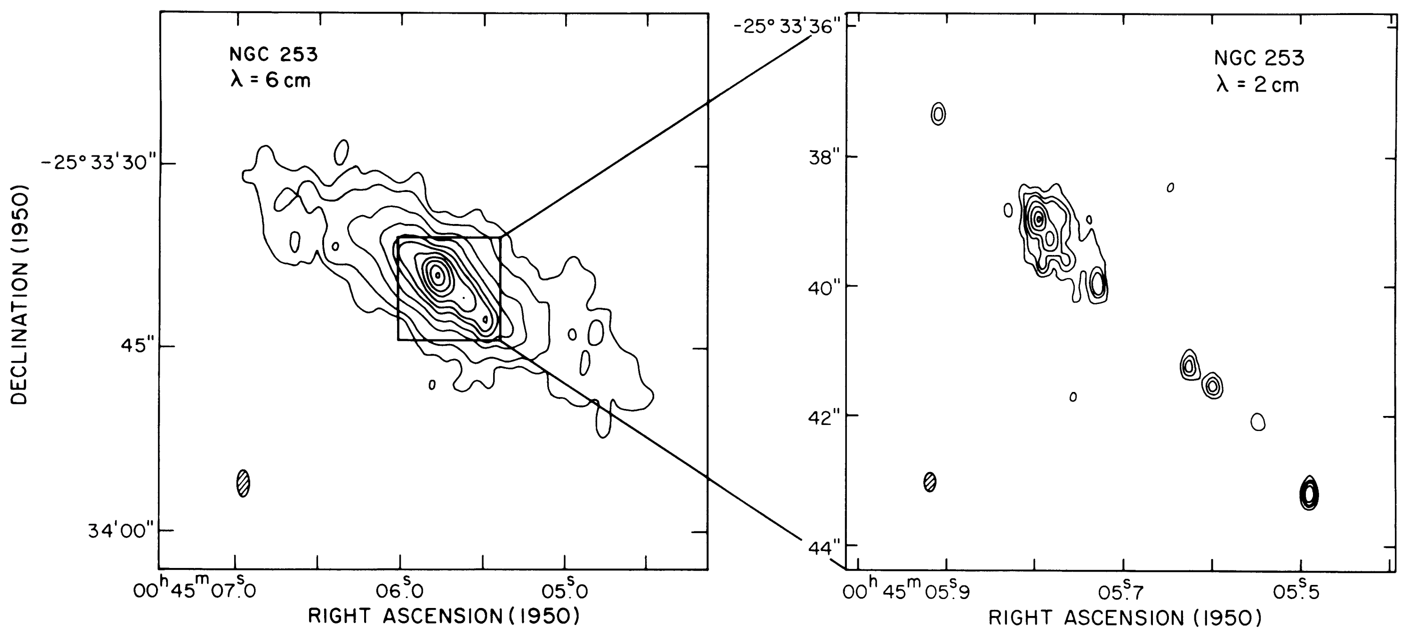

FIG. 1.—(*Left*) Six centimeter map of NGC 253 with an angular resolution of 2″ × 1″ (Turner and Ho 1983). (*Right*) Two centimeter map of NGC 253 with an angular resolution of 0″.2 × 0″.1. The map is made with natural weighting, and structures ≳ 3″ are resolved out. Contour levels are −2, −1, 1, 2, 3, 5, 10, 20, and 30 mJy per beam. The noise level is 0.13 mJy per beam. Conversion to brightness temperature is 261 K per mJy. Note that a number of condensations suggested in the lower resolution 6 cm map are clearly resolved in the 2 cm map. Deconvolved, the peak brightness temperature in the map is 9×10^4 K. The central source is clearly nonthermal. The other knots are possibly thermal. Note also the alignment of the knots which is at 19° E of N, when projected in the plane of the galaxy. At 2.5 Mpc, 1″ corresponds to 12 pc, and the 2 cm beam size is ∼ 1 pc.

compact (< 1″) features, the missing extended structure is not a limitation. From the 2 cm single-dish results of Klein and Emerson (1981), we estimate that ≳ 90% of the 2 cm emission within the inner 70″ of the galaxy is in structures ≳ 3″. The detected 2 cm flux density of 90 mJy indicates that we have mapped most of the flat spectrum emission estimated by Turner and Ho (1983).

The spatial distribution of the knots is remarkably aligned at position angle 44° ± 1°, close to the major axis position angle. The knots are therefore most likely in the plane of the galaxy. We assume an inclination of 78°.5 and the optical position angle of 51° (Pence 1981), and that the strongest radio source is located at the center of the galaxy. Least-squares fitting of a line to the knots after deprojection onto the sky yields a position angle of 19° ± 5°, and a correlation coefficient of 0.8. There is only a 0.4% chance that the nine knots are a random distribution of sources in the plane of the galaxy which appear aligned because of projection effects. The underlying physical process creating these knots is also unlikely to be a random function of position in the galactic plane.

TABLE 1

PROPERTIES OF COMPACT RADIO SOURCES IN NGC 253

Source	R.A. (1950)[a]	Decl. (1950)[a]	Size[b] (arcseconds)	Position Angle (degrees)	Flux Density[c] (mJy)	Brightness Temperature[b] (K)
1	00h45m05s.910	−25°33′37″.36	0.10 × 0.08	0 ± 20	2.1	1.4×10^3
2	00 45 05.795	−25 33 38.95	0.05 × 0.04	20 ± 10	29.9	8.7×10^4
3	00 45 05.792	−25 33 39.66	0.17 × 0.05	0 ± 5	3.3	2.0×10^3
4	00 45 05.783	−25 33 39.25	0.18 × 0.10	10 ± 10	9.5	2.9×10^3
5	00 45 05.768	−25 33 39.57	0.65 × 0.24	45 ± 20	2.3	8.1×10^1
6	00 45 05.729	−25 33 39.95	0.24 × 0.08	5 ± 5	3.5	1.0×10^3
7	00 45 05.626	−25 33 41.23	0.10 × 0.09	80 ± 40	3.3	2.2×10^3
8	00 45 05.599	−25 33 41.53	0.10 × 0.08	50 ± 20	3.3	2.4×10^3
9	00 45 05.490	−25 33 43.18	0.07 × 0.05	150 ± 10	8.6	1.5×10^4

[a] Positional errors of 0s.0005, 0″.005 largely reflect the signal-to-noise ratio, since the sources are very nearly unresolved. Errors quoted reflect relative positional accuracy and do not include systematic offset due to positional error in phase calibration of ≲ 0″.1. Positions and flux densities are derived from Gaussian fits to a uniformly weighted map.

[b] Errors in brightness temperature are dominated by errors in deconvolved source sizes, which are < 25%, except for the strongest source, in which the error is < 15%.

[c] Fluxes are measured with an effective bandwidth of 100 MHz centered at 14940 MHz.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...299L..77T

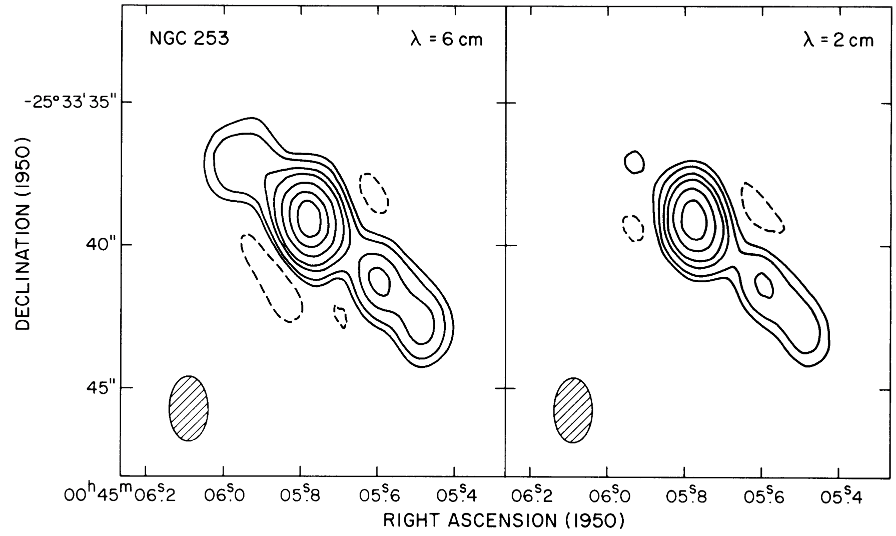

FIG. 2.—(*Left*) Low-resolution 6 cm map. (*Right*) Low-resolution 2 cm map. These data on NGC 253 are described in Turner and Ho (1983). The beam size is 2″.2 × 1″.3. The maps contain only (u, v) data with baselines > 50 kλ, which suppresses extended structures $\gtrsim 4''$. The maps are contoured at −2, −1, 1, 2, 4, 6, 10, 15, and 20 mJy per beam. We compute a spectral index of -0.2 ± 0.05 for the central knot and ~ -0.3 for the southwestern condensations. The flat spectral indices clearly distinguish the compact sources from the extended synchrotron emission which has a spectral index of −1 to −1.2.

Positions, peak flux densities, and position angles are listed in Table 1. The deconvolved sizes of the sources are $\lesssim$ 1 pc. These sizes were used in conjunction with the fluxes to obtain brightness temperatures, T_b. For the central source, $T_b \gtrsim 9 \times 10^4$ K: this is clearly not an H II region. The other condensations have lower values of T_b and may represent thermal emission. Most of the knots have position angles oriented nearly parallel to the beam, at p.a. = 0°, suggesting that the sources are unresolved. Exceptions are knot 7, which is nearly round, and knots 5 and 8, with p.a. = 45°–50°. The latter orientation is close to the radio axis, and may indicate further substructure along the axis.

An understanding of the radiative process responsible for the compact radio knots requires knowledge of the spectrum of the emission. Direct determination of the spectral index, $\alpha(S \propto \nu^{\alpha})$, at 0″.2 resolution will be possible in the future with improved 1 cm receivers. Matched-beam observations at a longer wavelength are not feasible since we are already using the largest VLA configuration. Existing lower resolution spectral index maps include substantial contributions from extended synchrotron emission. We have obtained the best present estimate of the spectral index of the knots by eliminating short spacings from lower resolution data, to suppress extended emission. Maps made with 6 cm (B array) and 2 cm (C array) data of Turner and Ho (1983), excluding the inner 50 kλ (u, v) data, are shown in Figure 2. The smooth synchrotron component has largely been eliminated. From these maps, we find that $\alpha = -0.2 \pm 0.05$ for the central component and ~ -0.3 for the two southwest knots. These spectral indices may become even flatter with higher resolution. Both the brightness temperatures and the spectra of the compact sources differentiate them clearly from the extended nuclear disk as seen in the 6 cm map of Figure 1.

Polarization maps were made for both the high-resolution 2 cm data and the lower resolution data of Figure 2. The percentage of polarized flux is $\lesssim$ 2% in the central source, $\lesssim$ 5%–10% in the next two stronger knots, and $\lesssim$ 20% in the rest. The low degree of polarization may reflect tangled magnetic fields within the unresolved knots and not a lack of intrinsic polarization.

IV. DISCUSSION

The two most notable features of the high-resolution 2 cm map (Fig. 1) are the high brightness temperature of the core source and the striking alignment of the knots.

a) *Nature of the Central Core*

The brightness temperature of the central source is clearly too high for an H II region. This does not rule out the presence of nuclear star formation; however, the dominant radio radiation mechanism cannot be bremsstrahlung from photoionized gas around young stars. The observed flux, spectral index, and size of the central core can instead be attributed to either supernova remnants, radio supernovae, or a compact synchrotron core.

The radio properties of the central source are consistent, but only marginally, with those of a supernova remnant. The monochromatic luminosity at 15 GHz, $L_{15\ \mathrm{GHz}} \approx 2 \times 10^{26}$ ergs s^{-1} Hz^{-1}, is approximately 50 times the luminosity of the strongest Galactic supernova remnant, Cas A, in a region less than a parsec in extent. The brightness temperature is therefore in rough agreement with an extrapolated Galactic Σ-D relation (Clark and Caswell 1976; Huang and Thaddeus 1985).

Radio emission from a recent supernova might also explain the large flux and small size of the core source. In M82 there are about 40 sources with rapidly declining fluxes which appear to be radio supernovae (Kronberg 1984). The luminosities and size scales of the compact knots in NGC 253 and in M82 are similar. If radio supernovae are detectable for 50 yr,

© American Astronomical Society • Provided by the NASA Astrophysics Data System

each of the compact sources would require a supernova rate of about 0.02 yr^{-1}, and a young stellar population of 10^5–10^6. This is consistent with estimates based on infrared recombination lines (Wynn-Williams *et al.* 1979; Beck and Beckwith 1984), and also with the total luminosity as measured in the far-infrared (Telesco and Harper 1980). However, it should be noted that only five radio sources to date have been confirmed among several dozen identified optical supernovae (Weiler 1985).

The most likely explanation for the central source in NGC 253 is a compact synchrotron source similar to those found in active galaxies and quasars. Nearby examples of compact sources are the VLBI sources in M81 (Kellermann *et al.* 1976; Bartel *et al.* 1982) and M104 (Shaffer and Marscher 1979). The flux density of the source in NGC 253 is below the detection limit of previous VLBI experiments (Hummel *et al.* 1982). It is interesting that NCG 253 is an Sc galaxy, since compact nuclear sources occur predominantly in early Hubble types (Preuss 1984). We favor a compact synchrotron source over a supernova remnant or radio supernova because of its unique location at the center of a ~ 0.5 kpc disk of strong, spectrally steep synchrotron emission (Condon *et al.* 1982; Turner and Ho 1983). The synchrotron disk is symmetric about the central source, unlike the compact knots. If we adopt a spectral index of -0.2, the total radio luminosity of the central source over 10^{11} Hz is $\sim 10^4\ L_\odot$, comparable to M81 (Bartel *et al.*) and substantially more luminous than the Galactic center at $L \sim 10\ L_\odot$ (Lo *et al.* 1985).

b) *Alignment of the Radio Knots*

The most striking property of the hot spots in NGC 253 is their alignment to within ~ 1° in projection and 5° in the plane of the galaxy. If the strongest radio source is at the galactic center, most of the knots are seen toward the southwest. The patchy dust pattern seen in the optical and near-infrared indicates stronger extinction toward the southwest (Burbidge, Burbidge, and Prendergast 1962; Rieke and Low 1973). The asymmetry in the nuclear extinction is common in barred spiral galaxies and led Burbidge *et al.* to postulate the existence of a bar in the core of NGC 253. This bar has since been detected convincingly in the near-infrared (Scoville *et al.* 1985).

The orientation of the radio structure is also suggestive. Deprojected onto the sky, the line of radio knots is oriented at position angle 19°. The central bar in NGC 253, as defined by 2 μm observations (Scoville *et al.* 1985), is located at position angle 108°. Thus we find that the radio knots in NGC 253 are aligned perpendicular to the bar. Although with the 10″ resolution of the 2 μm data it is not possible to determine whether the bar morphology persists into the central 10″, the alignment suggests that the two phenomena may be related.

c) *The Nature of the Radio Knots*

The radio knots have moderate brightness temperatures, $T \gtrsim 10^3$ K, show no detectable polarization, and are unresolved. Given these properties, the knots could be either radio supernovae, supernova remnants, H II regions, or ejecta from the central core. If the knots are H II regions, the brightness temperatures require optical depths of > 0.1, characteristic of compact H II regions. It is conceivable that the knots consist of very luminous complexes of compact H II regions, such as those seen in the galactic source W49 (Dreher *et al.* 1984). Determination of the nature of the knots will require monitoring of the fluxes and positions of the knots, as well as more accurate polarization measurements.

The alignment of the radio structure is more difficult to understand. The high degree of collimation nevertheless places a constraint on the time scale of the disturbance. Expansion times for H II regions or supernovae, radiative lifetimes for centrally ejected relativistic electrons, and differential rotation time scales are all of order 10^4 yr. To establish an aligned appearance over 100 pc requires velocities $\gtrsim 1000$ km s^{-1}. The maintenance of the pattern will depend upon the unknown velocity structure of the central region.

The alignment of the knots, their proximity to the nucleus, and the high velocities required to establish the structure suggest that the knots are related to a collimated ejection, or jet, originating in the nucleus. In an ejection model, the jet would provide the alignment mechanism, and the knots could be explained in a number of ways: as fossils left behind by a trail of star formation activity behind a jet, or perhaps as synchrotron hot spots in the jet itself. For the latter case, estimates of internal pressure based on equipartition arguments suggest rapid expansion and hence a high Mach number for the jet in order to maintain a collimated appearance. The required jet velocity is again on the order of 10^3 km s^{-1}. This is not the first time that ejection has been proposed for the nucleus of NGC 253; ejection has been invoked to explain the noncircular velocities in the nucleus observed in optical emission lines (Demoulin and Burbidge 1970; Ulrich 1978), H I (Combes, Gottesman, and Weliachew 1977), and OH (Turner 1985). Ejection has been suggested in the cores of other spiral galaxies, such as NGC 4258 (van der Kruit, Oort, and Mathewson 1972), NGC 1068 and NGC 4151 (Wilson and Ulvestad 1982; Schild, Tresch-Feinberg, and Huchra 1985), and NGC 1097 (Wolstencroft and Zealey 1975). If the observed structures in NGC 253 can be explained by nuclear ejection triggering star formation, we find that at least in *some* cases, the proverbial "starbursts" and "active nuclei" may be manifestations of the same phenomenon.

If the aligned radio structure in the nucleus of NGC 253 is the result of a collimated nuclear ejection, then its orientation perpendicular to the bar is suggestive. Since the size scales are vastly different, the physical relation between the two phenomena is unclear. Kormendy (1979) has suggested that barred galaxies frequently show triaxial bulges preferentially oriented perpendicular to the bar; perhaps the peculiar alignment of the knots in NGC 253 is related to the presence of an undetected oval bulge. Whether or not this is the case, elucidation of the relationship between the nuclear and the large-scale morphological structures of NGC 253 will be an important step in the study of nuclear activity.

We thank N. Bartel, M. Birkinshaw, D. Shaffer, and M. Reid for helpful comments.

1985ApJ...299L..77T

REFERENCES

Bartel, N. *et al.* 1982, *Ap. J.*, **262**, 556.
Beck, S. C., and Beckwith, S. V. 1984, *M.N.R.A.S.*, **207**, 671.
Burbidge, E. M., Burbidge, G. R., and Prendergast, F. H. 1962, *Ap. J.*, **136**, 339.
Clark, D. H, and Caswell, J. L. 1976, *M.N.R.A.S.*, **174**, 267.
Combes, F., Gottesman, S. T., and Weliachew, L. 1977, *Astr. Ap.*, **59**, 181.
Condon, J. J., Condon, M. A., Gisler, G., and Puschell, J. J. 1982, *Ap. J.*, **252**, 102.
Demoulin, M. H., and Burbidge, E. M. 1970, *Ap. J.*, **159**, 799.
Dreher, J. W., Johnston, K. J., Welch W. J., and Walker, R. C. 1984, *Ap. J.*, **263**, 632.
Fabbiano, G., and Trinchieri, G. 1984, *Ap. J.*, **286**, 491.
Huang, Y.-L., and Thaddeus, P. 1985, *Ap. J.* (*Letters*), **295**, L13.
Hummel, E., Fanti, C., Parma, P., and Schilizzi, R. T. 1982, *Astr. Ap.*, **114**, 400.
Hummel, E., Smith P., and van der Hulst, J. M. 1984, *Astr. Ap.*, **137**, 138.
Keel, W. 1984, *Ap. J.*, **282**, 75.
Kellermann, K. I., Shaffer, D. B., Pauliny-Toth, I. I. K., Preuss, E., and Witzel, A. 1976, *Ap. J.* (*Letters*), **210**, L121.
Klein, U., and Emerson, D. T. 1981, *Astr. Ap.*, **94**, 29.
Klein, U., Urbanik, M., Beck R., and Wielebinshi, R. 1983, *Astr. Ap.*, **127**, 177.
Kormendy, J. 1979, *Ap. J.*, **227**, 714.
Kronberg, P. P. 1985, in *Proc. of Supernovae as Distance Indicators*, ed. N. Bartel, *Lecture Notes in Physics*, **224**, 88.
Lo, K. Y., Backer, D. C., Ekers, R. D., Kellermann, K. I., Reid, M., and Moran, J. M. 1984, *Nature*, **315**, 124.
Pence, W. D. 1981, *Ap. J.*, **247**, 473.
Preuss, E. 1984, in *IAU Symposium 110, VLBI and Compact Radio Sources*, ed. R. Fanti, K. Kellermann, and G. Setti (Dordrecht: Reidel), p. 251.
Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., and Tokunaga, A. T. 1980, *Ap. J.*, **238**, 24.
Rieke, G. H., and Low, F. J. 1975, *Ap. J.*, **197**, 17.
Scoville, N. Z., Soifer, B. T., Neugebauer, G., Young, J. S., Matthews, K., and Yerka, J. 1985, *Ap. J.*, **289**, 129.
Shaffer, D. B., and Marscher, A. P. 1979, *Ap. J.* (*Letters*), **233**, L105.
Schild, R., Tresch-Feinberg, R., and Huchra, J. 1985, *A.J.*, **90**, 441.
Telesco, C. M., and Harper, D. A. 1980, *Ap. J.*, **235**, 392.
Turner, B. E. 1985, preprint.
Turner, J. L., and Ho, P. T. P. 1983, *Ap. J.* (*Letters*), **268**, L79.
Ulrich, M.-H. 1978, *Ap. J.*, **219**, 424.
van der Kruit, P. C., Oort, J. H., and Mathewson, D. S. 1972, *Astr. Ap.*, **21**, 169.
Weiler, K. W. 1985, in *Proc. of Supernovae as Distance Indicators*, ed. N. Bartel, *Lecture Notes in Physics*, **224**, 65.
Wilson, A. S., and Ulvestad, J. S. 1982, *Ap. J.*, **263**, 576.
Wolstencroft, R. D., and Zealey, W. J. 1975, *M.N.R.A.S.*, **173**, 51P.
Wynn-Williams, C. G., Becklin, E. E., Matthews, K., and Neugebauer, G. 1979, *M.N.R.A.S.*, **189**, 163.

P. T. P. Ho and J. L. Turner: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

© American Astronomical Society • Provided by the NASA Astrophysics Data System