Chapter 7

The gravitational lens system PKS 1830-211

7.1 Introduction

PKS 1830-211 is a compact flat-spectrum radio source and was identified as a candidate gravitational lens system by Rao & Subrahmanyan (1988) based on its peculiar morphology and spectral index. Its radio structure is made of two components, called the north-east (NE) and south-west (SW), separated by $\sim 1''$, each component consisting of a core-jet-knot configuration. Lower resolution observations (Jauncey, 1991) revealed an Einstein ring around the two components as well. Since this is the brightest known radio lens ($S_{1.4\text{GHz}}$=10 Jy), this is well studied in the cm and mm wavelengths. The components have comparable flux densities at cm-wavelengths and are highly variable at high frequencies (ν>8 GHz). Due to its proximity to the galactic centre (l=12°, b=−5.7°), the extinction in the optical as well as confusion in the infra-red makes the optical-IR identification of the background QSO and the lens galaxy difficult. Therefore the redshift of the background QSO was not known till the recent observations of Lidman (1999) when the NIR spectrum revealed the redshift to be 2.507±0.002. However, the redshift of the lens was known for quite some time, due to molecular absorption by the gas in the lens galaxy against the strong cm-mm continuum of the QSO. Wiklind & Combes (1996) discovered a host of molecular lines in absorption against the SW component, and derived the lens redshift to be 0.88582. Further observations (Wiklind & Combes, 1998) showed that there is much weaker molecular absorption against the NE component at the same redshift, but shifted in velocity by -147 km s^{-1} relative to the main absorption line against the SW image. HI and OH absorption were also detected by Chengalur, de Bruyn, & Narasimha (1999) using the WSRT. The strength of these absorption lines is maximum at the velocity of the molecular gas seen against the NE component and is weaker at the velocity corresponding to the SW component.

In addition to this lensing galaxy at z=0.886, Lovell et al. (1996) discovered a second lens system at z=0.193 through the detection of a feature at 1.2 GHz which they attributed to redshifted HI. Wiklind & Combes (1998) failed to detect any molecular line absorption at this redshift against either of the two components and derive an upper limit for the molecular gas mass of a few times 10^9 $M_\odot$. Hence the reality of this system at z=0.193 has since remained in doubt. The modelling of the lens parameters of PKS 1830-211 is not unambiguous (see Nair, Narasimha, & Rao 1993 and Kochanek & Narayan 1992 for two different models) and hence the possible existence of a second lens is important. Additionally, a measurement of the time delay in this lens has been obtained (time delay ~26 days; Lovell et al. 1998). Any attempt, therefore, at deriving the value of Hubble's constant from this lens system will depend on the detailed lens properties and geometry.

In order to confirm the existence of the second lens system at z=0.193, we searched for radio recombination line absorption at this redshift. This is a viable method of detecting this lens system since (1) An HI line has been seen and hence there exists substantial gas in this line of sight (2) the background source is strong and hence the geometry is favourable to detect stimulated recombination line emission due to the background continuum. Additionally, PKS 1830-211 is known to be highly variable at high frequencies and a single-epoch continuum spectrum would be useful for comparison. Hence we have also carried out observations to measure the single-epoch continuum flux density of PKS 1830-211 in the radio band.

7.2 Observations

We have carried out two different observations : (1) to measure the single-epoch continuum spectrum from 0.3–45 GHz using the VLA, (2) to search for RRLs at 1.4 GHz using the VLA. The observational procedure and the results for these observations are discussed below.

Table 7.1: Radio continuum spectrum of PKS 1830-211

Frequency (GHz)	Bandwidth (MHz)	Beam ($'' \times ''$)	rms (1σ)[a] (mJy)	Flux density (Jy)	Spectral[c] index
0.332	3.125	141×141	15	8.8±0.5	+0.09 ± 0.04
1.39	25	95×50	4	9.95±0.04	−0.14 ± 0.015
4.86	50	30×11	1	8.40±0.01	−0.03 ± 0.035
8.45	50	18×6	0.5	8.27±0.02	−0.43 ± 0.03
14.94	50	26×13	0.6	6.46±0.03	−0.68 ± 0.07
22.46	50	5×3	0.7	4.9±0.1	−1.1 ± 0.1
43.34[b]	50	3×1.5	2	2.4±0.1	—

[a]The 1σ noise listed is for each IF.

[b]The 45 GHz observations were carried out using only 8 antennas.

[b]Spectral index is calculated between that frequency and the one listed below.

7.2.1 Single-epoch radio continuum spectrum

The VLA was used in the D configuration on 27 October 1997 in the 4IF mode to measure the flux density of the source at all frequencies available at the VLA. The amplitudes were calibrated using 3C 286 at all frequencies with appropriate uv ranges. No phase calibrator was used. PKS 1830-211 is unresolved at all frequencies in this configuration and is bright even at the highest frequency. Hence the phases and amplitudes of the on-source visibilities were self-calibrated every 10 seconds, which was the integration time used. Final self-calibrated images were made for each IF at all the observed frequencies and flux densities were measured at each frequency. The 45 GHz observations were carried out without performing reference pointing. Further observational parameters and the measured flux densities are listed in Table 7.1. The 1σ rms in the single-IF images are also listed. The errors in the flux density measurements are derived from the images; the true uncertainties are probably larger. The data are plotted in figure 7.1 with error-bars which are assumed to be the greater of the tabulated value and 1% of the continuum flux density.

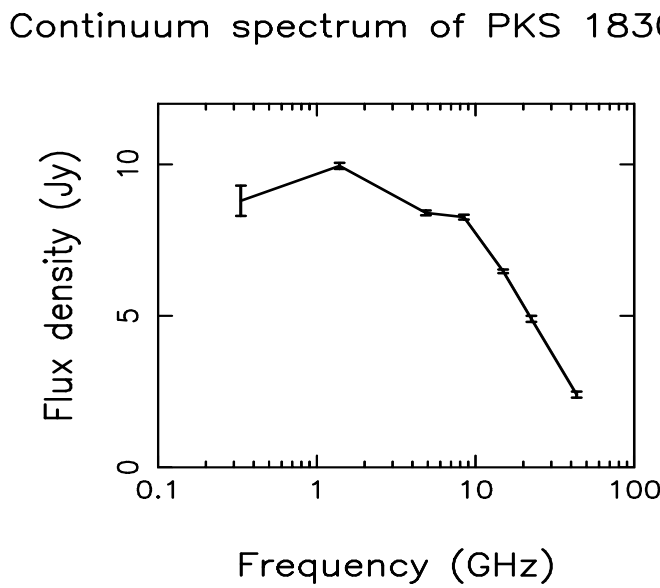


Figure 7.1: Single-epoch total flux density of PKS 1830-211 from 0.3 GHz to 45 GHz for the unresolved source. Error bars are the larger of the values listed in Table 7.1 and 1 % of the measured flux density. Observations were carried out on 27 October 1997.

7.2.2 Observations of H158α and H136α RRLs

The VLA was used in the A configuration at 1.4 GHz to search for RRLs in stimulated emission against the background radio continuum of the QSO. The correlator was used in the 4IF mode, yielding two different frequencies (IFs) of observation. One IF was tuned to detect the redshifted H158α line from the z=0.193 system and the other was tuned to detect the redshifted H136α from the z=0.886 system at the same time. These quantum numbers were chosen so that both the observing frequencies lie in the 1.4 GHz band of the VLA. Further observational parameters are listed in Table 7.2. A subsequent observation was made to detect the redshifted H158α RRL, leading to a lower noise level for this line data. In neither case was a line detected. The upper limits to the line optical depth are listed in Table 7.2. Extremely sensitive upper limits could be derived since (1) the background source is strong (S=10 Jy) and (2) it is unresolved and hence accurate self-calibration could be performed.

Table 7.2: VLA search for RRLs at 1.4 GHz : Observational Parameters

Parameter	z=0.193	z=0.886
Recombination line	H158α	H136α
Rest frequency (GHz)	1.652	2.586
Observed frequency (GHz)	1.384	1.371
Bandwidth (MHz)	1.56	3.125
Velocity resolution (km s^{-1})	5.3	21
$\tau_{\rm line}$ upper limit (5σ)	5$\times$10^{-5}	5$\times$10^{-4}

7.3 Modelling the ionized gas

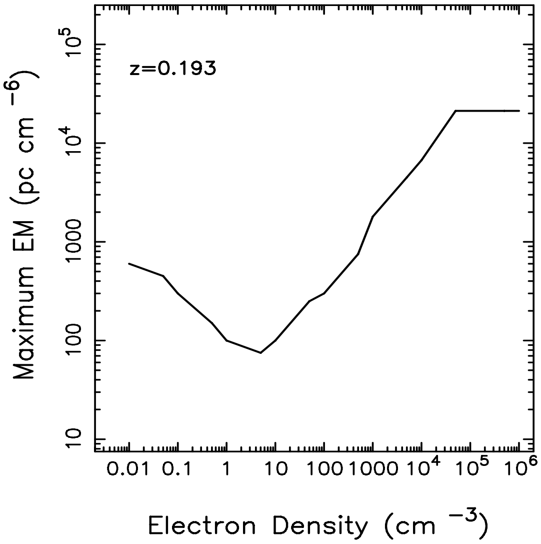
We assume that the continuum spectrum of PKS 1830-211 at frequencies below 5 GHz is indeed flat (Rao & Subrahmanyan, 1988). Any observed deviation from flatness can then be attributed to free-free absorption by ionized gas in the intervening lens galaxies. From the measured flux densities at 1.4 GHz and 330 MHz, we derive an upper limit of 0.13 for the continuum optical depth at 330 MHz. We assume that the beam filling factor of any absorbing gas is unity. The (beam averaged) emission measure of the gas, for an electron temperature of 7500 K, is therefore $\leq 4\times10^4$ pc cm^{-6} if the gas is at z=0.193 and is $\leq 10^5$ pc cm^{-6} if the gas is at z=0.886.

The derived upper limits to the RRLs are modelled as follows. The ionized gas is assumed to have a uniform density n_e and a line-of-sight path length l pc. This gas is modelled as an uniform slab in front of the SW and NE components of the background QSO. Each component is assumed to have a 1.4 GHz flux density of 5 Jy and a spatial extent of 0.3″. The values of n_e and l are varied between 10^{-2}–10^6 cm^{-3} and 10^{-6}–10^4 pc respectively. For each combination of n_e and l, the free-free continuum flux density and the RRL emission (arising due to spontaneous as well as stimulated emission) is calculated. Recently, Verheijen, Carilli, & Yun (2001) confirmed the existence of the HI line at z=0.193. Using the VLA along with the Pie-Town antenna, they were able to resolve the two components and detected the z=0.193 HI line against both the components with roughly equal optical depth, separated by ~40 km s^{-1}. A line width of 80 km s^{-1} was assumed for calculating the expected line strengths. The model predictions were compared with the following two constraints: (1) the predicted line emission must be less than the observed upper limit and (2) the continuum emission from the ionized gas must be an insignificant fraction of the observed continuum at any frequency, i.e., the free-free opacity must not affect the continuum spectrum above 5 GHz significantly. For every assumed density, the maximum value of l and hence emission measure EM consistent with the above constraints was derived. This modelling scheme was carried out for both the redshift systems. Hence we obtain the maximum allowable (beam averaged) EM of the ionized gas as a function of the assumed density for both the z=0.193 and the z=0.886 lens galaxies and these are plotted in Figure 7.2.

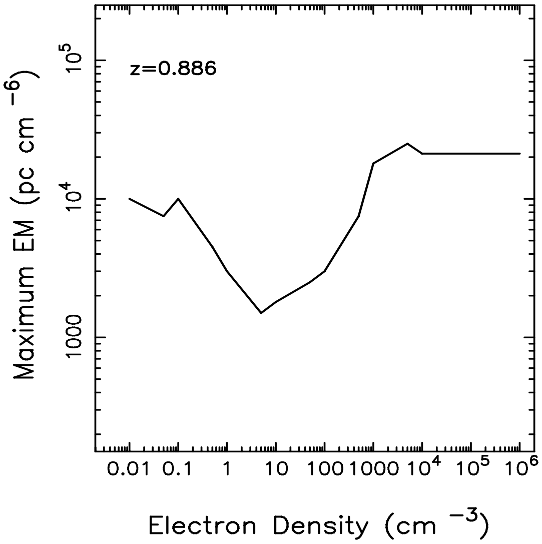
This figure shows that our experiment is most sensitive to low density gas (n_e =1–10 cm^{-3}) and indicates an upper limit to the *beam averaged* emission measure of 100 pc cm^{-6} for this gas in the z=0.193 system. If the line emitting gas is predominantly of density 5–10 cm^{-3}, then the size of such a region located anywhere in the observed beam is constrained to be less than 200–300 pc in size, assuming a homogeneous gas distribution. On the other hand, if the gas is in compact structures with density ~10^3 cm^{-3}, then its beam filling factor is constrained to be less than 6×10^{-4}. The limits to the z=0.886 system are about ten times higher and will not be discussed further.

7.4 Discussion

It is clear from the previous section that detecting classical HII regions from the lens system at z=0.193 might not be feasible with present day instruments. Due to the frequency dependence of the non-LTE optical depth, the experiment described above is most sensitive to low density gas. A similar observation at lower frequencies is desirable. RRL emission at 330 MHz, for



(a) For the z=0.193 system



(b) For the z=0.886 system

Figure 7.2: The maximum emission measure (EM) of the ionized gas in the **(a).** z=0.193 system and the **(b).** z=0.886 system which is consistent with the upper limits to the recombination line strengths, as a function of the assumed electron density. The kinks in the two curves are a result of numerical errors and are not significant.

example, will be more sensitive to the extended low density warm ionized medium (ELDWIM; Heiles, Reach, & Koo 1996; Roshi & Anantharamaiah 2001) in this galaxy. Though the primary motivation for the RRL observations was to confirm the existence of the z=0.193 system, it seems that a search for RRLs from the z=0.886 system might be more fruitful, since this system has a higher optical depth in various molecular lines. A 1.4 GHz RRL search at a sensitivity comparable to that achieved for the z=0.193 system as well as a search for lines at 330 MHz using the GMRT with a 1σ optical depth level of $\sim 10^{-5}$ should be attempted. The possibility of simultaneously observing multiple lines with the upgraded WSRT makes this optical depth limit attainable.

It is interesting that about two decades ago, it was expected that RRLs would be seen primarily from high redshift objects due to stimulated emission in the foreground ionized gas by the background radio bright nuclei (Shaver, 1978). In fact, study of RRLs at high redshifts were even thought to be useful for the determination of cosmological parameters (Sarazin & Wadiak, 1983) ! Hence, many searches had been conducted towards distant quasars (Churchwell & Shaver, 1979; Bell et al., 1984), but with no success. It was also generally believed that normal galaxies do not possess ionized gas of sufficient emission measure for RRLs produced purely by internal (or spontaneous) emission to be detectable. The observation described in this chapter seemed to offer the best possible chance to detect high redshift lines but were not fruitful. It is indeed ironic that all the extragalactic radio recombination line detections till date have been predominantly internal emission from nearby galaxies instead.

Bibliography

Aalto, S., Booth, R. S., Black, J. H., Koribalski, B., & Wielebinski, R. 1994, A&A, 286, 365

Allen, D. A., Wright, A. E., & Goss, W. M. 1976, MNRAS, 177, 91

Alonso-Herrero, A., Rieke, G. H., Rieke, M. J., & Scoville, N. Z. 2000, ApJ, 532, 845

Anantharamaiah, K. R., & Goss, W. M. 1990, in IAU Colloq. 125, Radio Recombination Lines: 25 Years of Investigations, ed. M. A. Gordon & R. L. Sorochenko (Dordrecht: Kluwer), 267

Anantharamaiah, K. R., & Goss, W. M. 1996, ApJ, 466, L13

Anantharamaiah, K. R., Viallefond, F., Mohan, N. R., Goss, W. M., & Zhao, J. -H. 2000, ApJ, 537, 613

Anantharamaiah, K. R., Zhao, J. -H., Goss, W. M., & Viallefond, F. 1993, ApJ, 419, 585

Andreani, P., Cimatti, A., Loinard, L., & Röttgering, H. 2000, A&A, 354, L1

Andreani, P., Cimatti, A., Röttgering, H. J. A., & Tilanus, R. 1999, Ap&SS, 266, 267

Antonucci, R. R. J. & Ulvestad, J. S. 1988, ApJ, 330, L97

Arnaboldi, M., Capaccioli, M., Cappellaro, E., Held, E. V., & Koribalski, B. 1995, AJ, 110, 199

Arp, H., & Sandage, A. 1985, AJ, 90, 1163

Arsenault, R. 1989, A&A, 217, 66

Auriemma, C., Perola, G.C., Ekers, R., et al. 1977, A&A, 57, 41

Baan, W. A., & Goss, W. M. 1992, ApJ, 385, 188

Baldwin, J. A., Spinrad, H., & Terlevich, R. 1982, MNRAS, 198, 535

Bally, J., O'Dell, C. R., & Caughrean, M. J. 2000, AJ, 119, 2919

Bally, J., Stark, A. A., Wilson, R. W., & Henkel, C. 1987, ApJSS, 65, 13

Barnes, J. E., & Hernquist, L. 1972, ARA&A, 30, 705

Beck, S. C., & Beckwith, S. V. 1984, MNRAS, 207, 671

Beck, S. C., Turner, J. L., Ho, P. T. P., Lacy, J. H., & Kelly, D. 1996, ApJ, 457, 610

Beck, S. C., Turner, J. L., Langland-Shula, E., Meier, D. S., Crosthwaite, L. P., & Gorjian, V. 2002, ApJ, in press

Bell, M. B., Seaquist, E. R. 1977, A&A, 56, 461

Bell, M. B., Seaquist, E. R. 1978, A&A, 223, 378

Bell, M. B., Seaquist, E. R., Mebold, U., Reif, K., & Shaver, P. 1984, A&A, 130, 1

Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393

Blain, A. W. 1999, MNRAS, 309, 955

Boisse, P., Casoli, F., & Combes, F. 1987, A&A, 173, 229

Böker, T., Krabbe, A., & Storey, J. W. V. 1998, ApJ, 498, L115

Briggs, D. 1999, Ph.D. Thesis

Broadbent, A., Osborne, J. L., & Haslam, C. G. T. 1989, MNRAS, 237, 381

Bruzual, A. G., & Charlot, S. 1993, ApJ, 405, 538

Bushouse, H. A., Telesco, C. M., & Werner, M. W. 1998, AJ, 115, 938

Caldwell, N., & Phillips, M. M. 1989, ApJ, 338, 789

Calzetti, D., Bohlin, R. C., Kinney, A. L., Storchi-Bergmann, T., & Heckman, T. M. 1995, ApJ, 443, 136

Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582

Calzetti, D., Meurer, G. R., Bohlin, R. C., Garnett, D. R., Kinney, A. L., Leitherer, C., & Storchi-Bergmann, T. 1997, AJ, 114, 1834 (CMB97)

Campbell, A., Terlevich, R., & Melnick, J. 1986, MNRAS, 223, 811

Canzian, B., Mundy, L. G., & Scoville, N. Z. 1988, ApJ, 333, 157

Carilli, C. L. 1996, A&A, 305, 402

Carilli, C. L., Holdaway, M. A., Ho, P. T. P., & de Pree, C. G. 1992, ApJ, 399, L59

Carilli, C.L., & Yun, M.S. 1999, ApJ, 513, L13

Carilli, C.L., & Yun, M.S. 2000, ApJ, 530, 618

Carlstrom, J. E. 1990, in ASP Conf. Ser. 12, The Evolution of the Interstellar Medium, ed. L. Blitz, 339

Carral, P., Turner, J. L., & Ho, P. T. P. 1990, ApJ, 362, 434

Casassus, S., Bronfman, L., May, J., & Nyman, L. -Å. 2000, A&A, 358, 514

Casoli, F., Willaime, M. -C., Viallefond, F., & Gerin, M. 1999, A&A, 346, 663

Chaisson, E. J., & Rodriguez, L. F. 1977, a[j, 214, 111

Chapman, S. C., McCarthy, P. J., & Persson, S. E. 2000, AJ, 120, 1612

Charmandaris, V., Stacey, G. J., & Gull, G. 2002, ApJ, 571, 282

Chengalur, J. N., de Bruyn, A. G., & Narasimha, D. 1999, A&A, 343, 79

Chevalier, R. A. & Fransson, C. 2001, ApJ, 558, L27

Churchwell, E. 1997, ApJ, 479, L59

Churchwell, E., & Shaver, P. A. 1979, A&A, 77, 316

Cimatti, A. 2000, in proceedings of the ESO/ECF/STScI workshop "Deep Fields" (astro-ph/0012057)

Cimatti, A. et al. 1999, A&A, 352, L45

Cimatti, A., Andreani, P., Röttgering, H. J. A., & Tilanus, R. 1998a, Nature, 392, 895

Cimatti, A., Andreani, P., Röttgering, H. J. A., & Tilanus, R. 1998b, in proceedings of the Xth Rencontres de Blois, "The Birth of Galaxies" (astro-ph/9810004)

Clark, B. G. 1980, A&A, 89, 377

Cole, G. H. J., Mundell, C. G., & Pedlar, A. 1998, MNRAS, 300, 656

Collison, P. M., Saikia, D. J., Pedlar, A., Axon, D. J., & Unger, S. W. 1994, MNRAS, 268, 203

Comeron, F., & Torra, J. 1996, A&A, 314, 776

Condon, J. J. 1992, ARA&A, 30, 575

Condon, J. J., Condon, M. A., Gisler, G., & Puschell, J. J. 1982, ApJ, 252, 102

Condon, J. J., Huang, Z.-P., Yin, Q. F., & Thuan, T. X. 1991, ApJ, 378, 65

Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693

Conti, P. S., & Vacca, W. D. 1994, ApJ, 423, L97

Corbin, M. R., Korista, K. T., & Vacca, W. D. 1993, AJ, 105, 1313

Cornwell, T. J., Uson, J. M., & Haddad, N. 1992, A&A, 258, 583

Cornwell, T. J., & Wilkinson, P. N. 1981, MNRAS, 196, 1067

Daddi, E., Cimatti, A., Pozzetti, L., et al. 2000a, A&A, 361, 535

Daddi, E., Cimatti, A., Renzini, A. 2000b, A&A, 362, L45

Dahlem, M. et al. 1990, A&A, 240, 237

Darling, J., & Giovanelli, R. 2002, ApJ, 572, 810

Das, M., Anantharamaiah, K. R., & Yun, M. S. 2001, ApJ, 549, 896

Davies, R. I., Sugai, H., & Ward, M. J. 1998, MNRAS, 295, 43

De Breuck C. 2000, Ph.D. Thesis

Deeg, H., -J., Brinks, E., Duric, N., Klein, U., & Skillman, E. 1993, ApJ, 410, 626

de Ruiter, H.R., Arp, H.C., & Willis, A.G. 1977, A&AS, 28, 211

Dey, A, Graham, J.R., Ivison, R.J., et al. 1999, ApJ, 519, 610

Downes, D., Radford, S. J. E., Guilloteau, S., Guelin, M., Greve, A., & Morris, D. 1992, A&A, 262, 424

Doyon, R., Nadeau, D., Joseph, R. D., Goldader, J. D., Sanders, D. B., & Rowlands, N. 1995, ApJ, 450, 111

Doyon, R., Puxley, P. J., & Joseph, R. D. 1992, ApJ, 397, 117

Draine, B. T. & Woods, D. T. 1991, ApJ, 383, 621

Dravskikh, Z. V., & Dravskikh, A. F. 1964, Astron. Tsirk., 282, 2

Dyson, J. E., & Williams, D. A. 1997, The physics of the interstellar medium, The graduate series in astronomy (2d ed.; Bristol: Institute of Physics Publishing)

Dyson, J. E., Williams, R. J. R., & Redman, M. P. 1995, MNRAS, 277, 700

Elston, R., Rieke, G. H., & Rieke, M. J. 1988, ApJ, 331, L77

Elston, R. et al. 2001, in preparation

Engelbracht, C. W., Rieke, M. J., Rieke, G. H., Kelly, D. M., & Achtermann, J. M. 1998, ApJ, 505, 639

Evans, R., Harper, A. & Helou, G. 1997, in Extragalactic Astronomy and the Infrared, ed. G. A. Mamon, T. X. Thuan, & J. T. T. Van (Paris: Ed. Frontieres), 143

Fabbiano, G., Heckman, T., Keel, W. C. 1990, ApJ, 355, 442

Falcke, H., Malkan, M. A., & Biermann, P. L. 1995, A&A, 298, 375

Fanaroff, B. L., & Riley, J. M. 1974, MNRAS, 167, 31

Feigelson, E. D., & Berg, C. J. 1983, ApJ, 269, 400

Feinstein, C., Vega, I., Mendez, M., & Forte, J. C. 1990, A&A, 239, 90

Fischer, J. et al. 1999, Ap&SS, 266, 91

Forbes, D. A., Boisson, C., & Ward, M. J. 1992, MNRAS, 259, 293

Forbes, D. A., Kotilainen, J. K., & Moorwood, A. F. M. 1994, ApJ, 433, L13

Forbes, D. A., Norris, R. P., Williger, G. M., & Smith, R. C. 1994, AJ, 107, 984

Forbes, D. A., Polehampton, E., Stevens, I. R., Brodie, J. P., & Ward, M. J. 2000, MNRAS, 312, 689

Forbes, D. A., Ward, M. J., Depoy, D. L. 1991, ApJ, 380, L63

Forbes, D. A., Ward, M. J., Rotaciuc, V., Blietz, M., Genzel, R., Drapatz, S., van der Werf, P. P., Krabbe, A. 1993, ApJ, 406, L11

Franco, J., Kurtz, S. E., Garcia-Segura, G., Hofner, P. 2000, Ap&SS, 272, 169

Frank, J., King, A. R., & Raine, D. J. 1985, Accretion power in astrophysics (Cambridge University Press)

Frayer, D. T., Ivison, R. J., Smail, I., Yun, M. S., & Armus, L. 1999, AJ, 118, 139

Frayer, D. T., Seaquist, E. R., & Frail, D. A. 1998, AJ, 115, 559

Fuerst, E., Reich, W., & Sofue, Y. 1987, A&AS, 71, 63

Gao, Y., & Solomon, P. M. 1999, ApJ, 512, L99

Garay, G., Rodriguez, L. F., Moran, J. M., & Churchwell, E. 1993, ApJ, 418, 368

Gavazzi, G. & Boselli, A. 1999, A&A, 343, 86

Gear, W. K. et al. 2001, MNRAS, in press

Gehrz, R. D., Sramek, R. A., & Weedman, D. W. 1983, ApJ, 267, 551

Gerola, H., & Seiden, P. E. 1978, ApJ, 223, 129

Gilbert, A. M. 2000, ApJ, 533, L57

Goldader, J. D., Meurer, G., Heckman, T. M., Seibert, M., Sanders, D. B., Calzetti, D., & Steidel, C. C. 2002, ApJ, 568, 651

Goldberg, L. 1966, ApJ, 144, 1225

Gonzalez-Riestra, R., Rego, M., & Zamorano, J. 1987, A&A, 186, 64

Gorjian, V. 1996, AJ, 112, 1886

Gorjian, V., Turner, J. L., & Beck, S. C. 2001, preprint (astro-ph/0103101)

Graham, J. A. 1981, PASP, 93, 552

Graham, J. R., & Dey, A. 1996, ApJ, 471, 720

Griem, H. R. 1967, ApJ, 148, 547

Guilloteau, S., Omont, A., Cox, P., McMahon, R. G., Petitjean, P. 1999, A&A, 349, 363

Haas, M., Klaas, U., Coulson, I., Thommes, E., & Xu, C. 2000, A&A, 356, L83

Habing, H. J., & Israel, F. P. 1979, ARA&A, 17, 345

Harper, D. A., & Low, F. J. 1973, ApJ, 182, L89

Harrison, A., Henkel, C., & Russel, A. 1999, MNRAS, 303, 157

Harwit, M., & Pacini, F. 1975, ApJ, 200, L127

Haynes, M. P., Giovaneli, R., & Roberts, M. S. 1979, ApJ, 229, 83

Heckman, T. M., Armus, L., & Miley, G. K. 1990, ApJ, 310, 227

Heiles, C., Reach, W. T., & Koo, B. -C. 1996, ApJ, 466, 191

Hibbard, J. E., van der Hulst, J. M., Barnes, J. E., & Rich, R. M. 2001, AJ. 122. 2969

Ho, L. C. 1999, ApJ, 516, 672

Högbom, J. 1974, apjs, 15, 417

Hollenbach, D., Johnstone, D., Lizano, S., & Shu, F. 1994, ApJ, 428, 654

Huang, Z. P., Thuan, T. X., Chevalier, R. A., Condon, J. J., & Yin, Q. F. 1994, ApJ, 424, 114

Huchtmeier, W. 1972, A&A, 17, 207

Huettemeister, S., Mauersberger, R., & Henkel, C. 1997, A&A, 326, 59

Hughes, D. H., Appleton, P. N., & Schombert, J. M. 1991, ApJ, 370, 176

Hughes, D. H., Dunlop, J. S., & Rawlings, S. 1997, MNRAS, 289, 766

Hummel, E., & van der Hulst, J. M. 1986, A&A, 155, 151

Hu, E. M., & Ridgway, S. E. 1994, AJ, 107, 1303

Isobe, T., Feigelson, E. D., & Nelson, P. L. 1986, ApJ, 306, 490

Israel, F. P., Maloney, P. R., & Baas, F. 1990, A&A, 237, 17

Jauncey, D. L. et al. 1991, Nature, 352, 132

Jenness, T., & Lightfoot, J. F. 1998, ADASS VII, Albrecht R., Hook R. N., Bushouse H. A. (eds), ASP Conf. Series, Vol. 145, 216

Jog, C. J., & Das, M. 1992, ApJ, 400, 476

Jog, C. J., & Das, M. 1992, ApJ, 473, 797

Johnson, K. E., Leitherer, C., Vacca, W. D., & Conti, P. S. 2000, ApJ, 120, 1273

Kalas, P., & Wynn-Williams, C. G. 1994, ApJ, 434, 546

Kardashev, N. S. 1959, Astron. Zh., 36, 838

Kennicutt, R. C., Jr. 1998, ApJ, 498, 541

Kennicutt, R. C., Jr., Edgar, B. K., & Hodge, P. W. 1989, ApJ, 337, 761

Keto, E., Ball, R., Arens, J., Jernigan, G., Meixner, M., Skinner, C., & Graham, J. 1993, ApJ, 413, L23

Keto, E., et al. 1997, ApJ, 483, 598

Keto, E., Hora, J. L., Fazio, G. G., Hoffmann, W., & Deutsch, L. 1999, ApJ, 518, 183

Kleinmann, D. E., & Low, F. J. 1970a, ApJ, 159, L165

Kleinmann, D. E., & Low, F. J. 1970b, ApJ, 161, L203

Klein, U., Weiland, H., & Brinks, E. 1991, A&A, 246, 323

Klein, U., & Wunderlich, E. 1987, in NASA, Washington Star Formation in Galaxies, 583

Knop, R. A., Soifer, B. T., Graham, J. R., Matthews, K., Sanders, D. B., & Scoville, N. Z. 1994, AJ, 107, 920

Kobulnicky , H. A., Dickey, J. M., Sargent, A. I., Hogg, D. E., & Conti, P. S. 1995, AJ, 110, 116

Kobulnicky, H. A., Skillman, E. D., Roy, J. -R., Walsh, J. R., & Rosa, M. R. 1997, ApJ, 477, 679

Kobulnicky, H. A., & Johnson , K. E. 1999, ApJ, 527, 154 (KJ99)

Kochanek, C. S., Narayan, R. 1992, ApJ, 401, 461

Koratkar, A. & Blaes, O. 1999, PASP, 111, 1

Koribalski, B., Dahlem, M., Mebold, U., & Brinks, E. 1993, A&A, 268, 14

Koribalski, B., Dettmar, R. -J., Mebold, U., & Wielebinski, R. 1996, A&A, 315, 71

Koribalski, B., Dickey, J. M., & Mebold, U. 1993, ApJ, 402, L41

Koribalski, B., Whiteoak, J. B., & Houghton, S. 1995, PASA, 12, 20

Kormendy, J. & bahcall, J. N. 1974, AJ, 79, 671

Kotilainen, J. K., Forbes, D. A., Moorwood, A. F. M., van der Werf, P. P., & Ward, M. J. 1996, A&A, 313, 771

Krabbe, A., Sternberg, A., & Genzel, R. 1994, ApJ, 425, 72

Kreysa, E. et al. 1998, in Advanced Technology MMW, Radio, and Terahertz Telescopes, ed. Phillips, T. G., proceedings of SPIE Vol. 3357, 319,

Kronberg, P. P., Biermann, P., & Schwab, F. R. 1985, ApJ, 291, 693

Kunth, D., & Sargent, W. L. W. 1981, A&A, 101, L5

Kurtz, S., Churchwell, E., & Wood, D. O. S. 1994, ApJSS, 91, 659

Lai, O., Rouan, D., Rigaut, F., Doyon, R., & Lacombe, F. 1999, A&A, 351, 834

Landau, L., & Lifshitz, E. 1959, Fluid Mechanics (Oxford: Pergamon)

Langston, G. I., Conner, S. R., Heflin, M. B., Lehar, J., & Burke, B. F. 1990, ApJ, 353, 34

Larson, R. B., & Tinsley, T. M. 1978, ApJ, 219, 46

Lebofsky, M. J., & Rieke, G. H. 1979, ApJ, 229, 111

Ledlow, M.J., & Owen, F.N. 1996, AJ, 112, 9

Lehnert, M. D., & Heckman, T. M. 1996, ApJ, 462, 651

Leitherer, C. et al. 1999, ApJSS, 123, 3

Lequeux, J. 1971, A&A, 15, 30

Lidman, C., Courbin, F., Meylan, G., Broadhurst, T., Frye, B., & Welch, W. J. W. 1999, ApJ, 514, 57

Lilly, S. J., & Longair, M. S. 1984, MNRAS, 211, 833

Lisenfeld, U., & Ferrara, A. 1998, ApJ, 496, 145

Liu, M. C., Dey, A., Graham, J. R., Bundy, K. A., Steidel, C. C., Adelberger, K., & Dickinson, M. E. 2000, AJ, 119, 2556

Lovell, J. E. J. et al. 1996, ApJ, 472, L5

Lovell, J. E. J., Jauncey, D. L., Reynolds, J. E., Wieringa, M. H., King, E. A., Tzioumis, A. K., McCulloch, P. M., & Edwards, P. G. 1998, ApJ, 508, L51

Low, F. J., & Kleinmann, D. E. 1968, AJ, 73, 868

Lutz, D. et al. 1996, A&A, 315, L137

McCarthy, P. J., Persson, S. E., & West, S. C. 1992, ApJ, 386, 52

McCarthy, P. J. et al. 2000, in proceedings of the ESO/ECF/STScI workshop "Deep Fields" (astro-ph/0011499)

McCarthy, P. J., van Breugel, W., & Heckman, T. 1987, AJ, 93, 264

McCray, R. 1983, in International Astronomical Union, General Assembly, Proceedings, Highlights of astronomy, Vol. 6 (Dordrecht: D. Reidel Publishing Co.), 565

Mebold, U., Shaver, P. A., Bell, M. B., & Seaquist, E. R. 1980, A&A, 82, 272

Méndezi, D. I., Esteban, C., Filipović, M. D., Ehle, M., Haberl, F., Pietsch, W., & Haynes, R. F. 1999, A&A, 349, 801

Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. R. 1995, AJ, 110, 2665

Mezger, P. G., Duschl, W. J., & Zylka, R. 1996, A&ARv, 7, 289

Mirabel, I. F. 1998, A&A, 333, L1

Mohan, Niruj R., Anantharamaiah, K. R., & Goss, W. M. 2000, in IAU Symp. 199, The Universe at Low Radio Frequencies, ed. A. P. Rao, in press (astro-ph/0004294)

Mohan, Niruj, R., Anantharamaiah, K. R., & Goss, W. M. 2001, ApJ, 557, 659

Mohan, Niruj, R., Anantharamaiah, K. R., & Goss, W. M. 2002, ApJ, 574, 701

Mohan, Niruj, R., Cimatti, A., Röttgering, H. J. A., Andreani, P., Severgnini, P., Tilanus, R. P. J., & Carilli, C. L. 2002, A&A, 383, 440

Moorwood, A. F. M. 1996, SSRv, 77, 303

Moriondo, G., Cimatti, A., & Daddi, E. 2000, A&A, 364, 26

Muñoz-Tuñón, C., Tenorio-Tagle, G., & Castañeda, H. O. 1996, AJ, 112, 1636

Nagar, N. M., Falcke, H., Wilson, A. S., & Ho, L. C. 2000, ApJ, 542, 186

Nair, S., Narasimha, D., & Rao, A. P. 1993, ApJ, 407, 46

Narayan, R., Mahadevan, R., & Quataert, E. 1998, in Theory of Black Hole Accretion Disks, ed. M. A. Abramowicz et al. (Cambridge University Press), 148ir, S., Narasimha, D., & Rao, A. P. 1993, ApJ, 407, 46

Natta, A., & Panagia, N. 1984, ApJ, 287, 228

Neff, S. G. & Ulvestad, J. S. 2000, AJ, 120, 670

Neugebauer, G., Becklin, E. E., Oke, J. B., & Searle, L. 1976, ApJ, 205, 29

Neugebauer, G. et al. 1984, ApJ, 278, L1

Newman, W. 1977, Ap&SS, 47, 99

Olnon, F. M. 1975, A&A, 39, 217

Omont, A., Cox, P., Bertoldi, F., McMahon, R. G., Carilli, C., Isaak, K. G. 2001, A&A, 374, 371

Paglione, T. A. D., Tosaki, T., & Jackson, J. M. 1995, ApJ, 454, L117

Panagia, N., & Felli, M. 1975, A&A, 39, 1

Peck, A. B. et al. 1997, ApJ, 486, 329

Pence, W. D. 1981, ApJ, 247, 473

Peng, R., Zhou, S., Whiteoak, J. B., Lo, K. Y., & Sutton, E. C. 1996, ApJ, 470, 821

Phookun, B., Anantharamaiah, K. R., & Goss, W. M. 1998, MNRAS, 295, 156

Pietsch, W. et al. 2001, A&A, 365, L174

Piña, R. K., Jones, B., Puetter, R. C., & Stein, W. A. 1992, ApJ, 401, L75

Pozzetti, L., & Mannucci, F. 2000, MNRAS, 317, L17

Prada, F., Manchado, A., Canzian, B., Peletier, R. F., McKeith, C. D., & Beckman, J. E. 1996, ApJ, 458, 537

Puxley, P. J., & Brand, P. W. J. L. 1995, MNRAS, 274, 77

Puxley, P. J., Brand, P. W. J. L., Moore, T. J. T., Mountain, C. M., & Nakai, N. 1991, MNRAS, 248, 585

Puxley, P. J., Brand, P. W. J. L., Moore, T. J. T., Mountain, C. M., Nakai, N., & Yamashita, T. 1989, ApJ, 345, 163

Puxley, P. J., Mountain, C. M., Brand, P. W. J. L., Moore, T. J. T., Nakai, N. 1997, ApJ, 485, 143

Quataert, E., Di Matteo, T., Narayan, R., & Ho, L. C. 1999, ApJ, 525, L89

Rao, A. P., & Subrahmanyan, R. 1988, MNRAS, 231, 229

Readhead, A. C. S., & Wilkinson, P. N. 1978, ApJ, 223, 25

Rickard, L. J., Baina, T. M., & Turner, B. E. 1982, ApJ, 252, 147

Rieke, G. H. 1978, ApJ, 226, 550

Rieke, G. H., & Lebofsky, M. J. 1978, ApJ, 220, L37

Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., Tokunaga, A. T. 1980, ApJ, 238, 24

Rieke, G. H., & Low, F. J. 1975, AJ, 197, 17

Rieu, N. -Q. 1969, A&A, 1, 128

Rodriguez, L. F., & Chaisson, E. J. 1980, ApJ, 238, 41

Roshi, A., & Anantharamaiah, K. R. 2001, ApJ, 557, 226

Russell, J. L., Lasker, B. M., McLean, B. J., Sturch, C. R., & Jenkner, H. 1990, AJ, 99, 2059

Sadler, E. M. et al. 2002, MNRAS, 329, 227

Sage, L. J., Salzer, J. J., Loose, H. -H., & Henkel, C. 1992, A&A, 265, 19

Saha, A., Sandage, A., Labhardt, L., Schwengeler, H., Tammann, G. A., Panagia, N., & Macchetto, F. D. 1995, ApJ, 438, 8

Saikia, D. J., Unger, S. W., Pedlar, A., Yates, G. J., Axon, D. J., Wolstencroft, R. D., Taylor, K., & Gyldenkerne, K. 1990, MNRAS, 245, 397

Salem, M., & Brocklehurst, M. 1979, ApJSS, 39, 633

Sams, B. J. III, Genzel, R., Eckart, A., Tacconi-Garman, L., & Hofmann, R. 1994, ApJ, 430, L33

Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749

Sarazin, C. L., & Wadiak, E. J. 1983, A&A, 123, L1

Sargent, W. L. W. 1970, ApJ, 160, 405

Sargent, W. L. W., & Searle, L. 1970, ApJ, 162, 151

Satyapal, S., Watson, D. M., Pipher, J. L., Forrest, W. J., Fischer, J., Greenhouse, M. A., Smith, H. A., & Woodward, C. E. 1999, ApJ, 516, 704

Savedoff, M. P., & Greene, J. 1955, ApJ, 122, 477

Schaerer, D., Contini, T., Kunth, D., & Meynet, G. 1997, ApJ, 481, L75

Schinnerer, E., Eckart, A., Quirrenbach, A., Böker, T., Tacconi-Garman, L. E., Krabbe, A., & Sternberg, A. 1997, 488, 174

Schmelz, J. T., Baan, W. A., & Haschick, A. D. 1987, ApJ, 315, 492

Schmelz, J. T., Baan, W. A., & Haschick, A. D. 1987, ApJ, 320, 145

Schmidt, M. 1959, ApJ, 129, 243

Schwab, F. R. 1984, AJ, 89, 1076

Scoville, N. Z., Soifer, B. T., Neugebauer, G., Young, J. S., Matthews, K., & Yerka, J. 1985, ApJ, 289, 129

Scoville, N. Z., et al. 2000, AJ, 119, 991

Seaquist, E. R. & Bell, M. B. 1977, A&A, 60, L1

Sersic, J. L., & Pastoriza, M. 1965, PASP, 77, 287

Shaver, P. A. 1975, Pramana, 5, 1

Shaver, P. A. 1978, A&A, 68, 97

Shaver, P. A. 1980, A&A, 91, 279

Shaver, P. A., Churchwell, E., & Rots, A. H. 1977, A&A, 55, 435

Shaver, P. A., Churchwell, E., & Walmsley, C. M. 1978, A&A, 64, 1

Shull, J. M. 1980, ApJ, 238, 860

Smail, I., Ivison, R., Blain, A., & Kneib, J. -P. 1999a, Ap&SS, 266, 279

Smail, I., Ivison, R. J., Kneib, J. -P., et al. 1999b, MNRAS, 308, 1061

Soifer, B. T., Matthews, K., Neugebauer, G., et al. 1999, AJ, 118, 2065

Soifer, B. T., Houck, J. R., & Neugebauer, G. 1987, ARA&A, 25, 187

Solomon, P. M. 2001, in Starburst Galaxies: Near and Far, ed. L. Tacconi, & D. Lutz (Heidelberg: Springer-Verlag), 173

Sorochenko, R. L., & Borodzich, E. V. 1965, Doklady AN UUSR, 163, 603

Spinrad, H., Dey, A., Stern, D., et al. 1997, ApJ, 484, 581

Spitzer, L. 1968, Diffuse matter in space (New York: Interscience Publication)

Sramek, R. A., & Weedman, D. W. 1986, ApJ, 302, 640

Stahler, S. W., Palla, F., Ho, P. T. P. 2000, Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: University of Arizona Press), 327

Stanford, S. A., Sargent, A. I., Sanders, D. B., & Scoville, N. Z. 1990, ApJ, 349, 492

Stark, A. A., Bally, J., Wilson, R. W., & Pound, M. W. 1989, in IAU Colloq. 136, The Center of the Galaxy, ed. M. Morris (Dordrecht: Kluwer), 129

Stiavelli, M., & Treu, T. 2001, in proceedings of "Galaxy Disks and Disk Galaxies", ASP conf. series 230, ed. Funes and Corsini (astro-ph/0010100)

Strelnitski, V. S., Ponomarev, V. O., & Smith, H. A. 1996, ApJ, 470, 1118

Strickland, D. K., Heckman, T. M., Weaver, K. A., & Dahlem, M. 2000, AJ, 120, 2965

Strickland, D. K. & Stevens, I. R. 1999, MNRAS, 306, 43

Sturm, E., Lutz, D., Tran, D., Feuchtgruber, H., Genzel, R., Kunze1, D., Moorwood, A. F. M., & Thornley, M. D. 2000, A&A, 358, 481

Sugai, H., Davies, R. I., Malkan, M. A., McLean, I. S., Usuda, T., & Ward, M. J. 1999, ApJ, 527, 778

Sugai, H., & Taniguchi, Y

Tacconi-Garman, L. E., Sternberg, A., & Eckart, A. 1996, AJ, 112, 918

Tan, J. C., & McKee, C. F. 2000, preprint (astro-ph/0012005)

Tarchi, A., Neininger, N., Greve, A., Klein, U., Garrington, S.T., Muxlow, T. W. B., Pedlar, A., & Glendenning, B. E. 2000, A&A, 358, 95

Taylor, G. B., Carilli, C. L., & Perley, R. A. 1999, "Synthesis Imaging in Radio Astronomy II", Sixth NRAO/NMIMT Synthesis Imaging Summer School, ASP Conference Series, Vol. 180

Telesco, C. M., & Harper, D. A. 1980, ApJ, 235, 392

Terashima, Y., Ho, L. C., & Ptak, A. F. 2000, ApJ, 539, 161

Terlevich, R., Tenorio-Tagle, G., Rozyczka, M., Franco, J., & Melnick, J. 1995, MNRAS, 272, 198

Thompson, D. et al. 1999, ApJ, 523, 100

Thompson, A. R., Moran, J. M., & Swenson, G. W. 1986, Interferometry and Synthesis in Radio Astronomy (New York: Wiley)

Toomre, A., & Toomre, J. 1972, ApJ, 178, 623

Turner, J. L., Beck, S. C., & Ho, P. T. P. 2000, ApJ, 532, L109 (TBH00)

Turner, J. L., & Ho, P. T. P. 1985, ApJ, 299, L77

Turner, J. L., Ho, P. T. P., & Beck, S. C. 1998, AJ, 116, 1212

Ulvestad, J. S. 2000, AJ, 120, 278

Ulvestad, J. S. & Antonucci, R. J. 1997, ApJ, 488, 621

Ulvestad, J. S. & Ho, L. C. 2001, ApJ, 562, 133

Vacca, W. D. 1994, ApJ, 421, 140

Vacca, W. D., & Conti, P. S. 1992, ApJ, 401, 543

Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914

van Breugel, W., De Breuck, C., Stanford, S.A., et al. 1999, ApJ, 518, L61

Van de Hulst, H. C. 1945, Nederladsch Tijdschrift voor Naturkundl, 11, 210

van den Bergh, S. 1971, A&A, 12, 474

van den Bergh, S. 1980, PASP, 92, 122

van den Bergh, S. 2000, PASP, 112, 932

Vanzi, L., Rieke, G. H., Martin, C. L., & Shields, J. C. 1996, ApJ, 466, 150

Verheijen, M. A. W., Carilli, C. L., & Yun, M. S. 2001, in ASP Conf. Ser. 240, Gas and Galaxy Evolution, ed. J. E. Hibbard, M. Rupen, & J. H. v. Gorkom (San Francisco: ASP), 69

Veŕon-Cetty, M. P., & Veŕon, P. 1985, A&A, 145, 425

Verstraete, L., Puget, J. L., Falgarone, E., Drapatz, S., Wright, C. M., Timmermann, R. 1996, A&A, 315, L337

Vigroux et al. 1996, A&A, 315, L93

Waller, W. H., Kleinmann, S. G., & Ricker, G. R. 1988, AJ, 95, 1057

Walsh, D.E.P., Knapp,G.R., Wrobel, J.M., & Kim, D.W. 1989, ApJ, 337, 209

Walsh, J. R., & Roy, J. -R. 1987, ApJ, 319, L57

Walsh, J. R., & Roy, J. -R. 1989, MNRAS, 239, 297

Walsh, J. R., & Roy, J. -R. 1993, MNRAS, 262, 27

Watson, A. M., et al. 1996, AJ, 112, 534

Weaver, K. A., Heckman, T. M., Strickland, D. K., & Dahlem, M. 2002, ApJ, 576, L19

Weedman, D. W., Feldman, F. R., Balzano, V. A., Ramsey, L. W., & Sramek, R. A. 1981, ApJ, 248, 105

Whitmore, B. C. 2000, preprint (astro-ph/0012546)

Whitmore, B. C., Zhang, Q., Leitherer, C., Fall, S. M., Schweizer, F., & Miller, B. W. 1999, AJ, 118, 1551

Whitmore, B. C., & Schweizer, F., 1995, AJ, 109, 960

Wiklind, T., & Combes, F. 1996, Nature, 379, 139

Wiklind, T., & Combes, F. 1998, ApJ, 500, 129

Wild, J. 1952, ApJ, 115, 206

Wilson, C. D., & Scoville, N. Z. 1990, ApJ, 363, 435

Witt, A. N., Thronson, H. A., & Capuano, J. M. 1992, ApJ, 393, 611

Wunderlich, E., & Klein, U. 1988, A&A, 206, 47 (WK88)

Wynn-Williams, C. G., & Becklin, E. E. 1974, PASP, 86, 5

Wynn-Williams, C. G., & Becklin, E. E. 1986, ApJ, 308, 620

Wynn-Williams, C. G., Eales, S. A., Becklin, E. E., Hodap, K.-W., Joseph, R. D., McLean, I. S., Simons, D. A., & Wright, G. S. 1991, ApJ, 377, 426

Xu, C., Klein, U., Meinert, D., Wielebinski, R., & Haynes, R. F. 1992, A&A, 257, 47

Yan, L., McCarthy, P. J., Weymann, R. J., et al. 2000, AJ, 120, 575

Yi, I. & Boughn, S. P. 1998, ApJ, 499, 198

Yorke, H. W., Tenorio-Tagle, G., & Bodenheimer, P. 1984, A&A, 138, 325

Yorke, H. W., & Welz, A. 1996, A&A, 315, 555

Yun, M.S., Reddy, N.A., & Condon, J.J. 2001, ApJ, 554, 803

Yun, M. S., Scoville, N. Z., & Knop, R. A. 1994, ApJ, 430, L109

Zhao, J. -H., Anantharamaiah, K. R., Goss, W. M., & Viallefond, F. 1996, ApJ, 472, 54

Zhao, J. -H., Anantharamaiah, K. R., Goss, W. M., & Viallefond, F. 1997, ApJ, 482, 186 (ZAGV97)

Zhao, J. -H., Goss, W. M., Ulvestad, J. S., & Anantharamaiah, K. R. 2001, in ASP Conf. Ser. 240, Gas and Galaxy Evolution, ed. J. E. Hibbard, M. Rupen, & J. H. v. Gorkom (San Francisco: ASP), 404