Mem. S.A.It. Vol. 79, 1003
© SAIt 2008

Memorie della

AGN: the central kiloparsec

A highly-biased, idiosyncratic introduction

J.H. Krolik

Department of Physics and Astronomy, Johns Hopkins University, Baltimore MD 21218, USA, e-mail: `jhk@jhu.edu`

Abstract. A very personal introduction to the topics of the meeting is presented in which I try to raise the principal questions we would like to answer about every layer in the AGN system, from the edge of the black hole to a kiloparsec out into the host galaxy. Among the topics discussed are: dynamics and thermodynamics of the inner portions of accretion disks; the "natural history" of the broad line region; the structure of the dusty obscuring torus; the growth of black hole mass; and interaction between the AGN and its host galaxy.

1. Introduction

The topics of this meeting cover a very broad range of phenomena within AGN, all the way from the central black hole to the galactic environment. Because there is a very large contrast in characteristic lengthscale from the event horizon of the black hole to the host galaxy, AGN can be thought of in terms of an "onion skin" model, in which each factor of 10–100 in lengthscale differs qualitatively from the next.

Because, in the end, it is relativistic gravity that rules the roost, the sort of behavior characteristic of each layer depends not so much on its absolute distance from the center in cm or pc as on its distance as measured in gravitational radii. That is, the fundamental unit of distance most relevant to AGN is

$$r_g \equiv \frac{GM}{c^2} = 1.47 \times 10^{13} \frac{M}{10^8 M_\odot} \text{ cm}, \qquad (1)$$

where M is the mass of the central black hole.

Measuring the principal subregions of AGN in terms of these units, we may construct a handy table:

Subregion	Scale
Inner accretion disk	$\sim 10 r_g$
Broad line region	$\sim 10^3$–$10^4 r_g$?
Dusty obscuration	$\sim 10^5 r_g$
Warm absorbers	$\sim 10^5 r_g$?
Galactic feedback arena	$\sim 10^6$–$10^9 r_g$??

As suggested by the question marks, a number of these regions have not yet been well demarcated empirically; indeed, some would argue that even the distance scales without question marks remain in dispute. Nonetheless, this table indicates the very large dynamic range—$\sim 10^9$—from the innermost regions relevant to AGN to the outermost.

The remainder of this review will be organized along the lines of this table, with each of these regions discussed in turn. For each, I will briefly summarize some recent work that has caught my attention, but also, and more importantly, I will raise some of the questions about each that we would most like to answer.

2. Computing the central engine: $r \sim (1 - 100) r_g$

It has long been recognized (Novikov & Thorne 1973; Shakura & Sunyaev 1973) that angular momentum transport is key to moving matter inward in an accretion flow, but it is only comparatively recently that its actual mechanism has been identified. We now have excellent evidence that correlated MHD turbulence, excited by the magneto-rotational instability, is the fundamental means by which angular momentum is removed from gas and sent outward, permitting matter to sift gradually inward (Balbus & Hawley 1998).

Although entirely intractable to analytic calculation, MHD turbulence can be simulated numerically. The equations defining its evolution are: the familiar Navier-Stokes equations generalized to include magnetic forces, gravity, and possibly radiation forces; the mass continuity equation; the Faraday induction equation; and the equation of energy conservation (or at least an equation of state). When necessary, these equations can all be written in fully relativistic form without undue complication. As a set of partial differential equations, they can certainly be messy, but solving multi-term nonlinear equations is just what computers are good for. With large contemporary compute clusters, simulating MHD turbulence in the accretion context is an entirely feasible program.

Certain results have already become well-established. In particular, contrary to the inner disk boundary condition guessed by Novikov & Thorne (1973), magnetic stresses (measured in the fluid frame) do not cease at the innermost stable circular orbit (ISCO); in fact, they persist deep into the plunging region, and, when the black hole spins, continue all the way to the event horizon (Fig. 1: Krolik et al. (2005)).

Nonetheless, in the present state of the art, not every problem has been solved. There are two principal issues that present difficulties for these simulations: relating dynamics to thermodynamics and radiation; and the question of whether, and if so, how, dissipation on microscopic lengthscales may affect the character of dynamics on much longer lengthscales.

While the latter question remains a subject of much debate and confusion (Fromang et al. 2007), there has been some recent forward motion on the former. This progress has come on two fronts: detailed coupling of radiation forces to the dynamics in disk annuli, and the global energetics of black hole accretion.

It is possible to achieve very high spatial resolution in a simulation by focussing in on a small segment of the total volume. In disks, the best method for doing so is to restrict attention to an annular segment of limited azimuthal extent. When its radial thickness is small compared to its distance from the center, and its azimuthal spread is small compared to a radian, it may be "straightened out" into a "shearing box", a rectangular solid in which the rotational frequency is taken to vary linearly with radius. Because accretion disks are expected to be very optically thick, it is reasonable to solve the radiation transfer problem within such a box in the diffusion approximation, applying a "flux-limiter" only near the top and bottom photospheres to ensure that the flux never exceeds the radiation energy density times c. In addition, energy conservation can be maintained to high accuracy by requiring that any magnetic or kinetic energy lost to numerical error be transferred to gas thermal energy at every time-step in every cell (Hirose et al. 2006).

With these techniques, a thirty year-old question has now been settled: whether radiation-dominated disks are thermally unstable (Shakura & Sunyaev 1976). This is an important question because the generic state of the inner regions of all reasonably bright disks around relativistic central objects is one in which radiation dominates gas pressure (Shakura & Sunyaev 1973). By "inner regions", one means

$$r < 170 r_g \dot{m}^{16/21} (M/M_\odot)^{2/21}, \tag{2}$$

where $\dot{m}$ is the accretion rate in Eddington units. Thus, the part of the disk where the great majority of the light output is made should be radiation-dominated whenever the accretion rate is more than a small fraction of Eddington.

The original prediction of thermal instability for radiation-dominated disks was based

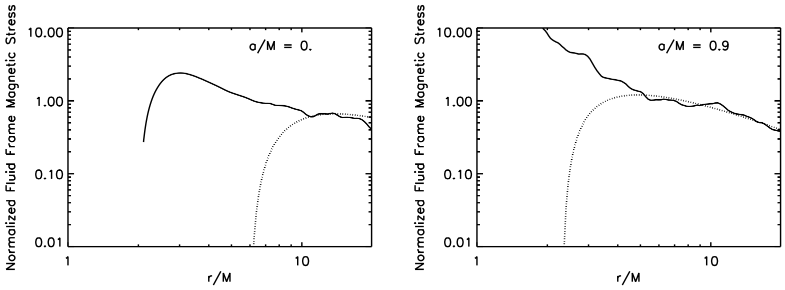

Fig. 1. Shell-integrated electromagnetic fluid-frame stress (solid curve) at an individual moment in simulations with a non-rotating black hole (left panel) and one with spin parameter $a/M = 0.9$ (right panel). In both cases, the dotted curve is the prediction of the Novikov-Thorne model for the time-averaged accretion rate in each of the simulations. Both figures are from Krolik et al. (2005).

on following the α-model—that the stress is always proportional to the total pressure—to its logical conclusions. In that model, the vertically-integrated dissipation rate is $\sim \alpha p_r h$, for characteristic radiation pressure p_r and vertical thickness h. When radiation force is the primary support against the vertical component of gravity, h is proportional to the total radiation flux, which, in thermal balance, is identical to the vertically-integrated dissipation rate. So fluctuations in the pressure lead to new heating fluctuations of twice their fractional magnitude and a corresponding amplification of the pressure fluctuation.

This all sounds very plausible; it's just not what disks do when the stress is due to MHD turbulence (see Fig. 2, taken from Hirose et al. (2008)). When MHD turbulence is the primary motor of the system, its fluctuations control the dissipation rate, and turbulent dissipation generates the heat for radiation pressure, leading to a correlation between magnetic stress and pressure. However, there is no discernible back-reaction by which the amplitude of the turbulent stress is influenced by the time-dependent magnitude of the pressure; in fact, fluctuations in the magnetic energy *lead* fluctuations in the radiation energy by about a cooling time.

New efforts are also being made to recalculate the total radiative efficiency of black hole accretion. Because the classical estimate (Novikov & Thorne 1973) depends critically on the no-stress inner boundary condition, the recent findings on magnetic stresses near the ISCO re-open what had once been thought to be a solved problem. Two methods have been tried so far: estimating dissipation from local stresses in purely dynamical simulations (Beckwith et al. 2008b), and introducing an optically thin toy-model cooling function into dynamical simulations that employ an intrinsically conservative algorithm (Noble, Krolik & Hawley 2008). Both indicate interesting augmentations above the NT number, but the results are still preliminary.

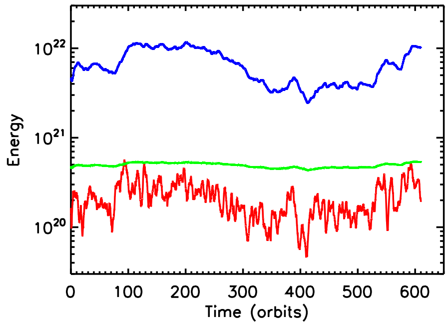

Fig. 2. Box-integrated radiation energy (blue curve), gas thermal energy (green curve), and magnetic energy (red curve) as functions of time in one of the two simulations reported by Hirose et al. (2008). The duration of the simulation, 600 orbits, was more than 40 cooling times.

Although these new developments are very interesting and suggestive, they do not touch several questions so important that, without answers to them, we cannot say we understand the central engines of AGN:

- Almost every AGN radiates $\sim$ 10% of its bolometric luminosity in X-rays, even though the characteristic temperature of their accretion disks cannot be much more than $\sim 10^5$ K. Presumably some sort of "coronal" gas exists whose temperature is $\sim 10^9$ K and receives $\sim$ 10% of the energy liberated by accretion: Where is it? Why does it receive so much power?
- Roughly $\sim$ 10% of the AGN population is "radio-loud" (Jiang et al. 2007), and therefore drives a strong jet. Why do some AGN produce much stronger jets than others? Although black hole spin has long been fingered as the factor most significant to jet strength (Blandford 1990; Wilson & Colbert 1995), the behavior of Galactic black hole binaries demonstrates that spin cannot be the *only* parameter regulating jet power. Recent simulational work suggests that magnetic topology may be a possible second parameter (Beckwith et al. 2008a); are there other factors as well?

3. The Broad Emission and Absorption Line Regions: $r \sim (10^3 - 10^4) r_g$

Although a topic of immense effort twenty and thirty years ago, this element of the AGN phenomenon has received far less attention recently. That this should be so reflects not so much the unimportance of the topic as its difficulty. Despite those years of hard work, we still do not know the answers to the most basic questions about this region: What *is* the broad line region? What is its relation to the accretion flow that powers AGN? Is it part of the disk or separate? Is it a smooth flow or large numbers of individual clouds? What forces—gravity, radiation, gas pressure, magnetic, . . .—are most important in determining its dynamics? Our understanding of these issues has advanced distressingly little since, for example, the review of Osterbrock & Mathews (1986), written more than twenty years ago.

Instead, in recent years AGN broad emission lines have been studied more for their diagnostic power in potentially revealing the mass of the central black hole rather than as an object of study in their own right (Peterson & Bentz 2006). But these efforts all rely on the assumption that the emitting gas's motions are entirely determined by simple orbital mechanics in a point-mass potential—if forces other than gravity are significant, the virial mass estimator $M \propto L^{1/2}(\Delta v)^2$ may not be meaningful (Marconi et al. 2008). Given the importance of black hole mass distributions in the context of galaxy evolution studies, this question demands a clear answer.

Virtually the same list of questions applies to the broad absorption line region—we know nothing about its place in the grand scheme of AGN. In fact, matters are even worse for the broad absorption line region than for the broad emission line region. Reverberation mapping (and photoionization analysis) provide good measures of the size scale of the broad emission line region, but they provide no help for placing the broad absorption line gas. All we can say with any confidence is that it must lie outside the emission line region because absorption features commonly cut into emission line profiles.

A new development may contribute to constraining models for emission line gas. A few years ago, Jeremy Goodman argued that AGN disks may not survive fragmentation due to their own gravity beyond $\sim 10^3 r_g$ from the central engine (Goodman 2003). If so, it would be very difficult to associate the broad emission line region with a smooth disk outflow. There may now be a direct observational constraint on this question: spectropolarimetry of six quasars has shown how the characteristic $F_\nu \propto \nu^{1/3}$ spectrum expected from thermally-radiating disks extends into the near-IR, revealing a conventional disk structure out almost to the radius where fragmentation might happen (Kishimoto et al. 2008). If these efforts can be carried to slightly longer wavelengths, we might be able to observe directly the part of the disk where either fragmentation or a disk-associated broad emission line region might occur.

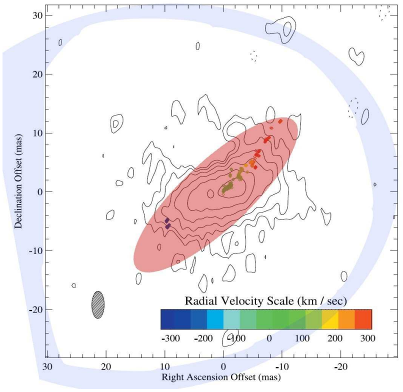

Fig. 3. Superimposed on an image of the radio continuum (black contours) and the H_2O masers (colored spots, radial velocity calibrated as shown in the color bar), the pink oval shows the resolved near-IR emission of the obscuring torus in NGC 1068, and the blue band shows an estimate of the scale of the (over-resolved) longer-wavelength IR (Raban et al. 2008). The beam-size in the near-IR is shown by the small gray oval in the lower-left corner.

4. Dusty obscuration: $r \sim 10^5 r_g$

Ever since the pioneering work of Antonucci & Miller (1985), we have known that in many (perhaps nearly all) AGN, there is a roughly toroidal belt of very optically thick dusty gas lying somewhere between the broad and narrow emission line regions. Although its presence can be made evident indirectly through spectropolarimetry (as in Antonucci & Miller (1985)) or through the creation of ionization cones or through its role in forming the infrared continuum, seeing its structure directly has been an elusive goal because its characteristic angular size, even in the closest examples, is only $\sim$ 10 milli arc-sec. Now that infra-red interferometry is a reality, this region can be directly imaged in at least a small number of especially favorable cases.

NGC 1068 (as always!) is the best example (Fig. 3: Raban et al. (2008)). Its warmest dust is spread over a region only $\simeq$ 1.5 pc in diameter, and considerably thinner in the transverse direction. This size is remarkably close to the what was estimated on the basis of its infrared luminosity many years ago (Pier & Krolik 1993). With renewed confidence that we have some understanding of the overall geometry of the obscuration, we can return to the effort to understand its dynamics and origin. From the very start, one of the principal questions regarding this gas is how it maintains a geometrically thick profile. Given orbital speeds of hundreds of km/s at its location, thermal motions capable of supporting it against the vertical component of gravity would be far too rapid to permit any dust to survive (Krolik & Begelman 1988). It is possible that the matter could be strongly enough clumped so as to make collisions (at highly supersonic speeds) relatively rare, but the stirring required to support these speeds poses a daunting puzzle(Krolik & Begelman 1988). Alternatively, this structure might be an example of a magnetized wind (Königl & Kartje 1994; Elitzur & Shlosman 2006).

One of the few things we know for certain about dynamics in this gas is that it must feel a strong radiation force. One way or another, a large part of the luminosity emitted by the central engine is reprocessed into the mid-IR by this matter (as demonstrated by the VLTI image and the strength and spectrum of the IR continuum); as this energy passes through the obscuration, it exerts a force whose associated acceleration is $\kappa\mathcal{F}/c$, where κ is the opacity per unit mass of the material and $\mathcal{F}$ is the magnitude of the local radiation flux. We know that this gas is dusty; if the ratio of dust/gas is the usual one, the thermally-averaged opacity for temperatures $\sim$ 100–1000 K, the temperature range most efficient in producing mid-IR light, is $\simeq$ 10–30 times the Thomson opacity (Semenov et al. 2003). It immediately follows that the radiation force is at least comparable to gravity if the potential in this region is dominated by the central black hole and its luminosity in Eddington units is at least $\sim$ 0.03–0.1 (Pier & Krolik 1992). With a few mathematical tricks, it is possible to compute the self-consistent structure of such an infrared radiation pressure-supported torus (an example is shown in Fig. 4a: Shi & Krolik (2008)).

Rather than beginning with forces and working toward structure, it is also possible to begin with the spectrum and work backward toward geometry. Elitzur and collaborators have argued on the basis of approximate inhomogeneous transfer calculations that the comparative weakness of silicate features in most Seyfert spectra suggests a highly clumped structure (most recently in Nenkova et al. (2008)). Interestingly, type 2 quasars sometimes *do* show strong silicate absorption, suggesting a possible change in internal structure as a function of luminosity (Zakamska et al. 2008). We already have good reason to believe that the solid angle covered by obscuration declines slowly with increasing luminosity (Ueda et al. 2003; Steffen et al. 2003; Barger et al. 2005; Hao et al. 2005; Treister et al. 2008), so further structural change dependent on luminosity would not be surprising. As genuine 3-d radiation transfer calculations become better able to handle strongly clumped media, more quantitative elucidation of these issues should become possible; a first assay at this problem may be seen in Fig. 4b (Schartmann et al. 2008). If further comparison with spectra provides stronger evidence for clumping, it will then become an interesting challenge to understand *why* the gas is clumped–does it merely reflect how the gas is injected into the torus, or is this a manifestation of some kind of thermal instability?

5. Black hole growth via mergers and accretion: $r \sim 1 - 10^9 r_g$

Much progress has been made in recent years in counting massive black holes. In the local Universe, the establishment of the bulge dispersion – black hole mass correlation (Gebhardt et al. 2000; Ferrarese & Merritt 2000) has permitted a reasonably secure census of the black hole mass function through the much easier avenue of counting stellar bulges (Yu & Tremaine 2002). However, the present-day mass function is only the end-product of a process that has lasted the lifetime of the Universe, in which black holes are first formed (by stellar collapse? by direct collapse of gas clouds?) and then grow by some combination of accretion and merger. We would like to know far more about how we arrived where we are.

A concise summary of these events would be contained in the answers to three questions:
- How many seed black holes contribute to a fully-grown black hole in a contemporary galactic nucleus?
- What fraction of all seed black holes end up in a galactic nucleus?
- What fraction of the mass in massive black holes today arrived as a result of accretion, and what fraction in black hole mergers?

"Seed black hole" is used here to denote an object with a newly-created event horizon.

A complementary set of questions may be asked about the galaxy side of the relationship:
- If AGN "feedback" can regulate star formation in the host, can we see clearer signs of this effect in contemporary, nearby galaxies?
- How does the galaxy regulate the accretion flow into the nucleus? What happens if the galaxy supplies mass at a rate greater than Eddington?

Unfortunately, in the present state of the art, it appears that the only way to attempt to answer these questions is through complicated numerical simulations with literally dozens of free parameters (e.g. Hopkins et al. (2006)). With these simulations, it is possible to create scenarios that appear to be plausible and reproduce many observable effects, but it remains very difficult to understand which as-

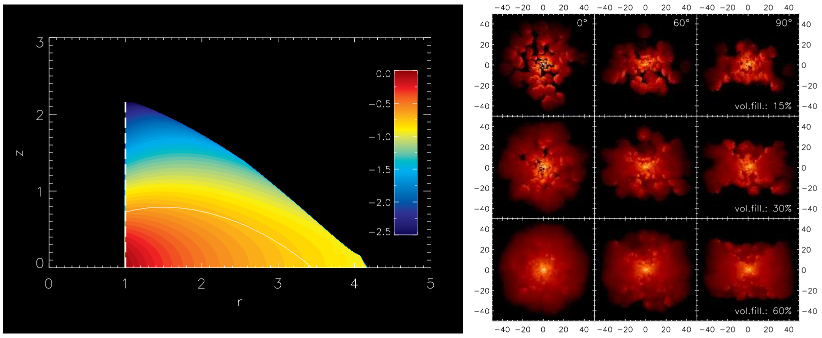

Fig. 4. (Left panel) Logarithmic contours of density in a self-consistent radiation-supported model (Shi & Krolik 2008). The thin white line marks the IR photosphere; the inner boundary is dashed because it is not well-defined in the model. (Right panel) Images of clumpy tori created with varying filling factors (rows from top to bottom are 15%, 30%, 60%) seen from different inclination angles (0°, 60°, 90° from left to right) (Schartmann et al. 2008).

pects of these scenarios are critical to which results, and which results can *only* be understood through the mechanisms employed. The generic problem is that many of the key mechanisms (e.g., star formation, heating of interstellar gas with energy derived from AGN) are treated with phenomenological prescriptions rather than physical ones.

As is so often the case in astrophysics, empirical methods may offer the best way forward. One such approach that offers hope for quantifying the role of black hole mergers is to detect directly the gravitational waves they generate. Recent advances in numerical relativity (e.g. Pretorius (2005); Baker et al. (2006); Campanelli et al. (2006)) have given us much greater confidence that we understand the strength and form of these waves. However, the only mission with a hope of detecting the gravitational radiation from massive black hole mergers (LISA) is likely 10–20 years away. In the interim, the best we can hope for is to learn what *photon* signals might indicate a black hole merger and search for them. There has been much activity in this area in the last few years (Milosavljevic & Phinney 2005; Kocsis et al. 2006; Shields & Bonning 2008; Schnittman & Krolik 2008). The upshot (for the time-being—this is a very rapidly-developing subject) is that if there is enough gas surrounding the merger to generate a substantial luminosity, it will be so optically thick as to degrade nearly all the light into the infrared. Good-sized mergers may produce quasar-class IR luminosities for $\sim 10^5$ yr; summing over all the mergers in the Universe, existing surveys such as COSMOS may contain a handful of such objects.

Another approach is to explore how the relationship between bulge structure and black hole mass has evolved over cosmological timescales. Because we cannot use on distant galaxies the stellar kinematical techniques that yield black hole masses in nearby galaxies, most workers have resorted to estimating the mass by the line-width method mentioned earlier. Here, however, we run head-on into one of the questions raised in that context: how trustworthy are these estimates? Conceptual questions about this method were discussed earlier in this review; here we point out that a number of studies making the assumption that AGN masses are given by the line-width relation have returned seemingly anomalous results. For example, Woo et al. (2008) find that even at redshifts as low as 0.3–0.5, the black hole masses given by this method are substantially larger than what would have been predicted on the basis of their host galaxies' bulge dispersions and the local correlation. It is hard to imagine how such a large change in galactic structure could have taken place over such a short time.

6. Conclusions

An introductory speaker's job is only to pose questions, not to answer them. I have every hope that subsequent talks will take up the implicit challenge.

Acknowledgements. I am grateful to the organizers for their special logistical efforts that made it possible for me to attend this meeting.

References

Antonucci, R.R.J. & Miller, J.S. 1985, ApJ 297, 621

Baker, J.G., Centrella, J., Choi, D.-I. & Koppitz, M. 2006, PRL 96, 111102

Balbus, S. A., & Hawley, J. F. 1998, Rev. Mod. Phys., 70, 1

Barger, A. J., et al. 2005, AJ, 129, 578

Beckwith, K., Hawley, J.F. & Krolik, J.H. 2008, ApJ 678, 1180

Beckwith, K., Hawley, J.F. & Krolik, J.H. 2008, MNRAS in press

Blandford, R.D. 1990, in Active Galactic Nuclei, ed. T. J.-L. Courvoisier & M. Mayor (Saas-Fee Advanced Course 20) (Berlin: Springer)

Campanelli, M., Lousto, C.O., Marronetti, P. & Zlochower, Y. 2006, PRL 96, 111101

Elitzur, M. & Shlosman, I. 2006, ApJ Letts. 648, L101

Ferrarese, L. & Merritt, D. 2000 ApJ Letts. 539, L9

Fromang, S., Papaloizou, J., Lesure, J. & Heinemann, T. 2007, A & A 476, 1123

Gebhardt, K. et al. 2000, ApJ Letts. 539, L13

Goodman, J. 2003, apJ 339, 937

Hao, L., et al. 2005, AJ, 129, 1795

Hirose, S., Krolik, J.H. & Stone, J.M. 2006, ApJ 640, 901

Hirose, S., Krolik, J.H. & Blaes, O.M. 2008, submitted to ApJ

Hopkins, P. et al. 2006, ApJSuppl. 163, 1

Jiang, L. et al. 2007, ApJ 656, 680

Kishimoto, M. 2008, Nature 454, 492

Kocsis, B., Frei, Z., Haiman, Z. & Menou, K. 2006, ApJ 637, 27

Königl, A. & Kartje, J.F. 1994, ApJ 434, 446

Krolik, J.H. & Begelman, M.C. 1988, ApJ 329, 702

Krolik, J.H., Hawley, J.F. & Hirose, S. 2005, ApJ 622, 1008

Marconi, A. et al. 2008, ApJ 678, 693

Milosavljevic, M. & Phinney, E.S. 2005, ApJ Letts. 622, L93

Nenkova, M. et al. 2008, ApJ in press

Noble, S.C., Krolik, J.H. & Hawley, J.F. 2008, in preparation

Novikov, I.D. & Thorne, K.S. 1973, in Black Holes, ed. C. DeWitt & B. S. DeWitt (New York: Gordon & Breach), 343

Osterbrock, D.E. & Mathews, W.G. 1986, Ann. Rev. Astron. Astrop. 24, 171

Peterson, B.M. & Bentz, M.C. 2006, New AR 50, 796

Pier, E.A. & Krolik, J.H. 1992, ApJ Letts 399, L23

Pier, E.A. & Krolik, J.H. 1993, ApJ 418, 673

Pretorius, F. 2005, PRL 95, 121101

Raban, D. et al. 2008, submitted to M.N.R.A.S.

Schartmann, M. et al. 2008, A. & A. 482, 67

Schnittman, J.D. & Krolik, J.H. 2008, ApJ in press

Semenov, D., et al. 2003, A. & A., 410, 611

Shakura, N.I. & Sunyaev, R.A. 1973, A&A, 24, 337

Shakura, N.I. & Sunyaev, R.A. 1976, MNRAS, 175, 613

Shi, J.-M. & Krolik, J.H. 2008, ApJ 679, 1018

Shields, G.A. & Bonning, E.S. 2008, ApJ 682, 758

Steffen, A.T. et al. 2003, ApJ Letts., 596, L23

Treister, E., Krolik, J.H. & Dullemond, C. 2008, ApJ 679, 140

Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 598, 886

Wilson, A.S. & Colbert, E.J.M. 1995, ApJ 438, 62

Woo, J.-H., Treu, T., Malkan, M.A. & Blandford, R.D. 2008, ApJ 681, 925

Yu, Q. & Tremaine, S. 2002, MNRAS 335, 965

Zakamska, N. et al. 2008, submitted to AJ