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NARROWBAND *HST* IMAGES OF M87: EVIDENCE FOR A DISK OF IONIZED GAS AROUND A MASSIVE BLACK HOLE[1]

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ABSTRACT

We present *HST* WFPC2 narrowband $H\alpha$ + [N II] images of M87 which show a small disk of ionized gas with apparent spiral structure surrounding the nucleus of M87. The jet projects $\sim 19\overset{\circ}{.}5$ from the minor axis of the disk, which suggests that the jet is approximately normal to the disk. In a companion *Letter*, Harms et al. measure radial velocities at $r = \pm 0\overset{''}{.}25$ along a line perpendicular to the jet, showing that one side of the disk is approaching at 500 ± 50 km s^{-1} and the other side of the disk is receding at 500 ± 50 km s^{-1}. Absorption associated with the disk and the sense of rotation imply that the apparent spiral arms trail the rotation. The observed radial velocities corrected for a 42° inclination of the disk imply rotation at ± 750 km s^{-1}. Analysis of velocity measurements at four positions near the nucleus gives a total mass of $\sim 2.4 \pm 0.7 \times 10^9\ M_\odot$ within 18 pc of the nucleus, and a mass-to-light ratio $(M/L)_I = 170$. We conclude that there is a disk of ionized gas feeding a massive black hole in the center of M87.

Subject headings: black hole physics — galaxies: individual (M87, NGC 4486) — galaxies: ISM — galaxies: kinematics and dynamics — galaxies: nuclei

1. INTRODUCTION

The energetics and rapid variability of active galactic nuclei (AGNs) both argue for an efficient means of producing power within a small volume, a requirement easily satisfied by accretion onto a black hole (Salpeter 1964; Zeldovich & Novikov 1964; Lynden-Bell 1969). The need to discard excess angular momentum argues strongly for the formation of disks or flattened structures near the black hole to transport material inward and angular momentum outward. Near the black hole the material may form a classical "accretion disk" which could radiate a substantial fraction of the continuum luminosity. At larger radii the material may form an obscuring torus of cold molecular material, as proposed in unified models of Seyfert galaxies (Antonucci & Miller 1985; Krolik & Begelman 1986). The alignment of radio structures with the ionization cones produced by the inferred shadows of such tori suggests that the angular momentum in the disk may determine the direction of the radio jets (Wilson & Tsvetanov 1994). The discovery by Jaffe et al. (1993, hereafter J93) of a small disk of gas and dust around the nucleus of the second-brightest radio galaxy in the Virgo cluster, NGC 4261 (3C 270), suggests that the engines of radio-loud ellipticals may be supplied with material and aligned in a similar way.

M87 is an obvious choice for seeking further evidence that radio ellipticals have central engines fed by a surrounding disk. The optical synchrotron jet, nonthermal radio source, and large velocities of ionized gas in the nucleus singled out M87 as one of the earliest examples of a galaxy with an active nucleus (see Biretta 1994 for references and an excellent review of the jet). Many authors (e.g., Sargent et al. 1978; Dressler & Richstone 1990; Jarvis & Peletier 1991; Jarvis & Melnick 1991; van der Marel 1994) have measured a large velocity dispersion near the nucleus of M87. Others (e.g., Young et al. 1978; Jarvis & Melnick 1991; Kormendy 1992; Carter & Jenkins 1992; Lauer et al. 1992; Crane et al. 1993) have investigated the nonthermal point source and the nuclear cusp in the stellar light distribution. After deconvolution of the spherically aberrated WFPC1 images of M87, Lauer et al. (1992) determined that the stellar surface brightness within $R < 3''$ ($R < 220$ pc for an assumed distance of 15 Mpc for M87) varies approximately as $\mu(R) \sim R^{-0.26}$, steepening for $R > 10''$ ($R > 730$ pc) to a relation $\mu(R) \sim R^{-1.3}$. They conclude from analysis of the deconvolved surface brightness profile that there is a central black hole with a mass of $2.6 \times 10^9\ M_\odot$, although this solution is not unique without additional kinematic evidence.

Although the observations and arguments provide compelling reasons to think there is a massive black hole in the center of M87, they have not been definitive for several reasons. Foremost is the fact that ground-based seeing makes it difficult to resolve features close enough to the center to see the unmistakable gravitational signature of a massive black hole and simultaneously avoid dilution of the spectrum by light from the nonthermal source in the nucleus. A second problem is that the mass derived from the stellar velocity dispersion is model dependent, making it possible to explain the observed velocity dispersion by being suitably clever with velocity anisotropy (Dressler & Richstone 1990). The apparent light cusp resulting from stars collecting in the deep potential surrounding a massive black hole is highly suggestive, but it does not provide a direct measurement of the gravitational potential.

Spectroscopic observations of ionized gas in circular motion close to the nucleus can provide a powerful and straightforward way to look for the Keplerian rotation curve which would be the signature of a massive black hole. Consequently, we used the WFPC2 to take narrowband images of M87 to look for organized structure in the ionized gas. These images, discussed below, suggest that the ionized gas in the nucleus has

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settled into a rotating disk. If this is true and there is a massive black hole in the center, the rotation velocity in the disk will rise toward the center rather than decrease to zero as in a galaxy with no central mass. In a companion *Letter* (Harms et al. 1994, hereafter H94) we present observations which measure the radial velocity at two diametrically opposed positions along the major axis on either side of the nucleus. The velocities lead us to conclude that we are observing a disk of ionized gas rotating around a black hole with a mass of $\sim 2.4 \pm 0.7 \times 10^9\ M_\odot$.

2. OBSERVATIONS AND REDUCTIONS

The images of M87 were taken with the WFPC2 camera on-board *HST* on 1994 February 26. The nucleus of the galaxy was placed near the center of the PC CCD, and two exposures of 1400 and 1300 s were taken through the F658N (effective wavelength/width 6590/28 Å) filter which isolates the redshifted Hα + [N II] line complex. Two 400 s continuum images were taken with the F547M (5454/487 Å) filter. The image scale on the PC is 0".0455 pixel^{-1}.

The images were initially processed through the standard pipeline reductions at the Space Telescope Science Institute. This includes masking of known bad pixels, A/D correction, bias level removal, dark image subtraction, and flat-field correction. The alignment of images in each filter was checked from the positions of several globular clusters in the PC images and found to be ≤ 0.1 pixel. Pairs of images were then combined to remove the cosmic-ray events, and, before combining, one of the F658N frames was adjusted for a small pipeline error of oversubtracting the bias level. This method does a very good job of removing CR hits, but leaves most of the hot pixels in place since they appear similar on both frames. We further identified most of the remaining hot pixels (excluding the immediate vicinity of the nucleus) by comparing the flux in the F547M and F658N filters. The flux ratio peaked strongly at ~ 2.7 for hot pixels and was close to 0.25 in the line-free regions, rising only to ~ 1.0 in the line-emitting regions. The hot pixels were masked and replaced by the local median. The images were registered by applying small shifts (a fraction of a pixel in each coordinate) determined from the positions of the brightest nine globular clusters. The continuum-subtracted Hα + [N II] image was then produced by subtracting the scaled F547M image from the F658N image.

At the 1280 km s^{-1} observed heliocentric systemic velocity of M87, [N II] λ6548 is redshifted to the blue edge of the F658N filter's flat top, Hα is redshifted to the center of the filter, and [N II] λ6583 is redshifted onto the red shoulder at a position where the transmission is 35% of the filter's peak transmission. Because [N II] λ6583 is three to four times stronger than Hα in the nucleus of M87 (Ford & Butcher 1979; H94), gas which is blueshifted with respect to M87 by several hundred kilometers per second will appear brighter than redshifted gas. We do not think that this bias has significantly altered the morphology seen in Figures 1 and 2 (Plates L17–L18).

3. DISCUSSION

Figures 1*a* and 1*b*, respectively, show false color reproductions of the F658N Hα + [N II] on-band image and the F547M off-band image. We found that the low-contrast features in the ionized gas are difficult to reproduce without using color and a nonlinear stretch. Figure 1*a* shows that the ionized gas in the center of M87 has a "disklike" structure with two or more "spiral arms" which wrap clockwise from the outside to the inside. The disk is approximately elliptical in shape and has a minor axis close to the projected position of the synchrotron jet. Although ionized gas near the core of M87 has been observed extensively in the past on larger angular scales, this is the first detection of this very small, well-organized structure. Two faint dust lanes can be seen in Figure 1*b*. When Figures 1*a* and 1*b* are superposed there is an exact correspondence between the dust lanes and two filaments or arms of gas. Sparks, Ford, & Kinney (1993, hereafter SFK) previously showed that dust is associated with several of the filaments and argued that these filaments are on the near side of M87. The same argument suggests the side of the disk opposite to the jet is the near side of the disk.

Figure 2*a* shows the F658N Hα + [N II] on-band image with the stellar continuum removed by subtracting the F547M off-band image. Several of the brighter globular clusters were used to shift and register the F547M image against the F658N image before subtraction. The F547M image was multiplied by 0.245 and then subtracted from the F658N image. The apparent spiral structure with arms wrapping clockwise persists into the nucleus. The presence of the spiral features seen in projection may also rotate the apparent position of the major axis from the true position.

The maximum radius of the disklike structure is $\sim 1''$. At an assumed distance of 15 Mpc to the Virgo cluster, this corresponds to 73 pc. The isophotes in the disk are more extended on the east side of the nucleus than on the west side. The STSDAS task "Ellipse" was used to fit ellipses to the isophotes to derive the apparent ellipticity of the disk and the position angle of the major axis. The fits give consistent results at radii between 0".27 and 0".82. The formal average value of the angle between the normal to the disk and our line of sight is 42° ± 5° for seven ellipses between 0".27 and 0".82. The average values of the position angles of the major and minor axes are, respectively, 1° ± 5° and 271° ± 5°. Two independent analyses, including one that did not fit ellipses, give comparable results; the smallest value is 1° derived here, and the largest value is 9°. The position angle of the jet in Figure 1 is taken to be 290°.5. Consequently, the angle between the jet and the minor axis is between 11° and 20°, suggesting that the jet is nearly normal to the disk.

Figure 2*b* shows the difference image rebinned to 3 × 3 pixels to improve the contrast of the fainter filaments. The faint filaments can be matched to filaments seen in the deeper but lower resolution images in SKF. The extended structure nearest the jet, filaments 1 and 2 in SFK, appears to be three wrapped filaments. The wrapped filaments have a morphology reminiscent of the braided structure seen in the SE nonthermal arm which emanates from the nucleus of NGC 4258 (Ford et al. 1986; Cecil, Wilson, & Tully 1992). SFK noted that the large-scale filaments in M87 appear to be edge brightened ribbons or double strands. Careful inspection of Sparks's (1992) NTT image of M87 also suggests that the filament nearest the jet has at least two wrapped strands. At least one of the strands seen in Figure 2*b* appears to originate at the end of one of the spiral features in the disk. Because the filament is blueshifted with respect to M87 and shows absorption against M87 is continuum light, SKF argued that the filament is gas which in flowing outward from the nucleus. The apparent morphological similarity to the nonthermal arm in NGC 4258

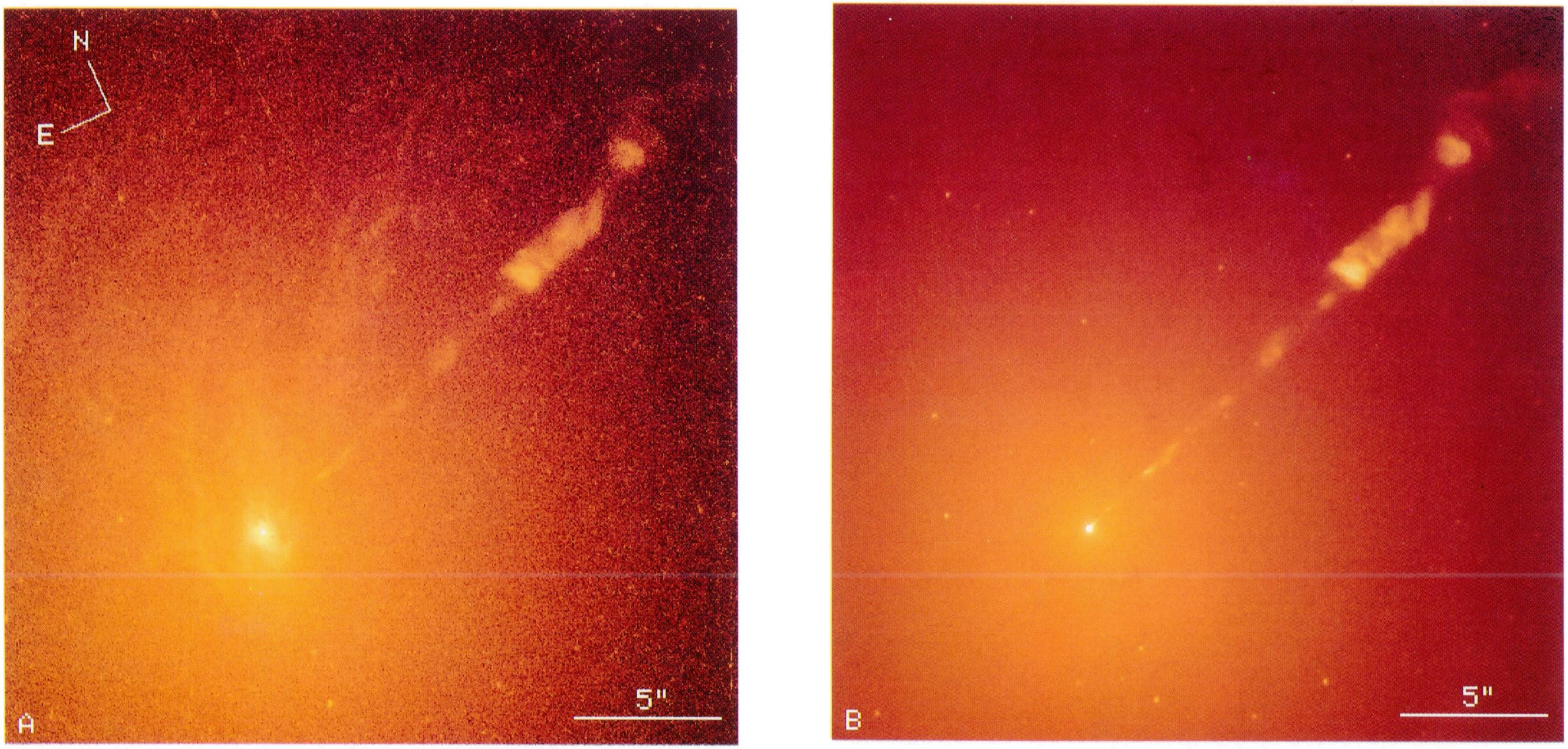

FIG. 1*a*

FIG. 1*b*

FIG. 1.—(*a*) The averaged *HST* F658N Hα + [N II] on-band images. The image is 546 pixels (24$''\!.8$) on each side. All the figures have the orientation shown in (*a*). The nonthermal jet is visible from continuum emission in the bandpass of the narrowband filter. The jet emanates from the center of a disklike structure which has a semimajor axis $\sim 1''$ and three spiral arms. (*b*) The combined *HST* F547M off-band images. The image is 546 pixels (24$''\!.8$) on each side. The faint dust lane immediately opposite the jet at $r = 2''$ corresponds to a bright emission line arc in (*a*). The dust lane which is darkest at $\sim 87°$ clockwise from the jet at $r = 2''$ appears to coincide with the arm of ionized gas in (*a*) and Fig. 2*a* which originates at $r \sim 0''\!.8$ from the nucleus at a position angle 180° from the jet.

FORD et al. (see 435, L28)

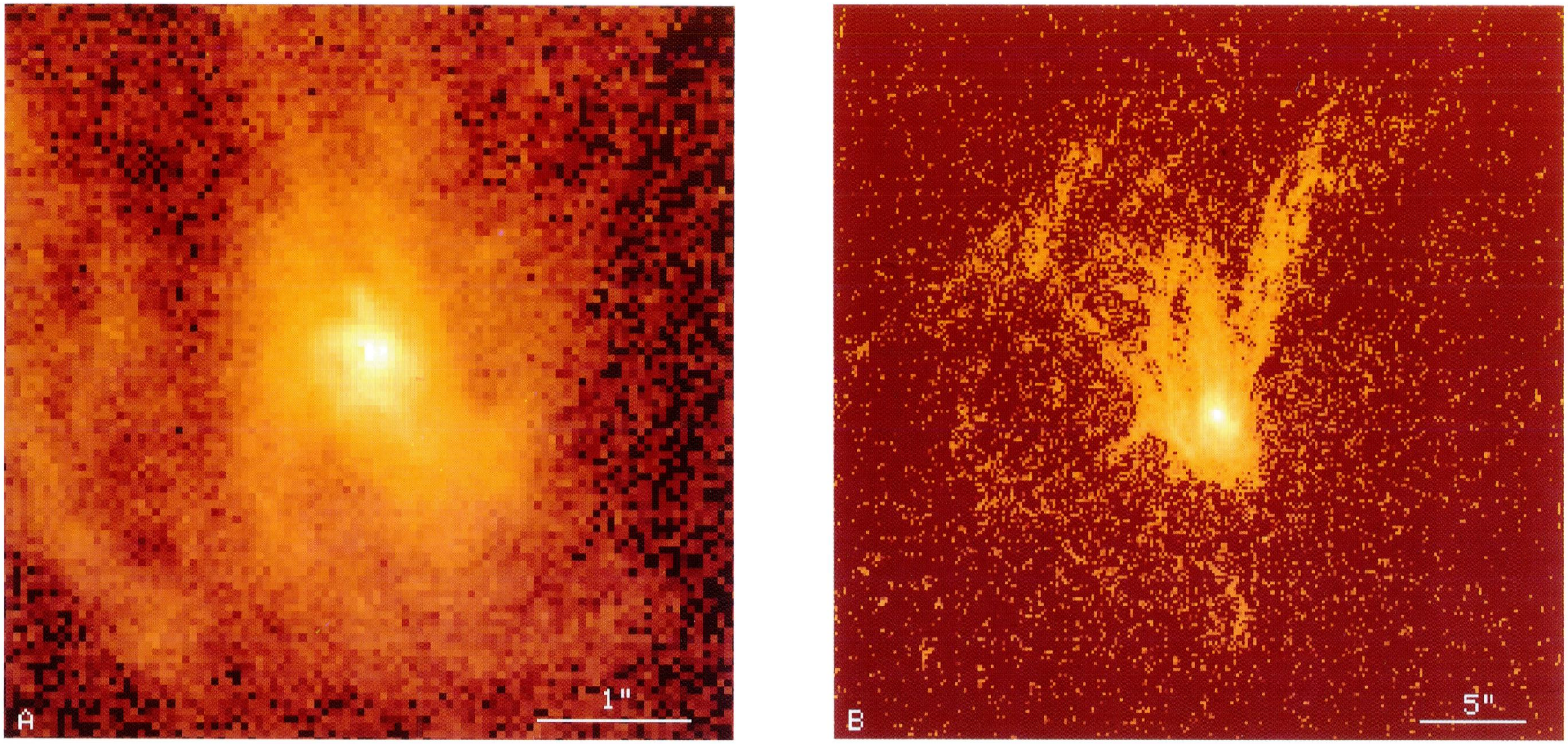

FIG. 2*a*

FIG. 2*b*

FIG. 2.—(*a*) The *HST* F658N on-band image minus the scaled and registered HST F547M off-band image. The image is 100 pixels (4."6) on each side. The spiral structure is more evident in this image than in Fig. 1*a*. A faint linear feature extends along the direction of the jet to $r = 1''$ and ends in a slightly resolved knot. The features could be gas entrained by the jet, or a slight misregistration between the on-band and off-band images. (*b*) The F658N on-band image minus the scaled and registered *HST* F547M off-band image block-averaged 3 × 3 to show the fainter large-scale structure. The image is 34."0 on each side. The emission feature 27° counterclockwise from the jet, which SKF concluded is outflowing gas, appears to be three wrapped filaments.

FORD et al. (see 435, L28)

strengthens this conclusion. The wrapped appearance could be due to angular momentum being carried away from the disk.

The approximately elliptical shape of the gas in the nucleus and the presence of spiral structure suggest that we are seeing a rotating disk of ionized gas. The fact that the jet projects near the minor axis of the disk suggests that the jet is approximately perpendicular to the disk. Although the inclination of the jet to the line of sight is not directly measured, Biretta (1994) infers from models that the angle is ~40°. The angle between the normal to the disk and the line of sight derived above is ~42°, reinforcing the previous conclusion that the jet is approximately perpendicular to the disk. The dust seen in Figure 1*b* suggests that the southeast side of the disk is the nearer side, as must be the case if the jet is approximately normal to the disk.

The mass of ionized gas in the disk can be calculated from the observed Hα flux and the electron density. We converted PC counts to flux by first dividing the observed FOS $0''.26$ diameter aperture Hα + [N II] fluxes at five positions in the disk (shown in H94) by the counts measured at corresponding positions in Fig. 2*a*. Because the large redshifts and blueshifts in the disk modulate the Hα + [N II] flux transmitted by the F658N filter, the flux-to-count ratio varies by a factor of ~2.4 from redshifted to blueshifted positions. Using the average flux-to-count ratio, the observed Hα + [N II] flux within $1''$ of the nucleus is $2.0 \pm 0.7 \times 10^{-13}$ ergs cm^{-2} s^{-1}. The average ratio of the Hα flux to the total flux at the five FOS positions in H94 is 0.22; multiplying the Hα + [N II] flux by this factor, the observed Hα flux is $4.4 \pm 1.5 \times 10^{-14}$ ergs cm^{-2} s^{-1}. We adopted the value of Jacoby, Ciardullo, & Ford (1990) for interstellar extinction toward the Virgo cluster, $E(B-V) = 0.017$, and used Seaton's (1979) extinction curve to calculate the small correction factor 1.04 for the true flux. Assuming a distance of 15 Mpc to M87, a 10% He abundance by number, and a temperature of 10^4 K in the gas, the mass of ionized gas is $M_T = F(\mathrm{H}\alpha)_0/n_e \times 8.83 \times 10^{19}\ M_\odot$. The electron density derived from the [S II] λ6717/6730 ratio in the FOS spectra is ~1000 cm^{-3}. The total mass of ionized gas in disk within $1''$ is then $\sim 3.9 \pm 1.3 \times 10^3\ M_\odot$. Given the variations in density across the disk, and the dependence of the transmitted flux on redshift, the true uncertainty in the total ionized mass is probably close to a factor of 2.

Turland (1975) used radio observations at 5 GHz to estimate that the radio luminosity of M87's halo is $\sim 4.5 \times 10^{42}$ ergs s^{-1} (corrected from 20 to 15 Mpc). If the gas in the disk accretes onto a central black hole with 10% conversion of potential energy into radio luminosity, the mass of ionized gas within $1''$ can power the radio source for $\sim 5 \times 10^6$ yr. The minimum energy in the radio-emitting plasma at 15 Mpc is 4.5×10^{57} ergs (Turland 1975). If we assume protons are present, the minimum energy is $U(\mathrm{min}) \sim 5 \times 10^{60}$ ergs. The age of the radio lobes will be $\sim U(\mathrm{min})/L \sim 3 \times 10^9$ yr. Again assuming 10% efficiency, the minimum mass to power up the radio lobes is $\sim 2.5 \times 10^6\ M_\odot$. The mass in the disk is insufficient to produce the present radio lobes. Heckman et al. (1989) estimate that the total ionized mass within M87 is 4.6×10^4 $M_\odot$. Consequently, there is not enough mass in the entire filamentary system to account for the radio source. That and the long life of the radio source suggest that the observed gas is the result of a continuous process such as a cooling flow. Multiple captures of satellite dwarf galaxies over the lifetime of the lobes could also keep the radio source powered for a sufficiently long time, but the geometry of the lobes would require all these accreting galaxies to have roughly the same angular momentum, which is unlikely.

In H94 we show that the radial velocities of the ionized gas at radii of $\pm 0''.25$ diametrically paired across the nucleus along a line perpendicular to the jet are $+500 \pm 50$ km s^{-1} and -500 ± 50 km s^{-1} with respect to the velocity at the position of the nucleus. We conclude that the combined morphology and radial velocities are strong evidence for a rapidly rotating disk of ionized gas around the nucleus of M87. The large radial velocities at the small projected distance of ~18 pc show that the gas is responding to the gravitational force of a large mass. H94 assume circular motion in a disk which is inclined to the line of sight by 42°. The velocities measured at radii of $\pm 0''.25$ and two additional positions at radii of $0''.35$ and $0''.56$ and respective position angles of 135° and 153° are a good fit to a Keplerian disk inclined to the line of sight by 42°. The analysis suggests that the kinematic line of nodes is perpendicular to the jet. Using that model, H94 derive a total mass of $2.4 \pm 0.7 \times 10^9\ M_\odot$ interior to $r = 0''.25$. Using Lauer et al.'s light distribution, H94 derive $(M/L)_I = 170$. This large mass-to-light ratio is strong and unambiguous evidence that a black hole with a mass of $\sim 2.4 \times 10^9\ M_\odot$ resides at the center of M87.

The origin of collimated emission (e.g., optical jets, radio jets, and ionization cones) is of particular interest for understanding the nature of active galaxies. For Seyfert galaxies in particular, Wilson & Tsvetanov (1994) showed that the radio axis is aligned with the cone axis to within the measurement errors for almost all the best cone examples. This strongly suggests that radio ejecta and ionizing radiation are collimated by the same or strictly coplanar structures, most likely disks. We note that in the obscuration/reflection scenario suggested by Antonucci & Miller (1985), the ionization cones result from shadowing of the nucleus by an optically thick parsec-scale torus, while the observations, and most of the theoretical attempts, suggest that radio ejecta collimation occurs on a much smaller, possibly accretion disk size scale.

J93 found a small ($d \sim 120$ pc), well-defined disk in the center of the luminous radio elliptical NGC 4261 (3C 270). The disk contains atomic, molecular, and ionized hydrogen, and dust with a face-on optical depth of ~0.3. The total mass of the disk is $\sim 5 \times 10^4\ M_\odot$ (Jaffe et al. 1994). The axis of the large-scale double-lobed radio source (Birkinshaw & Davies 1985) projects onto the minor axis of the disk. J93 concluded that the disk is the "outer accretion disk" of the central active nucleus and argued that the disk supplies fuel to the central engine, which is most likely a massive black hole. They further suggested that the angular momentum in the disk determines the direction of the collimated jets which originate near the black hole. O'Neil, Lynds, & De Young (1994) found a $1''.2 \times 0''.35$ dust disk in the nucleus of NGC 6251, a radio galaxy with a highly collimated radio jet with a length of ~1 Mpc. Based on the strong similarity between the nuclear light distributions in M87 and NGC 6251, Young et al. (1979) suggested that NGC 6251 hosts a massive black hole. As in NGC 4261, the major axis of the disk in NGC 6251 is perpendicular to the milliparsec-scale radio jet. Other *HST* observations (Fabbiano & Fassnacht 1993; Zeilinger 1994) have shown that small gaseous nuclear disks may be common in elliptical galaxies.

M87 is another example of an active galaxy which appears to have a disk of gas surrounding a central black hole. Nuclear disks may be a common denominator in active galaxies. These disks supply the fuel for the black hole, and determine the direction of the collimated jets and ionizing radiation geometrically and via the angular momentum in the disk gas, which feeds into the accretion disk. If the gas in the nuclear disk comes from the capture of a small galaxy, as suggested by SFK, the gas will settle into a plane determined by the angular momentum of the accreted galaxy and the shape of the nuclear potential. The direction of the jet will then vary from one fueling event to the next. Alternatively, if the nuclear gas in M87 is the result of a cooling flow (e.g., Ford & Butcher 1979), the axis of the disk and ensuing jet may reflect the angular momentum of the hot X-ray–emitting corona which produces the cooling flow. In this case the nuclear activity will be relatively constant, the jet and radio axis will have a direction which is constant over long periods of time, and the central black hole will have a large amount of angular momentum.

In summary, we have found a disk of ionized gas with apparent spiral structure surrounding the nucleus of M87. The jet projects near the minor axis of the disk, which suggests that the jet is approximately normal to the disk. Radial velocities measured at $r = \pm 0\rlap{.}''25$ show that one side of the disk is approaching at 500 ± 50 km s^{-1} and the other side of the disk is receding at 500 ± 50 km s^{-1}. Absorption associated with the disk and the sense of rotation imply that the apparent spiral arms trail the rotation. The observed radial velocities corrected for a 42° inclination of the disk imply rotation of ± 750 km s^{-1}. This gives a total mass of $\sim 2.4 \times 10^9\ M_\odot$ within 18 pc of the nucleus, and a mass-to-light ratio $(M/L)_I = 170$. We conclude that this is strong evidence for a massive black hole in the center of M87. We think the disk and evidence for a massive black hole show that radio loud ellipticals fit the unification scheme. The optical and radio luminosity will depend on the mass of the black hole and the fueling rate. The size and luminosity of the radio source will depend on whether or not the parent galaxy is largely gas free (an elliptical), or gas rich (a spiral). Finally, we speculate that the nature of the nuclear disk will depend on the mass of the black hole. The potential of a black hole with a mass $\sim 2\text{–}3 \times 10^9\ M_\odot$ will dominate the stellar potential out to a radius of ~ 300 pc. Shearing in the differentially rotating disk will induce spiral structure as we observe in M87, and viscous heating will destroy most of the dust. Disks around black holes with masses $\sim 4 \times 10^7\ M_\odot$ will show solid body rotation in the stellar potential of typical ellipticals down to a radius of ~ 50 pc. In the absence of heating induced by differential rotation, neutral gas, molecular gas, and dust can survive in the disk, as observed in NGC 4261.

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