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A DISPLACED SUPERMASSIVE BLACK HOLE IN M87*

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ABSTRACT

Isophotal analysis of M87, using data from the Advanced Camera for Surveys, reveals a projected displacement of 6.8 ± 0.8 pc ($\sim 0''.1$) between the nuclear point source (presumed to be the location of the supermassive black hole, SMBH) and the photo-center of the galaxy. The displacement is along a position angle of $307^\circ \pm 17^\circ$ and is consistent with the jet axis. This suggests the active SMBH in M87 does not currently reside at the galaxy center of mass, but is displaced in the counter-jet direction. Possible explanations for the displacement include orbital motion of an SMBH binary, gravitational perturbations due to massive objects (e.g., globular clusters), acceleration by an asymmetric or intrinsically one-sided jet, and gravitational recoil resulting from the coalescence of an SMBH binary. The displacement direction favors the latter two mechanisms. However, jet asymmetry is only viable, at the observed accretion rate, for a jet age of >0.1 Gyr and if the galaxy restoring force is negligible. This could be the case in the low-density core of M87. A moderate recoil ~ 1 Myr ago might explain the disturbed nature of the nuclear gas disk, could be aligned with the jet axis, and can produce the observed offset. Alternatively, the displacement could be due to residual oscillations resulting from a large recoil that occurred in the aftermath of a major merger ≤ 1 Gyr ago.

Key words: black hole physics – galaxies: individual (M87) – galaxies: nuclei

Online-only material: machine-readable table

1. INTRODUCTION

It is generally assumed that supermassive black holes (SMBHs) reside at the centers of their host galaxies. However, SMBHs can be significantly displaced from their central locations by asymmetric forces during a merger or by a second SMBH (Komossa 2006). In addition, if a binary SMBH forms and coalesces, anisotropic emission of gravitational waves can result in initial impulsive kick velocities of several thousand km s^{-1} (e.g., Pretorius 2007). Even if the kick velocity is small enough for the coalesced SMBH to remain in the galaxy, N -body simulations have shown that the SMBH can oscillate within the bulge for ~ 1 Gyr before coming to rest (Gualandris & Merritt 2008). Alternatively, if the galaxy contains a radio source, the SMBH may experience sustained acceleration due to intrinsic asymmetries in jet power (e.g., Tsygan 2007).

The most direct way to find a displaced SMBH is to observe a spatial offset between the SMBH and the center of its host galaxy. This requires data at the highest possible spatial resolution. E/S0 galaxies that are minimally affected by extinction and contain an active galactic nucleus (AGN) provide good candidates; bulge isophotes determine the position of the galaxy center and the AGN (point source) determines the position of the SMBH. M87 is an ideal target for a displaced SMBH search. It is nearby, has a regular bulge, is relatively free of dust, hosts an AGN and a jet (e.g., Perlman et al. 2001), and has been extensively observed by the *Hubble Space Telescope* (HST). In this Letter, we report the discovery of a 6.8 ± 0.8 pc projected displacement between the center of M87, as defined by the galaxy isophotes, and the SMBH.

2. THE DATA

Our analysis uses the archived *HST* data listed in Table 1. All data had the standard STScI on-the-fly re-processing applied. Each image was rotated to the same reference frame and shifted to a common position using a two-dimensional cross-correlation register. The data were combined using a median filter to remove residual cosmic rays and bad pixels and to minimize the effect of the High Resolution Channel (HRC) coronagraphic aberration.

The IRAF task ELLIPSE (Jedrzejewski 1987) was used to determine the photo-center of the galaxy. Beginning with a semimajor axis (SMA) of 1 pixel, centered on the nuclear point source, ellipses of progressively increasing SMA were independently fitted to the data. The SMA was incremented by 1 pixel in each successive fit and the center of the ellipse found. The x - y pixel co-ordinates of the ellipse centers were thus determined as a function of SMA. To estimate the precision with which offsets can be recovered and to check whether masking degrades accuracy, we applied this technique to a set of simulated galaxies containing a nuclear point source. The simulated galaxies were given an $r^{1/4}$ surface brightness profile and an ellipticity of 0.2. Point sources, with offsets of 0, 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0 pixels in both x and y , were added to create 64 total models. Each model was convolved with the *HST* point-spread function as generated by TinyTim (Krist 1995) and populated with random noise. First, isophotal fits were performed without a mask. In this case, the offsets were recovered to ~ 0.2 pixels (Figure 1(a)). Second, isophotes were fitted with a mask that simulated an extended jet crossing the galaxy center, multiple globular clusters (GCs), and areas of extinction. These offsets were also recovered to ~ 0.2 pixels (Figure 1(b)); any observed offsets will not be a result of masking.

Figure 2 shows the median combined HRC data in F814W, both with and without the mask. A distance modulus of

* Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

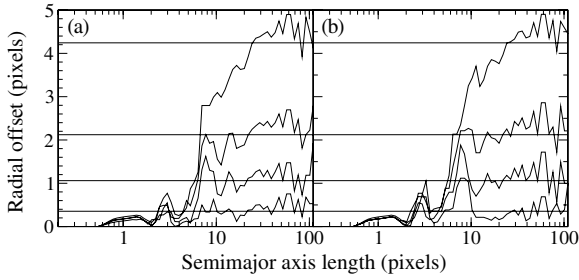


Figure 1. Accurate recovery of simulated SMBH-galaxy displacements. (a) Without and (b) with a mask. Horizontal lines show the model displacements. Offsets are recovered for SMA < 10 pixels.

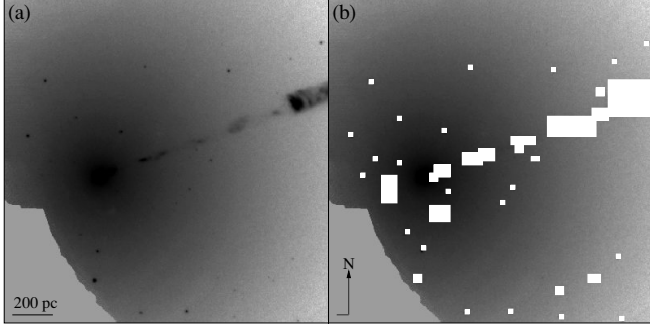


Figure 2. (a) ACS HRC F814W median combined image of M87 with a logarithmic stretch. (b) The mask overlaid on (a).

Table 1
Archived ACS Data

Data Set	Aperture	Filter	Exposure Times	PID
j8q0*	HRC	F606W	2 × 75 s	9829
j92j*	HRC	F606W	4 × 80 s, 5 × 48 s	10133
j9ei*	HRC	F606W	6 × 80 s, 3 × 45 s	10617
j9qf*	HRC	F606W	2 × 80 s, 1 × 45 s	10910
j8l0*	HRC	F814W	5 × 100 s	9705
j8q0*	HRC	F814W	8 × 50 s	9829
j92j*	HRC	F814W	4 × 50 s	10133
j9ei*	HRC	F814W	6 × 48 s	10617
j9qf*	HRC	F814W	2 × 48 s	10910
j9e0*	WFC	F606W	3 × 500 s	10543
j9e0*	WFC	F814W	3 × 1440 s	10543

Note. Details of the archived ACS data used. PID is the *HST* program ID number.

31.0 ± 0.2 (Tonry et al. 2001) puts M87 at 16.1 ± 0.2 Mpc (77.9 pc arcsec $^{-1}$). The Advanced Camera for Surveys (ACS) pixel scales of $0''.027$ (HRC) and $0''.049$ (Wide Field Channel, WFC) are then 2.1 and 3.8 pc, respectively.

3. RESULTS

Table 2 presents the ellipse fits to the HRC and WFC data in F606W and F814W. The ellipticity and position angle (P.A.) of the fits are uncorrelated with SMA, show no evidence for bulge asymmetry, and are consistent with the results of Ferrarese et al. (2006) who note that the isophotes are regular. At each SMA, the radial offset of the ellipse center is given with respect to the nuclear point source. Figure 3 presents the x and y co-ordinates of the ellipse centers and the radial offset as a function of SMA. Note that the inner jet region is seen as “pear-shaped” contours in Figures 3(a) and (b). This feature was masked out during the fits. The elongated contours in Figures 3(c) and (d) are an effect of charge bleeding from the strong point source and result in

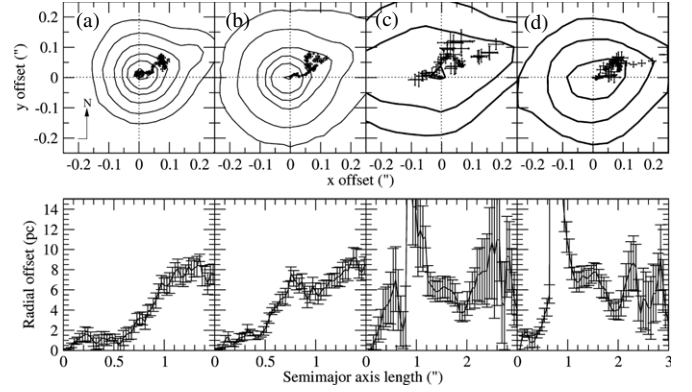


Figure 3. Top row: x and y ellipse centers overlaid on ACS contours. The point source is at (0,0). (a) and (b) HRC ellipse centers for SMA < $1''.5$. The jet (masked out for the fits) can be seen as an N–W extension. (c) and (d) WFC ellipse centers for SMA < $3''.0$. (a) and (c) F606W, (b) and (d) F814W. Bottom row: radial offsets of the ellipse centers.

Table 2
Radial Offsets of Ellipse Centers

SMA ($''$)	HRC		SMA ($''$)	WFC	
	Offset (pc)			Offset (pc)	
	F606W	F814W		F606W	F814W
0.027	0.000	0.000	0.049	0.000	0.000
0.054	0.110	0.187	0.098	0.122	1.405
0.081	0.513	0.453	0.147	0.602	1.779
0.108	0.889	1.155	0.196	1.272	1.718
0.135	0.982	1.350	0.245	2.071	0.870

Note. SMA vs. radial offset for all ACS data.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

larger uncertainties and the anonymously large offsets seen at $\sim 1''.0$.

All ellipses with SMA > $1''.0$ show a clear offset relative to the nuclear point source. For SMA < $1''.0$, the measured offsets show the transition between isophotes dominated by the AGN and the bulge.

The mean radial offset from both the HRC and the WFC ($1''.0 < \text{SMA} < 3''.0$), weighted by the uncertainties, is 6.84 ± 0.07 pc. The error on the mean is substantially less than the 0.2 pixel uncertainty implied by the simulations (corresponding to 0.76 pc in the WFC data), which we prefer to adopt as a conservative estimate of the offset uncertainty. Therefore, the best estimate of the radial offset is 6.8 ± 0.8 pc. The uncertainty weighted P.A. between the offset and the point source is $306^\circ \pm 17^\circ$, consistent with the jet axis (e.g., Owen et al. 1980).

4. ORIGIN OF THE DISPLACEMENT

The observed offset between the bulge photo-center and the AGN suggests that the SMBH in M87 is displaced from the stellar center of mass. The projected displacement is ~ 7 pc ($\sim 0''.1$) approximately in the counter-jet direction. Here, we consider several mechanisms that might produce this displacement.

4.1. Jet Asymmetry

The P.A. of the displacement suggests a connection with the M87 jet. Shklovski (1982) first noted that one-sided jets can

accelerate SMBHs. However, the standard interpretation for one-sided jets is relativistic beaming (e.g., Eichler & Smith 1983). In the case of M87, there is very long baseline interferometry and Very Long Baseline Array (VLBA) evidence for a probable counter-jet (Ly et al. 2007; Kovalev et al. 2007), the large-scale radio structure shows evidence for two-sided jet activity in earlier epochs (Owen et al. 2000), and *Chandra* images show symmetric X-ray inner cocoons (Forman et al. 2007) that could be used to constrain the jet asymmetry. Models in which the SMBH is accelerated by two-sided, but intrinsically asymmetric, jets have been explored by Wang et al. (1992) and Tsygan (2007). In this case, the SMBH acceleration is

$$a_{\text{BH}} \approx 2.1 \times 10^{-6} f_{\text{jet}} \dot{m} \text{ cm s}^{-2} \quad (1)$$

(Kornreich & Lovelace 2008) where f_{jet} is the luminosity of the asymmetric part of the jet, expressed as a fraction of the accretion luminosity. The mass accretion rate (\dot{m}) is in units of $\dot{M}_{\text{Edd}} = L_{\text{Edd}}/(\epsilon c^2)$, where ϵ is the accretion efficiency.

As M87 has a large, low-density core (e.g., Lauer et al. 1992; Ferrarese et al. 2006), we first assume the restoring force from the galaxy is negligible. The displacement (Δr) and velocity (Δv) of the SMBH would increase with time as

$$\Delta r \approx 340 \text{ pc } f_{\text{jet}} \dot{m} t_6^2, \quad (2a)$$

$$\Delta v \approx 660 \text{ km s}^{-1} f_{\text{jet}} \dot{m} t_6, \quad (2b)$$

where t_6 is the time in Myr since the jet turned on. Assuming the SMBH is offset in the counter-jet direction, a projected displacement of $6.8 \pm 0.8 \text{ pc}$, and a jet orientation of $15^\circ \pm 5^\circ$ (Biretta et al. 1999), gives a physical Δr of 26^{+18}_{-9} pc . However, this could be as small as $\sim 10 \text{ pc}$ for a jet orientation of 45° (Ly et al. 2007). An upper limit to the jet lifetime is set by age of the outer radio halo ($\sim 0.1 \text{ Gyr}$; Owen et al. 2000), assuming it is still powered by the jet. Alternatively, if the outer halo is a relic, then a lower limit to the jet lifetime is given by the age of the inner lobes ($\sim 1 \text{ Myr}$; Bicknell & Begelman 1996). Equations (2a) and (2b) therefore give

$$3 \times 10^{-6} \left(\frac{\Delta r}{10 \text{ pc}} \right) \leq f_{\text{jet}} \dot{m} \leq 3 \times 10^{-2} \left(\frac{\Delta r}{10 \text{ pc}} \right), \quad (3a)$$

$$0.2 \left(\frac{\Delta r}{10 \text{ pc}} \right) \text{ km s}^{-1} \leq \Delta v \leq 20 \left(\frac{\Delta r}{10 \text{ pc}} \right) \text{ km s}^{-1}. \quad (3b)$$

Di Matteo et al. (2003) report $\dot{m} \approx 10^{-4}$ in M87. A 1 Myr jet then requires $f_{\text{jet}} \gg 1$ and can be ruled out. However, for a $\sim 0.1 \text{ Gyr}$ jet, $f_{\text{jet}} \approx 0.03$, i.e., the jet asymmetry amounts to only $\sim 3\%$ of the accretion luminosity. Therefore, the displacement could result from acceleration by a long-lived jet if the galaxy restoring force is negligible.

In the presence of a restoring force, the SMBH is expected to come to rest where the force from the galaxy matches the jet force. Adopting units such that $G = r_c = \sigma = 1$, where $r_c \approx 500 \text{ pc}$ is the M87 core radius and $\sigma \approx 330 \text{ km s}^{-1}$ is the 1d core stellar velocity dispersion, the equation of motion of an accelerated SMBH in a fixed galaxy core is (e.g., Gualandris & Merritt 2008)

$$\ddot{x}_i + 2\gamma \dot{x}_i + \beta^2 x_i = a_i, \quad (4)$$

where the x_i are Cartesian coordinates and

$$\gamma \equiv \frac{9}{\sqrt{2\pi}} F \frac{M_\bullet \ln \Lambda}{M_c} \quad (5a)$$

$$\beta^2 \equiv 3C_i \equiv \omega_i^2 \quad (5b)$$

$$a_i \equiv -3.6 \frac{r_{500}}{\sigma_{300}^2} f_{\text{jet}} \dot{m} \lambda_i. \quad (5c)$$

The third term on the left-hand side of Equation (4) represents the restoring force on the displaced SMBH from the stars, assuming that the motion takes place in a homogeneous core; the C_i values are related to the shape of the core and are unity for a spherical galaxy (e.g., Chandrasekhar 1987). The second term represents the dynamical friction force from the stars and has been expressed in terms of the core mass, $M_c \equiv 4\pi\rho r_c^3/3$; $\ln \Lambda$ is the Coulomb logarithm and $F \lesssim 1$ is a ‘‘fudge factor’’ accounting for the fact that the frictional force on massive objects in galaxy cores is found to be somewhat less than predicted by Chandrasekhar’s formula (Gualandris & Merritt 2008; Inoue 2009). Finally, $\lambda_i = \hat{e}_j \cdot \hat{e}_i$ where \hat{e}_j is a unit vector in the direction of the jet, and $r_{500} \equiv r_c/(500 \text{ pc})$, $\sigma_{300} \equiv \sigma/(300 \text{ km s}^{-1})$.

In the absence of dynamical friction ($\gamma = 0$), the solutions to Equation (4) are

$$x_i(t) = -X_i (\cos \omega_i t - 1), \quad X_i = \frac{a_i}{\omega_i^2}, \quad (6)$$

i.e., continued oscillation about the point \mathbf{X} where the jet acceleration is balanced by the gravitational force. Unless the core is very non-spherical, \mathbf{X} will point approximately opposite the jet direction.

In the presence of dynamical friction, the oscillations are damped and asymptote to \mathbf{X} . Furthermore, since M_\bullet is of order M_c , the damping time is expected to be comparable to the core crossing time, $T_c = r_c/\sigma_c \approx 1.5 \text{ Myr}(r_{500}/\sigma_{300})$. This is somewhat larger if $F < 1$, but is nevertheless comparable with the lower limit on the jet lifetime set by the age of the inner lobes.

Reintroducing dimensional variables,

$$\Delta r \simeq 500 \text{ pc} (f_{\text{jet}} \dot{m}) r_{500}^2 \sigma_{300}^{-2}. \quad (7)$$

This implies $0.02 \lesssim f_{\text{jet}} \dot{m} \lesssim 0.05$ for $10 \text{ pc} \lesssim \Delta r \lesssim 25 \text{ pc}$. Even assuming $f_{\text{jet}} = 1$ (one-sided jet), the observed offset requires $\dot{m} \approx 0.02$, i.e., several magnitudes more than observed. In addition, while the AGN in M87 may have been more active in the past, the offset requires the jet to have remained at this high level of activity for $\gtrsim 1 \text{ Myr}$.

4.2. Binary SMBH

If the SMBH in M87 is one component of a bound pair, with mass ratio $q \equiv M_2/M_1 \leq 1$, then

$$\Delta r \approx q \Delta r_2 \approx 10 \text{ pc} \left(\frac{q}{0.1} \right) \left(\frac{\Delta r_2}{100 \text{ pc}} \right), \quad (8)$$

where Δr_2 is the separation of the smaller SMBH from the binary center of mass (located at the galaxy center). A binary separation of $\sim 100 \text{ pc}$ is not unreasonable given the high merger rate expected for a luminous galaxy at the center of a rich cluster and given the gradual rate of in-spiral expected in the low-density core.

The velocity of the larger SMBH with respect to the binary center of mass (assuming a circular orbit) would be much greater than in the jet scenario:

$$V_1 = \frac{q}{1+q} \sqrt{\frac{G(M_1 + M_2)}{a}} \quad (9a)$$

$$\approx 400 \text{ km s}^{-1} \frac{q}{1+q} \left(\frac{M_1 + M_2}{4 \times 10^9 M_\odot} \right)^{1/2} \left(\frac{a}{110 \text{ pc}} \right)^{-1/2}, \quad (9b)$$

where a is the binary separation. However, the line-of-sight velocity is $V_{\text{los}} = V_1 \sin i \sin \phi$, where i and ϕ are the unknown inclination and phase of the orbit. If the nuclear gas disk is in the orbital plane then $i \approx 50^\circ$ (Macchetto et al. 1997), which gives $V_{\text{los}} \approx 220 \text{ km s}^{-1}$ when $\phi = 45^\circ$.

A non-active second SMBH would be extremely hard to detect, but a likely consequence of such a binary would be jet precession (e.g., Romero et al. 2000). Several jet knots have strong helical morphologies, but their widths are consistent with a steadily expanding cone with near-zero width at the nucleus (Lobanov et al. 2005). Since there is no evidence of a $0'.1$ scale “wobble” of the jet direction in both *HST* and VLBA data, any precession must be several orders of magnitude smaller than that expected from a binary.

4.3. Massive Perturbers

Any SMBH will experience gravitational perturbations from stars and more massive objects, e.g., GCs, open clusters, etc. The result is a Brownian motion of the SMBH, with mean square velocity

$$\frac{1}{2} M_\bullet \langle V_{\text{SMBH}}^2 \rangle \approx \frac{3}{2} \tilde{m} \tilde{\sigma}^2. \quad (10)$$

Here, \tilde{m} is the second moment of the mass distribution of perturbing objects and $\tilde{\sigma}$ is the velocity dispersion of the perturbers measured within $\sim 0.5 r_i$ (r_i is the SMBH’s influence radius; Merritt et al. 2007). The rms displacement of the SMBH is then given by the virial theorem:

$$\Delta r_{\text{rms}} \approx \left(\frac{\tilde{m}}{M_\bullet} \right)^{1/2} r_c. \quad (11)$$

Assuming that GCs constitute a fraction $\sim 10^{-3}$ by mass of M87 (McLaughlin et al. 1994) and that the mass of one GC is $10^5 M_\odot$, Equation (11) implies $r_{\text{rms}} \lesssim 0.1 \text{ pc}$. This is likely an overestimate since the density profile of GCs is flatter than that of the galaxy light. Unless there is another population of “massive perturbers” in M87 (Perets et al. 2007), it is unlikely that the observed displacement can be due to gravitational perturbations.

4.4. Gravitational Wave Recoil

A kick velocity of $v_k \approx 500 \text{ km s}^{-1}$ would displace the coalesced SMBH a distance $\sim r_c$ from the center of M87, in a direction orthogonal to the orbital plane of the preceding binary (van Meter et al. 2010), and aligned with the jet axis. Such a velocity is easily produced during the coalescence of two modestly spinning, comparably massive SMBHs (e.g., Tichy & Marronetti 2007). Larger kicks (but smaller than the escape velocity) would result in SMBH-core oscillations that damp on a time scale

$$T_{\text{damp}} \approx 15 \frac{\sigma^3}{G^2 \rho M_\bullet} \approx 2 \times 10^8 \text{ yr } \sigma_{300}^{-3.86} r_{500}^2 \quad (12)$$

(Gualandris & Merritt 2008). The rms displacement of the SMBH with respect to the galaxy center decreases with time as

$$r_{\text{rms}}(t) \approx r_c e^{-(t-t_c)/2T_{\text{damp}}}, \quad t > t_c, \quad (13)$$

where t_c is the time at which the amplitude of the oscillations has damped to a scale of $\sim r_c$. A current displacement of $\sim 20 \text{ pc} \approx 0.05 r_c$ implies that $\sim 6T_{\text{damp}} \approx 10 \text{ Gyr}$ have elapsed since t_c . Thus, a major SMBH merger during the formation of M87 could have generated a kick consistent with the current displacement.

5. DISCUSSION

Four displacement scenarios have been considered: jets, binaries, perturbers, and gravitational recoil. Perturbers cannot produce the observed displacement amplitude, and the observed jet–offset alignment must be fortuitous in the binary case. On the other hand, jet acceleration and gravitational recoil provide natural explanations for the jet–offset alignment.

These mechanisms predict displacement velocities that are either $\lesssim 10 \text{ km s}^{-1}$ or $\gtrsim 100 \text{ km s}^{-1}$. For example, jet acceleration of the SMBH produces an rms velocity $v_{\text{rms}} \approx 0 \text{ km s}^{-1}$ in the presence of a restoring force, and $\Delta v \approx 20 \text{ km s}^{-1} t_6^{-1}$ without. For SMBH-core oscillations induced by a large and early kick, the rms velocity of the SMBH is

$$v_{\text{rms}} \approx \sigma \frac{r_{\text{rms}}}{r_c} \approx 12 \text{ km s}^{-1} \sigma_{300} r_{500}^{-1} \frac{r_{\text{rms}}}{20 \text{ pc}}, \quad (14)$$

independent of the time since the kick or the kick amplitude. However, a velocity of several hundred km s^{-1} is possible if the SMBH is undergoing a large amplitude oscillation following a recent ($\leq 1 \text{ Myr}$) kick. A similar velocity is expected in the binary SMBH scenario.

It may be possible to distinguish between the high- and low-velocity displacement mechanisms by comparing the relative recessional velocities of stars at the galaxy center and gas around the SMBH. Unfortunately, this will be difficult; the low central surface brightness will limit the accuracy with which velocities can be determined from stellar absorption lines. Alternatively, wide field VLBA astrometry, referenced against background quasars (Davies et al. 2009), may allow the proper motion of the nuclear point source to be determined. However, it will be difficult to distinguish between the cluster motion of M87 and the intrinsic kinematics of the SMBH.

The central gas disk (Harms et al. 1994; Ford et al. 1994) may provide alternative constraints on the displacement velocity. For example, a displaced SMBH retains gas whose Keplerian velocity exceeds the kick velocity (Merritt et al. 2006). Ford et al. (1994) estimated the disk-like structure in M87 to extend to $\sim 80 \text{ pc}$. Assuming this represents the portion of the disk that remains bound to the SMBH, we can infer an initial kick velocity $\sim 400 \text{ km s}^{-1}$. This would produce strongly shocked regions in the disk, as it passes through the ambient gas, that may explain several observed properties. For example, while the gas in the central $\pm 0'.4$ region of the disk is photoionized (Macchetto et al. 1997; Sankrit et al. 1999) and has a closely Keplerian velocity field (Harms et al. 1994; Macchetto et al. 1997), at larger radii non-circular motions and morphological distortions are present (Ford & Tsvetanov 1999; Bradley et al. 2004). In addition, gas in the outer parts of the disk is evidently excited by a 265 km s^{-1} shock (Dopita et al. 1997), rather than the central UV continuum source.

Two further consequences from a kick velocity $v_k \approx 400 \text{ km s}^{-1}$ are noted. First, the shocked gas may be hot

enough ($T \sim 2 \times 10^6$ K) to produce X-ray emission. Second, at this velocity the observed displacement is reached after $\sim 25,000(\Delta r/10 \text{ pc})$ yr, i.e., significantly less than the minimum jet age discussed earlier. If this minimum jet age corresponds to the time since the kick, the SMBH cannot be on its initial outward trajectory. Gualandris & Merritt (2008) show for $v_k < 50\%$ of the escape velocity, the SMBH motion is rapidly damped and undergoes only one large amplitude oscillation on a time scale of 1 Myr. Therefore, it is possible the SMBH is on a return trajectory.

6. SUMMARY

We find that the SMBH in M87 is displaced relative to the galaxy photo-center by a projected distance of 6.8 ± 0.8 pc ($\sim 0''.1$) in the counter-jet direction. Four explanations have been considered: jet-induced acceleration, a binary SMBH, massive perturbers, and a gravitational wave kick. Perturbers only produce offsets of ~ 0.1 pc, and precession of an SMBH binary would produce “wiggles” in the jet that are not seen. Neither can explain the observed alignment with the jet axis. Jet acceleration cannot be ruled out, but it requires both that the jet age be $\gg 1$ Myr and that the restoring force exerted by the galaxy be small. The displacement could also be explained by a moderate (a few hundred km s^{-1}) kick which occurred ~ 1 Myr ago. This could produce the alignment with the jet axis and may also explain the disturbed nature of the nuclear gas disk. Alternatively, the displacement may be from SMBH-core oscillations following a kick that occurred $\lesssim 1$ Gyr ago.

The displacement processes discussed are likely to be common in early-type galaxies; they are partly assembled via mergers and often host AGN-powered radio sources. It is plausible, therefore, that there is a high incidence of SMBH displacements among the E/S0 population. A systematic effort to determine the statistical distribution of displaced nuclei will provide important insights into merger histories, the frequency with which SMBH binaries form and coalesce, and/or jet launch physics. Whatever the mechanism, displaced SMBHs have important consequences for accretion flows, for stellar dynamics in galactic nuclei, and for our fundamental understanding of galaxy evolution.

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