The Event Horizon of M87

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THE EVENT HORIZON OF M87

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ABSTRACT

The $6 \times 10^8 \ M_{\odot}$ supermassive black hole at the center of the giant elliptical galaxy M87 powers a relativistic jet. Observations at millimeter wavelengths with the Event Horizon Telescope have localized the emission from the base of this jet to angular scales comparable to the putative black hole horizon. The jet might be powered directly by an accretion disk or by electromagnetic extraction of the rotational energy of the black hole. However, even the latter mechanism requires a confining thick accretion disk to maintain the required magnetic flux near the black hole. Therefore, regardless of the jet mechanism, the observed jet power in M87 implies a certain minimum mass accretion rate. If the central compact object in M87 were not a black hole but had a surface, this accretion would result in considerable thermal near-infrared and optical emission from the surface. Current flux limits on the nucleus of M87 strongly constrain any such surface emission. This rules out the presence of a surface and thereby provides indirect evidence for an event horizon.

Subject headings: black hole physics – galaxies: individual (M87) – gravitation – radio continuum: galaxies – infrared: galaxies – ultraviolet: galaxies

1. INTRODUCTION

It is now widely accepted that active galactic nuclei (AGN) are powered by supermassive objects (reaching $10^{10} \ M_{\odot}$) that are sufficiently compact to exclude all other astrophysically credible alternatives to black holes (Rees 1984). However, it is less clear that these objects possess the defining characteristic of a black hole: an event horizon. The existence of black hole event horizons plays a central role in a number of puzzles associated with black holes, e.g., the information paradox. A number of recent results suggest that a resolution of these puzzles may result in modifications on horizon scales (e.g., Mathur 2011, Almheiri et al. 2013, Mathur 2014), which provides strong motivation for seeking astronomical evidence for the reality of event horizons.

Accretion onto compact objects with a surface, e.g., white dwarfs, neutron stars, results in the formation of a boundary layer in which any remaining kinetic energy contained within the accretion flow is thermalized and radiated. In contrast, gas accreting onto a black hole is free to advect any excess energy to the horizon without further observational consequence. If the mass accretion rate, $\dot{M}$, can be independently estimated, this difference provides an observational means to distinguish between the presence of a surface, or more accurately a "photosphere," and a horizon.

The above argument has already been used to argue for the existence of event horizons in X-ray binaries by comparing neutron star and black hole systems in aggregate (Narayan et al. 1997, García et al. 2001; Narayan & Heyl 2002; Done & Gierlinski 2003; Narayan & McClintock 2008). However, the advent of horizon-resolving observations, enabled by millimeter-wavelength very long baseline interferometric observations (mm-VLBI) carried out by the Event Horizon Telescope (EHT, Doeleman et al. 2009, Doeleman 2010, Doeleman et al. 2008, Fish et al. 2011, Doeleman et al. 2012), has made it possible to extend the argument to individual systems. This is primarily because restricting the size of any photospheric emission to horizon scales enables two important simplifications:

1. Any putative photosphere that lies within the photon orbit is expected to radiate to a good approximation like a blackbody, independently of the details of its composition (Broderick & Narayan 2006, 2007). This is because a majority of the photons emitted from the photosphere will be strongly lensed back onto the photosphere, thermally coupling the photosphere to itself and to the emitted photon field. As the redshift of the surface increases, the blackbody approximation becomes increasingly accurate.

2. The expected temperature of the photosphere emission, as seen by distant observers, is dependent upon the mass accretion rate $\dot{M}$ and the apparent photosphere size, the latter of which is fixed when the photosphere lies within the photon orbit. Thus, assuming that the system has reached steady state, any independent estimate of the additional gravitational time delay for radiation to escape from...
$M$ immediately determines both the luminosity and the radiation spectrum as seen by a distant observer.

Essentially, by restricting the surface to be sufficiently compact, it is possible to robustly predict the properties of any putative photosphere emission, independent of the specific properties of the radiating surface. Direct flux limits can then be used to constrain and/or exclude the presence of a photosphere.

The above argument has already been successfully employed in the case of Sagittarius A* (Sgr A*), the supermassive black hole at the center of the Milky Way (Narayan et al. 1998; Broderick & Narayan 2006, 2007; Narayan & McClintock 2008; Broderick et al. 2009), where limits on $M$ were obtained from the observed bolometric luminosity, assumed to arise from the accretion flow during infall. It was shown that, for physically reasonable radiative efficiencies, it is impossible to accommodate a photosphere. Therefore, Sgr A* must have an event horizon behind which the kinetic energy of the infalling accreting gas is hidden.

The supermassive black hole at the center of the nearby giant elliptical galaxy M87 (which we will refer to as M87* hereafter) is a second target for which the EHT has provided horizon-scale limits upon the extent of its mm-wavelength emission. Here we explore the implications of these and related observations for the existence of an event horizon in M87*.

In what follows we assume a mass of $6.16 \times 10^8 M_\odot$ and distance of 16.5 Mpc for M87*, reported in the recent review by Kormendy & Ho (2013). The mass estimate is based on the stellar dynamical modeling described in Gebhardt et al. (2001), and is roughly a factor of two larger than the value obtained by gas dynamical measurements (Walsh et al. 2013); both methods are potentially complicated by the fact that M87* is offset from the center-of-light by as much as 10 pc, impacting the underlying assumptions regarding orbital isotropy (Batcheldor et al. 2010). However, our qualitative conclusions are insensitive to this difference, being marginally stronger with the smaller black hole mass.

M87* is nearly three orders of magnitude more massive than Sgr A*, probing a mass regime more relevant for the bright AGN observed at high redshift. Unlike Sgr A*, whose mm and radio emission seems to be primarily from the accretion flow (Yuan & Narayan 2014), the mm/radio emission of M87* is dominated by a powerful relativistic jet.

Two lines of argument strongly imply that the relativistic jet in M87 originates near the black hole. First, astrometric measurements of the radio core position reveal a wavelength-dependent shift, asymptoting to a fixed position at short wavelength. Thus, the jet may be powered by black hole rotation (Blandford & Payne 1982), the jet and the lower-velocity wind are ultimately powered by the gravitational potential energy released by the accreting gas. Thus the jet luminosity is limited by the overall efficiency of the disk,

$$\eta_{\text{jet}} \equiv \frac{L_{\text{jet}}}{Mc^2} < \frac{L_{\text{jet}} + L_{\text{wind}} + L_{\text{radiation}}}{Mc^2} = \eta_{\text{disk}},$$

where the disk efficiency $\eta_{\text{disk}}$ is determined by the radius of the inner edge of the disk, i.e., the radius $r_{\text{ISCO}}$ of the innermost stable circular orbit (ISCO) of the space-time (Novikov & Thorne 1973),

$$\eta_{\text{disk}} = 1 - \sqrt{1 - \frac{2}{3r_{\text{ISCO}}}}.$$  

The efficiency $\eta_{\text{disk}}$ varies from 0.057 for a non-spinning black hole up to 0.42 for a maximally spinning black hole. A typical value is probably $\sim 0.1 - 0.2$. This means that, for disk-powered jets, the mass accretion rate implied by a given jet luminosity is roughly

$$M \approx 10 \frac{L_{\text{jet}}}{c^2}.$$  

Alternatively, the jet may be powered by black hole rotation (Blandford & Znajek 1977). In this case, the jet is launched by large-scale ordered magnetic fields that penetrate the horizon, and the total jet power is

$$L_{\text{jet}} = \frac{k}{4\pi} \Omega H \Phi^2,$$

where $\Omega_H \equiv a_c/c_2r_+$. The angular velocity of the horizon, located at $r_+ = (GM/c^2)(1 + \sqrt{1 - a_c^2})$ where $a_c = a/M$ is almost certainly launched in the intermediate environment of the black hole.

All current potential mechanisms for launching relativistic jets invoke an accretion flow. This is trivially true for disk-launched outflows (e.g., Blandford & Payne 1982), but it is also the case for black hole spin-powered jets (e.g., Blandford & Znajek 1977). In the latter case, the accretion disk is needed to confine the horizon-penetrating magnetic flux which enables the black hole’s rotational energy to be tapped. While jet efficiencies, defined as $\eta_{\text{jet}} \equiv L_{\text{jet}}/Mc^2$ where $L_{\text{jet}}$ is the total jet luminosity (radiative, magnetic and mechanical), can instantaneously exceed unity as a result of the electromagnetic tapping of the black hole spin (Tchekhovskoy et al. 2011), instabilities at the jet-disk interface limit how high $\eta_{\text{jet}}$ can be in practice. Thus, even for black hole spin-powered jets, $L_{\text{jet}}$ may be used to estimate $M$, and thus address the existence of an event horizon in M87*.
the dimensionless spin of the black hole, $\Phi$ is the magnetic flux threading the horizon, and $k \approx 0.045$ is a dimensionless coefficient that varies modestly with black hole spin (see Tchekhovskoy et al. 2010 for a numerical calculation of this dependence). As Eq. (4) shows, the jet power increases quadratically with both black hole spin and magnetic flux. The former is limited by the condition $a_* < 1$, and the latter is limited by the requirement that the magnetic field through the horizon has to be confined by the accretion flow. As a rough estimate, one could say that the accreting gas is virialized and exerts a ram pressure of order

$$P_{\text{acc}} \approx \rho v_k^2,$$

where $v_k$ is the local Keplerian velocity. At the disk-funnel interface, assumed to occur at a cylindrical radius $r_{\text{eq}}$, the ram pressure must balance the magnetic pressure within the jet, and thus

$$L_{\text{jet}} \approx \frac{k\Omega v_k^2}{4\pi c} (2\pi r_{\text{eq}} B_{\text{eq}})^2 \approx \frac{2k\pi}{r_k^2} r_{\text{eq}}^4 \rho_{\text{eq}} v_k r_{\text{eq}},$$

where $B_{\text{eq}}, \rho_{\text{eq}},$ and $v_k r_{\text{eq}}$ are the magnetic field strength, gas density and Keplerian velocity at $r_{\text{eq}}$ and we have assumed $a_* \approx 1$. 

At the disk-funnel interface, the heavier gas is supported on top of an otherwise buoyant magnetic field, and thus a balanced configuration is generally unstable. The interchange instability, a close relative to the more commonly discussed Raleigh-Taylor instability, results in the growth of gas fingers that interpenetrate the magnetosphere, allowing accretion to occur on timescales comparable to the Keplerian period at $r_{\text{eq}}$ and we have assumed $a_* \approx 1$. 

The event horizon of M87

2.2. Estimates of Jet Power in M87

A variety of estimates of M87’s jet power may be found in the literature, covering a wide variety of distances from the black hole and thus timescales probed. All the estimates are consistent with a jet power of roughly $10^{44}$ erg s$^{-1}$.

Surrounding M87 is an extended radio-bright structure (Bolton et al. 1949; Mills 1952; Baade & Minkowski 1954), reaching radial distances of nearly 30 kpc, and believed to be powered by the central AGN (Owen et al. 2000). Estimates of the jet power may be obtained by estimating the energy required to grow the radio halo and dividing it by the buoyancy timescale; this gives $L_{\text{jet}} \approx 10^{44}$ erg s$^{-1}$ (Owen et al. 2000). Recent efforts to estimate the synchrotron age of the halo using LOFAR observations give roughly 40 Myr, resulting again in $L_{\text{jet}} \approx 10^{44}$ erg s$^{-1}$, depending on the assumed particle content (de Gasperin et al. 2012). These necessarily represent estimates averaged over the buoyancy time at 10 kpc, roughly 10 Myr. As a result, inferring the current instantaneous jet power requires some assumption regarding the recent history of activity in M87. 

Like many radio-loud AGN, on kpc scales M87 exhibits X-ray cavities and regions of enhanced emission associated with shocks. These are presumed to be driven by the AGN jet, and thus provide an additional measure of jet power. Estimates of the shock energetics alone require a power source of $2.4 \times 10^{43}$ erg s$^{-1}$ (Forman et al. 2005; 2007). The power inferred from the nearby cavity inflation is sensitively dependent on the gas pressure profile, and estimates range from $10^{43}$ to $10^{44}$ erg s$^{-1}$ (Young et al. 2002; Rafferty et al. 2006; Allen et al. 2006). Again, these are time-averaged over the buoyancy time, in this case roughly $\sim 1$ Myr because of the smaller scale (1 kpc), with the attendant caveats regarding variability.

Knot A is a bright optical feature within the jet at approximately 0.9 kpc. While comparable to the distance of the closest cavities, knot A is one of a number of superluminal features within the jet, with apparent velocities of up to 1.6c, implying that it moves relativistically (Meyer et al. 2013). Interpreting knot A as an oblique shock within the jet results in a jet power estimate of $(1 - 3) \times 10^{44}$ erg s$^{-1}$ (Bicknell & Begelman 1996); values much in excess of this are expected to over-produce the emission at knot A (Reynolds et al. 1996). Equally importantly, the time delays associated with estimates from knot A are roughly $2 \times 10^3$ yr, three orders of magnitude shorter than those associated with the large-scale radio and X-ray morphology.

Finally, located 60 pc from M87* is the HST-1 complex, comprised of stationary and superluminal components with apparent velocities of up to 6c (Biretta et al. 1999; Giroletti et al. 2012). At these distances, HST-1 provides the most contemporaneous estimates of the jet power, with a time delay of roughly 30 yr. If identified with a recollimation shock, the stationary component of HST-1 implies a jet power of $\approx 10^{44}$ erg s$^{-1}$.
This is grossly consistent with estimates obtained when the shock structure is modeled in more detail (Bromberg & Levinson 2009).

Overall, the typical estimate for the bolometric power of M87’s jet is \( \sim 10^{44} \text{ ergs}^{-1} \), with perhaps a factor of few uncertainty. The implied mass accretion rate is \( M \sim 10^{-3} M_\odot \text{ yr}^{-1} \).

### 3. 1.3MM VLBI SIZE OF M87

The detection of emission at the core of M87 on the scale of several times the Schwarzschild radius is robust. Observations on an array including telescopes in California (CARMA), Hawaii (JCMT) and Arizona (SMT) provided projected baseline lengths ranging from \( 6 \times 10^8 \lambda \) to \( 3.4 \times 10^9 \lambda \). Fim detection of M87 on the longest baselines alone requires the existence of compact structure with an upper size limit of \( \sim 60 \) microarcseconds, corresponding to a diameter of \( \sim 16GM/c^2 \) at the presumed mass and distance of M87. When modeled as a single circular Gaussian brightness distribution (Doeleman et al. 2012), the Full Width Half Maximum is \( 11 \pm 1GM/c^2 \) with calibration errors included in the 3-\( \sigma \) parameter estimate.

Other instrumental factors can affect the estimated 1.3 mm VLBI size but were determined to be negligible. These include the stability of Hydrogen Maser frequency standards used at each VLBI station and the polarization purity of the telescope receivers which were configured for Left Circular Polarization. On short (\( \sim 1 \) s) timescales, the Masers were compared to ultra-stable quartz oscillators, and longer-term stability was determined through timing comparisons with GPS. Polarization characteristics at each antenna were determined by injecting known polarization signals into the receiver feeds at the single dish sites, and through separate polarization calibration observations at CARMA.

The main source of uncertainty in the true size and shape of the compact 1.3mm emission is the limited VLBI baseline coverage, which is insufficient to exactly determine the brightnes morphology. The VLBI data can also be fitted, for example, with a uniform disk of diameter 16-\( GM/c^2 \), comparable to that inferred from the the long-baseline correlated flux measurements alone. In this work we adopt the circular Gaussian diameter of \( 11GM/c^2 \) with the proviso that future EHT observations with improved Global coverage will be able to image and model M87 in detail. The disk and more complex models typically predict “nulls” in the VLBI signal as a function of baseline length that are not yet seen, but which may emerge as EHT sites enabling longer baselines are added to the array.

Doeleman et al. (2012) associate the 1.3mm compact emission with the ISCO of the M87 black hole, enlarged by the strong gravitational lensing that occurs at small radii. Location of this emission close to, or at, the black hole is supported by phase referenced multi-frequency VLBI observations at longer wavelengths, which show the core of M87 to shift towards a convergent point with shorter observing wavelength (Hada et al. 2011). Extrapolation of this shift to the observed size at 1.3mm places the emission within a few Schwarzschild radii of the black hole, making the derived 1.3mm size a good estimate for the photosphere of a putative surface.

While it is possible that the 1.3mm emission arises some distance from the black hole, the EHT-derived size can still serve as an upper limit on the spatial extent of an intrinsic photosphere. Theoretical models of electromagnetic jets, both semi-analytical estimates and numerical simulations, uniformly show an expanding jet width profile with increased distance from the central engine. These expectations are quantitatively consistent with jet observations on scales covering six orders of magnitude (Hada et al. 2013; Nakamura & Asada 2013) confirm a parabolic jet shape to within \( \sim 20GM/c^2 \) of the black hole. There is, in short, no compelling mechanism to suggest that an electromagnetic jet launched from a photosphere later converges to a markedly smaller size.

### 4. THE SED OF THE NUCLEAR AGN SOURCE IN M87

Tables 1 and 2 list the optical and near-infrared SED data that are used in Figures 1 and 2. Table 2 lists the measurements made in the Perlman et al. (2011) five-year campaign to measure nuclear variability. Table 1 lists the rest of the data.

Most flux measurements were made with the Hubble Space Telescope (HST) and various imaging cameras. Also, unless otherwise noted, nuclear flux measurements were made using a correction for the galaxy light under the central PSF that is based on measuring and fitting the profile at larger radii (see, e.g., Lauer et al. 1995, Sparks et al. 1996). Various profile fit models such as Sérsic functions (Sérsic 1968) and ones with a core (see Lauer et al. 1995) are used. Also unless otherwise noted, the innermost jet knot HST-1 is not included in the measurements, although faint extensions of the jet at smaller radii are included (see, e.g., Sparks et al. 1995, Perlman et al. 2001). The measurements are discussed in their source papers. A few details are noteworthy here:

An estimate by Young et al. (1978) of \( V \sim 16.69 \pm 0.05 \) (see Lauer et al. 1992) corresponding to \( F_\lambda = 0.80 \pm 0.04 \) mJy is consistent with the results in Table 1 but is not used in this paper. The epoch was 1975 Mar 14 – 1977 May 22 and the Palomar Observatory 200-inch Hale telescope was used. We omit this measurement because the seeing FWHM was \( 1'' \) – hence the exclusion of jet knots is uncertain – and because the galaxy subtraction was not consistent with our HST-era understanding of the cuspy cores of elliptical galaxies (e.g., Lauer et al. 1992, 1995).

The (Lauer et al. 1992) HST PC F785L images (\( \lambda_{\text{rest}} = 8900 \text{ Å} \)) were taken with the unrefurbished HST but allow a clear separation of the nuclear AGN from the innermost jet knots N1 and M at \( \sim 0''1 \) and \( \sim 0''18 \) from the center (see their Figure 5). These knots are included in most HST photometry and all ground-based photometry. Lauer et al. (1992) measure them separately and show that, at 8900 Å and on 1999 Jun 1, the nucleus contributed 89% of the combined flux including N1 and M. We have used their measurement of the nuclear flux at 8900 Å. They also measure the total flux of the nucleus plus N1 plus M in the F555W band at almost the same time as the F785L measurements. We assume that the fraction of this total that comes from the nucleus is also 89% and correct their total measurement to a nuclear estimate of 0.637 mJy. This correction has not been applied to any other measurements, because we cannot know the variability of the nucleus, of N1, and of M separately. All these other measurements include the innermost part of the jet interior to knot HST-1.

We repeated the F55W galaxy subtraction to get the estimated error \( \pm 0.059 \) on the F555W flux. The Sparks et al. (1996) measurements were made with pre-COSTAR HST using the ground-based photometry by Young et al. (1978) as the galaxy model. The latter is probably not a problem; they note that corrections for galaxy light are
amplitude of the nuclear source. This amplitude is in general larger than the errors of the SED measurements. Column (6) provides the HST ID and Column (7) lists the HST camera or the telescope used. Column (8) gives the source of the measurement.

Table 2

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Note. — Notes – The first four columns list fluxes $F_\nu$ (mJy) for the four filters and their pivot wavelengths as listed in the table headers. Columns (5) – (7) are explained in their headers.

Galaxy light underlying the AGN was removed using an iterative procedure to separate the stellar brightness profile from the central source. That source was measured inside a 2.8'-diameter aperture, i.e., one that is large enough to include jet knot HST-1. The knot is not visible in their image, and the higher-resolution HST images in Sparks et al. 1996 suggest that it contributed negligibly at that time. There are jet components closer to the center (e.g., Lauer et al. 1992); these
are included even in most HST measurements. We therefore use the Sparks et al. (1996) measurements as published. The Chiaberge et al. (1999, 2002) measurements were made by subtracting from the nuclear flux the galaxy flux at radius 0.′′23 in the $R$ band and at radius 0.′′17 in the ultraviolet band. Since the galaxy’s profile is a shallow power law inside the cuspy core (Lauer et al. 1992), the resulting fluxes are strictly speaking upper limits. However, the galaxy contribution to the measurements is smaller than the amplitude of the variability of the M 87 nuclear source.

The four HST WFPC2 points from this paper were measured by E.S.P. following the procedures of Perlman et al. (2001) in February of 1998. Knot HST-1 was about 1% of the central source at this time and is not included in the measurement. Prior to measuring the nuclear flux, a galaxy model (made with the IRAF tasks ellipse and bmodel) was subtracted from each of these images. The Perlman et al. (2011) measurements listed in Table 2 were made in the same way.

We have not included the UV photometry of the nucleus published by Madrid (2009) because all of those fluxes have been referenced to a single wavelength based on an unpublished spectral model. Instead, we use the measurements published by Perlman et al. (2011), which include all of the epochs between 2004-2006 that were included in Madrid (2009) but does not apply any spectral model in their calibration. It should be noted that when the spectral referencing applied by Madrid (2009) is removed, the measurements of Perlman et al. (2011) and Madrid (2009) agree to within the errors (Madrid 2011).

5. PHOTOSPHERE EMISSION

Were a photosphere present in M87* instead of a horizon, it would be heated by the constant deposition of kinetic energy from the accretion, resulting in an additional component in the spectrum. Since the infall time is only logarithmically dependent upon the photosphere redshift, it is natural to assume that the surface will reach a steady state in which the emitted luminosity and the impinging kinetic power from the accretion flow are balanced.

The gravitational binding energy liberated per unit time by the infalling material necessarily depends on the size of the putative photosphere, approaching $M c^2$ for radii comparable to that of the horizon. That is, typically,

$$L_{\text{surf}} \approx \frac{GM}{c^2 R} M c^2,$$

where $R$ is the radius of the surface.\(^4\)

The radius of any such surface is strongly limited by the 1.3mm VLBI observations discussed in Section 3. These already constrain the 1.3mm emission region to within the vicinity of the photon orbit, expected to have a diameter of roughly $10.4GM/c^2$ in projection and depending very weakly on the assumed black hole spin.\(^5\) Moreover, at millimeter wavelengths and longer M87 still exhibits the flat radio spectrum indicative of a self-absorbed synchrotron jet (see, e.g., Blandford & Königl 1979). This interpretation receives strong support from the evolution of the radio core location with wavelength, with the offset evolving $\propto \lambda^{0.94 \pm 0.09}$ presumably due to the shrinking of the photosphere (Hada et al. 2011). Thus, at infrared and optical wavelengths the size of the photosphere is expected to be smaller than the $11GM/c^2$ limit from the mm-VLBI observations described in Section 3 – if the optically thick to thin transition completes at a wavelength of 1.1mm or shorter, this will lie within the projected photon orbit. This conclusion is only strengthened if the emission arises from a significant distance from the central engine, as described in Section 3.

However, the efficiency with which the jet is driven depends on the surface in a similar fashion, becoming larger for more compact objects. For disk driven jets, the surface and jet efficiencies are approximately equal (see Equation 1), implying that $L_{\text{surf}} \approx L_{\text{jet}}$. For black hole rotation driven jets the efficiency scales roughly as $v_j$ due to the competition between the lower $\Omega_f$ and higher $\Phi$ as the surface increases in size (see the Appendix). As a result, once again $L_{\text{surf}} \approx L_{\text{jet}}$, with an additional factor of order unity that depends only very weakly on the photosphere size. Thus, here we make the conservative assumption that $L_{\text{surf}} \approx L_{\text{jet}}/2$ as described in Equation 9.

Since the size constraints placed by EHT observations at 1.3mm already limit the size of any putative photospheric emission in M87* to scales comparable to, or smaller than, the photon orbit, the photosphere will necessarily be thermalized by the strong lensing, resulting in a gravitational analog of the standard blackbody cavity (see the discussion in Broderick & Narayan 2006, 2007). Thus, surface should be temperature as seen by a distant observer is related to the accretion rate via

$$4\pi R^2 a T^4 \approx \frac{L_{\text{jet}}}{2c^2} \rightarrow T_\infty \approx \left( \frac{L_{\text{jet}}}{8\pi R^2 c^2 a} \right)^{1/4},$$

where $a$ is the Stefan-Boltzmann constant and $R_a \approx 5GM/c^2$ is the apparent radius of any object lying within the photon orbit. Note that the temperature estimate depends only weakly on $M$, and thus on the uncertainties associated with the jet power and jet efficiency. For the accretion rate inferred in Section 2, for M87*, $T_\infty \approx 8.5 \times 10^3$ K, which means that the surface emission will peak in the optical band. The observed spectral flux from the surface is given by

$$F_{\nu,\text{ph}} = \frac{R_a^2}{D^2} \frac{2h\nu^5}{e^{h\nu/kT_\infty} - 1},$$

where $D$ is the distance to M87. This predicted flux may be directly compared to observations and thereby we can hope to constrain whether or not M87* has a surface.

6. DISCUSSION

A direct comparison of the putative photosphere spectrum to the measured fluxes listed in Table 1 is shown in Figure 11. Because of the intrinsic uncertainty in $M$, we show predicted spectra spanning a wide range of $M$, corresponding to variations in the jet efficiency or measured jet power. In all cases, photospheric emission is excluded at high confidence. This conclusion is further supported by Figure 2 which shows the ratio of the measured fluxes to that implied by a photosphere as a function of $M$. At all physically reasonable accretion rates the measured fluxes lie at least an order of
Inferred infrared-optical spectrum from a putative photosphere for $L_{\text{photo}} = 10^{43} \text{ erg s}^{-1}, 10^{44} \text{ erg s}^{-1},$ and $10^{45} \text{ erg s}^{-1}$ (solid lines, from bottom to top) compared to the empirical limits on the SED of M87* listed in Tables 1 and 2 (colored dots). The dark-red dotted line indicates the estimated limit arising from the intrinsic jet spectrum, and thus presumably the confusion limit. All points in Table 2 are plotted in order to provide some indication of the variability of the source. Those data that provide the constraints presented in Figure 2 are shown in red. Note that photospheric emission at a level of $10^{44} \text{ erg s}^{-1},$ as expected based on current estimates of the jet power (§2), is ruled out with high confidence.

This argument may be evaded in a variety of ways, though all require speculative new physics and most invoke black hole alternatives. First, M87* could fail to reach steady state, preventing the use of the accretion rate as a proxy for the surface luminosity. This requires unphysically high heat capacities (which the gravastar model of Mazur & Mottola 2004 apparently does possess, see Chapline 2005), already excluded in many cases (Broderick & Narayan 2007), or exotic alternatives like suitably tuned wormholes (e.g., Damour & Solodukhin 2007). Second, the surface could fail to thermalize, though this is strongly argued against by the compact emission observed at millimeter wavelengths, and may be excluded altogether by the development of a baryonic atmosphere. Third, the efficiency factor could be much larger than implied by current jet launching models, requiring mechanisms qualitatively different from those currently favored. For example, if M87* were a rapidly spinning compact object with a strong magnetic field, the accreting gas could be stopped at a magnetospheric radius and flung out in a jet without any gas reaching the underlying photosphere (e.g., the neutron star propeller model of Illarionov & Sunyaev 1975). In any such model, the magnetospheric radius can be only slightly larger than the surface (e.g., Kulkarni & Romanova 2008). In addition, the material that is stopped and flung out by the magnetosphere is likely to dissipate a good fraction of its kinetic energy where it meets the rotating magnetosphere, resulting in thermalized radiation not very different from that expected from a photosphere. We regard this propeller model as strictly physically possible but astrophysically implausible. Thus, our argument magnitude below that required in the absence of an event horizon.

Improvements in the measured flux limits will necessarily result in increased confidence with which any photospheric emission may be ruled out. However, the intrinsic emission from the observed jet component provides a natural limit. Assuming a spectral index of 1.2, consistent with a transition from optically thick to optically thin near 1mm, and the optical flux limits, we estimate the corresponding floors on the infrared-optical spectrum and flux ratio, shown by the dotted, dark-red lines in figures 1 and 2, below which the emission from the jet-launching region must be modeled in detail. Note that this is rather uncertain: variations in the spectral index between the core and larger scale jet emission arising, e.g., from an evolution in the relativistic particle distributions, could easily harden the core spectrum sufficiently to fully account for the vast majority of the fluxes shown in Figure 1. Nevertheless, even if this is not the case, it appears that the current flux limits are within an order of magnitude of the confusion limit, below which careful modeling of the jet emission will be required to obtain stronger constraints.

Despite the astrophysical uncertainty in the relationship between the jet power and mass accretion rate, we have shown in this paper that, within the context of current jet launching paradigms, we can rule out the existence of an observable photosphere in M87* within which the kinetic energy of the accreting gas is deposited. The implication is that the kinetic energy of the gas is advected past an event horizon, beyond which it is no longer visible to distant observers. In other words, M87* must have an event horizon.
will be strengthened in the near future as key components to the current jet paradigm are critically tested by mm-VLBI observations of M87.

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**APPENDIX**

A. BLANDFORD-ZNAJEK JET EFFICIENCY FOR SURFACES

The relationships between accretion rate and both surface luminosity and jet power are dependent upon the assumed surface size. In detail this depends upon the specific jet launching mechanism assumed. Here we consider the question in the context of Blandford-Znajek jets, for which the jet luminosity is related to the properties of the central object via Equation 4. For an object with a large surface there are two important modifications: the angular velocity is limited to \( \Omega_H < c/R, \) and \( \Phi < 2\pi R^2 B_{eq}. \) Thus,

\[
L_{jet} \lesssim \frac{\pi k c R^2}{2 \pi k v_{eq} c} \rho_{eq} v_{eq} c \dot{M} c^2, \tag{A1}
\]

where we assumed \( \dot{M} \approx 4\pi R^2 \rho_{eq} v_{eq} \) and equipartion near the surface (i.e., \( r_{eq} \approx R \)). This must be compared to

\[
L_{surf} \approx \frac{GM}{c^2 R} \dot{M} c^2 \approx \dot{M} v_{eq}^2, \tag{A2}
\]

which gives

\[
\frac{L_{surf}}{L_{jet}} \approx \frac{1}{2\pi k c} \frac{v_{eq}}{c} \propto (\frac{GM}{c^2 R})^{1/2}. \tag{A3}
\]

This is a weak function of \( R \). For the range of surface radii consistent with the recent mm-VLBI limits, it introduces at most a factor of two.

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