The Astronomical Journal, 127:1977–1981, 2004 April

VLBI OBSERVATIONS OF THE GIGAHERTZ-PEAKED SPECTRUM GALAXY PKS 1934−638

Roopesh Ojha
Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 1710, Australia; rojha@atnf.csiro.au

Alan L. Fey and Kenneth J. Johnston
US Naval Observatory, 3450 Massachusetts Avenue, NW, Washington, DC 20392-5420

and

David L. Jauncey, Anastasios K. Tzioumis, and John E. Reynolds
Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 1710, Australia
Received 2003 November 7; accepted 2004 January 8

ABSTRACT

We present 8.4 GHz VLBI observations of the gigahertz-peaked spectrum source PKS 1934−638 made with the Australian Long Baseline Array. Our observations confirm the compact double nature of the source and yield measured separations of 42.7 ± 0.4 mas at epoch 2002 July and 42.6 ± 0.3 mas at epoch 2002 November, which, when combined with previous observations, yield a rate of separation of 23 ± 10 μas yr^{-1}. This result suggests that over a timescale of 32.1 yr, the separation of the two components has changed marginally. Nominally, this provides support to the emerging consensus that compact symmetric objects (CSOs) are young sources. Our measurement of hot spot separation has, to our knowledge, the longest temporal coverage for a CSO reported in the literature.

Key words: galaxies: active — galaxies: individual (PKS 1934−638) — galaxies: jets — galaxies: kinematics and dynamics

1. INTRODUCTION

Gigahertz-peaked spectrum (GPS) radio sources are powerful ($L_{\rm radio} \approx 10^{45}$ ergs s^{-1}), compact (10–100 mas, 10–1000 pc) objects with a characteristic narrow convex spectrum that peaks in a range of about a decade around 1 GHz (O'Dea, Baum, & Stanghellini 1991). The spectrum often has a very steep low-frequency turnover, thought to result from either synchrotron self-absorption (Slysh 1963; Kellerman 1966; Readhead et al. 1996) or external absorption (induced Compton [Bicknell, Dopita, & O'Dea 1997] or free-free [Kuncic, Bicknell, & Dopita 1998]). GPS sources exhibit low fractional polarization (Stanghellini et al. 1998) and low flux variability and include both quasars and galaxies. Compact steep-spectrum (CSS) sources (Fanti & Spencer 1995) share most properties of GPS sources but are larger (1–20 kpc) and peak at lower frequencies (<500 MHz).

GPS quasars, which are found in similar numbers to GPS galaxies, are frequently found at higher redshifts ($1 \lesssim z \lesssim 4$) than GPS galaxies, which is consistent with some Doppler boosting of the centimeter-wavelength radio emission in the quasars. GPS quasars show core-jet or complex structures and may appear shortened by projection. GPS galaxies tend to be at redshifts $0.1 \lesssim z \lesssim 1$. GPS galaxies are also larger and often doubles or triples, with the central compact component the putative center of activity. Thus, GPS radio galaxies meet the definition of compact symmetric object (CSO), a term used to describe subkiloparsec-scale extragalactic radio sources with symmetric radio structure (Wilkinson et al. 1994). Although all GPS galaxies have the simple double or triple structure of a CSO, the more structurally complex CSOs do not have a GPS spectrum. In general, GPS quasars are not CSOs, and they may constitute a separate class of objects altogether (O'Dea 1998 and references therein).

The source PKS 1934−638 is a GPS radio galaxy of magnitude 18.9 at a redshift of 0.183 (Penston & Fosbury 1978). Jauncey et al. (1986) found the radio source to be within 0″.1 of the center of the brighter of a pair of compact galaxies that are 2″.9 apart, which share a common low surface brightness envelope.

The source PKS 1934−638 was first reported to have an unusual "curved" spectrum by Bolton, Gardner, & Mackey (1963). They found a peak flux of 15.6 Jy at a frequency close to 1.4 GHz. This peak frequency was confirmed by observation at several frequencies between 0.3 and 5 GHz by Kellerman (1966), who found a spectral index of approximately −1.2 at higher frequencies with a steep drop in flux density with decreasing frequency. Slysh (1963) showed that if this drop in flux density below 1 GHz is due to self-absorption, then the source must be small and most likely quite young.

Gubbay et al. (1971) made the first VLBI observations of this source. They modeled its morphology as a double source, with similar-sized components separated by 41.9 ± 0.2 mas at a position angle $90^\circ \pm 1^\circ$. Their modeling raised the possibility of a third, weak, point component. Subsequent VLBI observations made by the Southern Hemisphere VLBI Experiment (SHEVE; Preston et al. 1989) are reported in Tzioumis et al. (2002, 1989) and King (1994). These observations confirm the near-equal compact double nature of this source but also model an elongated component aligned with and connecting the two compact components. While their data allow the possibility of a weak core between the two main components, there is little evidence for its existence.

The two main components of PKS 1934−638 correspond to the "hot spots" commonly found at the extremities of CSOs. Hot spots are identified with the working surface of jets as they propagate through the ISM. Measurements of the proper motion of hot spots are of great astrophysical interest; not only do they constrain the dynamics of radio source evolution, they also provide the most direct way of estimating the age of a CSO. Such estimates enable us to discriminate between the different scenarios for the origin of CSOs (see § 4).

Early measurements or limits on hot spot velocity (Tzioumis et al. 1989; Conway et al. 1994) in CSOs suggested very small separation rates making multiepoch observations over the longest possible time period critical for reliable estimates. In this paper, we evaluate measurements of hot spot separation for PKS 1934−638 over a time baseline of 32.1 yr, which, to our knowledge, is the longest temporal coverage for a CSO reported in the literature.

2. CURRENT OBSERVATIONS

The source PKS 1934−638 was observed at a frequency of 8.4 GHz using the five telescopes that make up the Australian Long Baseline Array (LBA)[1] in 2002 July and November. Details of these telescopes are summarized in Table 1. At our observing frequency of 8.4 GHz, this array yielded an angular resolution 4.0 by 3.6 mas (3.8 by 2.9) in size with major axis at position angle -76° (70°) at the first (second) epoch. These observations are part of an ongoing project to image International Celestial Reference Frame (ICRF) (Ma et al. 1998) extragalactic radio sources located in the southern hemisphere. The target source was observed in 11 (10) scans of approximately 7 minutes each on 2002 July 17 (November 15).

The data were recorded in S2 format (Cannon et al. 1997) and correlated at the Australia Telescope National Facility (ATNF) correlator in Sydney (Wilson, Roberts, & Davis 1995). The correlated data were processed using the National Radio Astronomy Observatory's (NRAO) Astronomical Image Processing System (AIPS) software (Bridle & Greisen 1994; Greisen 1988). The data were loaded using the locally written AIPS task ATLOD, which is needed to read the data in the format that the LBA generates. Thereafter, data inspection, initial editing, and fringe fitting were done in the standard manner using AIPS.

Overall amplitude calibration was improved by using observations of sources known from existing VLBA images to be compact (Fey, Clegg, & Fomalont 1996), with $\geq$90% of their correlated flux in a compact core. A single amplitude gain correction factor was derived for each antenna based on fitting a simple Gaussian source model to the visibility data of the respective compact source after applying only the initial calibration based on the measured system temperatures and gain curves. Gain correction factors were calculated based on the differences between the observed and model visibilities. The resulting set of amplitude gain correction factors was then applied to the visibility data of the target sources.

The visibility data for PKS 1934−638 at both epochs were Fourier inverted and CLEANed using the Caltech DIFMAP package (Shepherd 1997). The data were then self-calibrated following the hybrid imaging technique of Pearson & Readhead (1984) to correct for residual amplitude and phase errors.

3. RESULTS

A contour plot of our 8.4 GHz, naturally weighted image of PKS 1934−638 at epoch 2002 November 15 is shown in Figure 1. This image shows a nearly equal-brightness double-component structure. To obtain estimates of the parameters of the source, Gaussian component models were fitted to the visibility data from both epochs using the model fitting routine in Difmap. The fitted models are reported in Table 2. At both epochs, the source is well fitted by two Gaussian components separated by approximately 43 mas with the western component at a position angle of about -92°. The western component is about 70% of the brightness of the eastern component. The eastern component is elongated with its major axis along position angle $\approx 80^\circ$. The western component is marginally resolved. There is no sign of a compact core between the two main components. We also do not see the extended component reported by Tzioumis et al. (1989) at 2.3 GHz. This might be because this component has a steeper spectrum than the main components. As the structure of PKS 1934−638 is so similar at both observing epochs, we do not show the image from epoch 2002 July.

The small number of antennas and the limited number of short baselines available with the LBA limit the dynamic range of our images. In particular, only 65% of the total flux density of 2.78 Jy is accounted for in our VLBI image at epoch 2002 July. At epoch 2002 November, when the synthesized beam is smaller, this decreases to about 50%. This strongly suggests the presence of extended, low surface brightness structure that the LBA is not able to register. However, this result is strongly dependent on the reliability of the amplitude calibration of the data, which is estimated to be good to about 20%.

4. DISCUSSION

In order to investigate the kinematics of the source, we searched the literature for all available values of component separation. These, as well as our current results, are listed in Table 3 and plotted in Figure 2. We used a conservative estimate of one tenth of the synthesized beamsize to calculate the error in our separation measurements. Although the separation measurements listed in Table 3 were made at two different frequencies, there are a number of reasons to believe the following analysis is reliable. First, the observed structures at the two frequencies are very similar and are centrally peaked. Second, at both 2.3 and 8.4 GHz, PKS 1934−638 has a steep spectrum and thus is unlikely to possess optically thick components. Hence, the structure at 2.3 GHz is likely to be similar to that at 8.4 GHz. Finally, it has been shown (Polatidis & Conway 2003) that when a GPS source is monitored at more than one frequency, the derived velocities are similar. Nonetheless, we cannot completely rule out the possibility that the change in separation we see is a result of a systematic shift in the position of the two components due to optical depth effects at the two observing frequencies.

We fit a linear function to the separation measurements to estimate the proper motion and obtained a value $23 \pm 10\ \mu\mathrm{as\ yr^{-1}}$.

[1] The Long Baseline Array is part of the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

TABLE 1
LONG BASELINE ARRAY

Telescope	Diameter (m)	Location
Parkes	64	Parkes, New South Wales
ATCA	5 × 22	Narrabri, New South Wales
Mopra	22	Coonabarabran, New South Wales
Hobart	26	Mount Pleasant, Tasmania
Ceduna	30	Ceduna, South Australia

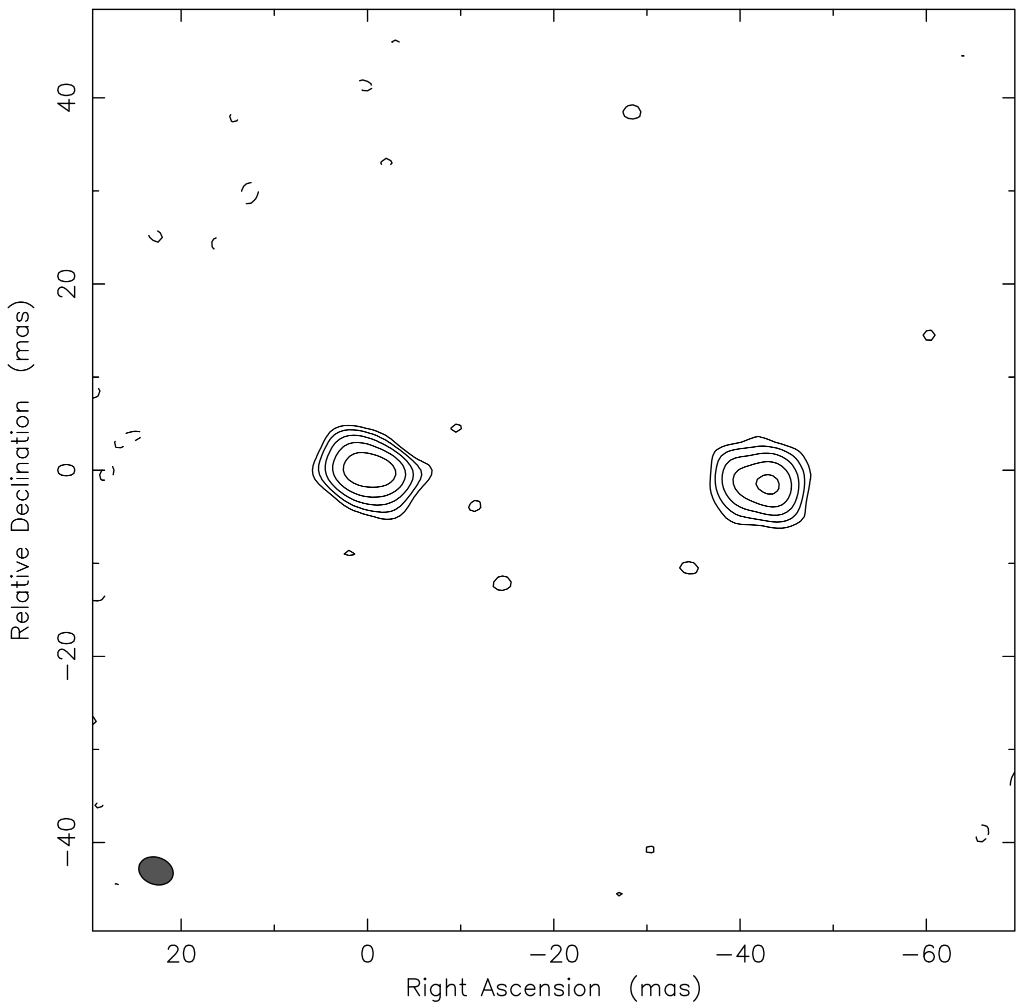

Fig. 1.—LBA image of PKS 1934−638 at 8.4 GHz observed on 2002 November 15. The contour levels are −1, 1, 2, 4, 8, 16 times 0.0135 Jy beam^{-1} (3 σ).

This fit is shown as a solid line in Figure 2. Note that for this fit, we did not use the separation measurements at epochs 1988.9 and 1991.9 as there were no reported errors. If we assume a value of 0.3 mas for the error in separation for both of these epochs and include them in the fit, we get a value of 20 ± 9 μas for the proper motion, which is entirely consistent with the former result. However, for the rest of the discussion, we use the value from the fit to only the points with reported errors.

At a redshift of $z = 0.183$ (Penston & Fosbury 1978) and for $H_0 = 100\ h^{-1}$ and $q_0 = 0.05$ (hereafter, we assume these values for all calculations), our measured proper motion yields an apparent separation velocity of $\beta_{\mathrm{app}} = (0.18 \pm 0.08)\ h^{-1}$. This marginal ($\approx$2 σ) detection of proper motion over 32.1 yr is of the same order as the proper motions of other CSOs reported by Polatidis & Conway (2003).

The angular separation between the two components corresponds to a projected linear separation of 88 h^{-1} pc. To obtain an estimate of the kinematic age, we divided the linear separation by the estimated proper motion. For $\beta_{\mathrm{app}} = (0.18 \pm 0.08)\ h^{-1}$, this results in a minimum kinematic age for this source of $\approx$1600 yr. Evaluating this at the 1 σ points, we get a lower limit of 1100 yr and an upper limit of 2900 yr for the minimum kinetic age, although a zero proper motion (and effectively infinite age) cannot be entirely ruled out. This

TABLE 2

Gaussian Models Fitted to PKS 1934−638[a]

Epoch	Component	S (Jy)	r (mas)	θ (deg)	a (mas)	b/a	ϕ (deg)
2002.5............	1	1.020	0.0	. . .	4.85	0.32	81
	2	0.773	42.7	−92	3.21	1.00	. . .
2002.9............	1	0.816	0.0	. . .	4.93	0.53	81
	2	0.542	42.6	−92	3.56	1.00	. . .

[a] The models fitted to the visibility data are of Gaussian form with flux density S and FWHM major axis a and minor axis b, with major axis of position angle ϕ (measured north through east). Components are separated from the (arbitrary) origin of the image by an amount r in position angle θ, which is the position angle (measured north through east) of a line joining the components with the origin.

TABLE 3
VLBI Component Separations for PKS 1934−638

Epoch	Separation (mas)	Position Angle (deg)	Frequency (GHz)	Reference
1970.8	41.9 ± 0.2	−90 ± 0.1	2.3	1
1982.3	42.0 ± 0.2	−90.5 ± 0.1	2.3	2
1988.9	41.3	−89	2.3	3, 4
1991.9	42.3	−88	8.4	3, 4
2002.5	42.7 ± 0.4	−92 ± 0.5	8.4	5
2002.9	42.6 ± 0.3	−92 ± 0.4	8.4	5

Note.—For ease of comparison, the position angles from the literature have been quoted in the sense north through east, the convention used in this paper.

References.—(1) Gubbay et al. 1971; (2) Tzioumis et al. 1989; (3) King 1994; (4) Tzioumis et al. 2002; (5) this paper.

age and its limits are consistent with the ages of other CSOs reported by Polatidis & Conway (2003).

The above calculation assumes the linear separation rate is uniform over the lifetime of the source. It is possible that the source may be expanding at varying rates with most of the expansion occurring in rapid bursts when a low-density medium is encountered. If we happen to be measuring the expansion speed during such a burst, the above age would be an underestimate. While this cannot be ruled out for any individual source, the existence of comparable measured expansion speeds for a high fraction of other GPS sources (Polatidis & Conway 2003) would suggest this expansion rate is likely to be representative of the mean expansion rate for this source.

Phillips & Mutel (1982) first proposed the ‘‘youth’’ scenario, suggesting CSOs were young sources that would evolve into classical double sources. They cited the ‘‘striking resemblance’’ in the morphology and spectra of compact and extended symmetric sources as proof that the same basic physical processes drive both types of objects. Further, they explained the observed lower (compared to compact doubles) turnover frequencies of extended doubles in terms of a mechanism that maintains the electron energy distribution in the radio lobes. So as the lobes expand, they become optically thin, and the turnover frequency decreases.

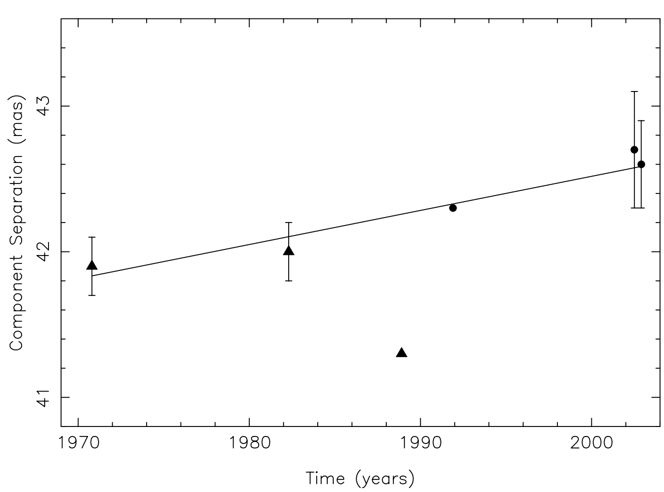

Fig. 2.—Component separation as a function of observation epoch for the GPS source PKS 1934−638. These values are listed in Table 3. Triangles and circles indicate measurements made at 2.3 and 8.4 GHz, respectively. The values at epochs 1988.9 and 1991.9 are reported in the literature without error bars and are plotted accordingly. They are not included in the fit for proper motion shown here.

CSOs could also be ‘‘frustrated’’ sources (Carvalho 1994, 1998) confined by a dense and turbulent environment that inhibits their growth. Up to a tenth of GPS sources show diffuse extended radio emission, which could be evidence of episodic nuclear activity (the diffuse emission being the remnants of earlier episodes) or an indication of a recent sharp increase in gas density, with this dense clumpy medium restricting the jet to the nuclear region. The latter idea is supported by optical evidence for galaxy interaction or mergers in GPS sources (Stanghellini et al. 1993; O’Dea et al. 1996). Such confined radio sources would not be young but have ages comparable to extended doubles.

Readhead et al. (1994) argue that for CSOs to be precursors of Fanaroff-Riley II (FRII) objects (Fanaroff & Riley 1974), the former would need to evolve in jet power, narrow line luminosity, and radio luminosity by implausibly large factors. They cite the possibility of strong cosmological evolution in CSOs (which Fanaroff-Riley I objects do not exhibit), as well as morphological differences between CSO objects and the central components of FRIs (as well as FRIIs), to rule out CSOs as precursors of FRI objects as well. Thus they suggest that some CSOs could be young sources that die young. O’Dea & Baum (1997) find that the radio power of GPS and CSS sources must decrease with linear size more rapidly than it does for large sources, suggesting that the GPS/CSS sources may evolve into much weaker objects. They find that their sample of GPS sources cannot be the progenitors of classical doubles, although they might evolve into FRI sources. However, Snellen et al. (2000) and Alexander (2002) suggest that self-similarity is an important characteristic of the growth of CSOs (at least on long timescales; see Tschager et al. 2000). Snellen et al. (2000) show that CSOs could evolve into large radio sources, if the individual luminosity development of the former is qualitatively different from that of the latter, resulting in a flatter overall luminosity function. They envisage an increase in radio power until the source grows beyond a certain size, after which the radio power declines. In such a scenario, a randomly aged sample of CSOs will be biased toward higher luminosities than a sample of large radio sources. This is consistent with the theoretical picture (Alexander 2000) of a flat density profile in the core of the host galaxy, with a decrease in density outside this core.

A fourth possibility is that CSOs show intermittent radio activity on timescales of $\approx 10^4$–10^5 yr (Reynolds & Begelman 1997). In this scenario, the radio luminosity of a source will decline rapidly during the first few inactive periods, but the source will remain intact as it can maintain highly supersonic expansion.

Taken at face value, our marginal detection of proper motion suggests that PKS 1934−638 is probably a young object. Apart from measurements of hot spot separation in this and other sources, this conclusion is supported by estimates of spectral age (Readhead et al. 1996; Murgia et al. 1999; Murgia 2003), which give similar results. The assumption of minimum energy and equipartition between particles and fields in CSOs draws support from the agreement noted here.

The lack of a detected core in PKS 1934−638 prevents us from measuring any difference in speed between the two hot spots. Such differences have been detected in a few cases (Owsianik & Conway 1998) and suggest variation of hot spot speed, which may result from hydrodynamically induced internal pressure changes or changes in density of the ambient material. Even if detected (by deeper imaging and/or observing at higher frequencies), the core is likely to be weak, so detailed proper motion study will require phase referenced observations. Such observations would also address the issue of "side-to-side" motion of a hot spot (Scheuer 1982).

5. CONCLUSIONS

Our measurement of hot spot separation in PKS 1934−638 over 32.1 yr implies it is probably a young object. This result agrees with other kinematic and spectral age estimates for this and other CSOs. Thus, CSOs are likely to evolve into classical double sources, which have a similar morphology, simply scaled up by a factor of about 1000, or they may be young sources with a short lifetime. In addition, this result strongly constrains the formation and acceleration of jets by suggesting that they exist within ≈1000 yr of a source "turning on." Further observations, preferably using phase referencing, are necessary to confirm or refute these results, to address different hot spot speeds in the same source, to look for side-to-side motions, and to measure any changes in hot spot separation velocity.

This research has made use of NASA's Astrophysics Data System Abstract Service.

REFERENCES

Alexander, P. 2000, MNRAS, 319, 8
———. 2002, MNRAS, 335, 610
Bicknell, G. V., Dopita, M. A., & O'Dea, C. P. 1997, ApJ, 485, 112
Bolton, J. G., Gardner, F. F., & Mackey, M. B. 1963, Nature, 199, 682
Bridle, A. H., & Greisen, E. W. 1994, AIPS Memo 87
Cannon, W. H., et al. 1997, Vistas Astron., 41, 297
Carvalho, J. C. 1994, A&A, 292, 392
———. 1998, A&A, 329, 845
Conway, J. E., Myers, S. T., Pearson, T. J., Readhead, A. C. S., Unwin, S. C., & Xu, W. 1994, ApJ, 425, 568
Fanaroff, B. L., & Riley, J. M. 1974, MNRAS, 167, 31P
Fanti, R., & Spencer, R. E. 1995, in IAU Symp. 175, Extragalactic Radio Sources, ed. R. Ekers, C. Fanti, & L. Padrielli (Dordrecht: Kluwer), 63
Fey, A. L., Clegg, A. W., & Fomalont, E. B. 1996, ApJS, 105, 299
Greisen, E. W. 1988, AIPS Memo 61
Gubbay, J. S., Robertson, D. S., Craske, N., & Nicolson, G. 1971, AJ, 76, 965
Jauncey, D. L., White, G. L., Batty, M. J., & Preston, R. A. 1986, AJ, 92, 1036
Kellerman, K. I. 1966, Australian J. Phys., 19, 195
King, E. 1994, Ph.D. thesis, Univ. Tasmania
Kuncic, Z., Bicknell, G. V., & Dopita, M. A. 1998, ApJ, 495, L35
Ma, C., Arias, E. F., Eubanks, T. M., Fey, A. L., Gontier, A.-M., Jacobs, C. S., Sovers, O. J., Archinal, B. A., & Charlot, P. 1998, AJ, 116, 516
Murgia, M. 2003, Publ. Astron. Soc. Australia, 20, 19
Murgia, M., Fanti, C., Fanti, R., Gregorini, L., Klein, U., Mack, K.-H., & Vigotti, M. 1999, A&A, 345, 769
O'Dea, C. P. 1998, PASP, 110, 493
O'Dea, C. P., & Baum, S. A. 1997, AJ, 113, 148
O'Dea, C. P., Baum, S. A., & Stanghellini, C. 1991, ApJ, 380, 66
O'Dea, C. P., Stanghellini, C., Baum, S. A., & Charlot, S. 1996, ApJ, 470, 806
Owsianik, I., & Conway, J. E. 1998, A&A, 337, 69
Pearson, T. J., & Readhead, A. C. S. 1984, ARA&A, 22, 97
Penston, M. V., & Fosbury, R. A. E. 1978, MNRAS, 183, 479
Phillips, R. B., & Mutel, R. L. 1982, A&A, 106, 21
Polatidis, A. G., & Conway, J. E. 2003, Publ. Astron. Soc. Australia, 20, 69
Preston, R. A., et al. 1989, AJ, 98, 1
Readhead, A. C. S., Taylor, G. B., Xu, W., & Pearson, T. J. 1996, ApJ, 460, 612
Readhead, A. C. S., Xu, W., Pearson, T. J., Wilkinson, P. N., & Polatidis, A. G. 1994, in Compact Extragalactic Radio Sources, ed. J. A. Zensus & K. I. Kellermann (Green Bank: NRAO), 17
Reynolds, C. S., & Begelman, M. C. 1997, ApJ, 487, L135
Scheuer, P. 1982, in IAU Symp. 97, Extragalactic Radio Sources, ed. D. Heeschen & C. M. Wade (Dordrecht: Reidel), 163
Shepherd, M. C. 1997, in ASP Conf. Ser. 125, Astronomical Data Analysis Software and Systems VI, ed. G. Hunt & H. E., Payne (San Francisco: ASP), 77
Slysh, V. I. 1963, Nature, 199, 682
Snellen, I. A. G., Schilizzi, R. T., Miley, G. K., de Bruyn, A. G., Bremer, M. N., & Rottgering, H. J. A. 2000, MNRAS, 319, 445
Stanghellini, C., O'Dea, C. P., Baum, S. A., & Laurikainen, E. 1993, ApJS, 88, 1
Stanghellini, C., O'Dea, C. P., Dallacasa, D., Baum, S. A., Fanti, R., & Fanti, C. 1998, A&AS, 131, 303
Tschager, W., Schilizzi, R. T., Rottgering, H. J. A., Snellen, I. A. G., & Miley, G. K. 2000, A&A, 360, 887
Tzioumis, A. K., et al. 1989, AJ, 98, 36
———. 2002, A&A, 392, 841
Wilkinson, P. N., Polatidis, A. G., Readhead, A. C. S., Xu, W., & Pearson, T. J. 1994, ApJ, 432, L87
Wilson, W. E., Roberts, P. P., & Davis, E. R. 1995, in Proc. 4th Asia-Pacific Telescope Workshop, ed. E. A. King (Sydney: ATNF/CSIRO), 16