M84 - Can the AGN Affect The Orientation of The Disk?\textsuperscript{1}

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ABSTRACT

In M84 dust features are not aligned with the galaxy isophotes but are perpendicular to the radio jets. We estimate the timescale that the gas disk should precess in the galaxy. Since this timescale is short ($\sim 2 \times 10^7$ years at 100 pc) we consider mechanisms that could cause the gas disk to be misaligned with the galaxy. One possibility is that a cooling flow replenishes the disk on this timescale and at angles that vary with radius. Another possibility is that there is a pressure on the disk that is large enough to overcome the torque from the galaxy. We estimate this pressure and find that it can be provided by ram pressure from an energetic interstellar medium that is consistent with velocity dispersions observed in ionized gas and densities estimated from the X-ray emission. We therefore propose that an AGN associated energetic interstellar medium is responsible for causing the gas disk in M84 to be misaligned with the galaxy isophotal major axis for $r \lesssim 600$ pc. We propose that AGN associated outflows or kinetic motion in low density media could be responsible for jet/disk alignments observed on 100 pc scales in nearby radio galaxies.

1. Introduction

Recent HST imaging and spectroscopic studies of active elliptical galaxies have established that there are gas disks in the central few hundred pc of these galaxies which could be feeding the massive $\sim 10^9 M_\odot$ black holes at their centers (e.g M84; Bower et al. 1997, Bower et al. 1997, M87; Harms et al. 1994 and NGC 4261; Ferrarese, Ford, & Jaffe 1996). These gas disks are observed to be nearly perpendicular to the jets, establishing a link between the angular momentum of the disk and the direction of the jet. Kotanyi & Ekers (1979) performed a survey of the observed angular difference, $\Psi$, between radio and disk axes in radio ellipticals and found a statistically significant peak in the distribution at $\Psi = 90^\circ$. This established that radio jets are generally perpendicular to gas disks on large (kpc) scales in nearby radio galaxies, even though

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no correlation between the radio axis and the galaxy isophotal major axis exists at low redshift (Sansom et al. 1987). The strong peak at $\Psi = 90^\circ$ has been confirmed at smaller (100 pc) scales by van Dokkum & Franx (1995) using HST images.

Strangely, the jet direction is not necessarily expected to be correlated with the angular momentum of the gas feeding the black hole (and so the orientation of the disk) because of Lense–Thirring precession, otherwise known as ‘dragging of inertial frames’ (Rees 1978). A spinning black hole causes a gas disk near the gravitational radius, $r_g = GM/c^2 \sim 10^{14}$ cm, to precess, and so the disk or torus near the black hole is expected to fill a volume that is axisymmetric and aligned with the spin axis of the black hole itself (Rees 1984, Bardeen & Petterson 1975). This inner torus is the proposed site for jet collimation and acceleration (Rees et al. 1982) so we expect that the jet should be aligned with the spin axis of the black hole but not necessarily the angular momentum of the disk well outside of $r_g$. A massive spinning black hole can be described as an angular momentum reservoir that does vary in momentum but only very slowly with the influx of fuel. The rate of change of angular momentum is expected to be particularly slow ($\sim 10^8$ years) in radio galaxies where the black holes are massive ($\sim 10^9 M_\odot$) and the fueling rates are probably low ($\sim 10^{-4} M_\odot/yr$; Rees 1978). This reservoir could also be responsible for stabilizing jets (Rees 1978). If the black hole does not spin significantly, then the jet axis would be determined by the angular momentum of the inner disk. This disk, because of its lower mass, could vary in orientation on shorter timescales than the black hole axis (for a spinning system). However, the observed alignment of jet and disk axes would then require that the orientation of this inner disk be coupled to that of the outer disk (at $\gtrsim 100$pc). Possible mechanisms for the alignment of the jet with the disk at 100 pc scales (well beyond $r_g$) have not been explored.

To explore alignment mechanisms, we consider the geometry of the warped dust features and ionized emission in M84 (NGC 4374, 3C 272.1), a radio elliptical in the Virgo cluster. M84 has a dusty disk seen in extinction in optical images (see Fig. 1) and in emission in H$\alpha$ + [NII] that although nearly perpendicular to the jet, is misaligned with the galaxy isophotes (Hansen, Norgaard-Nielsen, & Jorgensen 1985, van Dokkum & Franx 1995, Jaffe et al. 1994, Bower et al. 1997a, Baum et al. 1988). van Dokkum & Franx (1995) noted that the timescale for the disk to settle into the galaxy plane of symmetry is probably short; $\sim 10^8$ years. These authors therefore suggested that the misalignment could be explained by a rapid inflow of gas into the central region of the galaxy (to radii smaller than $r \lesssim 600$ pc). However if this is the case, it is difficult to explain the S-shape of the H$\alpha$ + [NII] emission (Baum et al. 1988). This emission is elongated and lies within $20^\circ$ of PA $\sim 70^\circ$ for $r \lesssim 7''$ but at this radius the disk twists to PA $\sim 115^\circ$ on either side of the nucleus. It is difficult to imagine how a cooling flow could generate such a morphology. As an alternative to this possibility, we also consider an interaction between the gas disk and an energetic interstellar medium (ISM) as a possible mechanism for aligning the disk perpendicular to the jet.

Throughout this paper we adopt a distance to M84 of 17Mpc (Mould et al. 1995; $H_0 = 75$km
s\(^{-1}\) Mpc\(^{-1}\)). At this distance 1" corresponds to 82 pc.

2. Misalignment of the Dust Features with the Galaxy

That the dust features are misaligned with the galaxy isophotes in M84 for \(r \lesssim 600\) pc was emphasized by van Dokkum & Franx (1995). The galaxy isophotes have a major axis PA = 129\(^\circ\) (van Dokkum & Franx 1995; see Fig. 1) whereas the dust features are elongated along PA = 80 − 65\(^\circ\) (for \(r < 7''\)) depending upon the region used to estimate the angle (Bower et al. 1997a, van Dokkum & Franx 1995). This is a misalignment of \(\Psi = 50 − 65\)\(^\circ\) of the dust features with respect to the galaxy major axis.

Misalignment between gas and stellar isophotes is not necessarily rare, (e.g. see van Dokkum & Franx 1995). When there are kpc scale gas/galaxy misalignments usually the misalignment is the result of a merger (e.g. Tubbs 1980 and Steiman-Cameron, Kormendy, & Durisen 1992). A gas disk in a non-spherical but axisymmetric galaxy will precess about the galaxy axis of symmetry. At a radius of a few kpc the time for a gas disk to precess about the galaxy axis of symmetry is long, \(\sim 10^8\) years, requiring a merger event to have occurred within this time if a merger is responsible for the gas/galaxy misalignment. Because the precession is faster in the center of the galaxy in the central regions the warp can be multiply folded and in the outer regions where the precession is slower the angle of the disk is more directly related to the orbital angular momentum of the merger event (Quillen, Graham, & Frogel 1993).

After some time an initial planar disk that is precessing freely will become multiply warped and the dust in the inner region will form a band of absorption that is roughly perpendicular to the galaxy axis of symmetry (e.g. Steiman-Cameron et al. 1992, Sparke 1996, Quillen et al. 1993, Tubbs 1980). This is expected since a gas ring in one precession period will trace out a cylindrical surface that is axisymmetric and perpendicular to the galaxy axis of symmetry. The morphology of the dust lanes in M84 resembles those of Cen A and NGC 4753 which are caused by multiply folded thin dusty surfaces (Quillen et al. 1993, Steiman-Cameron et al. 1992). However precession in the galaxy potential is an unlikely explanation for the warp in M84 since the band of absorption in the multiply folded region is not aligned with the galaxy isophotes as is true in Cen A (Tubbs 1980) and NGC 4753 (Steiman-Cameron et al. 1992).

In M84 the position angle of the dust features and ionized emission varies with radius. At \(r \sim 4''\) the dust features are nearly perpendicular to the radio jet, but at \(r \sim 1''\) there is a line of extinction north of the nucleus at PA ~ 65\(^\circ\) (see Fig. 1). The H\(\alpha\) emission has PA = 58\(^\circ\) for radii 0''-25 − 0.''.5 (Bower et al. 1997a) however a disk at this angle did not yield a good fit to the velocity profiles. A good fit was achieved with a disk more nearly perpendicular to the jet at PA ~ 80\(^\circ\) (Bower et al. 1997b). The jet has PA \(\approx 10\)\(^\circ\) on the pc scale and PA \(\approx 0\)\(^\circ\) on the 100 pc scale (Jones, Sramek, & Terzian 1981).
3. The Precession Timescale

van Dokkum & Franx (1995) emphasized that the timescale for the gas disks to settle into the plane of the galaxy is short in the central few hundred pc. The timescale for a gas ring to precess about the galaxy axis of symmetry, is shorter still. The angular precession frequency $\frac{d\alpha}{dt}$ about the galaxy axis of symmetry for a gas ring of radius $r$ and inclination $i$ with respect to the galaxy axis of symmetry is

$$\frac{d\alpha}{dt} = \epsilon_{\Phi} \Omega \cos i \quad (1)$$

(e.g. Gunn 1979) where $\epsilon_{\Phi}$ is the ellipticity of the gravitational potential which we assume is axisymmetric and $\Omega \equiv v_c/r$ for $v_c$ the velocity of a particle which has only a gravitational force on it in a circular orbit. Except in the case of a polar ring ($i \sim 90^\circ$), the dependence on $i$ is weak. In a time

$$t_p \sim \frac{3}{\epsilon_{\Phi} \Omega} \quad (2)$$

which we refer to as a precession time, rings that differ in radius by a factor of 2 should have an angular difference of $\sim \pi/2$. Here we have omitted the dependence on $i$. After this time, an initially planar disk which is observed to be aligned with the galaxy major axis at $r$, will at $r/2$ be maximally misaligned with this axis (e.g eqn. 7.4 of Quillen et al. 1992). Since in M84 the dust is misaligned with the galaxy for $r \lesssim 600$ pc, a mechanism operating at a timescale faster than the above timescale, $t_p$, must be causing the disk to remain at an angle differing from the galaxy isophotes.

To calculate the precession timescale we need to estimate the circular velocity, $v_c$. This velocity can be estimated using Eqn. (4-55) of Binney & Tremaine (1987) from the observed stellar velocity dispersion ($\sigma_\star = 303 \pm 5$ km/s for $r \lesssim 5''$ Davies & Birkinshaw 1988) assuming that the galaxy is axisymmetric. For a mild anisotropy of $\beta = 0.4$ (where $\beta \equiv 1 - \frac{v_\theta^2}{v_r^2}$ is the ellipticity of the velocity ellipsoids), the circular velocity would be $v_c \sim 1.1 \sigma_\star \sim 330$ km/s (where we have assumed that $\rho \propto r^{-2}$ consistent with the small variation in $\sigma_\star$ with radius). A smaller anisotropy would result in a higher circular velocity. The minimal galaxy rotation ($< 8$ km/s; Davies & Birkinshaw 1988) suggests that the axis ratio and anisotropy are not high (using the virial equations).

To calculate the precession rate we must also estimate the ellipticity of the gravitational potential, $\epsilon_{\Phi}$, which is directly related to the ellipticity of the isophotes (see Fig. 1). Here the ellipticity $\epsilon \equiv 1 - b/a$ where $b/a$ is the axis ratio of the isophotes. In M84 van Dokkum & Franx (1995) measured an ellipticity of 0.21 between 10'' and 12'' and Ferrarese et al. (1994) measured $0.187 \pm 0.002$ for $5 < r < 15''$. Both of these works found slight decreases in the ellipticity with increasing radius at $r < 15''$, which extends into the outer parts of the galaxy ($r > 100''$) where $\epsilon < 0.1$ (Peletier et al. 1990). Only minimal deviations from the shape of a pure ellipse were observed (van den Bosch et al. 1994, Peletier et al. 1990). Measurement of the isophote ellipticity in the optical images is complicated by the presence of the dust features in the inner region (see Fig. 1). In the near-infrared 2.2$\mu$m (Ks) image of M84 from Pahre & Mould (1994) the isophotes
are completely symmetrical, do not vary in position angle, and show little extinction from dust. The ellipticity from this image agrees with the other measurements and show that there is no change in ellipticity to $r \sim 2''$, but it does not have sufficient spatial resolution (seeing $\sim 1''$) to accurately measure it for $r \lesssim 2''$. A higher resolution near infrared image may be able to see if the ellipticity extends to smaller radii.

From this we now estimate the ellipticity of the gravitational potential. For power-law potentials (with a core) $\epsilon_\Phi \sim \epsilon_\rho/3$ (see Binney & Tremaine 1987, Figure 2-13), where $\epsilon_\rho$ is the ellipticity of the density distribution. Using $\epsilon_\rho = 0.15$ close to that measured from the isophotes we estimate $\epsilon_\Phi \sim 0.05$. This is actually a lower limit since projection causes the measured ellipticity to be less than $\epsilon_\rho$ and in the core $\epsilon_\Phi$ could be higher than $\epsilon_\rho/3$.

With the above values for $\epsilon_\Phi$ and $v_c$ we estimate a precession time of

$$t_p = 2 \times 10^7 \text{ yr} \left(\frac{0.05}{\epsilon_\Phi}\right) \left(\frac{r}{100 \text{ pc}}\right) \left(\frac{330 \text{ km/s}}{v_c}\right).$$

Since in M84 the dust is misaligned with the galaxy for $r \lesssim 600$ pc, a mechanism operating at a timescale faster than the above timescale must be causing the disk to remain at an angle differing from the galaxy isophotes.

In the above discussion we have assumed that M84 is axisymmetric, and not triaxial. The cuspiness observed in the isophotes of many ellipticals (Gebhardt et al. 1990), including M84 (Ferrarese et al. 1994), coupled with theoretical work measuring mixing timescales for stochastic orbits in cuspy potentials (Merritt & Fridman 1996) suggest that triaxiality can only be short lived in the central regions of M84. There is little twist in the isophotes of M84 (van den Bosch et al. 1994, Peletier et al. 1990) which should be observed if the galaxy is strongly triaxial and not oriented with an axis coincident with the line of sight. In addition van Dokkum & Franx (1995) found that triaxiality could not explain the observed disk/galaxy misalignments in a sample of elliptical galaxies. Whereas precession times are similar, disk settling times in triaxial galaxies are substantially faster than in axisymmetric systems (Habe & Ikeuchi 1985). The possible warped equilibrium state in a tumbling triaxial galaxy (van Albada, Kotanyi, & Schwarzschild 1982) is unlikely because there is little stellar rotation observed in M84 (Davies & Birkinshaw 1988).
galaxy. However, mass lost from stars in the galaxy should not be rotating since the stars have no observed net rotation (Davies & Birkinshaw 1988). The cooling flow could perhaps be influenced by the cluster environment, and thus gain some angular momentum. If the cooling flow quickly replenishes the gas disk then we would expect that it would have orientation that does not vary with radius and so should not exhibit the S-shape noted by Baum et al. (1988) in Hα + [NII] emission (see Fig. 1).

If the galaxy disk has a large radial inflow rate then a quasi-stationary warp could develop (e.g. Steiman–Cameron & Durisen 1988) where the gas flows in faster than it can turn by precession. A radial inflow velocity greater than $v_r > v_c \epsilon \Phi \approx 16 \, \text{km/s}$ is needed for this to occur. This inflow rate is so fast that the mass inflow rate would be much higher than that needed to power the AGN, requiring some place to put the accreted mass, such as a wind, a dense inner disk, or advection-dominated accretion into the black hole (e.g. Abramowicz et al. 1988, Abramowicz & Lasota 1996). Also the lifetime of the disk would then be of the same time as the precession timescale $t_p$ either requiring a substantial gas reservoir at radii larger than 600 pc or implying that the lifetime of the disk is only a few times $10^7$ years. Such high inflow rates could only be achieved in an isolated accretion disk with a very high viscosity and velocity dispersion. However, if the cooling flow were contributing low angular momentum gas to the disk (e.g. Gunn 1979) a thinner lower dispersion disk might be able to sustain such high inflow rates. In this case some precession in the galaxy potential could occur. It is unclear if this scenario could account for the observed disk morphology.

Recently Pringle (1996) has proposed that radiation from an AGN can drive a warp in an accretion disk. However this mechanism operates only when the force from radiation pressure is significant compared to the gravitational force. Maloney, Begelman, & Pringle (1996) find that only in the Keplerian regime in particularly luminous AGN can this occur. We roughly estimate that the AGN in M84 would have to be 100 times more luminous (the radio bolometric luminosity is $6 \times 10^6 L_\odot$; Herbig & Readhead 1992) for a radiatively driven warp to operate on an optically thick disk at 100 pc.

### 4.1. Pressure Required to Overcome the Galaxy Torque

Here we consider the possibility that the misalignment of the disk with the galaxy is caused locally. There is ample observational evidence for AGN associated outflows and energetic ISM both at high and low redshift. 10 – 20% of optically selected quasars, known as broad absorption line quasars (BALs), show blueshifted broad absorption lines (Weymann et al. 1991) in the same resonance lines that are seen in emission in most QSO spectra (including the BALs). In nearby active systems there is evidence for complex velocity structure and velocity gradients suggestive of outflow across the narrow line region (NLR) (NGC 1068; Evans et al. 1991, NGC 5252; Acosto-Pulido et al. 1996, Markarian 1066; Bower et al. 1995).
AGNs are expected to impart kinetic energy to the surrounding media. Murray et al. (1995) propose that a wind “can be driven up out of the disk by a combination of radiation pressure and gas pressure”. Whittle (1992a) and (1992b) finds that [OIII] lines are significantly broader in Seyferts with a high radio luminosity, suggesting that jets also accelerate clouds in the narrow line region. HST images of the narrow line region in some Seyfert galaxies show conical features in emission lines interpreted to be ionized gas entrained in a jet, or material ionized by an anisotropic or shielded central source (e.g. Storchi-Bergmann, Mulchaey, & Wilson 1992). Jets can cause large scale shocks in the ISM of a galaxy (Dopita & Sutherland 1989, Pedlar, Dyson, & Unger 1985), as has been observed in NGC 4258 (Cecil, Morse, & Veilleux 1995) and Mkn 573 (Pogge & de Robertis 1995).

Radio galaxies put a substantial fraction of their luminosity into the kinetic energy of their jets (e.g. Rees et al. 1982). Emission in Hα + [NII] commonly shows high velocity dispersions of the order of a few hundred km/s (Baum, Heckman, & van Breugel 1992, Tadhunter, Fosbury, & Quinn 1989, Axon et al. 1989). In radio galaxies there is strong evidence that the jets themselves impart significant motions in the surrounding ISM. In Cygnus A and 3C 265, two narrow line emitting components near the jets are separated by velocities as large as 1600-1800 km/s (Tadhunter 1991). Large line widths have also been observed in Seyferts with jets (Capetti et al. 1995a, Axon et al. 1997, Capetti et al. 1995b). If the jets are responsible for motions in the surrounding ISM then there should be a differential in this medium, with the largest motions nearest the jets, and the lowest motions in the plane perpendicular to the jets.

If the disk orientation is affected by the local medium then there must be a pressure on the gas disk greater than that of the gravitational potential which would be causing it to precess. The torque per unit mass on a ring of radius r is

\[ \tau = \epsilon_\Phi \cos(i) v_c^2 \] (4)

and so the pressure required to keep the disk from precessing is

\[ P > \epsilon_\Phi \cos(i) \Sigma v_c^2 / r \] (5)

where \( \Sigma \) is the mass per unit area in the gas disk. If we assume that a hot gas with density \( \rho_h \) and motions with velocity \( v_h \) exerts a ram pressure \( \rho_h v_h^2 \) on the disk then given the density of the hot gas surrounding the disk we can estimate the velocity dispersion, \( v_h \), required to overcome the galaxy torque. From the X-ray emission, Thomas et al. (1986) find an electron density that is \( n_e \approx 0.5(100pc/r)cm^{-3} \) (where we have extrapolated from their profile which ranges from 0.5 – 20 kpc). From this we estimate

\[ v_h \approx 50km/s \left( \frac{\epsilon_\Phi}{0.05} \right)^{1/2} \left( \frac{\Sigma}{1M_\odot/p^2} \right)^{1/2} \left( \frac{0.5cm^{-3}}{n_e(r=100pc)} \right)^{1/2} \left( \frac{v_c}{330km/s} \right) \] (6)

where we have assumed that \( n_e \propto 1/r \) and ignored the weak dependence on inclination.
The random velocity component required depends on the surface density, $\Sigma$, of the disk which is difficult to estimate. From the extinction in the dust features, van Dokkum & Franx (1995) and Bower et al. (1997a) estimate a total disk mass of $10^6 M_\odot$ and $9 \times 10^6 M_\odot$ respectively. For a disk of constant surface density truncated at $r = 400$ pc these mass estimates give $\Sigma = 2 - 18 M_\odot$ pc$^{-2}$. We expect that the density would increase with decreasing radius, and so that the density would be higher than these values at small radii and lower at large radii. The resulting velocity $v_h$ required to overcome the torque from the galaxy could be a few times higher than the above 50 km/s.

Is there evidence for an energetic medium in M84 that has velocities of a few hundred km/s? The profiles in [NII] by (Bower et al. 1997b) have a FWHM $\sim 200$ km/s, so that the velocity dispersion observed in the ionized gas is quite high, even when observed at their high angular resolution ($0.1''$). This suggests that the high dispersion is not an artifact caused by ‘beam smearing’ or by sampling a large region in a cold slowly rotating disk. In the lower angular resolution ($\sim 1''$) observations of Baum et al. (1990) the velocity dispersions are $\sim 150$ km/s along the major axis of the H$\alpha$+[NII] emission increasing to 300 km/s in the central few arcsecs. Dispersions measured along the minor axis are higher still with values of 200–400 km/s. We note that along the minor axis in a rotating disk, artifacts caused by beam smearing should be minimal because the line of sight velocity is equal to the systemic velocity of the system. The higher dispersion along the minor axis (which also corresponds to the radio jet axis) suggests that motions are largest nearest the jets.

As described by Bower et al. (1997a) the H$\alpha$ + [NII] appears to have 3 components: a rotating disk, an ionization cone along the radio jet axis, and outer filaments that coincide with emission seen in the image of Baum et al. (1988). The [NII] velocity profiles of Bower et al. (1997b) and Baum et al. (1990) suggest that these components contain complex velocity structure with motions of few hundred km/s. We conclude that there is evidence for an energetic ISM with motions and density large enough that this medium could contribute sufficient ram pressure to overcome the galactic torque.

Even though Bower et al. (1997b) and Baum et al. (1990) observe velocities consistent with rotation in a disk along the major axis in the H$\alpha$ + [NII] emission, the rotational velocity ($< 200$ km/s) is substantially lower than $v_c \sim 330$ km/s which we estimated above. The axis ratio of the emission is consistent with a nearly edge-on disk which therefore would be observed at the full rotational velocity if undergoing circular motion. Because the observed rotational velocity is low there must be non-gravitational forces on the ionized gas. For a disk containing clouds with random motions the mean rotational velocity is expected to be lower than $v_c$ because of the radial pressure force on the disk, (similar in nature to asymmetric drift, e.g. see Binney & Tremaine 1987, Eqn. 6-24). However if this force is large enough to significantly lower the rotational speed then radial inflow would necessarily be rapid, and the disk should be quite thick. Hydrostatic equilibrium in a nearly round gravitational potential requires that $\frac{h}{r} \sim \frac{\sigma}{v_c}$ for $h$ the thickness of the disk and $\sigma$ the velocity dispersion of clouds in the disk. The velocity dispersion of the H$\alpha$...
emission contrasts sharply with the sharpness of the dust features seen in absorption (Fig. 1). This sharpness suggests that the disk is quite thin and so implies that the velocity dispersion in the cold gas associated with the dust cannot be large ($\lesssim 30$ km/s for $h/r \lesssim 10$). This is strong evidence that we are not observing the same material in Hα+[NII] as in absorption from dust. If the pressure gradient in the ionized disk itself is not sufficient to cause the low disk rotational velocity, then it is more likely that the low rotation seen in the Hα + [NII] disk is a symptom of an interaction between a non-rotating energetic medium and the rotating cold disk. Gunn (1979) considered the interaction of a cold gas disk in an elliptical galaxy containing a hot X-ray emitting gas. He pointed out that since the X-ray gas is pressure supported, it should not be rotating. This causes a velocity shear between the hot gas and the cold disk which would result in Kelvin-Helmholtz instabilities, and an additional force on the disk which could lower its rotational velocity and increase its accretion rate.

5. Summary and Discussion

In this paper we have estimated the timescale of a gas disk to precess in the non-spherical gravitational potential of M84. This timescale is a few times $10^7$ years at 100 pc where the dust features are misaligned with the galaxy isophotes. For the disk to remain misaligned with the galaxy potential some mechanism must operate faster than this. While a cooling flow could replenish the disk on this timescale it is difficult to explain why the disk is at a roughly constant angle within $r < 7''$ and yet twists at this radius forming an overall S-shape in the Hα + [NII] emission (Baum et al. 1988). Extremely fast accretion through the disk itself would require a substantial gas reservoir at large radii or a very short disk lifetime. It would also require a place to put the excess accreted gas mass, such as a wind, an inner disk or advection-dominated accretion into the black hole. A combination of fast accretion and replenishment by a cooling flow could possibly result in inflow faster than the precession rate, but it is not clear whether this combination could account for the disk morphology. The AGN is not luminous enough for the radiative induced warp mechanism of Pringle (1996) to operate.

As an alternative to these external mechanisms we consider the possibility of a local (presumably AGN associated) force on the disk. We estimate the ram pressure required to overcome the torque from the galaxy and find that energetic motions of the scale observed in the ionized gas and the density inferred from the X-ray gas could provide this pressure. That the velocity dispersion seen in Hα + [NII] emission is higher along the jet than along the disk major axis suggests that there is a pressure differential in the hot medium with motions lowest in the plane perpendicular to the jet. The low rotational velocity of the Hα + [NII] emission implies that there are significant non-gravitational forces on the gas. We therefore propose that an energetic low density medium in M84 is responsible for causing the gas disk to be perpendicular to the jet on the scale of a few hundred pc.

The pressure required to overcome the galactic torque depends on the ellipticity of the
potential, and it is difficult to measure the ellipticity of the isophotes from optical images because of the dust features themselves. For example at small radii where the density of the disk is expected to be highest the galaxy could be nearly spherical. At \( r \sim 1'' \), the galaxy surface brightness profile has a shoulder or cusp \( \text{(Ferrarese et al. 1994)} \). If this shoulder has been caused by the black hole \( \text{(Young 1980)} \) then this radius would be a likely place for a change in the ellipticity of the galaxy. A higher resolution near infrared image may be able to see if the ellipticity extends to smaller radii.

We note that the X-ray observations of \( \text{Thomas et al. (1986)} \) did not have sufficiently high angular resolution to see if the electron density profile is a power law all the way into the nucleus. The cooling time \( (\propto n_e^{-1}) \) of their last measured point at \( r = 500 \text{ pc} \) is only \( \sim 2 \times 10^7 \text{ years} \) which suggests that substantial mass and energy input is required near the nucleus if the electron density increases all the way into the nucleus. Higher resolution X-ray observations could determine if this is the case. Pressures estimated from the [SII] 6717, 6731Å lines in cooling flow galaxies (including M87 within \( r < 200 \text{ pc} \)) in the central regions are high, \( \sim 1 - 2 \times 10^{-9} \text{ dynes cm}^{-2} \) \( \text{(Heckman et al. 1989)} \) and not inconsistent with high central densities extrapolated from the lower resolution X-ray estimated pressures. Higher spectral resolution observation of these [SII] lines could therefore be used to estimate the pressures at small radii in the \( 10^4 \text{K} \) gas (which should be nearly in near pressure equilibrium with the X-ray emitting \( 10^7 \text{K} \) gas). If there is energetic dense gas mixed in with the X-ray emitting gas, then this medium could exert a higher pressure on the gas disk than the hot gas alone.

The velocity profiles of a large region of the disk could determine the orientation of the disk as a function of radius, as well as the velocity structure of the ionization cones and filaments. The extent that motions in this medium are ordered rather than random could be studied with such a data set. If the jet itself is a source of kinetic energy input into the low density medium, then the velocity structure of gas nearest the jet should differ from that outside it. If there is indeed a large pressure from an energetic ISM on the gas disk in M84 then we would expect shocks, associated heating and mixing layers. The location and conditions of these processes can be probed with emission line diagnostics.

Recent investigations find that almost all ellipticals have dust \( \text{(van den Bosch et al. 1994)} \). In cases of non-active elliptical galaxies having dusty disks misaligned with the galaxy isophotes, the misalignment might be caused by another mechanism (perhaps a cooling flow or a galaxy merger). van Dokkum & Franx’s (1995) sample contains only five galaxies with radio power log \( P_{\nu} \) (6 cm)< 20 (W/Hz) and misaligned dust features. Further investigation is needed with a larger sample to determine how common these non-AGN misaligned cases are.

If it is indeed true that AGN associated energetic ISM can change the orientation of a gas disk then it would be interesting to investigate correlations between the AGN and the properties of the disk. For example massive disks would require a larger force to align them. A more energetic and higher density ISM should be able to more easily align a disk, suggesting that the radius past
which a disk ceases to be aligned with the jet should be correlated with the pressure and velocities observed in the hot material and the radio or jet luminosity. The outer parts of the jet would be related to the outer parts of the disk rather than the angular momentum of the outer part of the disk determining the future alignment of the jet. The outflow of an AGN could also affect its own accretion rate. It could either destroy its own disk, or increase the velocity dispersion and inflow rate in the accretion disk as has been proposed in the case of the starburst/AGN interaction (von Linden et al. 1993).

Hydrodynamic simulations of jets sometimes show backflows which result in over-pressured jets but also cause higher pressures and energetic motions in the plane perpendicular to the jet (e.g. Hardee & Norman 1990). These authors have noted that the boundary condition in the plane perpendicular to the jet can have a substantial effect on the jet hydrodynamics. One possibility is that the backflow is partly responsible for the ram pressure which we propose here affects the alignment of the disk. Jet simulations could be used to explore the forces on the disk as a function of ISM and jet physical parameters.

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Fig. 1.— HST/WFPC2 continuum imaging of the center of M84 from Bower et al. (1997a), with a resolution of 0.1” (8 pc). The grayscale shows the (V-I) map, with values of (V-I) ranging linearly from 2.0 (black) to 1.3 (white). The reddest color in the data is (V-I) = 1.7. Contours from the V-band image are superimposed, where the contour interval corresponds to a factor of $\sqrt{2}$ in intensity. The jet has PA $\approx 10^\circ$ on the pc scale and PA $\approx 0^\circ$ on the 100 pc scale (Jones, Sramek, & Terzian 1981). The dotted lines show the approximate morphology of the S-shape twist in the larger scale H$\alpha$ + [NII] emission map of Baum et al. (1988). Within these dotted lines the large scale emission is aligned with the dust lanes.
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