DRAFT VERSION OCTOBER 18, 2009
Preprint typeset using LATEX style emulateapj v. 08/13/06

POWERING CENTRAL CLUSTER AGN BY ACCRETION OR BLACK HOLE SPIN

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Draft version October 18, 2009

ABSTRACT

We investigate the possibility that AGN in brightest cluster galaxies (BCGs) are powered by angular momentum released by spinning, supermassive black holes (SMBH). Spin is poorly constrained by observed jet power alone because spin models require a finite accretion rate to tap the black hole's angular momentum. Nevertheless, assuming all systems are accreting at a constant fraction of the Eddington accretion rate, their jet powers estimated from X-ray cavities are consistent with a broad distribution of spin parameter. Using the highest power AGN i.e., with $P_{\rm jet} > 10^{46}$ erg s^{-1} such as MS0735 and Hercules A, we are able to constrain the (model dependent) critical transitional accretion rate between radiatively inefficient accretion flows (ADAFs) and quasars to be $\dot{m}_{\rm crit} \simeq 0.02$, which is consistent with other estimates. The high accretion rate required to power the AGN outburst in MS0735 relative to its meager gas supply, and the need for spin parameters uncomfortably close to unity suggest a high efficiency of spin powering i.e., $P_{\rm jet} > \dot{M}c^2$, or that its SMBH mass substantially exceeds the Magorrian value. We show that sufficient levels of cold molecular gas are available in most systems to power their AGN by accretion. However, no correlation is found between AGN power and the molecular gas supply in central cluster galaxies, as might be expected if their AGN are powered by accretion alone.. This lack of correlation suggests that AGN power is governed not by the overall gas supply, but perhaps by processes near to the SMBH. Bondi accretion from hot atmospheres is generally unable to fuel AGN outbursts in clusters.

Subject headings: galaxies: clusters: general – galaxies: cooling flows – Active Galactic Nuclei

1. INTRODUCTION

Feedback from active galactic nuclei (AGN) has emerged in recent years as a fundamental process shaping massive galaxies and the hot atmospheres surrounding them (Benson 2005, Hernquist et al. 200X, McNamara & Nulsen 2007). AGN are thought to be powered by gravitational binding energy released by accretion onto supermassive black holes (SMBH). While much of the accretion energy may be released promptly in the form of radiation and mechanical outflows, accreted angular momentum may spin-up the central SMBH, storing rotational energy that may be released over longer timescales.

There are good reasons to consider spin-powered feedback in clusters. They include: (1) The energy available in a spinning black hole is significant with respect to the thermal energy of the X-ray atmosphere. A $10^9 M_\odot$ black hole spinning near its maximal rate stores $\sim 10^{62}$ erg of energy. At late times, this energy may be released in the form of mechanically-dominated jets that couple efficiently to their surrounding hot atmospheres (Bîrzan et al. 2004, Merloni & Heinz 2007). Furthermore, AGN may contribute significantly to the excess entropy (energy) in hot halos, and would be able to suppress cooling and star formation in galactic bulges at late times (Voit & Donahue 2005). (2) Gas accretion at some level is required to maintain the poloidal magnetic field near the black hole (i.e., $\dot{M} \propto B_p^2$) which couples the jet to the black hole's rotational energy. The coupling between jet power and $\dot{M}$ provides a natural means to regulate power output through feedback (McNamara et al. 2009). (3) While most central cluster galaxies in cooling flows have sufficient molecular gas reserves to power their AGN by accretion alone, no clear trend between molecular gas mass and jet power, as might be expected in rapidly accreting systems, is found (see below). Some systems (e.g., MS0735.6+7421) are low on fuel reserves compared to the accreted mass required to power their AGN. The implied accretion efficiency (ratio of accreted mass to fuel supply) is uncomfortably high in some systems making spin an appealing alternative to accretion alone.

Radio jets are thought to form in radiatively inefficient, advection-dominated accretion flows (ADAFs) associated with hot, thick disks accreting far below the Eddington accretion rate (Narayan & Yi 1995, Narayan & Quataert 2005, Wu & Cao (2008)). In this context, several models have been proposed to power and collimate them ****(Begelman, Blandford & Rees 1984)**** including the Blandford-Znajek (BZ) mechanism (Blandford and Znajek 1977) and its variants. The BZ mechanism derives power from a spinning black hole through torques applied by magnetic field lines threading the horizon and inner region of the accretion flow. Open field lines wind up along the hole's spin axis creating a collimated outflow in the form of a radio jet. Variants of the BZ model, so-called hybrid models, are able to boost the power output per gram of accreted mass through magnetic flux trapping in the plunge region of the hole (Reynolds et al. 2006; Beckwith, et al. 2009), and frame-dragging (Meier 2001).

Several recent studies have attempted to test BZ models against observation. Cao & Rawlings (2004) found that BZ failed to power the most luminous 3CR radio galaxies and suggested that FR 1 galaxies are powered instead by hidden accretion disks. Using a hybrid variant, Wu & Cao (2008) showed that a BZ-based model is able to explain the dichotomy between FR I and FR II galaxies, provided that FRIs harbor advection dominated flows (ADAFs) where ADAFs are geometrically thick, optically thin disks accreting below

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the critical rate. Using an updated hybrid model, Nemmen et al. (2007) argued that rapidly-spinning black holes in elliptical galaxies fueled by Bondi accretion would be powerful enough to heat their hot halos and to quench cooling flows.

In this *Letter* we evaluate the potential role of spin in generating powerful AGN outbursts in the cores of clusters by comparing their total jet power to the hybrid spin model. ***As mentioned above, the hybrid spin model generally provides more power than its BZ counterpart by further amplification of the magnetic field through dragging of the frame based on the results explored by many authors such as Ghosh & Abramovicz (1997), Meier (2001), Nemmen et al. (2007), and Wu & Cao (2008). We here follow Nemmen et al. (2007)'s implementation of the hybrid spin model within the context of a self-simliar ADAF structure (Narayan & Yi 1995).*** Accretion and spin power are degenerate in ***spin models*** because a substantial level of accretion, whose value cannot be measured directly, is generally required to extract the spin energy. We therefore assume at the outset that all systems are ADAFs accreting at the maximum rate, normalized to the Eddington value, and explore its implications. Our analysis is unique in our use of jet power derived from X-ray cavities, which is more accurate than other methods and can be compared directly to jet models. ***Our*** sample includes 30 objects taken from the literature with jet powers in the range $P_{\rm jet} \sim 10^{42} - 10^{46}$ ergs^{-1} based on X-ray cavities and shock front measurements from the literature. Black hole mass estimates were derived from R-band absolute magnitudes taken from Rafferty et al. (2006), and folded through the black hole mass versus bulge magnitude relation of Lauer et al. (2007).

2. TAPPING THE POWER OF A ROTATING BLACK HOLE

BZ jet power is given by the expression,

$$P_{jet}^{BZ} = \frac{1}{32}\omega_F^2 B_p^2 R_H^2 j^2 c. \tag{1}$$

$R_H = [1+(1-j^2)^{1/2}]GM_{bh}/c^2$ is the horizon radius, $j \equiv J/GM_{bh}^2/c$ is the black hole spin parameter, and $\omega_F \equiv \Omega_F(\Omega_H - \Omega_F)/\Omega_H^2$ describes the angular velocity of the field lines Ω_F relative to that of the hole, Ω_H. When $\omega_F = 1/2$ the power output is maximized. B_p is the poloidal magnetic field at $R = R_{ms}$. R_{ms} is the marginally stable orbit of the accretion disk or the jet formation region (see Nemmen et al. 2007). The black hole is assumed to reside in a geometrically thick hot disk associated with ADAF.

This expression shows that for a given black hole mass and spin parameter, the jet power depends primarily on the poloidal magnetic field strength (pressure) threading the disk and ergosphere which exerts a torque on the spinning hole. Hybrid spin models (eg., Meier 2001, Nemmen et al. 2007) are able to enhance jet power by including field amplification from the rotation of the accretion disk as well as spin of the black hole. A key aspect of hybrid models is that the poloidal magnetic field strength is not an arbitrary parameter. The magnetic filed is maintained by the accretion rate through the disk and ergosphere such that $B_P^2 \propto \dot{m}$ (Meier 1999, 2001, Nemmen et al. 2007). Because a substantial level of accretion is required to tap spin power, observational estimates of the spin parameters of radio galaxies (eg., Cao & Rawlings 2004, McNamara et al. 2009, Daly 2009) cannot be decoupled from the accretion rate, an issue we focus on here.

3. EVALUATING AGN CAVITY POWER VERSUS SPIN POWER: SPIN-ACCRETION DEGENERACY

In Fig. 1 we plot jet power based on X-ray cavity measurements against the estimated black hole mass of their central cluster host galaxies. The jet powers span the range 10^{42} erg s^{-1} to $10^{46.5}$ erg s^{-1}, and their black hole masses range between $\sim 10^{8.5} - 10^{10}$ M$_\odot$. Four objects with dynamically determined black hole masses are highlighted in blue. All fall reassuringly within the range of black hole masses estimated from bulge luminosities.

The total energy associated with a maximally spinning, 10^9M$_\odot$ black hole corresponds to $\sim 10^{62}$ erg. Its potential power output would be $P_{rot} \approx 10^{44\rightarrow 47}$ erg s^{-1} for spin-down timescales of $10^{7\rightarrow 10}$ yr (Martini 2004). The power output assuming a spin-down period of 10^8 yr, shown as the upper solid line labeled "Pure Rotation" in Fig. 1, lies well above the observations and clearly demonstrates that spin is a potentially important power source.

Whether AGN release energy in the form of radiation from a disk or in a jetted outflow is thought to depend on the the mass of the black hole and its accretion rate. When the accretion rate relative to the black hole mass is large, AGN power emerges primarily as radiation from an optically thick, geometrically thin disk. When the accretion rate falls below a critical value in Eddington units $\dot{m}_{\rm crit} = \dot{M}_{\rm crit}/\dot{M}_{Edd}$, radio emission dominates and a jetted outflow is formed. Observations of Galactic X-ray binaries suggest $\dot{m}_{\rm crit} \sim 10^{-4} - 10^{-1}$ (Gallo, Fender, & Pooley 2003, Churazov et al. 2005). The objects in Fig. 1 are dominated by jets, and show little evidence for strong nuclear emission. They are consistent with being radiatively inefficient accretion flows or ADAFs accreting near to or below $\dot{m}_{\rm crit}$. Lacking measurements of their true accretion rates, we assume initially that all are accreting at the critical rate $\dot{m}_{\rm crit}$, and we evaluate their spin parameters, j, using the Nemmen et al. (2007) model. We further assume a viscosity parameter $\alpha = 0.2$, as in the range expected in a turbulent accretion flow (see Meier 2001, Nemmen et al. 2007).

The solid line labeled "critical accretion" in Fig. 1 shows the calculated jet power from holes with a spin parameter $j = 1$ as a function of their mass. The broken parallel lines show the calculated jet power as the spin parameter declines. In order to achieve sufficiently high jet powers to include all of the data in Fig. 1, the model requires an accretion rate $\dot{m}_{\rm crit} = 0.02$ for spin parameters approaching unity in MS0735 and Hercules A. Overall, the data imply spin parameters lying in the range $0.01 \lesssim j \lesssim 1$ and with a median value of $\simeq 0.6$. As expected, we are generally unable to place interesting constraints on spin.

The assumption of constant $\dot{m}_{\rm crit}$ implies a physical mass accretion rate $\dot{M}$ that increases in proportion to black hole mass. For example, With a black hole mass of about $10^{9.8}$M$_\odot$, M87 would be accreting at $\dot{M}_{\rm crit} \sim 1.4$ M$_\odot$ yr^{-1}. Accretion at this rate would deplete its gas reservoir in less than 10^7 yr. Moreover, the gravitational binding energy released by accretion would dramatically exceed the observed jet power and radiation emerging from the nucleus, implying that it is being advected into the SMBH. Accretion at this level further implies that its SMBHs grew by $\sim 10\%$ of its dynamical mass over the past 100 Myr without commensurate growth of the bulge by star formation. Such high accretion rate is prohibitively large compared to its hot and cold gas supply (see arguments in McNamara et al. 2009 and below). Therefore, the assumption that all systems are accreting at or near the critical rate seems to be unrealistic.

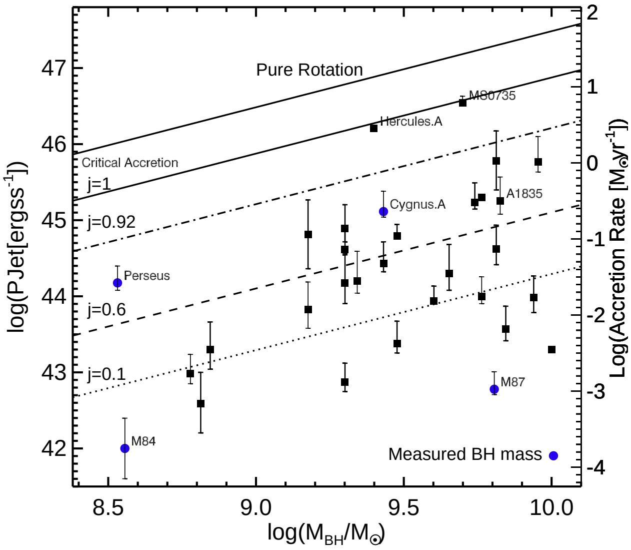

FIG. 1.— The jet (cavity) power versus black hole mass. The top line labeled "Pure Rotation" represents the classical energy available from a maximally rotating black hole. The remaining lines represent the jet power of hybrid model from critically accreting black holes, $\dot{m}_c = 0.02$, with spin parameters between 1 to 0.1. The filled blue points represent jet powers from central cluster galaxies with measured black hole masses (Wilman et al. 2005; Gebhardt & Thomas 2009). Cavity and shock front data are from Rafferty et al. (2006), Wise et al. (2007), Nulsen et al. (2005), and McNamara et al. (2009).

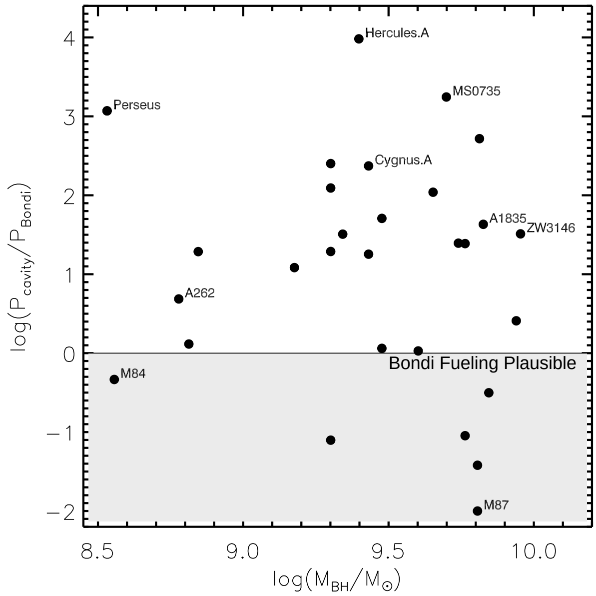

FIG. 2.— The ratio of jet power, P_{Cavity}, to Bondi accretion power, $P_{Bondi} = 0.1\dot{M}_{Bondi}c^2$, for 28 objects against their black hole mass.

Alternative interpretations of the dispersion in observed jet power include that all systems harbor SMBHs with high spin parameters but vary broadly in their accretion rates, or that both the accretion and spin rates are varying in such a way as to produce the observed variation of jet power. At the moment there is little hope of placing interesting constraint on spin in individual objects, perhaps with the exception of the most powerful systems.

3.1. *A Constraint on $\dot{m}_{\rm crit}$*

Although we cannot discriminate between spin and accretion power without appealing to additional constraints, we are able to place interesting limits on the plausible range of $\dot{m}_{\rm crit}$.

Assuming all accreting black holes are governed by a single value of the critical accretion parameter, accretion rates as low as $\dot{m} \sim 10^{-4}$ would be unable to supply a sufficiently strong value of B_p to achieve the high jet powers shown in Fig. 1 using the Nemmen et al. (2007) model. To do so requires a remarkably high ratio of (spin) jet power to accretion power, ie.,*** $P_{jet} > \dot{\rm M}{\rm c}^2$***. Such a high efficiency cannot be achieved in Nemmen's model. Low values of $\dot{m}_{\rm crit}$ then seem unlikely.

The most powerful systems, MS0735 and Hercules A, are able to place interesting limits on the high end of $\dot{m}_{\rm crit}$. Neither of these systems show evidence of nuclear quasar activity (see McNamara et al. 2009, Nulsen et al. 2005), and are presumably accreting below the critical rate. As we discussed earlier, Nemmen's model is able to achieve their high jet powers assuming $j \simeq 1$ and $\dot{m} = 0.02$. This value corresponds to physical accretion rates of 2.2$M_\odot$ yr^{-1} for MS0735, and 1.1$M_\odot$ yr^{-1} for Hercules A respectively. If we ease back on the spin parameter, the critical rate would exceed 0.02, resulting in an accretion rate that is already too large relative to MS0735's gas supply and star formation rate (see McNamara et al. 2009). This problem may be avoided if ***$P_{jet} > \dot{\rm M}{\rm c}^2$***, which is a problem in current spin models. Alternatively, the same output power can be achieved with a lower spin parameter if the SMBH is more massive than the Magorrian relation predicts. The unusually large core in MS0735's central galaxy suggests that it may harbor a black hole exceeding 10^{10} $M_\odot$.

4. ACCRETION POWER: BONDI ACCRETION & COLD ACCRETION

Accretion releases gravitational binding energy that can emerge in the form of a radiation or a jet unless it is advected into the black hole. Ignoring spin for the moment, the accretion rate required to power the AGN in our sample assuming $P_{\rm jet} = \epsilon\dot{M}c^2$, where $\epsilon = 0.1$, is shown on the right hand side of Fig. 1. The accretion rates vary between $\dot{M} \simeq 10^{-4}\,M_\odot\,{\rm y}^{-1}$ in the gE galaxy M84 to several $M_\odot\,{\rm y}^{-1}$ in Hercules A and MS0735. Assuming the fuel is supplied by Bondi accretion of the hot atmosphere, the accretion rate would scale as $\dot{M}_{\rm B} \propto n_e(kT)^{-3/2}M_{BH}^2$, where n_e is the halo gas density, T is its temperature, and M_{BH} is the black hole mass. Bondi accretion will be effective only when the hot atmosphere is sufficiently dense near the Bondi radius to feed the SMBH at a rate consistent with $P_{\rm jet}$. [This is apparently not true for most objects in our sample (see Rafferty et al. 2006).?]

In Fig. 2 we plot the ratio of cavity power to Bondi accretion power against black hole mass. We assume $P = \eta\epsilon\dot{M}c^2$ where the efficiency of accretion through the Bondi sphere $\eta = 1$, ie., all of the mass reaching the Bondi radius is accreted onto the hole. Fig. 2 shows that with the exception of the lower power systems residing in the grey region of the plot, Bondi accretion would be unable to power the outbursts.

A combination of falling gas temperature and rising gas density near the (unresolved) Bondi radii, in addition to the possibility that the black hole masses may in some cases be underestimated would increase the number objects that could be powered by Bondi accretion in Figure 2 (see Rafferty et al. 2006 for a thorough discussion). However, the assumption that $\eta = 1$ is overly optimistic. Mass lost in winds blowing

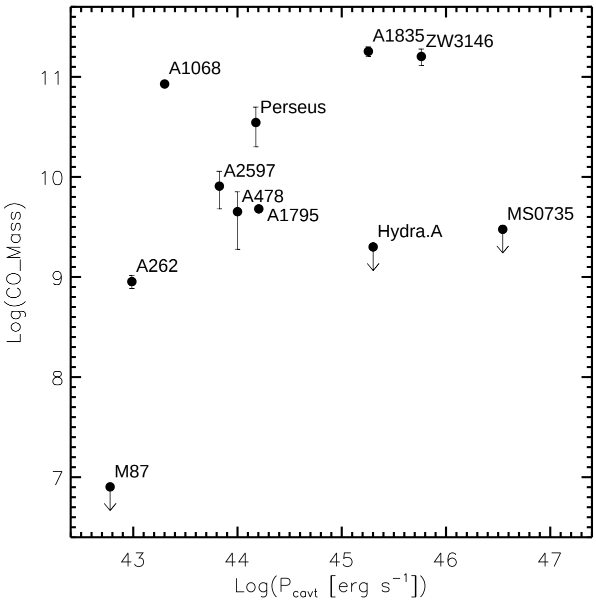

FIG. 3.— Molecular gas masses from Edge et al. (2001), Salome and Combes (2003, 2004, 2006), Salome et al. (2008), and Tan et al. (2008) versus jet power. The upper limits are 3σ.

from the accretion disk, angular momentum stalling of the accreting gas (eg., Neilsen & Lee 2009, Proga 2009), and other factors will drive η well below unity (Merloni & Heinz 2008, Benson & Babul 2009), reinforcing our conclusion that Bondi accretion alone cannot power these systems. Furthermore, unless $j \sim 1$ and **$P_{jet} > \dot{\mathrm{M}}\mathrm{c}^2$**, the Bondi mechanism would be unable to supply enough fuel to tap spin in the most powerful outbursts.

Cold molecular gas is a more likely fuel source. In Fig. 3 we plot molecular gas masses against jet power for the subset of our objects with CO measurements available in the literature. The molecular gas masses typically lie between $10^9 - 10^{11}\ M_\odot$. Only M87's upper limit $< 8 \times 10^6\ M_\odot$ lies substantially below this range.

If these AGN are powered by accretion or spin, one would naively expect the gas supply to correlate with jet power, but it does not. For example, Abell 1835's jet power lies nearly two orders of magnitude below MS0735's, while its molecular gas mass lies more than two orders of magnitude above MS0735's. This large discrepancy between the available gas supply and AGN power possibly reflects large temporal variations in their accretion history and suggests that process near to the black hole, not the overall gas supply, determine jet power. Nevertheless, the overall level of molecular gas or their upper limits are sufficient to power the AGN in most systems. The required masses $M_{acc} \sim E_{cav}/(0.1c^2)$ are 10^6 to $10^9 M_\odot$, within the range observed in Figure 3. Exceptions include MS0735 and possibly Hercules A, whose gas supplies are probably inadequate to fuel their AGN by accretion alone (McNamara et al. 2009).

5. DISSCUSION

AGN in the cores of cooling flow clusters can be plausibly powered by black hole spin, but with a broad range of spin parameter provided disk accretion proceeds at a rate $\dot{m} = \dot{m}_{\rm crit} \approx 0.02$, which may be close to the critical accretion rate below which ADAFs form. Because of the dependence of spin power on accretion we are unable to distinguish between spin and accretion powered systems. By virtue of their high jet power, MS0735 and Hercules A provide the most interesting constraints on both spin parameter and the value of $dotm_{\rm crit}$. In order to achieve high jet powers while avoiding excessive accretion rates, the efficiency must be high, i.e., $P_{jet} > Mc^2$ or the black hole mass must be larger than the Magorrian value (see McNamara et al. 2009). High efficiencies may be achieved in theory in systems where j approaches unity (Benson and Babul 2009), systems with retrograde spin relative to the angular momentum axis of the accretion disk (Garofalo 2009), or possibly when the magnetic pressure becomes enhanced in the plunge region beyond the last stable orbit (Reynolds et al. 2006).

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