ISOTROPIC HEATING OF GALAXY CLUSTER CORES VIA RAPIDLY REORIENTING ACTIVE GALACTIC NUCLEUS JETS

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Received 2012 September 17; accepted 2013 March 3; published 2013 April 9

ABSTRACT

Active galactic nucleus (AGN) jets carry more than sufficient energy to stave off catastrophic cooling of the intracluster medium (ICM) in the cores of cool-core clusters. However, in order to prevent catastrophic cooling, the ICM must be heated in a near-isotropic fashion and narrow bipolar jets with $P_{\text{jet}} = 10^{44-45} \text{ erg s}^{-1}$, typical of radio AGNs at cluster centers, are inefficient in heating the gas in the transverse direction to the jets. We argue that due to existing conditions in cluster cores, the supermassive black holes (SMBHs) will, in addition to accreting gas via radiatively inefficient flows, experience short stochastic episodes of enhanced accretion via thin disks. In general, the orientation of these accretion disks will be misaligned with the spin axis of the black holes (BHs) and the ensuing torques will cause the BH’s spin axis (and therefore the jet axis) to slew and rapidly change direction. This model not only explains recent observations showing successive generations of jet–lobe–bubbles in individual cool-core clusters that are offset from each other in the angular direction with respect to the cluster center, but also shows that AGN jets can heat the cluster core nearly isotropically on the gas cooling timescale. Our model does require that the SMBHs at the centers of cool-core clusters be spinning relatively slowly. Torques from individual misaligned disks are ineffective at tilting rapidly spinning BHs by more than a few degrees. Additionally, since SMBHs that host thin accretion disks will manifest as quasars, we predict that roughly 1–2 rich clusters within $z < 0.5$ should have quasars at their centers.

Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: clusters: intracluster medium – galaxies: jets – X-rays: galaxies: clusters

1. INTRODUCTION

The cool-core conundrum poses a critical challenge for theoretical models seeking to explain the observed properties of clusters of galaxies. The intracluster medium (ICM) in cool-core clusters should, according to simple theoretical arguments and direct observations of X-ray emission (Fabian et al. 1984), be cooling and dropping out at prodigious rates, yet only relatively meager amounts of cold gas is seen in cluster centers. High-resolution X-ray and radio observations of the cores of these clusters indicate that the dominant central galaxy (hereafter referred to as the BCG—the brightest cluster galaxy) invariably shows evidence of active galactic nucleus (AGN) behavior, often in the form of powerful bipolar jets and pairs of approximately spherical depressions in the X-ray emissions, typically interpreted as being due to bubbles of relativistic plasma that have been inflated in the ICM by the jets. The inferred power of the jets is comparable to the radiative losses in the ICM and the case—based on theoretical arguments and observational inference—in favor of this radio-mode AGN energy injection into the ICM being the most likely explanation for the diminished cooling is fairly robust (McNamara & Nulsen 2007). However, the precise manner in which this energy is injected into and distributed within the ICM remains an open question. The mechanics of how an apparently narrow bipolar outflow is able to heat the ICM in a near-isotropic fashion is particularly vexing (cf. Vernaleo & Reynolds 2006).

In a recent simulation study, Gaspari et al. (2011) claim to have solved the “isotropy” problem in cool-core galaxy clusters and successfully stave off catastrophic cooling over a cosmological timescale. In their most successful and best explored scheme, the jets are modeled as explosive, massive, subrelativistic outflows with $P_{\text{jet}} = 10^{47-48} \text{ erg s}^{-1}$ and a duty cycle of $\sim 6\%$. The nearly isotropic heating of the cool core is affected by local shocks and strong turbulence induced by the powerful, explosive outbursts (see also Gaspari et al. 2012). Success, however, comes at a cost. The mass accretion rate (onto the black hole, BH) required to power the jets is $M \approx 0.8 (P_{\text{jet}}/10^{47} \text{ erg s}^{-1}) M_{\text{Edd}}$, where $M_{\text{Edd}} \equiv (L_{\text{Edd}}/0.1 c^2) \approx 22 M_{\odot} M_{\odot} \text{ yr}^{-1}$ is the Eddington accretion rate and $M_{\odot} \equiv (L_{\odot}/10^9 M_{\odot})$ is the BH mass in units of $10^9 M_{\odot}$. Apart from the jets, an AGN accreting at such high rates will also radiate copiously and will be identified as a quasar. Observations, however, do not support this. Neither H1821+643 nor B0910+410, the only two AGNs at the centers of cool-core clusters in the $z < 0.5$ universe that are quasars, shows any evidence of current jet activity (Russell et al. 2010; O’Sullivan et al. 2012). While the AGN in M87, though actively driving a jet, is not a quasar and neither was the recent burst of jet activity by the central AGN in Perseus (Nagai et al. 2010) accompanied by quasar-like emissions.

Recent detailed observational studies of individual cool-core groups and clusters suggest an alternate solution to the “isotropy” problem. Many of the systems show evidence of multiple generations of radio jets and cocoons as well as X-ray cavity pairs (cf. McNamara et al. 2001; Dunn et al. 2006; Wise et al. 2007; Forman et al. 2007; Giacintucci et al. 2011; Randall et al. 2011; O’Sullivan et al. 2012). In a number of these systems (e.g., M87 [Virgo], NGC 1275 [Perseus], NGC 4636, NGC 5044, NGC 5813, Hydra A, MACS J0913.7+4056 [also known as CL09104+4109 and hereafter referred to as CL09]), successive generations of jet–lobe–bubbles are significantly offset from each other in the angular direction on the sky, with respect to the cluster center. If the AGN jet byproducts can
trace a nearly isotropic angular distribution about the cluster center, then so should the associated heating. If the timescale over which the jet energy is redistributed is shorter than the cooling time, then the isotropy problem is not an issue. In the following discussion, we assert that “isotropic heating” and the angular misalignment of jet byproducts are related processes. The question then is: what is the most likely explanation for the observations given the conditions in the cores of cool-core clusters?

Potential explanations can be classified into two broad categories: the first invoke interactions between the jet and the “ICM weather,” i.e., large-scale turbulence, wakes, and bulk velocities induced either by mergers and orbiting substructure (Heinz et al. 2006; Morsony et al. 2010). Undoubtedly, jet–ICM interactions must be occurring at some level; however, there are a number of factors that suggest that its impact in cores of real cool-core clusters is less than in the simulations. For example, the simulation study by Morsony et al. (2010) shows that strong large-scale turbulent flows triggered by mergers can result in large angular displacement of the low-density jet material (e.g., bubbles) from the jet axis; however, the required flow velocities are present only in unrelaxed cluster cores; i.e., cores that are either being churned by an ongoing major merger or are in the recovery phase following a major merger. Most cool-core clusters do not show any evidence of disturbances associated with recent major mergers (Poole et al. 2007). In fact, comparative analyses of X-ray and lensing cluster data (e.g., Mahdavi et al. 2008, 2013; Zhang et al. 2010) indicate that cool cluster cores are dynamically relaxed. Additionally, the simulations show that large-scale merger-induced turbulence has no impact on the direction of the high-velocity jet flow on small scales and, therefore, cannot account for the apparent change of orientation in the jet directions on subkiloparsec to kiloparsec scales as observed in, for example, CL09, Virgo, and Perseus (cf. Section 2, Table 1).

The alternate class of models invokes changes in the orientation of the spin axis of the supermassive black holes (SMBHs) that are powering the jets to explain the misalignment between the successive generations of jets–lobes–bubbles. This explanation is premised on the understanding that (1) the angular position of any particular feature (jet/cavity/bubble) is indicative of the direction of the jet axis at the time when the feature was formed and (2) the jet axis is always coincident with the BH’s spin axis. The spin orientation of BHs can change as a result of precession (cf. Pizzolato & Soker 2005b; Lodato & Pringle 2006; Liu & Chen 2007; Campanelli et al. 2007b, and references therein), spin flips (cf. Merritt & Ekers 2002; Campanelli et al. 2007a; Kesden et al. 2010 and references therein), or slewing (or tilting) of the BH spin axis (cf. Scheuer & Feiler 1996; King et al. 2005; Lodato & Pringle 2006). We will consider these options in more detail in Section 2, after we review some of the most compelling observations of repeated reorientation of the jet axes in galaxy groups and clusters. For now, we will simply note that the only two viable scenarios are (1) precession associated with binary BH systems in the cluster cores and (2) stochastic slewing of the BH spin axis due to torques from recurring, short-lived, misaligned thin disks. In this paper, we argue that the observations are best understood in the context of the latter model.

In the next section, we will first review the most compelling observational evidence for recurring reorientation of the jet axes in cluster environments. We then assess the various scenarios involving changes in the direction of the BH’s spin axis and identify those that are both plausible and compatible with the observations. In Section 3, we motivate the case for our preferred model, which involves rapid, stochastic reorientations of the SMBH’s spin axis on relatively short timescales, summarize the associated physics and discuss why we expect this to be a recurrent phenomenon in cores of cool-core clusters. In Section 4, we discuss the astrophysical implications of our model.

2. Wandering Jet Axis: Assessing the Observational Evidence

Observations of “X-shaped” radio galaxies (XRGs; cf. Hodges-Kluck et al. 2010 and references therein), double–double radio galaxies (DDRGs; cf. Joshi et al. 2011 and references therein), and changes in the orientation of the jets on subkiloparsec scales in Seyfert galaxies (cf. Gallimore et al. 2006 and references therein) have long hinted at the possibility that AGN jets undergo discreet changes in direction by moderately large angles on relatively short (a few Myr to several tens of Myr) timescales. However, recent radio and X-ray studies of AGN activity in cool-core groups and clusters offer further and arguably more compelling evidence for “jet reorientation.” This evidence manifests in a variety of forms ranging from large-angle bends in the radio jets, to abrupt changes in direction from one jet episode to the next, to multiple generations of radio cocoons and X-ray cavities, some of which appear to trace out a nearly isotropic distribution in projection about the cluster center. Examples of such systems include CL09, M87 (Virgo), NGC 1275 (Perseus), NGC 4636, NGC 5044, NGC 5813, and Hydra A (Klein 1999; Dunn et al. 2006; Forman et al. 2007; Wise et al. 2007; Giacintucci et al. 2011; Randall et al. 2011; O’Sullivan et al. 2012).

In Table 1, we focus on the Virgo and Perseus clusters, two systems that have been the subject of a detailed, multi-wavelength observational campaign over the course of the past decade, and catalog most of the pertinent features seen in the radio and X-ray maps of these two systems typically associated with the radio-mode AGN activity of the central SMBH. Collectively, these observations of misaligned active and relic jets, as well as radio lobes, bubbles, and distinct X-ray cavities separated by large angles, strongly indicate that the underlying outflow responsible for forming these features changes direction between energetic jet “episodes” over timescales ranging from few Myr to few tens of Myr. (Figure 1 in Dunn et al. 2006 and Figure 5 in Forman et al. 2007 show this visually.) On the subparsec and parsec scales, this is indicated by changes in the direction of the jets themselves, and on kiloparsec scales and beyond, several generations of radio bubbles/X-ray cavities are observed and their distribution covers almost all projected angles, with many cavity pairs orientated nearly collinear with the SMBH. These relative changes in the orientation of the jet–counterjet features are more consistent with the rotation of the jet axis rather than the displacement of the source, which would tend to generate wide-angle tail-like geometries (e.g., Jetha et al. 2008 and references therein).

The most straightforward way to affect a change in the direction of the BH’s spin axis is via accretion. SMBHs in BCGs at the centers of cool-core clusters are thought to be accreting
Table 1
Features Indicating Jet Reorientation in Perseus and Virgo

| Feature                              | P.A. (North)$^a$ | P.A. (South)$^a$ | Timescale | Reference | Comment                                                                                                                                 |
|--------------------------------------|------------------|-----------------|-----------|-----------|------------------------------------------------------------------------------------------------------------------------------------------|
| Milliarcsecond jet                   | ⋯                | ∼170$^\circ$    | ⋯         | 1, 2      | Krichbaum et al. (1993) argue that the jet is nearly aligned with line of sight (los) very close to the core. On kiloparsec scales, however, it is ∼45$^\circ$ relative to los, implying a significant change in direction. |
| Cocoon-like feature at $r \sim 1.2$ mas | ⋯                | ∼210$^\circ$    | ⋯         | 1, 2, 3   |                                                                                                                                             |
| Parsec-scale cocoon at $r \sim 12$ mas | ∼5$^\circ$–10$^\circ$ | ∼180$^\circ$   | ∼25 yr    | 1, 3, 4   |                                                                                                                                            |
| Inner bubble                         | ∼345$^\circ$     | ∼155$^\circ$    | ∼10 Myr   | 5         |                                                                                                                                             |
| Outer bubble                         | ∼5$^\circ$       | ∼215$^\circ$    | ∼15–20 Myr| 5         | Note that, unlike here, angles in Dunn et al. (2006) were measured in the clockwise direction.                                           |
| Ghost bubble                         | ∼305$^\circ$     | ∼170$^\circ$    | ∼70–75 Myr| 5         | Based on the shape of the northern bubble and the kinematics of the trailing H$\alpha$ filaments, Dunn et al. (2006) argue that the bubble must be moving nearly perpendicular to the los—in the plane of the sky. |
| Ancient bubble                       | ∼345$^\circ$     | ∼230$^\circ$    | ∼100 Myr  | 5         |                                                                                                                                             |
| Jet                                  | 290$^\circ$      | 115$^\circ$     | ⋯         | 6, 7      | Biretta et al. (1995) argue that from 0.1 to 1000 pc, the observed jet (stretching to the northwest) is aligned at ∼40$^\circ$ to los. The counterjet is not observed but its direction is inferred from the location of the hot spot. |
| Inner lobes (in radio); jet/counterjet cavities (in X-ray) at ∼2.5 kpc | 270$^\circ$–275$^\circ$ | 120$^\circ$–130$^\circ$ | ⋯         | 6, 7, 8   | Ordered from closest to furthest in projection                                                                                                                                                             |
| Series of buoyant bubbles in the southeast | ⋯                | 160$^\circ$, 140$^\circ$, 120$^\circ$, 100$^\circ$ ($\Delta$age) $\sim$ 6 Myr | 8         |                                                                                                                                               |
| Intermediate east–west jets and lobes | 270$^\circ$      | 90$^\circ$      | ∼20 Myr   | 9, 10     | Following Klein (1999), we identify the eastern radio arm (Feature C in Figure 3 of Owen et al. (2000)), terminating in the “ear-like” Feature B, and the western extension of the jet along with “knot D” as jet–lobe features. Klein (1999) refers to Features B and D as “intermediate lobes.” |
| Outer X-ray cavity                   | 35$^\circ$–40$^\circ$ |    | 70 Myr    | 8         | This is the cavity discovered by Forman et al. (2007) and named “outer cavity.”                                                                                                       |
| Outer radio bubbles                  | 10$^\circ$       | 205$^\circ$     | 100 Myr   | 9, 10     |                                                                                                                                               |

Notes: $^a$ P.A. is the angle in the sky at the source location between north and the feature, measured in the counterclockwise direction.

References. (1) Dhawan et al. 1998; (2) Lister 2001; (3) Krichbaum et al. 1993; (4) Nagai et al. 2009; (5) Dunn et al. 2006; (6) Biretta 1994; (7) Biretta et al. 1995; (8) Forman et al. 2007; (9) Owen et al. 2000; (10) Klein 1999.

The fastest way to change the direction of an AGN’s jet axis is via spin flip, an abrupt change in the direction of a BH’s spin axis following a BH–BH merger. This mechanism is one of the leading explanations for the XRGs and misaligned DDRGs (Mezcua et al. 2012; Marecki 2012). Spin flips, however, are unlikely to explain the Virgo and Perseus observations, for instance, because one would need to invoke several BH–BH mergers.
mers over a duration of $\sim 100$ Myr to account for the $5-7$ episodes of changes in the direction of the jet axes over this period, which is implausible.

A number of authors, including Klein (1999), Pizzolato & Soker (2005b), Dunn et al. (2006), and Falceta-Goncalves et al. (2010), have invoked precession of the BH spin axis about a fixed axis to explain the distribution of radio and X-ray observations in Virgo and Perseus. To account for the observations, the precession of the BH must be combined with a jet model in which the outflows are intermittent and of short duration (compared to the precession period) so that the outcome is a sequence of discreet misaligned cavities. Precession can occur if the BH in question is part of a binary BH pair whose spins and the orbital angular momentum are misaligned. The precession timescale, when both BHs are of comparable mass, is (Merritt 2005; Key & Cornish 2011)

$$t_{\text{BH,prec}} \sim 2.4 \times 10^7 \text{ yr} \left(\frac{A}{1 \text{ pc}}\right)^{5/2} M_{\odot}^{-3/2},$$

(1)

where $A$ is the binary semi-major axis. This timescale is reasonable and unless the binary SMBHs are embedded in a massive, gaseous accretion disk, the lifetime of the binary ought to be more than long enough to span multiple precession cycles (Merritt & Milosavljevic 2005), which is what Dunn et al. (2006) require in order to account for the cavities in Perseus. Moreover, it is not inconceivable that the BCGs in cluster cores host binary SMBHs since the BCGs are thought to have been built up via mergers, including those involving giant elliptical galaxies, at $z \lesssim 1$. However, given the conditions in cores of cool-core systems, we would expect that if one of the BHs is powering jets, the other ought to be too. There appears to be no evidence of dual jets in the cores of Perseus and Virgo, nor are we aware of any additional evidence suggesting the existence of binary SMBHs in either Perseus, Virgo, or in any of other well-studied cool-core clusters.

Precession can also occur if the BH is surrounded by a geometrically thin accretion disk whose angular momentum is misaligned with the spin axis of the BH. This is the more commonly invoked of the two precessions schemes (e.g., Klein 1999; Falceta-Goncalves et al. 2010) to explain the observations in Perseus and Virgo. This scenario, however, is problematic for a number of reasons, the most important of which is that the thin disk-SMBH misalignment is a relatively short-lived phenomenon with a lifetime of tens of Myr and over this timescale, the BH will typically only undergo at the most one precession cycle. Both Dunn et al. (2006) and Falceta-Goncalves et al. (2010) find that the Perseus observations can only be understood if the BH undergoes several precession cycles over the course of $\sim 100$ Myr.

As discussed in detail in Lodato & Pringle (2006) and summarized in Section 3, the main reason for the short lifetime is that not only does a misaligned accretion disk induce precessional torques on the SMBH, it also induces torques that cause the BH spin axis to slew and move toward alignment with the total angular momentum of the BH+disk system. Once alignment is achieved, precession ceases. However, the fact that a misaligned accretion disk can cause a BH’s spin axis to tilt on timescales of tens of Myr (Scheuer & Feiler 1996; Natarajan & Pringle 1998; Lodato & Pringle 2006) is intriguing and forms the basis of our proposed model. Specifically, we assert that while AGNs at the center of cool-core clusters typically accrete gas at a relatively low rate via radiatively inefficient, geometrically thick flows, occasionally the mass accretion rate will spike and give rise to short-lived, geometrically thin accretion disks. In general, we do not expect the angular momentum vector of these recurring disks to be aligned with the direction of the SMBH’s spin. These recurring misaligned thin disks are central to our model because only geometrically thin structures can cause the BH to slew rapidly; geometrically thick flows do not appear to have the same effect on the SMBH (King et al. 2005; Fragile et al. 2007; Dexter & Fragile 2011).

### 3. TITLING SUPERMASSIVE BLACK HOLES

There are a number of questions to address in the context of our “misaligned accretion disk” model: do the existent conditions at the centers of cool-core clusters allow for the recurring formation of geometrically thin accretion disks? Are these disks likely to be massive enough to cause the SMBH’s spin axis to change direction significantly on short timescales?

#### 3.1. Recurring, Short-lived High Accretion Events in Cool-core Environments

Apart from the hot diffuse gas, central regions of BCGs in cool-core clusters also appear to be threaded by a filamentary network of cold gas (e.g. M87 [Virgo], Forman et al. 2007; CL09, O’Sullivan et al. 2012 and references therein; NGC 4696 [Centaurus], Crawford et al. 2005; NGC 1275 [Perseus], Conselice et al. 2001) that generally appear to cover a significant fraction of the 4\pi sr about the cluster center. Increasingly detailed kinematical studies of the filaments suggest that these likely have their origins in number of different physical processes, many of which are also expected to induce short-lived accretion events during which the instantaneous mass accretion rate onto the central SMBH can exceed 0.01 $M_{\odot}$, the threshold accretion rate above which the geometrically thick, radiatively inefficient flow is expected to transition to a geometrically thin, disk flow (Esin et al. 1997; Jester 2005). Such processes include buoyantly rising jet-inflated bubbles (Hatch et al. 2006; Pope et al. 2010), thermal instabilities (Pizzolato & Soker 2005a; Sharma et al. 2010; McCourt et al. 2012; Sharma et al. 2012), and small-scale turbulence induced, for example, by supernova blast waves (Hobbs et al. 2011) associated with star formation in the central regions of the BCGs (e.g., Bildfell et al. 2008) or even by the jets themselves (Gaspari et al. 2011).

In the case of buoyantly rising jet-inflated bubbles, the bubbles are expected to be trailed by filamentary wakes of cool gas involving $\sim 10^6 M_{\odot}$ of cool gas per bubble (Pope et al. 2010). In due course, this wake—either wholly or in fragments—will fall back toward the SMBH. Since the filaments are primarily radial in orientation, we expect that the fragments will have intrinsically low angular momentum (in magnitude) relative to the SMBH and have a high likelihood of ultimately settling and forming an accretion disk. Moreover, given the geometry involved, we expect this accretion disk to be oriented more or less perpendicular to the BH’s spin/jet axis.

As for thermal instabilities and small-scale supersonice turbulence, numerical simulation (e.g., Sharma et al. 2012; Gaspari et al. 2012; Hobbs et al. 2011) studies show that both give rise to gaseous filaments, streams, and high-density clouds that will then “rain” down onto the central regions of the BCG/cluster. In the thermal instability model, these structures are spawned during distinct cooling episodes in the cluster cores while in the case of turbulence, they are formed by convergent turbulent flows. Only those filaments and streams with angular momentum small
enough such that their circularization radius is ~0.1 pc will give rise to subparsec scale accretion disks. Treating individual streams and filaments as coherent structures, simulations (e.g., Hobbs et al. 2011) show that the orientation of successive accretion disks that are expected to arise will be uncorrelated and can differ by large angles.

3.2. Misaligned Accretion Disks and Spinning Black Holes

Given an accretion disk whose initial rotational axis is misaligned with the spin axis of the BH, frame dragging by the rotating BH will induce a torque on the inner regions of the disk that will cause it to precess differentially, an effect known as Lense–Thirring precession. Bardeen & Petterson (1975) showed that the viscous forces in the disk will damp the differential precession, and force the angular momenta of the disk to align5 with the total angular momentum of the system (King et al. 2005; Lodato & Pringle 2006). The alignment of the disk proceeds from inside out, with the transition radius between the inner disk and the outer disk demarcated by a warp. Since the process is primarily driven by frame dragging, the influence of which falls off rapidly with distance, the warp will stall at a radius $R_w$, where the rate at which the disk is twisted by Lense–Thirring precession is balanced by the rate at which viscous torques can dissipate the twist (Scheuer & Feiler 1996; King et al. 2005; Lodato & Pringle 2006). This radius is given by (see Equation (22) in King et al. 2005)

$$R_w \approx 2.7 \times 10^{-3} \frac{M_\bullet^{5/8} M_{\text{Edd}}^{-1/4} M_{\text{BH}}^{9/8}}{(\alpha/\dot{\alpha})^{-1/2} (\alpha/\alpha_1)^{-1/8}} \text{pc},$$

where $M_{\text{Edd}} \equiv (M/0.04 M_{\odot})$ and $j_\odot \equiv (j/0.1)$. Here, $j$ is the BH spin parameter scaled to $j_{\max} = (GM_\bullet/c)$, the maximum angular momentum of a Kerr BH: $0 \leq j \leq 1$. King and collaborators have argued in a series of related articles (cf. King et al. 2008 and references therein) that if BHs grow primarily via recurrent randomly oriented accretion events, they will tend to have low spins. For this reason, we have chosen to scale $j$ to a fiducial value of 0.1. Also, $\alpha_1$ in the above relationship is the usual accretion disk viscosity parameter characterizing the radially outward transport of gas angular momentum and the inward transport of matter, and $\alpha_2$ is the viscosity associated with vertical motions in the disk. For the purposes at hand, we assume that over the regions of interest, the $\alpha_1$ parameter is approximately constant and adopt $\alpha_1 \approx 0.1$ as a fiducial value. This is consistent with results from MHD simulations of magnetized accretion flows, which find that the effective value of $\alpha_1$ is ~0.1 over the bulk of the flow (e.g., Hawley & Krolik 2001, 2002). Moreover, Lodato & Price (2010) show that for a strongly warped disk, $\alpha_2 \sim 3$. In thin disks, the warp will propagate across the disk diffusively on a timescale $\alpha_2/\alpha_1$ shorter than the mass accretion timescale, which is determined solely by $\alpha_1$. Finally, we note that we have scaled the mass accretion rate to 0.04 $M_{\text{Edd}}$, which corresponds to ~1 $M_\odot$ yr$^{-1}$ for a 10$^6$ $M_\odot$.

The disk is not the only structure to experience a torque. The BH too will experience equal and opposite torques exerted by each differentially precessing disk annulus, which in turn will cause the BH’s spin axis to change direction. Disks whose outer radius is less than $R_w$ are not expected to impact the BH in any significant fashion; consequently, we will restrict ourselves to larger disk systems. In such cases, the torques on the BH are primarily due to the gas flowing through the warp (King et al. 2008). These torques can be resolved into two independent components: one that drives the precession of the hole’s spin about the total angular momentum axis of the disk+BH system and the other that drives the alignment of the BH’s spin with the total angular momentum. Lodato & Pringle (2006) and Martin et al. (2007) have investigated these two processes in detail and find that the BH precession timescale is comparable to, and in realistic cases perhaps even a factor of a few longer (Martin et al. 2007) than, the timescale over which the BH’s spin will align with the total angular momentum of the BH+disk system: i.e., $t_{\text{BH,prec}} \lesssim t_{\text{align}}$, where the BH alignment timescale (Equation (15) in Lodato & Pringle 2006; see also Scheuer & Feiler 1996; Natarajan & Pringle 1998) is

$$t_{\text{align}} \approx 2 \times 10^6 \frac{M_{\text{BH}}^{11/16} M_\bullet^{-7/8} M_{\text{Edd}}^{-1/16}}{(\alpha^2/\alpha_1)^{1/4} (\alpha/\alpha_1)^{15/16}} \text{yr}.$$ (3)

Consequently, the BH is unlikely to execute more than one precession cycle, if that, and once alignment is achieved, the torques driving the precession vanish as well.

Whether the BH attains full alignment during a given accretion event depends on the size (mass) of the accretion disk. The disk must be sufficiently long-lived to sustain gas flow (and therefore, the torques) over the duration $t_{\text{align}}$. However, we do not necessarily require the BH to achieve full alignment with the total angular momentum during each and every accretion event, only that the BH’s spin axis changes direction. This, as we discuss below, implies that only disks with $M_d > 10^6 M_\odot$ are of interest.

At the same time, if the radially inward flow of gas in the thin-disk mode is primarily due to local viscosity, the amount of gas that a BH can accrete during any one accretion episode cannot be arbitrarily large regardless of the amount of gas that is channeled into the nuclear region during the event. The accretion disks will be susceptible to gravitational fragmentation beyond a radius $R_{\text{frag}}$, where the disk mass exceeds (cf. Goodman 2003; Thompson et al. 2005; King & Pringle 2007; King et al. 2008 and references therein)

$$M_d(<R_{\text{frag}}) = f \left( \frac{H}{R} \right) M_\bullet,$$ (4)

where the factor $f$ ~ a few represents the uncertainty in this relationship due to poorly understood details such as the extent to which the magnetic pressure, radiation pressure, and stellar feedback augment thermal pressure due to viscous heating and contributes to the stability of the disk. Adopting a simple model of Collin-Souffrin & Dumont (1990) to describe the properties of the subparsec-scale thin accretion disk (see also King et al. 2008), the total disk mass inside radius $R$, where $R$ denotes the distance from the BH, is

$$M_d \approx 3 \times 10^6 M_{\text{Edd}}^{3/5} M_\bullet^{4/5} \left( \frac{\alpha_1}{0.1} \right)^{-4/5} R^{7/5} K_{\text{OBS}} M_\odot.$$ (5)
and the accretion disk scale height $H$ is

$$H \approx \frac{1.6 \times 10^{-3} M_{\odot}^{1/9} M_{\odot}^{-3/20} (\frac{a_1}{0.1})^{-1/10}}{R_{\odot,0.05}}. \quad (6)$$

Here, $R_{\odot,0.05} \equiv (R/0.05 \text{ pc})$. Using these equations, we find that

$$R_{\text{frag}} \approx 0.1 f_5^{28/27} M_{\odot}^{-8/27} M_{\odot}^{1/27} (\frac{a_1}{0.1})^{14/27} \text{ pc}. \quad (7)$$

Here, $f_5 = (f/5)$. Most of the gas at $R > R_{\text{frag}}$ is expected to either turn into stars or be expelled by stars that do form on timescales much shorter than those that govern the accretion flow. Since only gas that flows through the warp induces a torque on the BH (King et al. 2008), this means that the maximum amount of mass that can participate in the alignment process (derived from combining Equations (5) and (7)) is

$$M_{\text{d,max}} \approx 7.2 \times 10^6 f_5^{28/27} M_{\odot}^{-8/27} M_{\odot}^{1/27} \times M_{\odot}^{23/27} (\frac{a_1}{0.1})^{-2/27} M_{\odot}. \quad (8)$$

We note, however, that this mass constraint can be circumvented if the mass flow through the accretion disk is mediated by global gravitational torques (cf. Thompson et al. 2005; Hopkins & Quataert 2011).

Finally, we can estimate the maximum angle $\psi_{\text{max}}$ through which the BH’s spin axis will slew during any one accretion event where the initial misalignment between the disk angular momentum and the BH spin vector is characterized by angle $\theta_i$. Following King et al. (2008), we identify $J_d$, the “disk angular momentum,” as the total angular momentum of the gas ($\Delta M_{\text{gas}}$) flowing through the warp during an accretion event. That is,

$$J_d = (GM_{\odot} R_{\odot})^{1/2} (\Delta M_{\text{gas}}). \quad (9)$$

Straightforward geometry then gives

$$\sin \psi_{\text{max}} = \frac{J_d}{J_h} \sin(\theta_i - \psi_{\text{max}}). \quad (10)$$

The above equation differs slightly from that given by King et al. (2008) because the latter’s derivation implicitly assumes that $\psi_{\text{max}} < 1$. The extent of the tilt induced by an accretion disk depends on the initial misalignment between the disk’s angular momentum and the BH’s spin axis as well as on the ratio

$$\frac{J_d}{J_h} = \sqrt{\frac{3}{j}} \left( \frac{\Delta M_{\text{gas}}}{M_{\odot}} \right) \left( \frac{R_{\odot}}{R_S} \right)^{1/2}, \quad (11)$$

where $R_S \equiv 2GM/c^2 \approx 10^{-4} M_{\odot} \text{ pc}$ is the Schwarzschild radius. To affect a tilt of $\sim 5^\circ$ in the spin axis of a slowly spinning (i.e., $j \approx 0.1$) $10^6 M_{\odot}$ BH, the minimum amount of gas required is $\Delta M_{\text{gas}} \approx 10^6 M_{\odot}$. More generally, the maximum tilt (corresponding to $\theta_i = 90^\circ$) experienced by a $j \approx 0.1$ $10^7 M_{\odot}$ BH is given by

$$\psi_{\text{max}} \approx \tan^{-1} \left( 73.5 \frac{\Delta M_{\text{gas}}}{M_{\odot}} \right). \quad (12)$$

For accretion disks in which the mass flow is governed by local viscosity, maximal disks (i.e., $\Delta M_{\text{gas}} \approx M_{\text{d,max}}$) can tilt the BH by as much as $\sim 30^\circ$. In cases where the transfer of gas from the outer to the inner disk is mediated by global gravitational torques, the maximum possible angular displacement is only limited by the amount of mass available for accretion during any one accretion event. A relatively modest value of $\Delta M_{\text{gas}} \approx 3 \times 10^7 M_{\odot}$ is sufficient to affect a tilt of $\sim 65^\circ$. Rapidly spinning BHs (i.e., $j \approx 0.9$) are, on the other hand, much harder to tilt. A maximal disk can tilt a rapidly spinning ($j \approx 0.9$) $10^9 M_{\odot}$ BH by, at the most, $\sim 7^\circ$.

4. DISCUSSION, IMPLICATIONS, AND SUMMARY

To recap, we have argued that SMBHs at the centers of cool-core clusters will, in addition to the accretion of hot diffuse gas from its surroundings, experience short-lived, recurring episodes during which the instantaneous mass accretion rate onto the central SMBH can approach or even exceed $\sim 1 M_{\odot} \text{ yr}^{-1}$. We expect this phenomenon to be ubiquitous; it is a byproduct of a number of very different and distinct physical processes expected to be operating in cores of cool-core clusters. During such episodes, the flow in the immediate vicinity of the BH will transition to a geometrically thin flow and establish an accretion disk.

The current generation of simulation studies looking at the wide variety of processes at play at the centers of cool cluster cores is not detailed enough to provide a quantitative description of the spectrum of gas mass involved in individual high-density accretion events, the distribution of the time between accretion spikes, or a measure of how the angular momentum of gas varies between successive accretion events. They do, however, suggest that the detailed nature of the accretion history of an SMBH at the center of a cool-core cluster is, in general, complex. For instance, individual filaments may be prone to fragment into a train of clouds. The uninterrupted accretion of a single train would result in a sequence of accretion events occurring in quick succession on a timescale of the order of the free-fall time, i.e., $\sim 10 \text{ Myr}$, and give rise to a succession of disks whose orientations vary only by small angles. Depending on the masses of individual disks and the time between successive events, the SMBH’s spin could tilt through several discrete but correlated small angular displacements or one seemingly large displacement. Still, if one treats the accretion of an individual filament, stream, or a train of associated clouds as a single coherent event, the simulations do suggest that the direction of the spin axis of the SMBH will vary stochastically from event to event and over the course of many such events, the orientation of the BH’s spin axis will execute a random-walk over $4\pi$ sr.

Within the context of the turbulence model, we can attempt to estimate the mean time between accretion events. Turbulence is typically expected to give rise to streams and clouds with mass spectrum (Hopkins et al. 2012)

$$dN_{\text{cl}} \propto M_{\text{cl}}^{-1.8} dM_{\text{cl}}, \quad M_{\text{cl}} \lesssim f_{\text{gas}} M_{\text{gas}}(<R). \quad (13)$$

where $f_{\text{gas}}$ is the fraction of gas mass relative to the total enclosed mass. The mass of cold gas in cool-core cluster BCGs is $\sim a \times 10^{10} M_{\odot}$ within the central 10 kpc (Edge 2001; Salome & Combes 2003; Edge et al. 2010), which corresponds to $f_{\text{gas}} \approx 0.1$. In this case, the number of clouds with mass $M_{\text{cl}} \gtrsim 10^6 M_{\odot}$ is $\sim 2500$. (We choose this mass threshold because, as discussed in Section 3.2, less massive clouds have minimal impact on the SMBH.) Only a fraction of these clouds, with angular momentum small enough such that the circularization radius is $\sim 0.1 \text{ pc}$, will give rise to accretion disks. Assuming that the velocity distribution of the clouds is isotropic, with velocity dispersion $\sigma_v \approx 300 \text{ km s}^{-1}$, and that
the radial distribution of the clouds is approximately isothermal \((n_{\text{e}} \propto r^{-2})\), the mean time between accretion events is \(~\text{a few} \times 10^7 \text{ yr}\). This timescale is in agreement with that implied by the history of AGN activity in Perseus and Virgo, as summarized in Table 1: Perseus and Virgo data both suggest \(~5\) events over the past \(10^9 \text{ yr}\).

When an accretion event gives rise to a disk whose orientation is misaligned with the spin axis of the BH, the resulting torques between the gas flowing through the disk and the BH will cause the latter’s axis to swivel and change direction. The magnitude of the change in the direction of the BH’s spin axis depends on the degree of the initial misalignment between the disk’s angular momentum and the BH’s spin axis, the magnitude of the SMBH’s spin, and the amount of gas that flows through the disk and accretes onto the BH. If the inward flow of gas is mediated by local viscous stresses, we find that a misaligned disk can cause the spin axis of a slowly rotating (i.e., \(j = 0.1\)) SMBH to slew by as much as \(~30^\circ\). If, however, the inward flow is induced by global gravitational torques, the BH can potentially tilt by much larger angles.

Drawing on the considerable body of work indicating that jet production is most efficient when the accretion flow is geometrically thick and suppressed otherwise (Livio et al. 1999; Meier 2001; cf. also Nemmen et al. 2007; Benson & Babul 2009 and references therein), we expect that the jets will briefly wane in power during the thin disk phase. But once the accretion disk drains away and the geometrically thick flow re-establishes, the jets will also resume. Since the jet axis is the same as the spin axis, the post-tilt jets will point in a different direction from the pre-tilt jets. This scenario offers the simplest explanation of, for example, the apparently abrupt change in the direction between an older (larger) relic jet in CL09 and a subsequent jet episode (O’Sullivan et al. 2012).

The scenario outlined in this paper and summarized above has several important astrophysical implications that are as follows.

1. The recurring reorientation of AGN jets due to tilting of the SMBH spin axis offers a straightforward explanation for the distinct, randomly oriented jets/lobes/cavities observed in cool-core clusters such as Perseus, Virgo, and CL09.
2. Swiveling jets also offer a simple yet compelling resolution for the “isotropic heating” puzzle. Since the jets are expected to change directions several times over the cooling time in cores of cool-core clusters, the resultant heating will also be distributed over a large portion of \(4\pi\) sr on the same timescale.
3. Since geometrically thin accretion disks are radiatively efficient, our model predicts that whenever one forms, the host AGN ought to transform into a quasar. The quasar will be short-lived because the disks do not involve a lot of mass and are expected to drain quickly. We can estimate the likelihood of catching an AGN “in the act” as follows: the Perseus and Virgo data both suggest \(~5\) events over the past \(10^3 \text{ yr}\). Assuming that a typical accretion event involves \(~10^6\) \(M_\odot\) of gas and that the lifetime of the resulting disk is \(~\text{Myr}\), we expect a quasar duty cycle of \(~5\%\).
4. A \(~5\%\) duty cycle means that out of \(~250\) rich clusters \((T_e > 2 \text{ keV})\) with \(z < 0.5\) that have X-ray observations, we ought to expect 1–2 clusters to host a central quasar.

This estimate is based on the following: approximately \(35\%\) of rich clusters (Eckert et al. 2011) tend to be strong cool-core systems and of these only \(35\%\) show evidence of significant multiphase gas component in their cores (McDonald et al. 2010). Only the AGNs in the latter systems are likely to experience enhanced accretion events on a recurring basis. Interestingly, there are in fact only two known \(z < 0.5\) clusters that host quasars: MACS J0913.7+4056 (also known as CL0910+4109; O’Sullivan et al. 2012) at \(z = 0.44\) which hosts a dust enshrouded type 2 QSO at its center, and a \(z = 0.3\) cluster that hosts a highly luminous radio-quiet quasar, H1821+643 (Russell et al. 2010). Both quasars are located at the centers of cool-core clusters.

5. Finally, we note that our proposal—that SMBHs at the centers of cool-core clusters are repeatedly tilted by misaligned accretion disks—implicitly requires the SMBHs in such environments to be relatively slow rotators, which they are likely to be if they have accreted a non-negligible fraction of their mass via randomly aligned streams, filaments, and clouds. If they are shown to be spinning rapidly, our proposed mechanism cannot explain the observations. Thin misaligned disks cannot tilt rapidly spinning SMBHs by more than a few degrees.

The authors acknowledge the hospitality of the Kavli Institute for Theoretical Physics at the University of California Santa Barbara where this work was conceived. This research was supported in part by the National Science Foundation under grant No. NSF PHY05-51164 to KITP. A.B. acknowledges support from NSERC Canada through the Discovery Grant program and C.S.R. acknowledges support from the National Science Foundation under grant No. AST0908212. The authors also thank P. Ajith, A. Benson, F. Durier, N. Murray, and G. Novak for useful discussions.

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