M84 - A Warp Caused By Jet Induced Pressure Gradients?\footnote{Based on observations with the NASA/ESA Hubble Space Telescope obtained at the Space Telescope Science Institute which is operated by the Association of University for Research in Astronomy, Inc. (AURA), under NASA contract NASS-26555.}

A. C. Quillen\textsuperscript{2} & Gary A. Bower\textsuperscript{3}

**ABSTRACT**

In radio galaxies such as M84 dust features tend to be nearly perpendicular to radio jets yet are not aligned with the galaxy isophotes. The timescale for precession in the galaxy is short ($\sim 10^7$ years at 100 pc) suggesting that an alternative mechanism causes the gas disk to be misaligned with the galaxy. In M84 we estimate the pressure on the disk required to overcome the torque from the galaxy and find that it is small compared to the thermal pressure in the hot ambient ISM estimated from the X-ray emission. We therefore propose that pressure gradients in a jet associated hot interstellar medium exert a torque on the gas disk in M84 causing it to be misaligned with the galaxy isophotal major axis. We propose that AGN associated outflows or associated hot low density media in nearby radio galaxies could strongly affect the orientation of their gas disks on 100 pc scales. This mechanism could explain the connection between gas disk angular momentum and jet axes in nearby radio galaxies.

By integrating the light of the galaxy through a warped gas and dust disk we find that the geometry of gas disk in M84 is likely to differ that predicted from a simple precession model. We find that the morphology of the gas disk in M84 is consistent with a warped geometry where precession is caused by a combination of a galactic torque and a larger torque due to pressure gradients in the ambient X-ray emitting gas. Precession occurs at an axis between the jet and galaxy major axis, but nearer to the jet axis implying that the pressure torque is 2-4 times larger than the galactic torque. We estimate that precession has occurred about this particular axis for about $10^7$ years. A better model to the morphology of the disk is achieved when precession takes place about an elliptical rather than circular path. This suggests that the isobars in the hot medium are strongly dependent on angle from the jet axis.

\textsuperscript{1}The University of Arizona, Steward Observatory, Tucson, AZ 85721; aquillen@as.arizona.edu
\textsuperscript{2}Kitt Peak National Observatory, National Optical Astronomy Observatories, P.O. Box 26732, Tucson, AZ 85726; gbower@noao.edu.
1. Introduction

Recent imaging from the Hubble Space Telescope (HST) 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. 1997a, Bower et al. 1997b, M87; Harms et al. 1994 and NGC 4261; Ferrarese, Ford, & Jaffe 1996). These gas disks are often observed to be nearly perpendicular to the jets, establishing a link between the angular momentum of the disk and the direction of the jet. Surveys of the observed angular difference, $\Psi$, between radio and disk axes in radio ellipticals and find a statistically significant peak in the distribution at $\Psi = 90^\circ$ (Kotanyi & Ekers 1979, Möllenhoff, Hummel & Bender 1992). This has established that radio jets are generally perpendicular to gas disks on large (kpc) scales in nearby radio galaxies, even though no correlation between the radio axis and the galaxy isophotal major axis exists at low redshift (e.g., 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/WFPC 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 ($\gtrsim 10^9$ 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), though accretion of a second black hole could change the spin axis of the AGN on a very short timescale. If, however, 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 causing alignment between the jets and a 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 Hα + [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$\alpha + [\text{NII}]$ emission (Baum et al. 1988) and the detailed morphology of the dusty disk itself. 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 a hot ambient interstellar medium (ISM) as a possible mechanism for affecting the alignment of the disk. By integrating the light of the galaxy through a warped gas and dust disk we find that the geometry of gas disk in M84 is likely to differ that predicted from a simple precession model. We search for a simple physical model that can account for the observed disk morphology.

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 50 $- 65^\circ$ of the dust features major axis 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). A multiply warped disk will form a band of absorption that is roughly perpendicular to the galaxy axis of symmetry. The morphology of the dust lanes in M84 resembles those of Centaurus 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 an axisymmetric 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.
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 $d\alpha/dt$ about the galaxy axis of symmetry for a gas ring of radius $r$ and inclination $\theta_g$ with respect to the galaxy axis of symmetry is

$$\frac{d\alpha}{dt} = \epsilon_\Phi \Omega \cos \theta_g$$

(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 ($\theta_g \sim 90^\circ$), the dependence on inclination is weak. In a time

$$t_p \sim \frac{3}{\epsilon_\Phi \Omega}$$

which we refer to as a precession time, rings that differ in radius by a factor of 2 should have an angular difference of $\sim \pi/2$.

To calculate the precession timescale we estimate the circular velocity, $v_c \sim 1.1\sigma_\ast$ (for a mildly anisotropic velocity distribution) where $\sigma_\ast = 303 \pm 5$ km/s for $r \lesssim 5''$ (Davies & Birkinshaw 1988) is observed stellar velocity dispersion. The ellipticity of the gravitational potential, $\epsilon_\Phi$, which is directly related to the ellipticity of the isophotes (see Eq. 1) $\epsilon_\Phi \sim \epsilon/3$ (see Binney & Tremaine 1987, Figure 2-13). Here the isophote ellipticity, $\epsilon \equiv 1 - b/a$, where $b/a$ is the axis ratio of the isophotes. In the near-infrared NICMOS 2.2 $\mu$m and 1.6 $\mu$m images the isophotes of M84 are symmetrical, do not vary in position angle, and show little extinction from dust. The ellipticity from these NICMOS images shows that an $\epsilon > 0.1$ persists to well within the core break radius ($r_b \sim 2''$) to $r \lesssim 0.3''$ (Quillen, Bower & Stritzinger 1999). This results in

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

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.

2.1. Pressure Required to Overcome the Galaxy Torque

Here we consider the possibility that the misalignment of the disk with the galaxy is caused locally. Radio galaxies put a substantial fraction of their luminosity into the kinetic energy of their jets (e.g. Rees et al. 1982). Emission in H$\alpha +$ [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, implying that a significant fraction of the jet mechanical energy is dissipated locally in the surrounding ISM (e.g. De Young 1981; Begelman...
1982). If the jets are responsible for motions in the surrounding ISM then there should be a differential in this medium, with the largest pressures nearest the jets, and the lowest pressures 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

$$\tau = \epsilon \Phi \cos(\theta_g) \sin(\theta_g) v_e^2$$

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

$$P_{\tau} > \epsilon \Phi \cos(\theta_g) \sin(\theta_g) \Sigma v_e^2 / r$$

where $\Sigma$ is the mass per unit area in the gas disk. This pressure is

$$P_{\tau} \gtrsim 2 \times 10^{-11} \text{dynes cm}^{-2} \left( \frac{\epsilon \Phi}{0.05} \right) \left( \frac{\Sigma}{1 M_\odot / \text{pc}^2} \right) \left( \frac{v_e}{330 \text{km/s}} \right)^2 \left( \frac{100 \text{pc}}{r} \right) \cos(\theta_g) \sin(\theta_g)$$

and can be compared to that estimated from the hot medium based on the X-ray emission. From the X-ray emission, Thomas et al. (1986) find an electron density that is $n_e \approx 0.5 (100 \text{pc}/r) \text{cm}^{-3}$ (where we have extrapolated from their profile which ranges from 0.5 – 20 kpc). This extrapolation is somewhat justified by comparison of pressures estimated from the [SII] 6717, 6731 Å lines in cooling flow galaxies (including M87 within $r < 200$ pc) which are not inconsistent with high central densities extrapolated from the lower resolution X-ray estimated pressures (Heckman et al. 1989). The above density can be converted to a thermal pressure in the hot medium of

$$P_{\text{therm}}(r) \sim 10^{-9} \text{dynes cm}^{-2} \left( \frac{100 \text{pc}}{r} \right)$$

(using a temperature of 0.67 kev; Matsumoto et al. 1997). This pressure could be larger than that required to to overcome the galaxy torque. This suggests that hydrostatic forces could dominate the gravitational torque. If there is a pressure gradient aligned with the jet axis in the hot medium then it is likely that the disk orientation could be strongly affected by a torque from the hot ambient medium.

### 3. Modeling the Warped Disk in M84

We first discuss constructing geometrical models for the dust features in M84 where the light of the galaxy is integrated taking into account the opacity from a warped disk. We then consider two physical models for the disk geometry which are based on a disk made up of rings of gas which are precessing differentially. Precession is either caused by torques from a triaxial galaxy or a combination of torques from an oblate galaxy and due to a pressure gradient in the ambient X-ray emitting medium (as proposed above).
3.1. A geometrical model for the warp

We can begin with a model for the geometry of the gas disk which assumes the disk is made up of rings of material which precess about a given symmetry axis (e.g. used by Tubbs 1980, Quillen et al. 1993 and Steiman–Cameron, Kormendy, & Durisen 1992). Here we refer to this axis as $\vec{m}$ and orient it such that it is near the angular momentum axis of the gas disk. Since the disk rotates in a direction such that the eastern side is blueshifted with respect to the systemic velocity (Baum, Heckman, & van Breugel 1990; Bower et al. 1997b), $\vec{m}$ should be pointing near the north. We describe $\vec{m}$ by a position angle on the sky $\beta$ and an inclination angle $\theta$ which is the angle between this axis and the line of sight ($\theta = 0$ refers to a symmetry axis pointing towards us).

We assume that a gas ring with radius $r$, rotation velocity $v_c$ and angular momentum $\vec{L} = rv_c\hat{n}$ precesses about $\vec{m}$. We define the inclination angle, $\omega$, of a gas ring with respect to the symmetry axis as the angle between $\hat{n}$ and $\vec{m}$. The azimuthal or precession angle, $\alpha$, is defined as the angle in the equatorial plane (plane perpendicular to $\vec{m}$) of the projection of $\hat{n}$ into this plane minus the angle of the projection of the line of sight. $\alpha$ increases in the direction opposite the rotation (e.g., see Fig. 6 of Quillen et al. 1993). We can then describe the geometry of the disk with inclination and precession angles as a function of $r$;

$$\alpha(r) = \alpha_0(r) = \frac{d\alpha}{dt} \Delta T + \text{constant}$$
$$\omega(r) = \omega_0.$$  

(8)

(9)

Here we have assumed a planar initial state for the gas disk, and $\Delta T$ is the timescale since this initial condition. When the magnitude of the torque is known an estimate for the radial dependence of the azimuthal angle then yields an estimate for $\Delta T$. When the torque is $\propto r^{-1}$ then $\frac{d\alpha}{dr} \propto r^{-1}$; this true for the torque caused by an oblate or prolate galaxy when the rotation curve is nearly flat. We can then write

$$\alpha_0(r) = B \alpha \left( \frac{100 \text{pc}}{r} \right) + \alpha_c.$$  

(10)

To produce a model we integrate the stellar light of the galaxy taking into account the opacity caused by the warped disk. The surface brightness profile at 1.6$\mu$m can be well fit in the inner 20" with a blend of two power laws (e.g. from Ferrarese et al. 1994)

$$I(r) = \sqrt{2} I_c \left( \frac{r_b}{r} \right)^{\beta_1} \left[ 1 + \left( \frac{r}{r_b} \right)^{2(\beta_2-\beta_1)} \right]^{-1/2}$$

(11)

and fit as a function of semi-major axis. The break radius, $r_b$, is where the profile changes shape or can also be described as near a point of maximum curvature in log log coordinates. For our model we assume a light density in 3 dimensions which is consistent with the above profile,

$$\rho(r) \propto s^{-\gamma_1} \left( 1 + s^{2(\gamma_2-\gamma_1)} \right)^{-1/2}.$$  

(12)
where \( s \equiv \frac{1}{r_b} \sqrt{x^2 + y^2 + z^2/q^2} \) and \( q \) is the observed isophotal axis ratio. Here we found that \( \gamma_1 = 0.5 \) and \( \gamma_2 = 2 \) and the break radius measured at 1.6\( \mu \)m \( (r_b = 1.97 \pm 0.15'' \approx 160 \) pc, Quillen, Bower & Stritzinger 1999) yields a pretty good fit to the observed surface brightness profile (with \( \beta_1 = 0.12 \pm 0.04, \beta_2 = 1.30 \pm 0.06 \)). For the disk itself we assume a powerlaw form for the opacity of the disk (seen face on) \( \tau(r) = \tau_0 \left( \frac{r}{r_p} \right)^{-\tau_p} \). We then compared the resulting integration qualitatively with the morphology of the disk in an optical band (WFPC2/PC image). For the models shown in Fig. 2 we used \( \tau_0 = 1 \) at F547M (0.55\( \mu \)m) and \( \tau_p = 0.2 \).

Fig. 2 shows an example of such a model (referred to as Model 1) compared to the F547M band image. Qualitatively this model succeeds in having two self similar dust features which roughly correspond to the two broad features observed, one at large scales and one at smaller scales. The model, however does not reproduce the strong asymmetries. For example the galaxy dust features are wider on the eastern side than on the western side of the nucleus, but reach a minimum just north of the nucleus. The model on the other hand has a dust feature that is nearly constant width running from east of the nucleus to the north west. The observed dust features also extend more linearly to the west on the western side than the model does. A model which ‘wobbles’ would be required to exhibit these traits. By wobbling we mean that the ring angular momentum vector \( \vec{n} \) could follow an elliptical path (corresponding to variations in \( \omega \)) which has an azimuthally varying precession rate about this path (corresponding to azimuthal variations in \( d\alpha/dt \)).

### 3.1.1. A Geometrical description for wobble

We can increase the complexity of our geometric model with additional terms

\[
\alpha(r) = \alpha_0(r) + A_{\alpha 1} \cos (\alpha_0 - \alpha_d) + A_{\alpha 2} \sin 2(\alpha_0 - \alpha_d) \tag{13}
\]

\[
\omega(r) = \omega_0 + A_\omega \cos 2(\alpha_0 - \alpha_d) \tag{14}
\]

where \( \alpha_0(r) \) comes from our more simplistic model described above. \( \alpha_d \) refers to the orientation angle of the maxima of the \( \alpha \) azimuthal variations projected onto plane perpendicular to \( \vec{m} \). The inclination term only contains a \( \cos 2\alpha_0 \) dependence because an \( m = 1 \) dependence can be removed with a redefinition for the symmetry axis \( \vec{m} \). A model with these additional parameters (listed in Table 1, and referred to as Model 2) is also shown in Fig. 2. This model succeeds at reproducing the asymmetries of the observed dust features. Most of the features observed in the model are present in the galaxy. We infer that the dust disk is probably precessing in a way that is more complicated than described by the simple precession model (Eqns. 8-10) and which matches observations in galaxies such as Cen A (Quillen et al. 1993) and NGC 4753 (Steiman–Cameron et al. 1992). We now examine what kind of physical models can produce significant extra ‘wobble’ terms in Eqns. 13 and 14.
3.1.2. Triaxial models

In the above discussion we have assumed that M84 is axisymmetric, and not triaxial. To reproduce the alignment of dusty features we require a model with symmetry axis that is not aligned with the galaxy isophotal major axis. When the galaxy is triaxial, the axes of symmetry do not coincide with the projected isophotal axes (e.g. de Zeeuw & Franx 1989). Using equations for the projected angles listed in Appendix A of de Zeeuw & Franx (1989) and assuming a galaxy major axis inclination angle consistent with our fit to the warp geometry we find that either extreme axes ratios are required (one galaxy axis ratio lower than 0.7) or only a very small region (less than 10° in the azimuthal projection angle φ of de Zeeuw & Franx 1989) of possible galaxy projection angles is allowed, making it unlikely. The lack of galaxy rotation (< 8km/s; Davies & Birkinshaw 1988) makes it unlikely that the galaxy is tumbling (as explored in van Albada, Kotanyi, & Schwarzschild 1982).

Additional dynamical concerns also imply that the central region of M84 should not be triaxial. Stochasticity induced by the black hole (Merritt & Valuri 1996) should cause triaxiality to be short lived (of order the local dynamical time) in the central regions of the galaxy. 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. We also note that the warped disk appearance and its misalignment with the galaxy major axis persists to well within the break radius ∼ 2′′ ∼ 160 pc of the nucleus where the ellipticity is slightly reduced and the slight boxiness disappears (as seen in the NICMOS 1.6µm isophotes; Quillen, Bower & Stritzinger 1999). Mechanisms that reduce ellipticity and boxiness (such as scattering) are likely to destroy triaxiality as well. 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).

We can also determine if a triaxial model is viable based on the size and form of the ‘wobble’ terms introduced above, which are probably needed to describe the disk morphology. We associate the symmetry axis of the disk $\vec{m}$ with one symmetry axis of the triaxial galaxy. The amplitude of variation in inclination angle described by $A_\omega$ can be estimated from the azimuthal variation in the torque on a gas ring as the ring precesses. This results in a torque that causes the ring to change inclination (ω) rather than precession rate. This amplitude should be roughly equivalent to the size of the ellipticity of the gravitational potential in the plane perpendicular to $\vec{m}$ times the angle ω (for ω small). Since this angle is small in M84 and the ellipticity of the potential should be ∼ 1/3 the axis ratio of the density in this plane, $A_\omega$ should be quite small (we estimate less than a degree). This is far less than exhibited in our Model 2 described above. In a triaxial galaxy it makes sense that this amplitude should be small because the gravitational potential is always smoother than the actual density distribution. For a triaxial galaxy we also expect no sin(α0) variation in $d\alpha/dt$ (or $A_{\alpha1}$ term) which were a part of Model 2 discussed above. Dynamical models which neglect triaxiality for the disk kinematics and morphology in Centaurus A (e.g. Sparke...
1996, [Quillen et al. 1993] are successful despite the evidence that this galaxy probably is triaxial [Hui et al. 1995]. This supports our statement that triaxial galaxies are unlikely to result in disk precession models with large 'wobble' terms.

### 3.2. Warp model including a pressure torque

Above we proposed that the ambient X-ray emitting ISM could exert sufficient torque on the gas disk to affect the orientation of the gas disk. Here we elaborate on this possibility and search for a model that can accurately match the inferred geometry of the gas disk.

The disk rotates in a direction such that the eastern side is blueshifted with respect to the systemic velocity [Baum et al. 1990] [Bower et al. 1997]. The gas disk, if warped, has orientation such that with increasing radius the azimuthal angle of greatest disk inclination moves counter (retrograde) to the direction of rotation. This orientation would be consistent with an oblate galaxy potential (if the warp were indeed caused by the torque from the galaxy; e.g., Tubbs 1980). For an oblate galaxy potential the shape of the potential causes a force towards the galactic plane of symmetry, resulting in a 'retrograde' warp. If higher pressures exist in the ISM along the jet axis then the pressure gradient in this gas would exert a force on the gas disk towards the plane perpendicular to the jets. When the precession period decreases with increasing radius this again would cause a 'retrograde' warp but about a symmetry axis aligned with the jet rather than a galactic axis of symmetry.

We can estimate the torque resulting from the hot ISM as follows: As typically assumed for a non-axisymmetric galaxy, we can describe the pressure in the volume filling X-ray emitting ISM as having an the axis of symmetry, \( \hat{p} \), of the isobars in the hot gas. We chose to orient \( \hat{p} \) with a sign such that it is nearest the average angular momentum vector of the disk. The pressure gradient across a gas disk with mass surface density \( \Sigma \) and thickness \( h \) (corresponding to the vertical scale height) results in an average torque per unit mass (around a ring of radius \( r \))

\[
|\tau_p| = \frac{h}{2\Sigma} \frac{\partial P}{\partial \theta}
\]

where the direction of the torque on the ring is given by \( \hat{p} \times \hat{n} \).

The average torque per unit mass from a non-axisymmetric gravitational potential can be determined similarly with

\[
\tau_g = \epsilon \Phi v_r^2 \cos \theta_g(\hat{n} \times \hat{g})
\]

where we have assumed a \( \cos(2\theta_g) \) form for the non-axisymmetric part of the gravitational potential. Here \( \theta_g \) refers to the ring inclination with respect to the axis of symmetry of the galaxy, or the angle between \( \hat{n} \) and \( \hat{g} \), for \( \hat{g} \) the galaxy symmetry axis and \( \epsilon \Phi \) is the ellipticity of the gravitational potential. The total average torque per unit mass on a gas ring would then be given by the sum of the two torques \( \tau = \tau_g + \tau_p \).
Precession of the gas disk takes place approximately about a vector
\[ \vec{m} = \frac{\partial P}{\partial \theta} \frac{h}{2\Sigma} \hat{p} + \epsilon p v_c^2 \hat{g} \]  
(17)
where \( \frac{\partial P}{\partial \theta} \) is estimated at the average angle between \( \hat{n} \) and \( \hat{p} \). We can define orientation angles for the gas disk as a function of radius with respect to this vector \( \vec{m} \). As in §3.1 we define the inclination angle, \( \omega \), and \( \alpha \) for a ring with angular momentum axis \( \hat{n} \) with respect to the precession axis \( \vec{m} \). The total torque is
\[ \vec{\tau} \approx \vec{m} \times \hat{n} \]  
(18)
and the angular precession rate about \( \vec{m} \) is
\[ \frac{d\alpha}{dt} \approx \frac{\vec{m} \cdot \hat{n}}{rv_c} \]  
(19)

When the galaxy is oblate the gas disk will precess about an axis intermediate between the galaxy axis of symmetry (\( \hat{g} \)) and the pressure axis of symmetry (\( \hat{p} \), which we associate with the jet axis). However when the galaxy is prolate the sign of the galactic torque term changes (equivalent to setting \( \epsilon \Phi \) to be negative) and precession could occur about an axis which is not obviously between the two symmetry axes.

Because of the sense of the warp, in M84 we expect that the galaxy is nearly oblate and so that the gas disk should precess about an axis intermediate between the two symmetry axes. In fact we can measure the orientation of this axis and from it estimate the size of the pressure torque compared to the the galactic term (assuming that the galaxy is not strongly triaxial).

### 3.2.1. Ratio of pressure to galactic torque

In M84 we observe that the dust features are aligned at an angle (PA= 65 → 80°) intermediate between the jet axis (PA= 0; Jones et al. 1981) and the galaxy major axis (PA= 129°; van Dokkum & Franx 1995). Because the north and south jets are have similar intensities we assume that the jet axis is perpendicular to the line of sight. We find a rough fit to the warp with a symmetry axis with PA between −10 and −15°. So the angle between the jet and \( \vec{m} \) is about 10 − 15° and the angle between \( \vec{m} \) and the galaxy axis is about 35 − 40°. This suggests that the torque from the pressure is larger than the galactic torque so that
\[ \frac{\tau_g}{\tau_p} \approx 2 - 4 \]  
(20)
This lets us estimate the size of the azimuthal pressure component. For \( \frac{\partial P}{\partial \theta} \equiv \epsilon p P_0(r) \)
\[
P_0(r) \sim 3 \frac{\epsilon \Phi v_c^2 \Sigma}{\epsilon_p h} \\
\sim 3 \times 10^{-10} \text{dynes cm}^{-2} \left( \frac{\epsilon \Phi}{0.05} \right) \left( \frac{\epsilon_p}{1.00} \right)^{-1} \left( \frac{v_c}{300 \text{ km s}^{-1}} \right)^2 \left( \frac{\Sigma}{2M_\odot \text{pc}^{-2}} \right) \left( \frac{h/r}{0.1} \right)^{-1} \left( \frac{r}{100 \text{pc}} \right)^{-1}.
\]  
(21)
Here $\epsilon_p$ represents the ellipticity of the isobars. We have adopted a range for the surface density $\Sigma$ based on 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. An estimate for the disk mass based on the NICMOS images is consistent with the low end $\sim 10^6 M_\odot$. For a disk of constant surface density (consistent with a small $\tau_p$, see §3.1) truncated at $r = 400$ pc the lower of these mass estimates give $\Sigma \sim 2 M_\odot \text{pc}^{-2}$.

Although there are uncertainties in the parameters, the pressure we estimate above is similar to the thermal pressure we estimated from the ambient volume filling X-ray emission (see Eqn. 7). The alignment and precession of the disk therefore could be consistent with the model proposed here where a pressure exerted by the X-ray medium (aligned with the jet) and the non-axisymmetric galaxy both exert torques on the gas disk.

3.2.2. Warp timescale

As mentioned in §3.1, once the size and radial form of the torque is known, the radial dependence of $\alpha$ can be used to estimate a timescale. Here we have assumed a planar initial state for the gas disk, and $\Delta T$ is the timescale since this initial condition (see Eqn. 2). For a warp caused purely by torque from the galaxy $d\alpha/dt \sim \epsilon_p \Omega \propto r^{-1}$ when the rotation curve is nearly flat. From our modeling we estimate $B_\alpha = 1.2 \pm 0.3 \times 10^3$ radians pc yielding an estimate of

$$\Delta T = 1.8 \times 10^7 \text{yr} \left( \frac{B_\alpha}{1.2 \times 10^3 \text{radians pc}} \right) \left( \frac{\epsilon_p}{0.05} \right)^{-1} \left( \frac{v_c}{300 \text{km s}^{-1}} \right)^{-1} \left( \frac{\tau_p/\tau_g}{3} \right)^{-1} \tag{22}$$

This suggests that precession has occurred only about $10^7$ years since an event responsible for distributing the gas and dust, or causing the present orientation of the jets. Our model places time limits on the stability of the jet orientation. Here we link the morphology of the disk to the history of pressure asymmetries caused by the jets themselves. If the jets were at a different angle previously (as suggested from the large scale radio emission) then the large scale morphology of the disk could be linked to the past jet orientation. An alternate mechanism is then required to change the jet orientation in a way not related to the disk orientation (for example as proposed by Roos, Kaastra, & Hummel 1993 involving binary black holes).

3.2.3. Wobble

In general the sum of the two torques will lead to an elliptical path (or ‘wobble’) for the angular momentum vector of a gas ring, $\hat{n}$, about an axis $\approx \vec{m}$ which also varies in angular precession rate. This wobble corresponds to the variation in torque that a ring feels as it precesses. From a measurement of this ‘wobble’ we can determine if the pressure gradient is strongly dependent on $\theta_p$, the angle between $\hat{n}$ and $\hat{p}$. As in the case of a triaxial galaxy, for a $\cos 2\theta_p$
dependence we would expect that the wobble about simple precession should be small (less than a degree). However we achieve a better correspondence to the observed morphology with larger azimuthal variations in $\omega$ and $d\alpha/dt$ suggesting that the pressure is strongly dependent on the inclination angle $\theta_p$ from the jet axis.

We now estimate the difference in the torque as the angular momentum axis precessed about $\vec{m}$. As the ring precesses variation in the torque reach extremes nearest and furthest from the jet axis of the size

$$\Delta \tau \approx \left( \frac{\partial \tau_p}{\partial \theta} - \frac{\partial \tau_g}{\partial \theta} \right) \omega.$$  \hspace{1cm} (23)

This results in a variation in $\frac{d\alpha}{dt}$ that is proportional to $\cos(\alpha_0)$ (described in our model by $A_{\alpha 1}$). The component of $\Delta \tau$ in the plane perpendicular to $\vec{m}$ causes the ring to change inclination and is about the same size as $\Delta \tau$ times an additional factor of $\omega$ and results in a $\cos(2\alpha_0)$ dependence of $\omega$ which we described in our model by $A_\omega$. (The $\cos(\alpha_0)$ dependence can be removed by a redefinition of $\vec{m}$). Here our estimates have assumed that $\omega$ is small.

If both the pressure and gravitational torques show the same angular dependence (e.g. $\cos(2\theta)$) then the dependence of $\alpha$ cancels to first order in the angles $\theta_g$ and $\theta_p$ and $\frac{d\alpha}{dt}$ varies only to second order in $\omega$. The dependence on $\alpha$ can be approximated as

$$A_{\alpha 1} \approx \omega_0 (m^2 - 4) \cos(\alpha_0)$$  \hspace{1cm} (24)

where $m$ refers to the angular dependence of $\frac{\partial P}{\partial \theta}$ on $\theta_p$ and the variation in $\omega$ is $A_\omega \sim A_{\alpha 1} \omega$. $\alpha(r)$ is then described by Eqns. 8, 10 and 13 and $\omega(r)$ is described by Eqn. 14. The precession rate is expected to be fastest when the ring angular momentum vector is furthest from the pressure or jet axis, $\hat{p}$, and nearest $\hat{g}$, the galaxy symmetry axis. From this we can see that large azimuthal variations in the angular precession rate and inclination could be symptoms of a strong angular dependence of the isobars. The signs of $A_\omega$ and $A_{\alpha 1}$ in our Model 2 (see Table 1) suggests that the galaxy axis (to the north-west on the sky) is pointing somewhat towards us with the angle between it (projected on to the planet perpendicular to $\vec{m}$) and the line of sight $|\alpha_d| \approx 50^\circ$.

### 3.2.4. A note

We have ignored the possibility that the isobars might actually be affected by the galaxy potential. This situation would arise naturally to some extent because as energy is lost from the jet into the ISM energy would be transferred in the direction of least gravitational force, i.e. towards the galactic major axis. However if hydrostatic equilibrium applies, the sound speed of the gas sets a particular scale length in the hot gas whereby $h/r \sim \frac{c_s}{v_c}$. Because the sound speed in the hot gas $c_s \sim v_c \sim 300$ km/s hydrostatic equilibrium would set $h/r \sim 1$ and so the isobars are unlikely to be significantly affected by the gravitational potential, and are more likely to be determined by the nature of the dissipation from the jet into the ISM.
4. 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. None of these possibilities would provide a good explanation for the observed morphology of the gas and dust disk.

As an alternative to these external mechanisms we consider the possibility of a local force on the disk. We estimate the pressure required to overcome the torque from the galaxy and find that it is small compared to the thermal pressure inferred from X-ray observations. Pressure gradients in this ambient hot ISM could therefore overcome the galaxy torque. We therefore propose that pressure gradients in an energetic low density medium in M84 could strongly affect the orientation of the gas disk on the scale of a few hundred pc.

By integrating the light of the galaxy through a dusty warped disk we find that the gas disk in M84 is likely to differ from a simple precession model where the precession rate is constant with azimuthal angle and the angular momentum axis of a gas ring traces a circular path. A triaxial model for the galaxy, though it would explain the misalignment of the dust features with the galaxy isophotal major axis, is not a good explanation for a variety of reasons. Because of the expected weak dependence of the gravitational torque on the position angle wobble of the angular momentum axis of a gas ring is likely to be smaller than that we infer from the disk geometry. The misalignment also persists to small radii where the galaxy is expected to be oblate and not triaxial. We propose instead that the morphology of the gas disk in M84 is consistent with a warped geometry where precession is caused by a combination of a galactic torque and a pressure due to pressure gradients in the ambient X-ray emitting gas. The alignment of the disk can be used to estimate the ratio of these torques. Precession occurs at an axis between the jet and galaxy major axis, but nearer to the jet axis. This angle implies that the pressure torque is 2-4 times larger than the galactic torque. A rough model to the morphology of gas disk also allows us to estimate the degree of precession that has taken place. Assuming the initial condition of gas in a plane we estimate the timescale since then to be a few times $10^7$ years. A better model to the morphology of the disk is achieved when precession takes place about an elliptical rather than circular path and precesses fastest when the angular momentum vector is furthest from the
jet axis. This suggests that the isobars are strongly dependent on angle from the jet axis.

Recent investigations find that almost all ellipticals have dust (van den Bosch et al. 1994). In cases of non-active elliptical galaxies having dusty disks misaligned with the galaxy isophotes, the misalignment must 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 \( \log P_\nu (6 \text{ cm}) < 20 \) (W/Hz) and misaligned dust features. Further investigation is needed with a larger sample to determine how common these non-AGN misaligned cases are and if the models proposed here are applicable. One consequence of our proposed mechanism is that on very long timescales we expect the disk to become multiply warped or rippled. On a timescale of roughly 10 times the precession time we would then expect the disk to settle into a quasi-stationary surface nearly perpendicular to the jet axis. This might account for the observed alignments between jets and dust features. Comparison of high resolution X-ray morphology (such as will be possible with AXAF), dust morphologies and ionized gas kinematics should determine if the type of models introduced here are appropriate.

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Fig. 1.— The relative orientation of the gas disk and stellar isophotes in M84. HST/WFPC2/PC 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 alligned with the dust lanes. North is up and East is to the left.

Fig. 2.— Models compared to the WFPC2/PC F547M image. These figures are oriented with precession symmetry axis of the disk oriented up. North is at a position angle 10$^\circ$ east of the y axis. a) A circular precession model with no wobble (Model 1 with parameters listed in Table 1). b) A model with wobble (Model 2). c) F547M image.
Table 1. Model Parameters for M84’s Disk

| Model | $\beta$ | $\theta$ | $B_\alpha$ | $\alpha_0$ | $\omega_0$ | $A_{\alpha 1}$ | $A_\omega$ | $\alpha_d$ |
|-------|--------|--------|------------|------------|-------------|--------------|------------|-----------|
| (1)   | deg    | deg    | radians pc| deg        | deg         | deg          | deg        | deg       |
| 1     | -10    | 112    | $-1.2 \times 10^3$| 180        | 12          | 0            | 0          | 0         |
| 2     | -10    | 112    | $-1.2 \times 10^3$| 180        | 8           | -20          | 8          | -50       |

**NOTES.** Parameters are discussed in §3.1. Columns: (1) Model 1 has no ‘wobble’ and is shown in Fig. 2a. Model 2 is shown in Fig. 2b; (2) Position angle on the sky (E of N) of symmetry axis of warp, $\vec{m}$; (3) Inclination of $\vec{m}$. ($\theta = 0$ refers to a symmetry axis pointing towards us); (4) Dependence of $\alpha_0$ on radius, See Eqns. 8, 10 and 13; (5) Constant term for $\alpha_0$. See Eqns. 10 and 13; (6) Average disk inclination with respect to the warp symmetry axis, (angle between $\vec{m}$ and $\vec{n}$); see Eqns. 9 and 14. (7) Amplitude of $m = 1$ azimuthal variation in $\alpha$, see Eqn. 13; (8) Amplitude of $m = 2$ azimuthal variation in $\omega$, see Eqn. 14; (9) Angle where extrema of $\alpha$ and $\omega$ variation occurs. See Eqns. 13 and 14.
The relative orientation of the gas disk and stellar isophotes in M84. HST/WFPC2/PC 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$\alpha + [\text{NII}]$ emission map of Baum et al. (1988). Within these dotted lines the large scale emission is aligned with the dust lanes. North is up and East is to the left.
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