The Nuclear Ionized Gas in the Radio Galaxy M84 (NGC 4374)\textsuperscript{1}

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ABSTRACT

We present optical images of the nucleus of the nearby radio galaxy M84 (NGC 4374 = 3C272.1) obtained with the Wide Field/Planetary Camera 2 (WFPC2) aboard the Hubble Space Telescope (HST). Our three images cover the Hα + [N II] emission lines as well as the V and I continuum bands. Analysis of these images confirms that the Hα + [N II] emission in the central 5′′ (410 pc) is elongated along position angle (P.A.) ≈ 72°, which is roughly parallel to two nuclear dust lanes. Our high-resolution images reveal that the Hα + [N II] emission has three components, namely a nuclear gas disk, an ‘ionization cone’, and outer filaments. The nuclear disk of ionized gas has diameter ≈ 1″ = 82 pc and major axis P.A. ≈ 58° ± 6°. On an angular scale of 0′′5, the major axis of this nuclear gas disk is consistent with that of the dust. However, the minor axis of the gas disk (P.A. ≈ 148°) is tilted with respect to that of the filamentary Hα + [N II] emission at distances > 2″ from the nucleus; the minor axis of this larger scale gas is roughly aligned with the axis of the kpc-scale radio jets (P.A. ≈ 170°). The ionization cone (whose apex is offset by ≈ 0′′3 south of the nucleus) extends 2″ from the nucleus along the axis of the southern radio jet. This feature is similar to the ionization cones seen in some Seyfert nuclei, which are also aligned with the radio axes.

Subject headings: galaxies: active — galaxies: elliptical — galaxies: individual (M84) — galaxies: jets — galaxies: nuclei
1. Introduction

Recent high-resolution imaging surveys of nearby elliptical galaxies with HST (e.g., Jaffe et al. 1994; Lauer et al. 1995) have found that small ($\lesssim 200$ pc) axisymmetric structures in the nuclear regions are common. These structures include filaments or disks of dust and ionized gas. The identification of such disks in galaxies hosting an active galactic nucleus (AGN) is especially interesting, since AGNs are thought to be powered by the accretion of gas into the relativistically deep potential well of a supermassive black hole. In the context of this model, powering an AGN for a long duration requires that large amounts of gas in the galaxy’s ISM be transported to the nucleus for eventual accretion onto the central black hole. It is unlikely that this gas would arrive at the nucleus with no angular momentum, so the nuclear gas is expected to form a thin disk, which is thought to be responsible for collimating the jets in AGNs in a direction approximately perpendicular to the plane of the disk (Rees 1984).

Discovery of ionized gas disks in nearby radio galaxies is especially important because the kinematics of such disks might provide an estimate of the nuclear mass, if the gas exhibits Keplerian motion about the nucleus. Since high spatial resolution ($\lesssim 10$ pc) is required for such an analysis, the nearest radio galaxies, including the Virgo cluster elliptical galaxies M87 and M84, are the best targets. The nucleus of M87 is known to contain an ionized gas disk (Ford et al. 1994), the kinematics of which suggest the presence of a $2 \times 10^9$ $M_\odot$ black hole, if the gas is in circular motion (Harms et al. 1994). For M84, previous narrow-band imaging obtained by Hansen et al. (1985) and Baum et al. (1988) has shown that the H$\alpha + [N \text{ II}] \lambda\lambda 6548,6583$ emission in the circumnuclear region is $\approx 7'' \times 20''$ (570 pc $\times$ 1640 pc) in extent, and elongated in P.A. $\approx 83^\circ$. This elongated emission region is roughly perpendicular to the radio jet axis, which is at P.A. $\approx 10^\circ$ on the pc scale (Jones et al. 1981) and $\approx 170^\circ$ on the kpc scale (Laing & Bridle 1987). However, the morphology of the ionized gas is not clearly resolved by ground-based imaging. It could be a gas disk or filamentary emission associated with a cooling flow (Hansen et al. 1985). The kinematics of the H$\alpha + [N \text{ II}]$ emission region indicate that the gas is rotating about the nucleus (Baum et al. 1990, 1992) and that the rotation gradient across the nucleus is spatially unresolved (i.e., $> 100$ km s$^{-1}$ arcsec$^{-1}$), suggesting the presence of a high mass concentration at the nucleus. These data provide a tantalizing clue that M84 might indeed contain a nuclear gas disk. We have obtained higher resolution images of M84 with HST to determine if this preliminary inference is correct.

Throughout this paper, we adopt a distance to M84 of 17 Mpc (Mould et al. 1995). At this distance, 1'' corresponds to 82 pc. The Galactic extinction along the line of sight is $A_B = 0.13$ mag (Burstein & Heiles 1984).
2. Observations and Data Reduction

Images of the nuclear region of M84 were obtained with WFPC2 (Burrows 1995) aboard HST on 1996 March 4 with the telescope tracking in fine lock (nominal jitter $\approx 0''007$). The nucleus was placed in the Planetary Camera, which has a scale of $0''044$ pixel$^{-1}$ and provides a resolution of $\approx 0''1$ (8 pc). Two exposures were obtained with each of the filters F547M, F814W, and F658N, whose effective wavelengths/bandpass widths are 5454 Å/486 Å, 8269 Å/1758 Å, and 6590 Å/28.5 Å. These filters provide images in H$\alpha\lambda 6563 + [\text{N II}]\lambda\lambda 6548, 6583$ and the neighboring continua. Total exposure times through these filters were 1200 sec, 520 sec, and 2600 sec, respectively. Initial data reduction was accomplished by the HST pipeline software, after which the two sub-exposures in each filter were combined to reduce the effect of cosmic ray events. We adopted the flux calibration provided by the HST pipeline software. For the F547M and F814W images, we have transformed the instrumental magnitudes to Landolt V and I magnitudes, respectively, by using the calcphot task in the synphot package in STSDAS on a synthetic early-type galaxy spectrum from Bica (1988) that closely matches the spectrum of the stellar population in M84. Although the magnitudes that we quote in the present paper are in the Landolt system, the fluxes quoted are at the effective wavelengths given above. To register the images, we measured the positions of $\approx 20$ globular clusters in M84 in each of the images and found no rotational shifts and only small translational shifts ($\approx 0.5 - 1.0$ pixel) between the three images. After correcting for these shifts, the images are aligned to $\pm 0.1$ pixel ($\pm 0''004$). To the accuracy of alignment, the bright central point source is coincident in all three bandpasses. Thus, we adopt the central continuum peak as the location of the nucleus. Since this galaxy contains two prominent dust lanes near the nucleus (see §3), removing the continuum contribution from the F658N image to obtain the H$\alpha + [\text{N II}]$ image is more difficult than simply subtracting the F547M or F814W image. We constructed a synthetic image of the continuum at 6590 Å using the F547M image and the ratio of the F547M and F814W images in conjunction with the assumptions that (1) the unreddened spectrum of the stellar population matches that of the synthetic early-type galaxy spectrum used above, and (2) the internal reddening associated with the prominent dust lanes is described by the Galactic interstellar extinction curve. This synthetic 6590 Å continuum image was subtracted from the F658N image, yielding the H$\alpha + [\text{N II}]$ image. Since the individual exposure times of the two sub-exposures obtained in the filter F658N were long (1000 sec and 1600 sec), there were $\approx 100$ pixels that were affected by cosmic ray events in both sub-exposures and thus could not be removed by combining them. We removed these residual cosmic ray events from the H$\alpha + [\text{N II}]$ image by applying a median filter with dimensions of $3 \times 3$ pixels. The resolution of this smoothed image was determined to be $\approx 0''13$ by comparing the FWHM of a model PSF (Krist 1995) before and after it had been smoothed with an identical median filter. This median filter conserved
flux in the image to \( \lesssim 1\% \), except for pixels within 0\'13 of the nucleus, where the flux loss was typically 30\%. We converted the flux densities \( F_\lambda \) in the H\( \alpha \) + [N II] image to fluxes integrated over these emission lines by using the synphot task calcphot. We calculated values of \( F_\lambda \) for the F658N bandpass both for the synthetic early-type galaxy spectrum (see above) alone and for this synthetic spectrum with model H\( \alpha \) and [N II] \( \lambda \lambda 6548,6583 \) emission lines (whose relative line ratios were taken from Hansen et al. 1985) added. The difference in these predicted values of \( F_\lambda \) was compared with the H\( \alpha \) + [N II] flux in the model emission lines to show that the values of \( F_\lambda \) in the H\( \alpha \) + [N II] image should be multiplied by 25.7 (which is close to the effective bandwidth of the F658N filter of 28.5 Å) to obtain total H\( \alpha \) + [N II] fluxes.

3. Results

Fig. 1 (Plate X) shows grayscale representations of the F547M, F814W, (V−I), and H\( \alpha \) + [N II] images. The continuum images show a compact source at the nucleus (which lies at the photometric center of the galaxy), as well as two dust lanes (also seen by Jaffe et al. 1994) within the central 5\" whose orientation is roughly parallel to the filamentary H\( \alpha \) + [N II] emission extended on the same scale. Both dust lanes are oriented roughly in an east-west direction at \( \geq 1\" \) east of the nucleus. However, west of this point, they both bend toward the southwest by \( \approx 25^\circ \).

Fig. 1(f) shows that the H\( \alpha \) + [N II] emission closest to the nucleus has a very interesting distribution. A contour plot of this image (Fig. 2) shows that the isophote shapes change with increasing distance \( R \) from the nucleus. For \( R < 0\'5 \) (41 pc), the isophotes are nearly elliptical, as would be expected for an inclined, circular thin gas disk. Baum et al. (1990) found that the gradient of the rotational velocity across the nucleus is spatially unresolved, with the projected rotation axis lying at P.A. 0\(^\circ\) (Baum et al. 1990) or P.A. 24\(^\circ\) (Baum et al. 1992). This rotation axis direction is broadly consistent with the photometric minor axis of the gas distribution for \( R > 2\" \), suggesting that the gas forms a rotating disk. To determine the geometrical properties of this disk, we fitted model ellipses to these elliptical isophotes using the ‘ellipse’ task (see Jedrzejewski 1987) in the STSDAS package. During the fit, we allowed the ellipse center, intensity, position angle, and ellipticity to be free parameters. Successful fits were obtained for \( R < 0\'5 \), but outside this radius ellipses cannot fit the isophotes since they have irregular shapes. The main results of the fits to these inner isophotes are:

1. The isophotes are concentric to \( \pm 0\'05 \) (4 pc), and the center of the gas disk coincides with the nucleus (and with the H\( \alpha \) + [N II] peak; see §2). This alignment in M84 contrasts
with the offset of 13 ± 7 pc between the centers of the galaxy and dust disk in the radio galaxy NGC 4261 (Ferrarese et al. 1996).

(2) The average P.A. and ellipticity for radii 0′′.25–0′′.5 are 58°±6° and 0.17±0.07, respectively (the quoted errors are dominated by the noise in the image). The P.A. and ellipticity measurements for $R < 0′′.25$ were not included in these averages because the finite resolution and pixel sampling make the isophotes circular. The minor axis of the disk is not quite parallel to the radio jet axis, but is offset by 22°. By comparison, the minor axis of the gas disk in M87 is offset by 19° from its radio jet axis (Ford et al. 1994). If the disk is thin and circular, the above ellipticity implies an inclination of 34°±7°.

(3) The Hα + [N II] emission at the nucleus is very compact. Fig. 3 shows a comparison of the intensity profile given by the isophote fits with the shape of a model PSF generated by the program Tiny Tim (Krist 1995). A 3 × 3 median filter has also been applied to this model PSF, similar to the Hα + [N II] image (see §2). The total flux of the normalized PSF is $8.7 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$.

The observed spatial distribution of the dust closest to the nucleus indicates that it lies in the nuclear region (rather than simply lying in the foreground). A comparison of Figs. 1(a) and 1(c) shows that the compact nuclear continuum source (discussed in more detail below) is bluer than the other reddened regions in the central 1″. Fig. 1(e) shows the (V–I) color map of a 3″ × 3″ region centered on the nucleus. In this region, the reddening is greatest along the northern edge of the central dust lane and at the patch of dust centered on the nucleus with diameter ≈ 0″.3. The nuclear dust lane lies along the same P.A. as the gas disk, suggesting that it is associated with the gas disk. This dust morphology is also seen in the F547M and F814W images when displayed with suitable intensity scales, although not as prominently as in Fig. 1(e) because of the bright nuclear continuum source.

The Hα + [N II] emission outside the central gas disk appears to have two components (see Figs. 1(d) and 1(f)). The most prominent component is the filamentary emission extended parallel to the dust lanes, while the fainter component is a possible conical structure extending ≈ 2″ south from the nucleus with axis along P.A. ≈ 162°, which is consistent with the axis of the kpc-scale radio jet (P.A. ≈ 170°). This cone has a well defined, sharp, straight edge on at least the NE edge, suggesting shadowing of a nuclear source. There is also a hint of a similar conical structure to the north of the nucleus. Although the geometrical properties of the south cone are somewhat subjective, we find an opening angle of ≈ 73° at the apex (which is located ≈ 0″.3 south of the nucleus). The general appearance of these conical structures in our Hα + [N II] image of M84 resembles the ionization cones seen in some Seyfert galaxies (Wilson & Tsvetanov 1994 and references therein). The axis of M84’s conical structures is well-aligned with the radio jet axis, similar to the strong alignment seen
in Seyfert galaxies between these structures. The ionization cone in M84 is more closely aligned with the kpc-scale radio jets than with the axis of the pc-scale jet (P.A. $\approx 190^\circ$). Perhaps this suggests that the structure shadowing the nuclear source is located on scales $\gg 1$ pc. However, confirmation of this ionization cone requires HST imaging of M84 in a high-excitation emission line (e.g., [O III] $\lambda 5007$).

The apparent flux and color of the nuclear continuum source seen in Fig. 1 (also seen in an archival WFPC image; Jaffe et al. 1994) can be measured by fitting a model PSF (constructed with Tiny Tim; Krist 1995) to the nucleus. We determined the normalization of the model PSF to be such that subtracting it from the original image would yield an image in which the intensity is roughly constant within $\approx 0\farcs3$ of the nucleus. The flux and color (both corrected for Galactic extinction but not internal extinction) of the nuclear continuum source implied by this procedure are $V = 19.9$ and $(V-I) = 1.6$. These values are clearly affected by extinction and reddening by dust within M84.

M84’s dust and gas content can be estimated from our $(V-I)$ color map, assuming that light from the stars lying in the foreground of the embedded dust lanes is insignificant and that the extinction internal to M84 follows the Galactic interstellar extinction curve and gas-to-dust ratio. Fig. 4 shows a histogram of the $(V-I)$ values from Fig. 1(c) (after correcting for Galactic reddening) for only the region of the image encompassing the dust lanes. This region is represented by a rectangle 14$''$5 wide in right ascension and 8$''$4 high in declination (whose center lies 2$''$2 NNE of the nucleus). Although the $(V-I)$ at the peak of the distribution in Fig. 4 is 1.4, this probably is not representative of the unreddened color. Buta & Williams (1995) found that $(V-I) = 1.24 \pm 0.008$ inside the half-light radius of M84, while the mean $(V-I)$ for elliptical galaxies with the same Hubble type as M84 is 1.2. Adopting the latter value as the unreddened color of M84, the mean $(V-I)$ of 1.43 indicates a mean internal extinction of $\langle A_V \rangle = 0.54$ within the region encompassing the dust lanes. This provides an estimate of the mass in dust using $M_d = \Sigma \langle A_V \rangle / \Gamma_V$ (e.g., van Dokkum & Franx 1995; Sadler & Gerhard 1985), where $\Sigma$ is the surface area affected by dust extinction and $\Gamma_V$ is the visual mass absorption coefficient $\approx 6 \times 10^{-6}$ mag kpc$^2$ M$_{\odot}^{-1}$. The area of the rectangle is $\Sigma = 0.82$ kpc$^2$, so $M_d = 7 \times 10^4$ M$_{\odot}$. This agrees with the dust mass determined from the far-infrared fluxes measured by IRAS (e.g., Roberts et al. 1991; adjusted to our adopted distance), suggesting that our color map of M84 provides an adequate measure of the dust content. This agreement between optical and far-infrared dust masses contrasts with the optical dust “deficit” often found in other optical studies of elliptical galaxies when dust whose spatial distribution closely follows that of the stars is missed (Goudfrooij & de Jong 1995). Adopting the Galactic gas-to-dust ratio ($M_{\text{gas}}/M_d \approx 130$), the total mass of gas and dust within this central region of M84 is $9 \times 10^6$ M$_{\odot}$. The mass in ionized gas is a very small fraction of this total. The total flux in H$\alpha$ (corrected for Galactic and
internal extinction) is $6.3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ if we adopt the Hα/[N II] $\lambda\lambda 6548, 6583$ ratio measured by Hansen et al. (1985). Assuming case B recombination, $T_e = 10^4$ K, and $N_e = 10^3$ cm$^{-3}$, we find $M(H^+) \approx 6 \times 10^3 M_\odot$. Most of the gas must thus be neutral or molecular. Although searches for emission from HI 21 cm and CO (2 − 1) 1.3 mm have been unsuccessful (Huchtmeier 1994; Knapp & Rupen 1996), the upper limits (e.g., $M(HI) < 5 \times 10^8 M_\odot$) are not significant.

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References
Fig. 1.— HST/WFPC2 images of the nuclear region of M84, with resolution $\approx 0.1$ (8 pc), except for the H$\alpha$ + [N II] image in (d) and (f), which has resolution $\approx 0.13$. All images have the same orientation (north up and east to the left). Panels (a) − (d) have the same scale, while (e) and (f) are expanded views of the nucleus. (a) The F547M (5454 Å) image, and (b) the F814W (8269 Å) image. The displayed intensities in both (a) and (b) (in units of erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ arcsec$^{-2}$) range logarithmically from $1.2 \times 10^{-16}$ to $1.9 \times 10^{-15}$, while the peak intensities are $3.1 \times 10^{-15}$ and $3.6 \times 10^{-15}$, respectively. (c) The (V−I) color map, obtained from the ratio of (a) to (b). The displayed color values range linearly from $F_\lambda(5454$ Å)/$F_\lambda(8269$ Å) of 0.65 to 1.1, which corresponds to a range in (V−I) of 1.8 to 1.2. Darker shades represent redder colors. (d) The H$\alpha$ + [N II] image. The displayed intensities (in units of erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$) range logarithmically from $7.9 \times 10^{-16}$ to $2.6 \times 10^{-14}$, while the peak intensity is $1.9 \times 10^{-13}$. (e) The central $3'' \times 3''$ of the (V−I) color map presented in (c). The color values displayed range linearly from $F_\lambda(5454$ Å)/$F_\lambda(8269$ Å) of 0.6 to 1.1 (i.e., (V−I) of 1.9 to 1.2), with darker shades representing redder colors (as in (c)). (f) The central $5'' \times 5''$ of the H$\alpha$ + [N II] image presented in (d). The displayed intensities (in units of erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$) range logarithmically from $7.9 \times 10^{-16}$ to $3.9 \times 10^{-14}$.

Fig. 2.— A contour plot of the H$\alpha$ + [N II] image in Fig. 1(f), with the contour levels (in units of erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$) ranging from $3.0 \times 10^{-15}$ to $1.9 \times 10^{-13}$ (i.e., the peak intensity) with an interval of 0.5 mag. North is up and east to the left.

Fig. 3.— The intensity of H$\alpha$ + [N II] in erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ as a function of distance $R$ from the nucleus along the disk’s major axis (open circles). For comparison, the points connected by a line show a model PSF normalized so that its peak intensity matches the peak intensity of the observed H$\alpha$ + [N II] emission.

Fig. 4.— A histogram showing the number of PC2 pixels ($N_{\text{pix}}$) with a given value of (V−I) in Fig. 1(c) (after correcting for Galactic reddening). This histogram includes only the region of the image encompassing the dust lanes (see text).