Disk Outflows and the Accretion Rate Gap

Mitchell C. Begelman 1⋆, Annalisa Celotti2⋆

1 JILA, University of Colorado, Boulder, CO 80309-0440, USA
2 International School for Advanced Studies (SISSA/ISAS), via Beirut 4, 34014 Trieste, Italy

ABSTRACT

We argue that the observed “accretion rate gap” — between black holes in radio-loud active galactic nuclei (AGN) accreting at close to the Eddington limit and those accreting at considerably lower rates — can be explained in terms of the adiabatic inflow-outflow (ADIOS) scenario for radiatively inefficient accretion. Whenever the accretion rate falls below a threshold value (corresponding to a luminosity $L_{\text{crit}}$) that depends on the viscosity parameter, $\alpha$, the inner region of the accretion disk — extending from the marginally stable orbit to $\sim 1000$ Schwarzschild radii — is susceptible to becoming hot and radiatively inefficient. If this happens, the disk luminosity decreases by a factor of $\sim 100$, as most of the matter originally destined to be swallowed is instead expelled in a wind. According to our conjecture, accretion flows onto black holes never radiate steadily in the range $\sim 0.01 L_{\text{crit}} < L < L_{\text{crit}}$, hence the inferred accretion rate gap. We expect the gap to exist also for black holes in X-ray binaries, where it may be responsible for state transitions and the luminosity fluctuations associated with X-ray nova outbursts.

Key words: galaxies:active — galaxies:nuclei — quasars:general — radio continuum:galaxies — black hole physics

1 INTRODUCTION

Several observational indicators point to surprisingly low accretion luminosities in low power radio galaxies and BL Lac objects, compared to radio-loud quasars. Evidence includes the lack of strong emission lines, limits on nuclear photon densities, and low levels of X-ray emission (see, e.g., Urry & Padovani 1995 for a review; Celotti, Fabian & Rees 1998; O’Dowd, Urry & Scarpa 2002; Di Matteo et al. 2003). The radiated output is orders of magnitude lower than that corresponding to the (Bondi) accretion rate of the detected hot gas at the accretion radius for a 10 per cent efficiency (Fabian & Rees 1995, Di Matteo et al. 2003). Limits on the accretion luminosity are particularly stringent for Sgr A*, where the observational limits indicate nuclear emission corresponding to a few $10^{-9}$ of the Eddington luminosity $L_{\text{Edd}}$ of the associated black hole (e.g., Yuan, Quataert & Narayan 2003), and M87, where the limit from X-rays corresponds to $\sim 10^{-7} L_{\text{Edd}}$, and $\sim 10^{-4}$ of the Bondi luminosity for a 10 per cent radiative efficiency (Di Matteo et al. 2003).

Recently, Marchesini, Celotti & Ferrarese (2004) have found evidence for bimodal behavior of the nuclear emission, in the sense that there appears to be a paucity of sources with bolometric accretion luminosities in the range $10^{43}$ erg s$^{-1} \lesssim L_{\text{bol}} \lesssim 10^{45}$ erg s$^{-1}$. While the low nuclear luminosities associated with accretion in low-power radio sources (and even the origin of the FRI/FRII dichotomy) have long been ascribed to radiatively inefficient flow scenarios (Rees et al. 1982; Begelman 1986; Fabian & Rees 1995; Zirbel & Baum 1995; Reynolds et al. 1996a,b; Ghisellini & Celotti 2001), we concentrate here on the actual transition to such a regime. Motivated by the findings of Marchesini et al. (2004), we argue in this Letter that a bimodal luminosity distribution is a natural consequence of the adiabatic inflow-outflow (ADIOS) scenario (Blandford & Begelman 1999, 2004) for radiatively inefficient accretion. After summarizing the observational evidence in Section 2, we show how bimodality can result from ADIOS (Section 3). We discuss the observational implications of our results in Section 4.

2 OBSERVATIONAL EVIDENCE FOR A GAP IN THE ACCRECTION RATE

Recent work on a sample of radio-loud sources, comprising low- (FRI, Fanaroff & Riley 1974) and high-power (FRII) radio galaxies and radio-loud quasars, not only finds full agreement with the indications of low accretion luminosities in the former systems, but also shows the presence of a bimodal behavior in their inferred accretion rate properties.
(Marchesini et al. 2004). The accretion rate in Eddington units, $\dot{m} \equiv L/\eta \nu L_{\nu, 27}$, where $\eta = L/Mc^2$ is the radiative efficiency, has been estimated from the black hole mass, inferred from its correlation with the host bulge B-magnitude (Merritt & Ferrarese 2001, Gebhardt et al. 2003, Haring & Rix 2004) and from the nuclear optical luminosity measured from HST images via a bolometric correction.

It turns out that while the black hole masses span a relatively large range, they are clustered around $10^{8} - 10^{9}$ $M_\odot$ and there is no systematic difference in their values between FRI radio galaxies, FRII radio galaxies, and radio-loud quasars. However, the distribution in bolometric luminosity, and (even more so) in the corresponding mass accretion rate, appears to be bimodal, with peaks defined around $\dot{m} \sim 10^{-3}$ for FRIs and around $\dot{m} \sim 1$ for broad line galaxies + quasars (for $\eta = 0.1$). The behavior of FRII narrow line radio galaxies reflects their spectroscopic (nuclear line) properties, in the sense that low-excitation line galaxies behave as FRI, while high excitation FRII galaxies likely have obscured nuclei (as already proposed, e.g., by Laing et al. 1994; Jackson & Wall 1999; Chiaberge, Capetti & Celotti 2002). If the obscuration of the high excitation radio galaxies is taken into account, the distribution in $\dot{m}$ reveals a region between the two peaks, extending about two orders of magnitude, few $10^{-3} \lesssim \dot{m} \lesssim$ few $10^{-1}$, which is characterized by a marked deficiency of sources.

We stress that the sample has been selected on the basis of the extended radio properties and thus it is not biased by the nuclear emission. (While the whole sample is not complete, it includes a complete subsample of nearby $|z| < 0.3$ 3C radio galaxies, which also reveals the presence of such a gap.) We refer to Marchesini et al. (2004) for a critical discussion of the methods, the possible role of observational biases — which turned out not be responsible for the deduced bimodality — and the findings.

As briefly discussed in the above paper, one can envisage different processes leading to such a distribution and in particular to a transition and a gap. Here we focus on the possibility that such a transition and gap arise as the flow becomes radiatively inefficient below a certain $\dot{m}$ and thus becomes subject to significant mass outflow.

3 ADIOS AND THE ACCRETION GAP

Radiatively inefficient accretion, as implied by the low nuclear luminosities in inactive and some active galaxies, might occur naturally at low accretion rates if the accreting gas density is low enough to inhibit the energy coupling between protons and electrons. Under such conditions the flow radiates very inefficiently, remaining hot and attaining a geometrically thick configuration.

Initially, it was supposed that dissipated energy would be retained by the accreting gas and advected into the black hole (Ichimaru 1977, Rees et al. 1982, Narayan & Yi 1994, Abramowicz et al. 1995). However, attempts to model these flows dynamically revealed an inconsistency in this argument: the transport of angular momentum through the flow deposits so much energy in the accreting gas that it becomes unbound at all except the innermost radii (Narayan & Yi 1994, 1995a; Blandford & Begelman 1999, hereafter BB99). This suggests that enough energy — and presumably mass — must be lost from the flow to keep it bound. BB99 proposed that this mass loss could make the accretion rate onto the black hole much smaller than the rate at which mass is supplied at the outer boundary. According to their “adiabatic inflow-outflow solution” (ADIOS) scenario, the mass inflow rate through the disk declines as $\dot{m} \propto r^{-n}$ between some outer transition radius, $r_t$, where the flow becomes hot, and the marginally stable orbit, $r_{\text{ms}}$, where it is captured by the black hole. The mass flux index $n$ satisfies $0 < n < 1$; values in the upper half of this range are plausible (Blandford & Begelman 2004).

In the ADIOS model, extremely low luminosities are possible because the reduced accretion rate compounds the intrinsic radiative inefficiency of the flow. However, the luminosity cannot drop below that produced by the thin accretion disk at $r > r_t$,

$$L_{tr} \sim \frac{\dot{m}(r_t)}{r_t^2} L_E,$$

where $r_{tr}$ is expressed in units of the Schwarzschild radius. Note that our definition of $\dot{m}$ differs from that used in papers by Narayan and collaborators by one factor of the efficiency $\eta$ (for which we adopt a value of 10 per cent) at $r_{\text{ms}}$, i.e., our values of $\dot{m}$ should be larger than those used by Narayan by a factor $\eta^{-1} \sim 10$. We also assume that the inner, hot flow does not pump a large amount of energy into the thin disk, but rather loses most of it in the wind. As a result, the torque across the inner edge of the thin disk at $r_{\text{tr}}$ is smaller than the Keplerian value, and we do not expect the local dissipation rate at $r \geq r_{\text{tr}}$ to be $\sim 3$ times the local release of gravitational binding energy (Shakura & Sunyaev 1973).

If $n \sim 1$, the hot flow region will contribute at most a luminosity comparable to that produced in the thin disk region. If $n$ is smaller, the amount of radiation produced near the center depends on the rate at which electrons are heated directly (as opposed to receiving energy from the protons), e.g., by reconnection (Bisnovatyi-Kogan & Lovelace 1997). We suppose that the outer disk luminosity gives a reasonable estimate for the total luminosity in cases where the inner disk becomes hot.

A hot accretion flow can exist at a given radius $r$ only if the local accretion rate, $\dot{m}(r)$, is smaller than some critical value, $\dot{m}_{\text{crit}}(r)$, that depends on the Shakura-Sunyaev viscosity parameter, $\alpha$. For $r \lesssim 10^3$,

$$\dot{m}_{\text{crit}} \sim \dot{m}_{\text{crit,max}} \sim 10\alpha^2$$

(Rees et al. 1982, Narayan & Yi 1995b, Abramowicz et al. 1995), and is insensitive to radius provided that the electrons and ions are thermally coupled only through Coulomb scattering (thus allowing a “two-temperature” flow) (Narayan 1996). The coefficient of $\alpha^2$ depends on details of the radiation environment, magnetic field and flow geometry, and could be as small as a few or as large as $\sim 50$. At $r \gtrsim 10^3$, $\dot{m}_{\text{crit}}(r)$ declines with radius at a rate that lies between $\propto r^{-1/2}$ and $\propto r^{-3/2}$, depending on the importance of line cooling (Esin 1997). The change in slope of $\dot{m}_{\text{crit}}(r)$ at $r \sim 10^3$ is associated with the fact that the virial temperature is comparable to the electron rest mass at this radius. The radial dependence of $\dot{m}_{\text{crit}}(r)$ is shown schematically in Fig. 1 (analogous plots for ADAF-like solutions, i.e., without mass loss from the flow, can be found in Narayan & Yi 1995b; Esin, McClintock & Narayan 1997;
accretion rates estimated in sources like Sgr A* and M87 and the extremely low levels of emission detected from the nucleus.

The spectrum associated with low-luminosity accretion is expected to be dominated by a quasi–thermal (cold) multicolor blackbody (and lines) from $r \gtrsim r_{\text{tr}}$, with frequency peaking around a few $10^{13}$ Hz, and a smaller total luminosity contribution from optically thin bremsstrahlung and Compton emission plus thermal cyclo-synchrotron radiation. The optically thin component might well dominate at optical wavelengths, if the transition to an optically thin outflow solution is rapid within $r_{\text{tr}}$. A non-thermal component might also be present if a fraction of the flow energy is dissipated into a non-thermal electron population; at present we do not know how to calculate its magnitude. While the thermal component is expected to be weakly variable, a non-thermal contribution produced close to the black hole could give rise to rapidly flaring emission (such that observed from Sgr A*; e.g., Markoff et al. 2001; Yuan et al. 2003).

A prediction specific to this scenario is the presence of “slow” winds associated with low $\dot{m}$ sources. In particular, we would expect significant mass outflows, $\dot{m}_{\text{out}} \sim \dot{m}(r_{\text{tr}}) \sim 100 \dot{m}(r_{\text{ms}})$, with velocities $v_{\text{out}} \sim v_{\text{Kepl}}(r_{\text{tr}}) \sim 10^4$ km s$^{-1}$, while outflows from high-$\dot{m}$ sources would have speeds $\sim c$ and would emanate from close to the black hole.

It should also be noted that the available flow energy reaching $\sim r_{\text{ms}}$ amounts typically to $\sim 10^{42-43}$ erg s$^{-1}$ for black hole masses in the range $\sim 10^6-10^9 M_\odot$. This appears to be barely sufficient to energize the jets associated with these systems (e.g., M87, Owen, Eilek & Kassim 2000, Reynolds et al. 1996a; 3C 84, Fabian et al. 2002) unless the jet forms on larger disk scales — as might be indicated by the high resolution imaging of M87 (Biretta, Junor & Livio 2002) — or involves energy extraction from the spin of the black hole.

Finally, we note that the transition between luminosity states and the presence of a gap in the accretion properties of radio-loud AGN could be analogous to spectral state transitions in black hole X-ray binary systems and microquasars. The values of the transitional $\dot{m}$, the nuclear spectral properties and possibly even the onset and nature of jet production (e.g., Fender et al. 1999, Meier 2001, Fender 2003) could all be broadly similar. In the X-ray binary case, in fact, it appears that jets are associated only with accretion states (very high and low/hard) corresponding to high and low accretion rates. There appear to be some differences, however. First, the results by Marchesini et al. (2004) show that in the case of AGN, the gap in accretion rates is larger than that in the case of stellar-mass black holes (where it typically spans a factor $\sim 10$, e.g., Nowak 1995, Fender 2003). Secondly, a complete analogy between X-ray binaries and AGN would require the identification of a population of non-jetted AGN with intermediate accretion rates (corresponding to the high/soft state in binaries). So far, the existence of an accretion rate gap has been established only for radio-loud AGN. It remains to be seen whether intermediate accretion rates occur in the more numerous radio quiet AGN, or if such intermediate states are entirely absent for supermassive black holes.
ACKNOWLEDGMENTS

The project was partially supported by NSF grant AST-0307502 (MB) and the Italian MIUR and INAF (AC). AC thanks the Fellows of JILA, University of Colorado, for their warm hospitality.

REFERENCES

Abramowicz M. A., Chen X., Kato S., Lasota J. P., Regev O., 1995, ApJ, 438, L37

Begelman M.C., 1986, Nature, 322, 614

Biretta, J. A.; Junor, W.; Livio, M., 2002, New Astr. Rev, 46, 239

Bisnovatyi-Kogan G. S., Lovelace R. V. E., 1997, ApJ, 486, L43

Blandford R. D., Begelman M. C., 1999, MNRAS, 303, L1 (BB99)

Blandford R. D., Begelman M. C., 2004, MNRAS, 349, 68

Celotti A., Fabian A.C., Rees M.J., 1998, MNRAS, 293, 239

Chiaberge M., Capetti A., Celotti A., 2002, A&A, 394, 791

Di Matteo T., Allen S.W., Fabian A.C., Wilson A.S., Young A.J., 2003, ApJ, 582, 133

Esin A.A., 1997, ApJ, 482, 400

Esin A.A., McClintock J.E., Narayan R., 1997, ApJ, 489, 865

Esin A.A., Narayan R., Cui W., Grove J.E., Zhang S.-N., 1998, ApJ, 505, 854

Fabian A.C., Rees M.J., 1995, MNRAS, 277, L55

Fabian A.C., Celotti A., Blundell K.M., Kassim N.E., Perley R.A., 2002, MNRAS, 331, 369

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

Fender R.P. et al. 1999, ApJ, 519, L165

Fender R., 2003, in Compact Stellar X-Ray Sources, eds. W.H.G. Lewin and M. van der Klis, Cambridge University Press, in press (astro-ph/0303339)

Gebhardt K. et al., 2003, ApJ, 583, 92

Ghisellini G., Celotti A., 2001, MNRAS, 327, 739

Häring N., Rix H.-W., 2004, ApJ, 604, L89

Ichimaru S., 1977, ApJ, 214, 840

Jackson C.A., Wall J.V., 1999, MNRAS, 304, 160

Laing R.A., Jenkins C.R., Wall J.V., Unger S.W., 1994, in The First Stromlo Symposium: The Physics of Active Galaxies. ASP Conference Series, Vol. 54, eds. G.V. Bicknell, M.A. Dopita, and P.J. Quinn, 201

Markoff S., Falcke H., Yuan F., Biermann P.L., 2001, A&A, 379, L13

Marchesini D., Celotti A., Ferrarese L., 2004, MNRAS, in press (astro-ph/0403272)

Meier D.L., 2001, ApJ, 548, L9

Menou K., Esin A.A., Narayan R., Garcia M.R., Lasota J.-P., McClintock J.E., 1999, ApJ, 520, 276

Merritt D., Ferrarese L., 2001, in The Central Kiloparsec of Starbursts and AGN: The La Palma Connection, ASP Conf. Series, Vol. 249, eds. J.H. Knapen, J.E. Beckman, I. Shlosman and T.J. Mahoney, 335

Narayan R., Mahadevan R., Quataert E., 1998, Theory of Black Hole Accretion Disks, eds. M.A. Abramowicz, G. Bjornsson, J.E. Pringle, Cambridge University Press, 148

Narayan R., Yi I., 1994, ApJ, 428, L13

Narayan R., Yi I., 1995a, ApJ, 444, 231

Narayan R., Yi I., 1995b, ApJ, 452, 710

Novak M.A., 1995, PASP, 107, 1207

O’Dowd M., Urry C.M., Scarpa R., 2002, ApJ, 580, 960

Owen F.N., Eilek J.A., Kassim N.E., 2000, ApJ, 543, 611

Pellegrini S., Venturi T., Comastri A., Fabbiano G., Fiore F., Vignali C., Morganti R., Trinchieri G., 2003, ApJ, 585, 677

Rees M. J., Begelman M. C., Blandford R. D., Phinney E. S., 1982, Nature, 295, 17

Reynolds C.S., Fabian A.C., Celotti A., Rees M.J., 1996a, MNRAS, 283, 873

Reynolds C.S., di Matteo T., Fabian A.C., Hwang U., Canizares C.R., 1996b, MNRAS, 283, L111

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

Urry C.M., Padovani P., 1995, PASP, 107, 803

Yuan F., Quataert E., Narayan R., 2003, ApJ, 598, 301

Yuan F., Narayan R., 2004, ApJ, in press (astro-ph/0401117)

Zirbel E.L., Baum S.A., 1995, ApJ, 448, 521