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Observational evidence for binary black holes and active double nuclei

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Abstract. I review the observational evidence for the presence of supermassive binary black holes in galaxies and for the presence of active pairs of galaxies. According to hierarchical galaxy merger models, binary black holes should form frequently, and should be common in the cores of galaxies. The presence of massive black hole binaries has been invoked to explain a number of class properties of different types of galaxies, and in triggering various forms of activity. Coalescing massive black hole binaries are powerful emitters of gravitational waves. The search for such binary black holes is therefore of great interest for several topics in astrophysics ranging from galaxy formation to activity in galaxies.

Key words. galaxies – black holes – supermassive binary black holes

1. Introduction

Supermassive binary black holes (BBHs) are formed in the course of the merging of two galaxies (see Merritt & Milosavljevic 2004 for a detailed review). BBH detection and number estimates provide important constraints on models of galaxy formation and evolution (e.g, Hopkins et al. 2005a,b, and references therein). Their detection allows to study one possible route of BH growth, that by merging of BHs with each other, the frequency of these events, and their relevance for BH growth. BBHs were also suggested to play a role in increasing AGN activity (e.g, Gaskell 1985, Gould & Rix 2000), in triggering starburst activity (Taniguchi & Wada 1996), and in the formation of molecular tori (Zier & Bierman 2001, 2002) which are believed to be an important ingredient in unified models of AGN (Antonucci 1993). The possible relevance of BBHs in explaining different classes of radio-loud AGN was variously addressed (e.g., Basu et al. 1993, Wilson & Colbert 1995, Villata & Raiteri 1999, Valtonen & Heinämäki 2000, Britzen et al. 2001, Simkin & Roychowdhury 2003), and it was suggested that the misalignments between the direction of radio jets and disks in active galaxies (AGN) are possibly due to past black hole merges in these galaxies (Merritt 2002, 2004).

Mergers of massive binary black holes produce strong gravitational wave signals (e.g., Thorne & Braginsky 1976, Centrella 2003, Baker 2003) which will be detectable for the first time with the future space-borne gravitational wave interferometer mission *LISA* (e.g., Bender et al. 1998, Danzmann 1996, Haehnelt 1994) for masses in the range $\sim 10^{4-7}\,M_{\odot}$. Once *LISA* results become available, the gravitational waves from coalescing binary black holes will be used to infer merger rates and the merger history of BHs/galaxies (e.g., Haehnelt

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1994, Menou et al. 2001, Hughes 2002, Menou 2003), and possibly black hole masses (Hughes 2002, Menou 2003). In the future, gravitational waves of coalescing BHs may be used as cosmological standard candles, if the optical counterparts of these systems can be identified (Hughes & Holz 2003). After a short summary of the mechanisms of formation and evolution of BBHs, I give an overview of the different types of observations which point to the presence of BBHs.

2. Binary black hole formation and evolution

The major route of forming binary black holes is via mergers of galaxies (e.g., Begelman et al. 1980, Valtaoja et al. 1989, Milosavljevic & Merritt 2001, Yu 2002, and references therein). If both merging galaxies harbor supermassive black holes at their centers (e.g., Richstone 2002), these two black holes will finally sink to the center of the potential and will eventually merge. Hierarchical merger models of galaxy formation predict that binary black holes should be common in galaxies (e.g., Haehnelt & Kauffman 2002, Volonteri et al. 2003). The merging process will be enhanced in clusters and groups of galaxies. Under some circumstances, black holes may already form as binaries at the centers of the first galaxies (Bromm & Loeb 2003).

The merging of the two black holes basically proceeds in three stages (e.g., Fig. 1 of Begelman et al. 1980). In a first stage, the cores of the merging galaxies approach each other by dynamical friction (e.g. Valtaoja et al. 1989). The last, third stage is the actual merging of the two black holes by emission of gravitational waves (GWs). However, which processes are effective in the intermediate second stage and how efficiently they operate, i.e., how quickly the separation between the two BHs shrinks to a distance where GW emission becomes significant, is still a subject of intense theoretical study (see Merritt 2004, and Merritt & Milosavljevic 2004 for reviews). A number of processes which could lead to a hardening of the black hole binary were discussed, including stellar slingshot effects and re-filling of the loss cone (Saslaw et al. 1974, Quinlan & Hernquist 1997, Milosavljevich & Merritt 2001, Zier & Biermann 2001, Berczik et al. 2005, and references therein), black hole wandering (e.g. Merritt 2001, Hemsendorf et al. 2002, Chatterjee et al. 2003), interaction with surrounding gas and the accretion disk (e.g. Ivanov et al. 1999, Gould & Rix 2000, Haehnelt & Kauffmann 2002, Armitage & Natarajan 2002, Escala et al. 2004), and/or the Kozai mechanism (Blaes et al. 2002). Theoretical calculations show, that under some circumstances none of these mechanisms may operate in sufficient strength, with the consequence that the BBH is expected to stall at separations of 0.01-1 pc (e.g., Milosavljevich & Merritt 2001).

There is circumstantial evidence that most BBHs do actually merge in less than a Hubble time. Haehnelt & Kauffman (2002) argued, if the binaries lasted too long, some of them would be ejected from the nucleus in the course of a three-body interaction with a third black hole, once a new merger occurs. That would lead to the prediction of the existence of galaxies without BHs at their center, as opposed to observations that most galaxies do harbor SMBHs.

3. Observational evidence for binary black holes: spatially unresolved systems

3.1. X-shaped radio galaxies

About 15 radio galaxies show jets with very peculiar morphology; abrupt changes in jet direction, forming X-shaped patterns (e.g., Fig. 2 of Leahy & Williams 1984, Fig. 1 of Parma et al. 1985, Leahy & Parma 1992, Capetti et al. 2002, Wang et al. 2003), so-called X-shaped or 'winged' radio sources. The changes are more abrupt than in S-shaped radio galaxies. While the latter shapes are usually explained in terms of precession effects (e.g. Ekers et al. 1978), Parma et al. (1985) noted that the cross-shaped morphology is likely linked to an abrupt change in jet ejection axis, or is consistent with a precession phenomenon for a specific viewing geometry. Several different models to explain the X-shaped patterns were addressed in the literature, which either link the characteristic X-shape to a re-orientation of the jet axis, or to effects of backflow from the active lobes into the wings (see, e.g., Sect. 5,6 of Dennett-Thorpe et al. 2002 for a summary). According to Merritt & Ekers (2002), Zier & Biermann (2002) and Zier (2005), the X-shaped patterns reflect changes in the orientation of the black hole's spin axis, caused by the preceding merger with a second SMBH. Gopal-Krishna et al. (2003) suggested that the Z-symmetric radio sources represent an earlier evolutionary stage, on route to BH-BH coalescence.

3.2. Double-double radio galaxies

Secondly, so called double-double radio galaxies (Schoenmakers et al. 2000) were suggested to be remnants of merged BBHs (Liu et al. 2003). These are sources which exhibit pairs of symmetric double-lobed radio-structures, aligned along the same axis. Inner and outer radio lobes have a common center (Fig. 1-3 of Schoenmakers et al. 2000) and there is a lack of radio emission between inner and outer lobes. The most likely origin of these structures is an interruption and re-starting of the jet formation.

Several ideas were proposed to explain this phenomenon (see Sect. 5 of Schoenmakers et al. 2000). Liu et al. (2003, see also Liu 2004) favor the presence of binary black holes which have already merged in these systems. According to Liu et al. the inward spiraling secondary black hole temporarily leads to the removal of the inner parts of the accretion disk around the primary black hole, thus to an interruption of jet formation. Jet activity restarts after the outer parts of the accretion disk refill the inner parts of the disk.

3.3. Helical radio jet patterns

A third phenomenon exhibited by radio jets which was suggested to be linked to the presence of binary black holes (Begelman et al. 1980) is the presence of (semi-periodic) deviations of the jet directions from a straight line. Helical distortions and bendings of jets have been seen in a number of sources (including 3C 273, 3C449, BL Lac, Mrk 501, 4C 73.18, 3C 345, and PKS0420-014; see e.g., Fig. 1 of Roos et al. 1993, Fig. 3 of Tateyama et al. 1998), interpreted as manifestation of BBHs in these systems. While there is general agreement that the wiggles in radio jets are most plausibly caused by the presence of BBHs (see, e.g., Camenzind & Krockenberger 1992, Rieger 2004 for a discussion of alternatives), different mechanisms to explain the observations have been favored. These either link the observations to *orbital motion* of the jet-emitting black hole or to *precession effects*, either precession of the accretion disk around the jet-emitting black hole under gravitational torque (on shorter time scales), or to geodetic precession (acting on longer time scales); (e.g., Begelman et al. 1980, Kaastra & Roos 1992, Roos et al. 1993, Hardee et al. 1994, Katz 1997, Romero et al. 2000, Rieger 2004, Lobanov & Roland 2005). Correspondingly, black hole mass estimates in these systems are still subject to uncertainties by a factor ~10-100.

3.4. Semi-periodic signals in lightcurves

3.4.1. OJ 287

Another periodic phenomenon sometimes attributed to the presence of BBHs is (semi)periodic changes in lightcurves. The best-studied candidate for harboring a BBH, inferred from the characteristics of its optical lightcurve, is the BL Lac Object OJ 287. It exhibits optical variability with quite a strict period of 11.86 years (Silanpää et al. 1988, 1996, Valtaoja et al. 2000, Pursimo et al. 2000, and references therein). Optical observations of this source can be followed back to 1890 (e.g., Fig. 1 of Pursimo et al. 2000). How can the BBH model explain periodic optical variability ? Basically, two different classes of models were discussed: (a) accretion(disk)-related variations in the luminosity (e.g., Silanpää et al. 1988, Lehto & Valtonen 1996), or (b) jet-related variability due to Doppler-boosting of varying strength (Katz 1997, Villata et al. 1998). Variants of them have also been invoked to explain apparent periods in the data of other BL Lac objects. (a) According to the original idea of Silanpää et al. (1988), the tidal perturbation, when the secondary approaches closest to the accretion disk of the primary leads to increased accretion activity, thus a peak in the optical lightcurve. (b) Katz et al. (1997) studied a model in which precession of the accretion disk, driven by the gravitational torque of a companion mass (a second black hole), causes the jet to sweep periodically close to or across our line of sight. This then leads to a modulation of the observed intensity of light due to Doppler-boosting. Combining radio and optical observations of OJ 287, Valtaoja et al. (2000) recently favored a scenario in which the first optical peak is due to a thermal flare, when the secondary BH plunges into the accretion disk of the primary. Following the major optical flare, a second optical flare is observed about a year after the first peak, and (only) that second peak is accompanied by enhanced radio emission (Valtaoja et al. 2000). This second peak is traced back to the tidal perturbation, exerted by the secondary black hole upon closest approach to the accretion disk of the primary, which leads to increased accretion activity. The observed ~12 yr period (~9 yr in the rest frame) then corresponds to the orbital period of the BBH. A possible alternative to the BBH models, a well-defined duty-cycle model of accretion, is briefly mentioned by Valtaoja et al. (2000), but is considered as an unlikely explanation for the case of OJ 287, since OJ 287's periodicity is quite strict.

3.4.2. Other cases

Optical variability with indications for periodicity (N = a few, where N is the number of periodic oscillations) and periods on long (order 10-20 yrs) and intermediate (order 20 days - 1 yr) scales have been observed in other blazars (e.g., see Fan et al. 2002 and Tab. 1 and 2 of Xie 2003 for summaries). Among them a 336 day period of minima in the optical lightcurve of PKS1510-089 (Xie et al. 2002), a 14 yr period in optical data of BL Lac (Fan et al. 1998), periods of 1.4-17.85 yrs in a sample of radio selected BL Lacs (Fan et al. 2002), a 5.7 yr period of AO 0235+16 at radio frequencies (Raiteri et al. 2001), and a 23-26 day period of Mrk 501 at TeV energies (Hayashida et al. 1998). No other data set brackets as long a time interval as OJ 287, though, and periodicities are generally less conspicuous and less persistent as in OJ 287.

In some, but not all, cases it was suggested that the variability in the lightcurves is caused by the presence of a BBH, but different types of models were involved, most of which either relate the variability to real changes in the luminosity, or apparent changes due to Doppler-boosting effects. Rieger & Mannheim (2000, see DePaolis et al. 2002 for a generalization of their approach to other orbits) showed that the periodic variability of the BL Lac object Mrk 501 at TeV energies with a period of about 23 days and N=6 is possibly related to the presence of a BBH. According to their model, the observed flux modulation arises from a varying Doppler-factor due to slight variations in inclination angle of (a moving blob in) the jet, caused by the orbital motion of the less massive, jet-emitting black hole. The presence of a BBH in Mrk 501 was also discussed with respect to the complex radio jet morphology of this source (Conway & Wrobel 1985, Villata & Raiteri 1999), and in relation to peculiarities in its spectral energy distribution (Villata & Raiteri 1999).

3.5. *Double-peaked emission-line profiles*

If binary black holes exist in active galaxies, it can plausibly be expected that several are at nuclear separations such that their orbital motion causes observable effects on the profiles of the broad emission lines (e.g. Stockton & Farnham 1991, Gaskell 1996).

A number of AGN with double-peaked broad emission-lines are known. However, in cases closely examined the BBH interpretation (two BHs orbiting each other, each with its own BLR) was disfavored, mostly because he predicted temporal variations in the line profiles were not detected in optical spectroscopic monitoring programs (Halpern & Filippenko 1988, Eracleous et al. 1997), or for other reasons (Halpern & Eracleous 2000). Recently, Zhou et al. (2004) reported the detection of a double peaked structure of the forbidden [OIII]5007 emission line of SDSSJ104807+005543. They favored a BBH scenario to explain the observation.

3.6. Galaxies which lack central cusps

Essentially all evidence presented for the presence of BBHs is linked to some activity of at least one of the two black holes which form the pair (like radio jets, AGN-like emission-lines, etc.). There is one exception, which is some rather indirect hint for the presence of binary black holes. Lauer et al. (2002, see also Ravindranath et al. 2002) used *HST* to identify several early-type galaxies with inward-*decreasing* surface-brightness profiles. The presence of galaxies with such central 'holes' rather than cusps is expected in some models of BBH evolution (see Sect. 6 of Merritt 2004 for a summary), reflecting the ejection of stars from the core in the course of the hardening of the black hole binary.

4. Observational evidence for active double nuclei : spatially resolved systems

Essentially all the candidates for BBHs in close orbits discussed above are still controversial, because alternative explanations for the observational data do exist which do not involve the presence of a binary black hole. It is therefore of great importance to find black hole pairs of larger separations, directly *spatially resolvable* such that *both* SMBHs can be identified separately in nearby galaxies. Only few cases are know so far, described in the next Sections.

4.1. The X-ray active binary AGN of NGC 6240

Observations performed with the *Chandra* X-ray observatory let to the discovery of a pair of active black holes in the center of the (ultra)luminous infrared galaxy NGC 6240 (Komossa et al. 2003). The BBH in NGC 6240 is special in that it is the only known BH pair I am aware of at the center of a single galaxy, and spatially resolved such that both (active) BHs can be separately identified.

The galaxy NGC 6240 belongs to the class of (ultra)luminous infrared galaxies (ULIRGs) which are characterized by an IR luminosity exceeding $\sim 10^{12}\,L_{\odot}$ (see Sanders & Mirabel 1996 for a review). NGC 6240 is one the nearest (U)LIRGs and is considered a key representative of its class. NGC 6240 is the result of the merger of two galaxies, expected to form an elliptical galaxy in the future. It harbors two optical nuclei (Fried & Schulz 1983). Their nature remained unclear. In particular, no optical signs of AGN activity showed up in ground-based optical spectra. An active search for obscured AGN activity in NGC 6240 was carried out during the last two decades (see Sect. 1 of Komossa et al. 2003 for a summary) which let to the detection of absorbed, intrinsically luminous X-ray emission (Schulz et al. 1998) extending up to ∼100 keV (Vignati et al. 1999) from the direction of NGC 6240. Spatial resolution was insufficient to locate the source of the hard X-ray emission, though.

Employing the superb spatial imaging spectroscopy capabilities of the X-ray observatory *Chandra*, it was found that *both* nuclei of NGC 6240 are active, i.e. harbor accreting supermassive black holes (Komossa et al. 2003). The southern and northern nucleus show very similar X-ray spectra which are flat, heavily absorbed, and superposed on each is the presence of a strong neutral (or low-ionization) iron line. These kind of spectra have only been observed in AGN. The projected separation of the X-ray cores is 1.5 arcsec, corresponding to a physical separation of 1.4 kpc. Over the course of the next few hundred million years, the two black holes in NGC 6240 are expected to merge with each other.

5. Pairs of galaxies with active nuclei

5.1. X-ray active nuclei in the merging system IC694/NGC 3690 and ESO509/IG066

Some likely similar cases to NGC 6240 in wider pairs have recently emerged in X-rays. Firstly, based on *Chandra* and *XMM-Newton* observations, Ballo et al. (2004) found that the IR-luminous merging pair of galaxies IC694/NGC 3690 (Arp 299) harbors two X-ray active nuclei (their Fig. 1), one heavily obscured and intrinsically luminous, the other less obscured and less luminous. Both cores show hard spectra with iron lines superposed. The iron line of the second nucleus is ionized rather than neutral and could arise from ionized reflection (but see Zesas et al. 2003). Secondly, Guainazzi et al. (2005) reported XMM-Newton spectroscopy of the interacting pair ESO509/IG066 which shows that both galaxies have absorbed, luminous X-ray powerlaw spectra with intrinsic luminosities $L_x \approx 10^{43}$ erg/s which makes them AGN. Optically, only the western nucleus was previously classified as active (Sy 2).

5.2. Pairs of X-ray sources associated with SCUBA galaxies

Analysis of the *Chandra* Deep Field North (Alexander et al. 2003, 2004) and of deep *Chandra* fields around high-redshift radio sources (Smail et al. 2003) let to the detection that several bright submm SCUBA sources have X-ray counterparts, a number of which ($\approx$ 15-30%) come in pairs (e.g., Fig. 4 of Alexander et al. 2004). Projected distances of the X-ray sources range between ~20-80 kpc. The nature of these sources is still somewhat unclear. Most likely we are seeing interaction-triggered AGN activity (Smail et al. 2003, Alexander et al. 2004). These systems would then be similar to NGC 6240, but observed in a much earlier evolutionary stage (Alexander et al. 2004).

5.3. Binary quasars

A small fraction of (high-redshift) quasars are accompanied by a second nearby quasar (image) with the same redshift. These may either be gravitational lenses, true quasar pairs, or chance alignments. The majority of them are in fact the result of gravitational lensing.

Several pairs with separations 3-10″ were argued to be real pairs, i.e., physically distinct binary quasars (see, e.g., Tab. 1 of Mortlock et al. 1999 and of Kochanek et al. 1999, Sect. 2.5.8 of Schneider et al. 1992, Hennawi et al. 2006). The distinction between a real pair and a lensed quasar is mostly based on: (i) whether or not a lens is detected and (ii) whether or not the quasar spectra differ significantly, and/or whether or not there are other significant differences, like when one image is radio-loud, the other radio quiet. Lack of a detectable lens, and very different quasar spectra/properties strongly argue for real pairs. There is a growing number of quasar images identified as true pairs or as excellent candidates for true pairs (see Hennawi et al. 2006 on SDSS results), among them Q1343.4+2640 (with substantial spectral differences; Crampton et al. 1988), LBQS0103-2753 (the smallest-separation pair known, with very different optical spectra; Junkkarinen et al. 2001), LBQS0015+0239 (interpreted as probable binary system due to lack of an optically bright lens which then makes it the highest-redshift binary known, at z=2.45; Impey et al. 2002), LBQS1429-0053 (similar optical spectra but lack of a lens candidate; Faure et al. 2003),

UM 425 (similar optical/UV spectra but different amounts of absorption in X-rays and lack of a bright lens; Mathur & Williams 2003, Aldcroft & Green 2003), and Q2345+007 (Green et al. 2002). Q2345+007 at z=2.15 is an interesting case: Despite essentially identical optical spectra, no lens could be found in the optical and X-ray band (Green et al. 2002). The X-ray spectra of the quasars do differ, and Green et al. favor an interpretation in terms of a real quasar pair.

The smallest-separation known binary quasar is LBQS0103-2753 at redshift z=0.848. Its projected separation of 0.3″ corresponds to

$\sim$ 2.5 kpc. It remains uncertain, whether the projected separation reflects the true separation. For instance, the emission-line shifts in both quasar spectra (v=3900 km/s) indicate a much larger separation, but emission lines are not always good indicators of systemic redshift (Junkkarinen et al. 2001).

It is interesting to note that there appears to be a lack of small pair separations. Apart from LBQS0103-2753 other pairs have separations > 2″, and typically 3-10″. These projected separations convert to distances of ~10-80 kpc, given the redshifts of the quasars (see Fig. 7 of Mortlock et al. 1999 for an attempt to derive physical separations by a random deprojection method). In any case, a chance projection of the quasar pairs on average is very unlikely, because the pairs are in excess of what is expected from chance projections of single, unrelated sources. Open questions then are: are the host galaxies of the quasars interacting, are they bound to each other and in the process of merging ? At low redshifts, this question can be addressed by searching for morphological and kinematical distortions in the host galaxies. However, most binary quasars are at large redshifts ($z \approx 1-2$), and sometimes the host galaxies are not even detected.

Assuming the observed binary quasars are bound pairs, Mortlock et al. (1999) estimated that dynamical friction will drive them closer together on a time scale comparable to a Hubble time scale. Since this is longer than the typical activity time scale of quasars, these authors pointed out that closer pairs may already be beyond the phase of quasar activity (no fuel left in the center) and therefore not easily detectable.

5.4. Pairs of galaxies which both harbor radio-jets: 3C75 and J0321-455N,S

In the course of a VLA radio survey of Abell clusters, two elliptical galaxies with unusual radio morphology were discovered in the cluster of galaxies Abell 400 (Owen et al. 1985). Each of the galaxies possesses a radio-jet emitting core. Such a configuration is quite unusual, and an important question became: are these two galaxies interacting or merging with each other ? Generally, this can be decided upon examination of the isophotes and kinematics of the galaxies. For instance, asymmetric isophote distortions and tidal tails indicate an ongoing (advanced) merger (e.g. Lauer 1988). As regards 3C75, no distortions of the inner isophotes and no kinematic disturbances were found (Balcells et al. 1995, Govoni et al. 2000). However, the outer isophotes show an off-centering and twist (Lauer et al. 1988, DeJuan et al. 1994, Balcells et al. 1995, Govoni et al. 2000). These observations indicate, that the two galaxies are presently not bound to each other, but do interact with each other (Balcells et al. 1985). It was also argued that the galaxies likely are not spatially very distant from each other, because the jets show similar bends, i.e. should have passed similar regions of the ICM (Owen et al. 1985). Recently, a second pair of galaxies, J0321-455N,S, both with radio jets, was discovered in the outskirts of the cluster AS345 (Klamer et al. 2004).

6. Concluding remarks

In summary, various lines of evidence point to the existence of supermassive binary black holes at the centers of galaxies. Among these, the case of NGC 6240 is special because it is the first known case of a spatially resolved black hole pair at the center of a single galaxy and thus the pair could be uniquely identified.

According to BBH evolution models, the longest time scales in the evolution of the binary up to coalescence are likely those in which the binary is closely bound ($\sim$ 0.01-10 pc; see, e.g., Fig. 1 of Begelman et al. 1980); most BH pairs would therefore not be spatially resolved with present observational techniques. Once *LISA* operates, it will provide us with valuable information on the rate and merger history of binary black holes. Ideally, if *LISA* sources could be identified with optical counterparts, gravitational wave signals and observations across the electromagnetic spectrum could be combined to study BBH merger systems in detail. In particular, Milosavljevic and Phinney (2005) pointed out that the merging of the two black holes might be followed by an X-ray flare, once the accretion disk reforms. Future X-ray all-sky surveys will be well suited to search for these flares.

References

Aldcroft, T.L., Green, P.J., 2003, ApJ, 592, 710
Alexander, D.M., et al., 2003, ApJ, 125, 383, 2003
Alexander, D.M., et al., 2004, Astrophys. and Space Science Library, 301, (Kluwer, Dordrecht), 291
Antonucci, S., 1993, ARA&A, 31, 473
Armitage, P.J., Natarajan P., 2002, ApJ, 567, L9
Baker, J., 2003, Class. Quantum Grav., 20, S201
Balcells, M. et al., 1995, A&A, 302, 665
Ballo, L., Braito V., Della Ceca R., et al., 2004, ApJ, 600, 634
Basu, D., et al., 1993, A&A, 272, 417
Bender, P.L., 1998, in: Eighteenth Texas Symposium on Relativistic Astrophysics and Cosmology, A.V. Olinto et al. (eds), World Scientific, 536
Begelman, M.C., Blandford, R.D., Rees, M.J., 1980, Nature, 287, 307
Berczik, P., Merritt, D., Spurzem, R., 2005, ApJ, 633, 680
Blaes, O., Lee, M.H., Socrates, A., 2002, ApJ 578, 775
Bromm, V., Loeb, A., 2003, ApJ, 596, 34
Britzen, S. et al., 2001, A&A, 374, 748
Camenzind, M., Krockenberger, M., 1992, A&A, 255, 59
Capetti, A. et al., 2002, A&A, 394, 39
Centrella, J., 2003, in: The Astrophysics of Gravitational Wave Sources, AIP Conf. Proc. 686, J. Centrella (ed.), 219
Chatterjee, P., Hernquist, L., Loeb, A., 2003, ApJ, 592, 32
Conway, J.E., Wrobel, J.M., 1995, ApJ, 439, 98
Crampton, D. et al., 1988, ApJ, 330, 184
Danzmann, K., 1996, Class. Quantum Grav., 13, A247
Dennet-Thorpe, J. et al., 2002, MNRAS, 330, 609
De Juan, L. et al., 1994, ApJS, 91, 507
De Paolis, F., Ingrosso G., Nucita, A.A., 2002, A&A, 388, 470
Ekers, R.D., et al., 1978, Nature, 276, 588
Eracleous, M. et al., 1997, ApJ, 490, 216
Escala, A. et al., 2004, ApJ, 607, 765
Fan, J.H. et al., 1998, ApJ, 507, 173
Fan, J.H. et al., 2002, A&A, 381, 1
Faure, C. et al., 2003, A&A, 405, 415
Fried, J., Schulz, H., 1983, A&A, 118, 166
Gaskell, C.M., 1985, Nature, 315, 386
Gaskell, C.M., 1996, ApJ, 464, L107
Gopal-Krishna, Biermann, P.L., Wiita, P.J., 2003, ApJ, 594, L103
Govoni, F. et al., 2000, A&AS, 143, 369
Gould, A., Rix, H.W., 2000, ApJ, 532, L29
Guainazzi, M., Piconcelli, E., Jimenez-Bailon, E., Matt, G., 2005, A&A, 429, L9
Green, P.G. et al., 2002, ApJ, 571, 721
Haehnelt, M.G., 1994, MNRAS, 269, 199
Haehnelt, M.G., Kauffman, G., 2002, MNRAS, 336, L61
Halpern, J.P., Filippenko, A.V., 1988, Nature, 331, 46
Halpern, J.P., Eracleous, M., 2000, ApJ, 531, 647
Hardee, P.E., Cooper, M.A., Clarke, D.A., 1994, ApJ, 424, 126
Hayashida, N. et al., 1998, ApJ, 504, L71
Hemsendorf, M., Sigurdsson, S., Spurzem, R., 2002, ApJS, 81, 1256
Hennawi, J.F., et. al., 2006, ApJ, in press
Hopkins, F., et al., 2005a, ApJ, 630, 705
Hopkins, F., et al., 2005b, ApJ, in press [astro-ph/0506398]
Hughes, S.A., Holz, D.E., 2003, Class. Quantum. Grav., 20, S65
Hughes, S.A., 2002, MNRAS, 331, 805
Hughes, S.A., Blandford, R.D., 2003, ApJ, 585, L101
Impey, C.D. et al., 2002, ApJ, 574, 623
Ivanov, P.B., Papaloizou, J.C.B., Polnarev, D.G., 1999, MNRAS, 307, 79
Junkkarinen V., et al., 2001, ApJ, 549, L155
Kaastra, J.S., Roos N., 1992, A&A, 254, 96
Katz, J.I., 1997, ApJ, 478, 527
Keel, W.C., 1990, AJ, 100, 356
Klamer, I., Subrahmanyan, R., Hunstead, R.W., 2004, MNRAS, 351, 101
Kochanek, C.S., Falco, E.E., Munoz, J.A., 1999, ApJ, 510, 590
Komossa, S. et al., 2003, ApJ, 582, L15
Lauer, T.R., 1988, ApJ, 325, 49

Lauer, T.R. et al., 2002, AJ, 124, 1975
Leahy, J.P., Parma, P., 1992, in: Extragalactic radio sources, J. Roland, H. Sol, G. Pelletier (eds), 307
Leahy, J.P., Williams, A.G., 1984, MNRAS, 210, 929
Lehto, H.J., Valtonen, M.J., 1996, ApJ, 460, 207
Liu, F.K., Wu, X.-B., Cao, S.L., 2003, MNRAS, 340, 411
Liu, F.K., 2004, MNRAS, 347, 1357
Lobanov, A., Roland, J., 2005, A&A, 431, 831
Mathur, S., Williams R.J., 2003, ApJ, 589, L1
Menou, K., 2003, Class. Quantum Grav., 20, S37
Menou, K., Haiman, Z., Narayanan, V.K., 2001, ApJ, 556, 535
Merritt, D., 2001, ApJ, 556, 245
Merritt, D., 2002, ApJ, 568, 998
Merritt, D., 2004, in: Coevolution of Black Holes and Galaxies, L.C. Ho (ed.), Cambridge Univ. Press, 263
Merritt, D., Ekers, R.D., 2002, Science, 297, 1310
Merritt, D., Milosavljevic, M., 2004, to appear in Living Reviews in Relativity, astro-ph/0410364
Milosavljevic, M., Merritt, D., 2001, ApJ, 536, 34
Milosavljevic, M., Phinney, S., 2005, ApJ, 622, L93
Mortlock, D.J., Webster, R.L., Francis, P.J., 1999, MNRAS, 309, 836
Owen, F.N. et al., 1985, ApJ, 294, L85
Parma, P., Ekers, R.D., Fanti, R., 1985, A&AS, 59, 511
Pursimo, T. et al., 2000, A&AS, 146, 141
Quinlan, G.D., Hernquist, L., 1997, NewA, 2, 533
Raiteri C.M. et al., 2001, A&A, 377, 396
Ravindranath, S., Ho, L.C., Filippenko, A.V., 2002, ApJ, 566, 801
Richstone, D., 2002, in: Reviews in Modern Astronomy, R.E.Schielicke (ed.), Wiley-VCH, 57
Rieger, F.M., Mannheim, K., 2000, A&A, 359, 948
Rieger, F.M., 2004, ApJ, 615, L5
Romero, G.E. et al., 2000, A&A, 360, 57
Roos, N., Kaastra, J.S., Hummel, C.A., 1993, ApJ, 409, 130
Sanders, D.B., Mirabel, I.F., 1996, ARA&A, 34, 749
Saslaw, W.C., Valtonen, M.J., Svene, J.A., 1974, ApJ, 190, 253
Schneider, P., Ehlers, J., Falco, E.E., 1992, Gravitational Lenses, Springer-Verlag
Schoenmakers, A.P. et al., 2000, MNRAS, 315, 371
Schulz, H. et al., 1998, A&A, 330, 823
Sillanpää, A. et al., 1988, ApJ, 325, 628
Sillanpää, A. et al., 1996, A&A, 305, L17
Simkin, M.V., Roychowdhury, V.P., 2003, Complex Systems 14, 269
Smail, I. et al., 2003, ApJ, 599, 86
Stockton, A., Farnham, T., 1991, ApJ, 371, 525
Taniguchi, Y., Wada, K., 1996, ApJ, 469, 581
Tateyama, C.E. et al., 1998, ApJ, 500, 810
Thorne, K.S., Braginsky, V.B., 1976, ApJ, 204, L1
Valtaoja, E., Valtonen, M.J., Byrd, G.G., 1989, ApJ, 343, 47
Valtaoja, E. et al., 2000, ApJ, 531, 744
Valtonen, M.J., Heinämäki, P., 2000, ApJ, 530, 107
Vignati, P. et al., 1999, A&A, 349, L57
Villata, M. et al., 1998, MNRAS, 293, L13
Villata, M., Raiteri, C.M., 1999, A&A, 347, 30
Volonteri, M., Haardt, F., Madau, P., 2003, ApJ, 582, 559
Wang, T.G., Zhou, H.Y., Dong, X.B., 2003, AJ, 126, 113
Wilson, A.S., Colbert, E., 1995, ApJ, 438, 62
Xie, G.Z. et al., 2002, MNRAS, 334, 459
Xie, G.Z., 2003, in: China-Germany Workshop on the Multiwavelength View on AGN, Publications of the Yunnan Observatory, J. Wei et al. (eds), 107
Yu, Q., 2002, MNRAS, 331, 935
Zezas, A., Ward, M.J., Murray, S.S., 2003, ApJ, 594, L31
Zier, C., 2005, MNRAS, 364, 583
Zier, C., Biermann, P.L., 2001, A&A, 377, 23
Zier, C., Biermann, P.L., 2002, A&A, 396, 91
Zhou, H., et al., 2004, ApJ 604, L337