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Simultaneous multifrequency observations of the BL Lac MS 0205.7+3509

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Abstract. Radio and optical observations of the possible microlensed BL Lac source MS 0205.7+3509 were obtained simultaneously with ASCA x–ray measurements in February 1997. A single power law model, with a photon index of 2.61, is an adequate fit to the ASCA data, once hydrogenic absorption in excess of the Galactic value is permitted, confirming a previous ROSAT measurement. On the basis of our simultaneous data we have determined MS 0205.7+3509 to be a typical x–ray selected BL Lac, with $\alpha_{xox} = -0.82$. There is no indication of an inverse Compton (IC) component in the ASCA spectrum up to 10 keV. No evidence for variability on hour-long timescales is present in either the x–ray or the optical data. We discuss these results in the context of a gravitational microlensing scenario for MS 0205.7+3509.

Key words: X-rays: galaxies – cosmology: gravitational lensing – galaxies: BL Lacertae objects: individual: MS 0205.7+3509

1. Introduction

The primary distinguishing characteristics of BL Lacs, such as their high and variable polarisation, extreme variability at optical through radio wavelengths, apparent superluminal motion and their lack of prominent line emission (equivalent width < 5 Å), may be explained by relativistic beaming effects in jets which are oriented close to the line of sight (Urry & Padovani, 1995). Significant differences between x–ray selected BL Lacs (XBLs), discovered in x–ray surveys and radio-selected BL Lacs (RBLs), discovered in radio surveys, may be attributable to differences in jet direction relative to the observer and in the width of the cone into which the emitted radiation is beamed (Stocke et al., 1991; Stickel et al., 1991; Ghisellini & Maraschi, 1989). A smaller angle of the jet to the line of sight is inferred for RBLs on the basis of the greater optical variability and higher and more variable polarisation exhibited by these sources compared to XBLs (Januzzi et al., 1993; Januzzi et al., 1994). In this orientation model for BL Lacs there should be a significant population of sources with properties intermediate between those of XBLs and RBLs. The recent identification of such a population in the ROSAT All-Sky Survey/Green Bank (RGB) sample of BL Lacs provides further evidence in favour of the orientation hypothesis (Laurent-Muehleisen 1996). However, orientation effects alone might not be able to account for the different spectral energy distributions of RBLs and XBLs, which may require differences in intrinsic physical parameters of the jet (Sambruna et al., 1996).

In the context of unified schemes for Active Galactic Nuclei (AGN), BL Lacs are expected to reside in luminous elliptical galaxies and should be centred with respect to these host galaxies (Abraham et al., 1991; Wurtz et al., 1996; Stocke et al., 1995). However several BL Lacs have been identified (e.g. MS 0205.7+3509, AO 0235+164, PKS 0537-441 and W1 0846+561 (Wurtz & Stocke, 1993; Stocke et al., 1995)) which are not centred with respect to their hosts or their surrounding nebulosities. Furthermore, in a few cases (e.g. PKS 1413+135, OQ 530) the underlying host galaxy appears to be spiral rather than elliptical (McHardy et al., 1994). Excess soft x-ray absorption and/or an unusual morphology (i.e. spiral host galaxy or decentering of the nucleus) in these BL Lacs may indicate the presence of a foreground galaxy and suggests that microlensing effects may be important to explain all of the observed properties of these sources (Ostriker & Vietri, 1985; Gabuzda et al., 1993; Stickel, 1990). We note that HST imaging of PKS 1413+135 has been used to rule out the presence of gravitational lensing effects in this source (McHardy et al., 1994).

MS 0205.7+3509 is a candidate for microlensing due to the possible spiral nature of its ‘host’ galaxy and the excess soft x–ray absorption which has been determined from ROSAT PSPC observations (Stocke et al., 1995). A redshift of $z = 0.318$ has been determined from a MgII absorption feature in the opti-

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cal spectrum of MS 0205.7+3509 (Morris et al., 1991). However, the almost featureless optical spectrum makes the redshift uncertain and more recent attempts to confirm it have not been successful. MS 0205.7+3509 has been classified as an XBL in the complete BL Lac sample of the *Einstein* Extended Medium Sensitivity Survey (EMSS), where it was first identified (Morris et al., 1991; Gioia et al., 1990; Perlman et al., 1996).

In this paper, we present the results of simultaneous x–ray, optical and radio observations of MS 0205.7+3509, interpret the data and discuss the gravitational lensing hypothesis.

2. Observations and data reduction

Observations of MS 0205.7+3509 were made with the ASCA satellite (Tanaka et al., 1994) between 00:34 and 18:58 UT on 6 February 1997. There are four instruments on board ASCA, two Gas Imaging Spectrometers (GIS-S2 and GIS-S3) and two Solid-state Imaging Spectrometers (SIS-S0 and SIS-S1). The instruments have a well-calibrated energy range of 0.7–10.0 keV for the GIS and 0.5–10.0 keV for the SIS and only data in these energy ranges were used for spectral fitting. The total observation time per instrument was approximately 35 ks. The data were recorded in FAINT data mode and converted to BRIGHT-2 mode (Inoue, 1993) having corrected the SIS data for the Residual Dark Distribution (RDD) effect with the FTOOLS script 'correctrdd'.

Data from the SIS and GIS instruments were screened in a standard way, and were then reduced using the *FTOOLS* applications. An extraction region was defined around the source, giving an aperture of 4′ for the SIS detectors and 6′ for the GIS. There are no other sources in the extraction region down to a (6 cm) flux limit of 50 μ Jy (see Fig. 3). This spatial region was used to extract the source plus background counts. An estimate of the background was derived by taking an annulus around the extraction aperture and extracting counts from this region. An alternative background estimate was derived from separate dark-sky observations made by ASCA and results obtained using both types of background estimates were found to be consistent. The annulus background was subtracted from the extracted source plus background counts to obtain a source spectrum. The resulting spectra were rebinned to have a minimum of 10 counts per bin in order to ensure the validity of the Gaussian approximation.

The flux densities used in $log(S_x/S_r)$ and in calculating α_{ro}, α_{rx} and α_{ox} have been K-corrected by multiplying observed flux densities by $(1+z)^{\alpha-1}$, where α is the power-law spectral index in the appropriate energy band (Sambruna et al., 1996). α_r is derived from a linear interpolation of flux densities given by Stocke et al. (1995); α_o is derived from the optical spectrum of MS 0205.7+3509 (Morris et al., 1991); α_x is taken from these observations.

2.1. Spectral fitting

The combined binned spectra were fit simultaneously using the Levenberg-Marquardt algorithm in *XSPEC*. The data were fit to: (a) a model of a power law, with an absorber as defined by Morrison and McCammon (1983) fixed at the Galactic value (Stark et al., 1992), (b) a power law model, with a local absorber fixed at the Galactic value and a second absorber at a redshift $z = 0.318$ and (c) broken power law with a local absorber fixed at the Galactic value.

Table 1. Best-fit results obtained for model (b) with fixed local absorber $N_H = 6.1 \times 10^{20}\mathrm{cm}^{-2}$ (Stark et al., 1992) and variable absorber at $z = 0.318$. Fit results are shown for each ASCA instrument for comparison and consistency. Errors are 90% confidence intervals for 1 parameter of interest.

Det	$N_H \times 10^{20}$ (cm^{-2})	Γ	$F_{1\mathrm{keV}} \times 10^{-3}$ (ph keV^{-1} cm^{-2} s^{-1})	χ^2**/DoF**
S0	21 ± 7	2.5 ± 0.1	1.1 ± 0.1	83.51/118
S1	27^{+9}_{-8}	$2.4^{+0.2}_{-0.1}$	$1.1^{+0.2}_{-0.1}$	91.32/116
S2	22^{+37}_{-22}	$2.8^{+0.4}_{-0.3}$	$1.2^{+0.5}_{-0.3}$	157.68/167
S3	2^{+28}_{-2}	$2.6^{+0.3}_{-0.2}$	$1.1^{+0.3}_{-0.1}$	168.56/193

The fits to models (a) and (b) were compared using the F-test (Bevington & Robinson, 1992). Fits to models (b) and (c) were also compared in this way.

Data from the four ASCA instruments (the two SIS and the two GIS detectors are referred to from now on as S0, S1 and S2, S3 respectively) were compared for consistency, using the best fit model results (see Table 1) and were found to be compatible.

2.2. Optical and radio observations

Optical Johnson V-band observations were carried out under photometric conditions with the 1.23 m telescope at Calar Alto Observatory and with the 1 m JKT at La Palma on the nights of 5 and 6 February 1997 with typical exposure times of between 1200 s and 1800 s. Standard CCD aperture photometry techniques were used to reduce the data. The relative uncertainty (0.05 mag.) in the optical magnitude was brought below the absolute calibration uncertainty, by reducing the size of the aperture from which the flux was extracted to achieve optimal signal to noise. The flux in this optimal aperture could then be used to compare different observations of the object, on the same night, for evidence of relative variability. MS 0205.7+3509 was also monitored daily from February 4–7 1997 at 4986.99 MHz (6 cm) with the Westerbork Synthesis Radio Telescope for integration times of ~ 12 hours.

3. Results

The deconvolved photon spectra from one of the SIS instruments (SIS-S0) for the best fit power law with Galactic absorber and redshifted absorber (model (b)) is plotted in Fig. 1. The slight turnover at the soft end of the spectrum due to absorption is evident. A formal F-test yields $> 99.99\%$ confidence that a power law with Galactic absorber and redshifted absorber (model (b)) is a better representation of the data than a power law with Galactic absorber (model (a)). A broken power law with Galactic absorber (model (c)), does not yield a better fit despite having

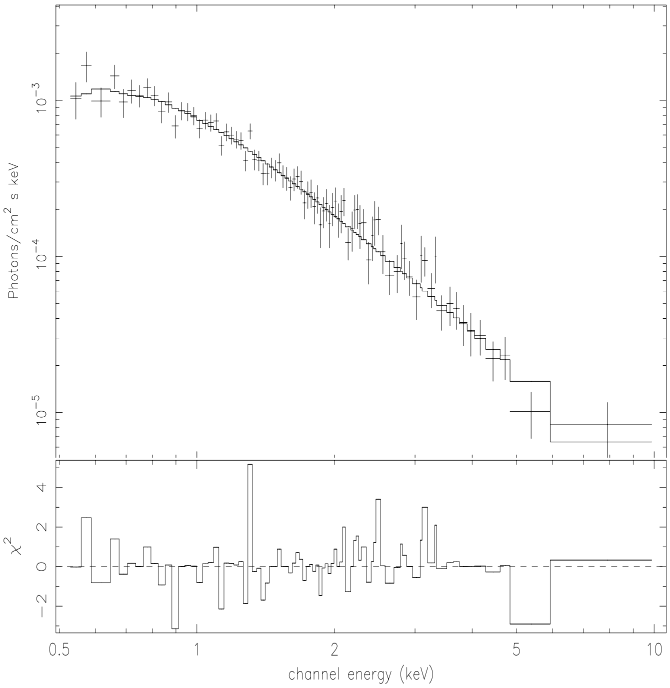

Fig. 1. Best fit photon spectrum and contributions to χ^2 to SIS-S0 data of MS 0205.7+3509 using the power law with Galactic absorber and redshifted absorber model.

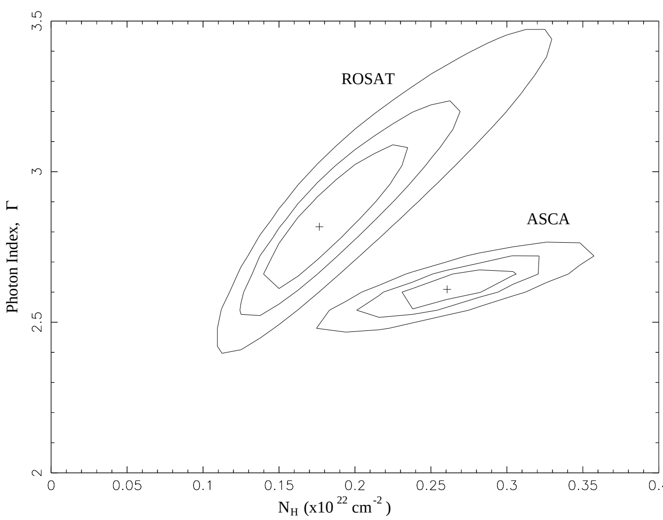

Fig. 2. A plot of 68%, 90% and 99% confidence contours for two parameters of interest, equivalent excess hydrogenic absorbing column (N_H) at a redshift of 0.318, and photon index (Γ) from a simultaneous fit to model (b), of the data from all four ASCA instruments. Confidence contours from the ROSAT observation (Stocke et al., 1995) are included for comparison.

one more free parameter than model (b), and is not considered further.

Confidence contours for the best fit model are plotted in Fig. 2 (for the two parameters, equivalent Hydrogen absorbing column (N_H) and photon index (Γ)).

The results of the spectral fitting to models (a) and (b) are presented in Table 2.

Table 2. ASCA best-fit results obtained for models (a) and (b) using combined SIS and GIS data. Both models have a fixed local absorber $N_H = 6.1 \times 10^{20} \mathrm{cm}^{-2}$ (Stark et al., 1992). Errors are 90% confidence intervals for 1 parameter of interest.

	Γ	$N_H \times 10^{20}$ (cm^{-2})	$F_{1\mathrm{keV}} \times 10^{-3}$ ($\mathrm{ph\,keV^{-1}\,cm^{-2}\,s^{-1}}$)	χ^2/**DoF**
a	2.22 ± 0.04	–	0.83 ± 0.02	635.72/604
b	$2.61^{+0.09}_{-0.08}$	26 ± 5	$1.20^{+0.09}_{-0.08}$	530.78/603

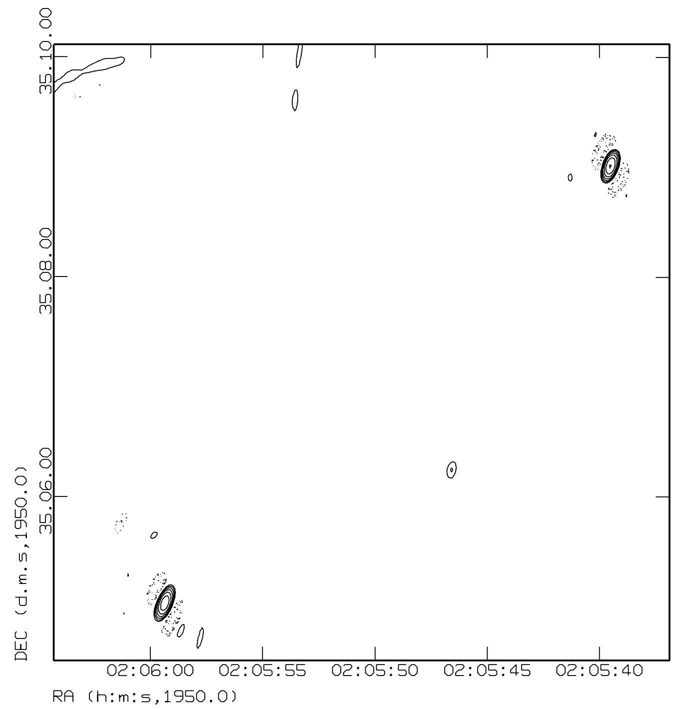

Fig. 3. Radio map at 6 cm of the field surrounding MS 0205.7+3509 observed with the Westerbork Synthesis Radio Telescope. MS 0205.7+3509 is at top right (RA (1950) = 02h05m39.51s, Dec (1950) = 35°09′00.94″). The coordinates and fluxes of the three sources in the field are given in Table 3.

Visual inspection of the x–ray lightcurve yields no evidence for variability greater than 3σ on timescales of hours. Optical photometry on February 5 and 6 yielded a V-band magnitude of 18.6 ± 0.2. No source variability was detected between the eight exposures above a level of 0.05mag.

Radio observations during the period 4–7 February yield a flux value of 5.75 ± 0.125mJy for MS 0205.7+3509, which is inconsistent with previous 6 cm measurements obtained at the VLA (4.91±0.02 mJy) (Stocke et al., 1995), a variability typical of BL Lacs (see for example Wagner et al. (1990)). Two radio sources were detected close to MS 0205.7+3509 (Fig. 3) and their fluxes and positions are given in Table 3.

As can be seen from Fig. 2, these ASCA results do not agree with the ROSAT measurement of 1992 (Stocke et al., 1995). When both data sets are compared over their overlapping energy range, 0.5–1.7 keV, the photon index, Γ and the equivalent

Table 3. Results of the 6 cm radio observations carried out at WSRT. The two other sources in the field are several arcminutes away from MS 0205.7+3509.

RA (B1950)	Dec (B1950)	Flux (mJy)
02:05:39.51	35:09:00.94	5.75
02:05:46.58	35:06:14.83	1.02
02:05:59.35	35:05:01.75	5.29

hydrogen column, N_H do not agree to within 2σ (two parameters of interest). Fixing the redshifted absorption at the ROSAT level, and fitting the ASCA data again over the overlapping energy region, an F-test indicates that this fit is not significantly better than a fit with freely variable absorption. For this fit the ROSAT $\Gamma = 2.8^{+0.3}_{-0.2}$ and ASCA $\Gamma = 2.5 \pm 0.5$.

4. Discussion

Although BL Lacs were originally classified as XBLs or RBLs depending on the energy band in which they were first discovered, recent work has focused on determining the physical distinctions between the two types of source (Padovani & Giommi, 1995; Fossati et al., 1997; Georganopoulos & Marscher, 1998). For example, the spectral energy distributions of XBLs and RBLs differ markedly, with the peak in synchrotron output occurring in the x–ray range for the former and the radio range for the latter. Such differences may arise due to changes in the dominant radiation mechanism occurring as a function of both the angle between the line of sight and the bulk velocity (Maraschi et al., 1986). Synchrotron emission is expected to dominate the x–ray spectra of XBLs (viewed at a large angle) while inverse compton (IC) emission should dominate the x–ray spectrum of RBLs (viewed at small angles and significantly Doppler boosted). Another interpretation of the different properties of XBLs and RBLs is based on the cut-off frequencies of the synchrotron spectral energy distribution (Padovani & Giommi, 1995). In this model BL Lacs with a cut-off in the IR/optical band are RBLs, while those with a cut-off in the UV/x–ray region are XBLs.

Empirically, a source may be classified as an XBL if it has $\log(S_x/S_r) \geq -5.5$, where S_x is the flux at 2 keV and S_r is the flux at 5 GHz, defined in the same units (Laurent-Muehleisen et al., 1997). MS 0205.7+3509 lies firmly in the XBL category, with $\log(S_x/S_r) = -4.17$ derived from the simultaneous observations presented here, suggesting that synchrotron emission is dominating the x–ray emission in the ASCA energy band.

The shape of the spectrum from optical to x–ray wavelengths is an indicator of the relative importance of the IC component to the continuum emission (Sambruna et al., 1996). The parameter $\alpha_{xox} = \alpha_{ox} - \alpha_x$, where α_x is the ROSAT PSPC energy index and

$$\alpha_{ox} = -\frac{\log(F_o/F_x)}{\log(\nu_o/\nu_x)}$$

is a measure of the concavity/convexity of the spectrum between optical and x–ray wavelengths. A positive value for α_{xox} (concave shape) implies the presence of a hard IC component. The following values are obtained for MS 0205.7+3509: $\alpha_{xox} = -0.82$, $\alpha_{ox} = 0.79$, $\alpha_{ro} = 0.32$ and $\alpha_{rx} = 0.48$. The simultaneous spectrum therefore shows no evidence of concavity out to $\sim$ 10 keV. On the basis of these data an IC component may be expected to become significant in the hard x–ray region (clearly above 10 keV) and this could be verified by spectroscopic observations in this energy band (Sambruna et al., 1996). Three nearby XBLs (Mkn 421, Mkn 501 and 1ES 2344+514) have been detected at TeV energies and this high energy emission may be attributable to IC scattering of the highest energy electrons off the synchrotron x–ray photons (Weekes et al., 1997; Catanese et al., 1997). Calculations of the opacity of the universal soft photon background to γ–rays suggest that MS 0205.7+3509 may be detectable above 100 GeV by future γ–ray telescopes (Salamon & Stecker, 1998). We note that MS 0205.7+3509 (like Mkn 501) was not detected by EGRET with a 2σ upper limit of 0.9×10^{-7} ph/cm^2/s at E$>$100MeV (Fichtel et al., 1994).

With $\log(S_x/S_r) = -4.17$ and $\alpha_{xox} = -0.82$, MS0205.7+3509 emerges as a typical XBL. It lies at the furthest extent of the XBL category on the α_{ro} vs. α_{xox} diagram and near the middle of the XBL category in the $\log(S_x/S_r)$ diagram. The convexity of the simultaneous multiwavelength spectrum indicates that the source is not a flat-spectrum radio quasar (FSRQ) which is being affected by microlensing as suggested by Stocke et al. (1995) since it does not have the characteristic FSRQ concave spectral shape (Sambruna et al., 1996). Furthermore on the basis of the x–ray spectrum only, we can rule out the possibility that MS 0205.7+3509 is an FSRQ since the x–ray power law photon indices of that class of AGN are significantly harder than those of XBLs, lying in the range 1.3–1.9 (Urry et al., 1996; Kubo et al., 1998).

The ASCA spectrum indicates variability in the x-ray flux of this object, compared to the spectrum taken with ROSAT in 1992 ($F_{1\mathrm{keV}}$ is $1.20^{+0.03}_{-0.03} \times 10^{-12}$ erg keV^{-1} cm^{-2} s^{-1} for the ASCA observation of February 1997, compared to 1.49 ± 0.05 for the ROSAT 1992 observation). We detect a change in either the photon index, Γ or the equivalent Hydrogen column, N_H. Assuming a change in the photon index, Γ, then it is interesting to note that this behaviour is quite similar to that observed by Madejski et al. (1996) in AO 0235+164 between their non-simultaneous ROSAT and ASCA observations.

The case for microlensing effects in this source (decentered nucleus from host, spiral host and the presence of excess soft x-ray absorption) has been questioned because results from a deep subarcsecond optical study have shown that there is a companion galaxy $2''$ away from the BL Lac. When it is removed, the BL Lac is centred with respect to the remaining nebulosity and the properties of the host galaxy do not look anomalous (Falomo et al., 1997). However, the existence of excess x–ray absorption in the ROSAT PSPC data is also clearly detected in the ASCA spectrum and may be attributable to the halo of this companion galaxy, if it is in a foreground location. Another possibility is that the BL Lac resides behind its nominal 'host' galaxy.

5. Conclusions

Simultaneous multiwavelength observations of MS 0205.7+3509 demonstrate that it is a typical XBL, with $\alpha_{xox} = -0.82$. No evidence for an IC component was observed in the ASCA spectrum and on the basis of these results such a component is expected to appear in the hard x–ray (> 10 keV) band. The ASCA spectrum confirms a soft x–ray absorption in excess of the Galactic value which was previously identified with ROSAT. However, the location and nature of this foreground absorber and its possible role in microlensing remains unclear. More extensive optical monitoring could reveal rapid variability indicating probable gravitational microlensing in MS 0205.7+3509 as has been done in the case of AO 0235+164 (Rabbette et al., 1996).

References

Abraham R.G., Crawford C.S., McHardy I.M., 1991, MNRAS 252, 482

Bevington P.R., Robinson D.K., 1992, in Data reduction and error analysis for the physical sciences, 2nd ed., McGraw-Hill, New York

Catanese M., Boyle P., Buckley J. et al., 1997, in C. Dermer, M. Strickman, J. Kurfess (eds.), Proceedings of the Fourth Compton Symposium, p. 1376, American Institute of Physics

Falomo R., Kotilainen J., Pursimo T., et al., 1997, A&A 321, 374

Fichtel C., Bertsch D., Chiang J., et al., 1994, ApJS 94, 551

Fossati G., Celotti A., Ghisellini G.L.M., 1997, MNRAS 289, 136

Gabuzda D.C., Kollgaard R.I., Roberts D.H., Wardle J.F.C., 1993, ApJ 410, 39

Georganopoulos M., Marscher A.P., 1998, ApJ 506, 621

Ghisellini G., Maraschi L., 1989, ApJ 340, 181

Gioia I.M., Maccacaro T., Schild R.E., et al., 1990, ApJS 72, 567

Inoue H., 1993, Experimental Astronomy (ISSN 0922-6435), vol. 4, no. 1, p.1-10 4, 1

Januzzi B., Smith P., Elston R., 1993, ApJS 85, 265

Januzzi B., Smith P., Elston R., 1994, ApJ 428, 130

Kubo H., Takahashi T., Madejski G., et al., 1998, ApJ 504, 693

Laurent-Muehleisen S.A., Kollgaard R.I., Feigelson E.D., 1997, in Contributed Paper to IAU 164: Radio Emission from Galactic and Extragalactic Compact Sources., p. 6102

Laurent-Muehleisen S.A., Kollgaard R.I., Feigelson E.D., Brinkmann W., 1998, ApJ, In prep.

Madejski G., Takahashi T., Tashiro M., et al., 1996, ApJ 459, 156

Maraschi L., Ghisellini G., Tanzi E., Treves A., 1986, ApJ 310, 325

McHardy I., Merrifield M., Abraham R., C.S.C., 1994, MNRAS 268, 681

Morris S.L., Stocke J.T., Gioia I.M., et al., 1991, ApJ 380, 49

Morrison R., McCammon D., 1983, ApJ 270, 119

Ostriker J.P., Vietri M., 1985, Nat 318, 446

Padovani P., Giommi P., 1995, ApJ 444, 567

Perlman E.S., Stocke J.T., Wang Q.D., Morris S.L., 1996, ApJ 456, 451

Rabbette M., McBreen B., Steel S., Smith N., 1996, A&A 310, 1

Salamon M., Stecker F., 1998, ApJ 493, 547

Sambruna R.M., Maraschi L., Urry C.M., 1996, ApJ 463, 444

Stark A.A., Gammie C.F., Wilson R.W., et al., 1992, ApJS 79, 77

Stickel M., 1990, in H. Araki, J. Ehlers, K. Hepp, R.L. Jaffe, R. Kippenhahn, D. Ruelle, H.A. Weidenmüller, J. Wess, J. Zittartz (eds.), Lecture Notes in Physics 377; Variability of Active Galaxies, pp 303–312, Springer-Verlag, Heidelberg

Stickel M., Fried J.W., Kuehr H., Padovani P., Urry C.M., 1991, ApJ 374, 431

Stocke J.T., Morris S.L., Gioia I.M., et al., 1991, ApJS 76, 813

Stocke J.T., Wurtz R.E., Perlman E.S., 1995, ApJ 454, 55

Stocke J.T. e. a., 1998, In prep.

Tanaka Y., Inoue H., Holt S.S., 1994, Publ. Astron. Soc. Jpn. 46, L37

Urry C.M., Padovani P., 1995, Publ. Astron. Soc. Pac. 107, 803

Urry C.M., Sambruna R.M., Worrall D.M., et al., 1996, ApJ 463, 424

Wagner S., Sanchez-Pons F., Quirrenbach A., Witzel A., 1990, A&A 235, L1

Weekes T., Aharonian F., Fegan D., Kifune T., 1997, in C. Dermer, M. Strickman, J. Kurfess (eds.), Proceedings of the Fourth Compton Symposium, p. 361, American Institute of Physics

Wurtz R., Stocke J.T., 1993, Bull. Am. Astron. Soc. 182, 0410

Wurtz R., Stocke J.T., Yee H.K.C., 1996, ApJS 103, 109