DIFFERENTIATING DISK AND BLACK HOLE DRIVEN JETS WITH EHT IMAGES OF VARIABILITY IN M87

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ABSTRACT

Millimeter-wavelength very long baseline interferometric (mm-VLBI) observations of M87 by the Event Horizon Telescope (EHT) should provide a unique opportunity to observe and characterize the origins of jet variability already seen at longer wavelengths. Synchrotron hot-spot models have been used to model variability near black holes; this work extends these by allowing hot-spots to shear and deform in the jet velocity field. Depending on the position of the hotspot, shearing forces can significantly alter the structure of the hot-spot, producing distinct signals in reconstructed images and light curves. The maximum density of the shearing spot can vary by as much as a factor of five depending on the spot azimuthal launch position, but the intensity decay time depends most significantly on the spot radial launch position. Spots launched by a black hole driven jet exhibit distinct arc structures in reconstructed images, and have bright but short-lived jumps in the light curve. Spots launched by a wind-driven jet have exhibit much simpler structures in the image, and have much longer-lived light curves than spots launched by a black hole driven jet.

Keywords: black hole physics – galaxies: individual (M87, NGC 4486) – galaxies: active – galaxies: jets – relativistic processes – submillimeter: general

1. INTRODUCTION

Of the most luminous extragalactic radio sources, nearly every one shares a similar double-lobe radio structure, with a bright radio galaxy or quasar sitting between the two lobes. These active galactic nuclei (AGN) all exhibit narrow, highly beamed relativistic jets with typical Lorentz factors of 10 to 100 and extend over wide range of intergalactic distances, from a few kpc to tens of Mpc. Assuming the large scale radio lobes are powered by the termination shock of these jets against the intergalactic medium, it is possible to estimate their energetic content to lie between $10^{43} \text{ erg s}^{-1}$ and $10^{48} \text{ erg s}^{-1}$ (Longair 2011). At these values, the power output of the central AGNs in the form of relativistic jets rivals their electromagnetic luminosities.

This extraordinary kinetic luminosity plays a central role in the evolution of galaxies and galaxy clusters. Via radio-mode feedback, AGN jets inject both energy and momentum in the circumgalactic and intracluster medium, suppressing star formation (McNamara & Nulsen 2012; Fabian 2012). Thus, the origin and content of AGN jets remain a critical input to understanding the evolution of structure in the universe. This, in turn, requires a well-developed model for how relativistic jets are launched and how this depends on the properties of the parent AGNs, e.g., the evolution of black hole spin (Worrall 2009).

The Event Horizon Telescope (EHT) is a global millimeter-wavelength, very-long baseline interferometer (mm-VLBI), capable of generating the first images of any AGN that resolve the horizons of the central supermassive black holes (Doelman et al. 2008). Currently, the EHT is comprised of nine telescopes located at six sites: the Submillimeter Array (SMA) and James Clerk Maxwell Telescope (JCMT) in Hawaii, the Arizona Radio Observatory Submillimeter Telescope (ARO-SMT) on Mt. Graham, the Large Millimeter Telescope (LMT) in Mexico, the Atacama Large Millimeter/Submillimeter Array (ALMA), Atacama Pathfinder Experiment (APEX) and Atacama Submillimeter Telescope Experiment (ASTE) in Chile, the South Pole Telescope (SPT), and the Institut de Radioastronomie Millimetrique 30m Telescope in Pico Veleta (PV). Future additions include the Kitt Peak National Observatory (KP), the Greenland Telescope (GLT), and the Northern Extended Millimeter Array in Plateau de Bure (PdB). Together, these present Earth-sized baselines to the primary EHT targets.

In April, 2017, the EHT observed with the full array in the 1.3 mm (230 GHz) atmospheric water window. Over the past decade, the EHT has observed with a subset of telescopes, including the now-decommissioned Combined Array for Research in Millimeter-wave Astronomy (CARMA) and Caltech Submillimeter Observatory (CSO), generating insufficient spatial-frequency coverage for imaging but probing horizon scales, nonetheless. In the future, the EHT will also observe in the 0.87 mm (345 GHz) atmospheric window, providing a multi-wavelength, horizon-resolving imaging capability. At these wavelengths, the resolution of the EHT ranges from 10 $\mu$as to 20 $\mu$as, well matched to the projected sizes of the lensed horizons of nearby supermassive black holes. Thus, it will be possible to directly probe the smallest region presumed to be responsible for the launching of relativistic jets.

M87, the giant elliptical galaxy at the center of the Virgo cluster, is one of two primary AGN targets of the EHT, the other being the supermassive black hole at the center of the Milky Way. With a mass and distance of $6.7 \times 10^9 M_\odot$ and 17.9 Mpc (Gebhardt et al. 2011), the projected horizon of M87 subtends an angular scale of 37 $\mu$as, and is thus resolvable with the EHT. It also exhibits a prominent relativistic jet across all wavelengths, extending to scales of 40 kpc (Junor et al. 1999; Ly et al. 2007; Sparks et al. 1996). The luminosity of M87’s jet roughly $10^{44} \text{ erg s}^{-1}$ as measured at a few different locations. On kiloparsec scales observations of X-ray cavities inflated by the jet can be used to estimate jet power to about $10^{43} \text{ erg s}^{-1}$ to $10^{44} \text{ erg s}^{-1}$ with timescales of approximately 1 Myr (Young et al. 2002). Below kiloparsec scales, superluminal optical features in the jet can be used to estimate the jet power, assuming...
they are the products of shocks. The bright feature Knot A sits 0.9 kpc from the jet base and exhibits superluminal velocities up to 1.6c (Meyer et al. 2013) and yields estimated jet power of a few ×10^{44} \text{ erg s}^{-1} (Bicknell & Begelman 1996) on a timescale of 10^{3} years. The bright optical feature HST 1 sits 60 pc from the jet base, and contains superluminal velocities with poloidal components moving away from the core at approximately 0.17c. The western side of the jet is much brighter, with two clear limb-brightened arms on the north and south. These arms contain smaller jet components with apparent velocities between 0.25c and 0.48c, but are most likely completely different components observing epochs (Ly et al. 2007). Similar observations at 86 GHz also exhibit similar jet components, and with definite variability over 4 months of observations. A weak, highly variable counter-jet exists within 0.25 mas of the jet core, with proper motions of approximately 0.17c. A pair of limb-brightened arms extend westward of the jet core, with multiple jet components in both the north and south arms. These components have apparent velocities between 0.25c and 0.48c, with proper motions approximately 1.0 mas yr\(^{-1}\) to 1.81 mas yr\(^{-1}\), with new components appearing on a timescale of a few months (Hada et al. 2016).

The extreme luminosity of AGN jets are thought to originate from the conversion of gravitational potential energy to radiation from deep inside the the potential well of supermassive black holes. The mechanism of this conversion is unconfirmed, though at present is believed to be mediated by the extraction of rotational energy via magnetic torques, the chief distinguishing factor being the energy reservoir and topology of the magnetic fields. These may be organized into two primary classes: jets driven by black holes (Blandford & Znajek 1977) and jets driven by accretion flows (Blandford & Payne 1982). In the former, the jet is powered by the extraction of rotational energy via large-scale electromagnetic fields near the horizon of the supermassive black hole, which become highly collimated far from the black hole (Blandford & Znajek 1977). In the latter, the outflows are associated with a massive disk wind emanating from a hot accretion disk around the black hole, where the disk electromagnetic fields provide the motive force and the disk particles provides the luminous material (Blandford & Payne 1982).

In either case, the structure of the resulting jet is very similar. The canonical jet model extracted from simulations features a force-free interior where the majority of the electromagnetic energy density is uncoupled from any particles in the jet (McKinney 2006; Hawley & Krolik 2006; Tchekhovskoy et al. 2008). The exterior of the jet is composed of a magnetically dominated wind where the magnetic pressure is much larger than the gas pressure. Both of these regions are, in turn, supported by a hot, thick accretion flow which provides the currents for the magnetic fields.

Simulated EHT images, which show sub-horizon scale emission structure, have been produced using a simplified, stationary, force-free model of the jet-interior (Broderick & Loeb 2009). In this model, magnetic field lines that are anchored in a putative accretion flow, setting the boundary conditions.
Figure 3. Density evolution of a non-shearing and shearing spot launched at $\rho = 0.5 \rho_{\text{crit}}$ and $\phi = 270^\circ$ for $30 t_g$ in gravitational time. The top set of spots are a non-shearing spot with a Gaussian density profile in the spot-center reference frame, and the bottom set of spots are a shearing spot with the same initial launch position and density profile. The shearing spot develops an extended tail within a few $t_g$ of launch, producing a very different density profile than the non-shearing spot.

Figure 4. Density and velocity profiles for the spot launched at $\rho = 0.75 \rho_{\text{crit}}$ (left) and $1.25 \rho_{\text{crit}}$ (right) at $t = 0 t_g$ (bottom) and $30 t_g$ (top). The velocity profile for the outer spot (bottom two blobs) exhibits much less shearing, resulting a more spherically symmetric spot as it evolves than the interior spot.

for the force-free region. Those field lines that anchor in the inner most stable circular orbit define a critical surface which exhibits the largest accelerations and highest Lorentz factors. These field lines also serve as a convenient boundary of the jet and an important reference position when initializing our simulations, whose perpendicular distance from the jet axis we will call $\rho_{\text{crit}}$. These simulations differ from images generated from general relativistic magnetohydrodynamic (GRMHD) simulations primarily through the distributions of the synchrotron emitting lepton populations. In those simulations, the magnetic energy and mass densities in the jet-launching region are fixed by a numerical floor governed by the simulation resolution (Dexter et al. 2012). Non-thermal particle emission in the jet-launching region could arise from turbulence or magnetic reconnection events well below the simulation resolution, and efforts to produce a self-consistent model for the evolution of the non-thermal particle distribution has been difficult (Mościbrodzka et al. 2016). Because of this, jet variability in these GRMHD simulations are strongly dependent on numerical noise in the jet-launching region and may not adequately model observed variability in M87.

We add variability to these stationary force-free jet models, and explore its qualitative and quantitative impacts on EHT imaging. We do this by introducing compact emission regions within the jet-launching zone, but do not allow these compact regions to affect the field structure of the jet. While outside the
sions are collected in Section 4.

Throughout the paper we specify distances in $r_e \equiv GM/c^2 = 1.0 \times 10^{15}$ cm and time in $t_e \equiv GM/c^2 = 9.2$ hr. Where appropriate, values in other units will be provided for convenience.

Figure 5. Snapshots at late times ($25\tau_e$) of a Gaussian and Shearing spot launched at $\rho = 0.5 \rho_{\text{acc}}$ and $\phi = 270^\circ$. The non-shearing spot stays compact and bright, but the shearing spot develops complicated emission structures in the image plane. The dashed circle is the radius of the black hole shadow, and the bright emission immediately around it comes solely from the jet.

In Section 2 we describe how spots are modeled in detail. In Section 3 we explore a variety of different injection sites and spot parameters, identifying qualitative trends and quantitative signatures of black hole-driven and disk-driven jets. Conclusions are collected in Section 4.

While our Gaussian spots should adequately model the general motion of over-densities in the jet, the shearing forces near the black hole non-trivially affect the structure of these spots as they evolve. In order to confidently explore the impact of this type of jet variability on EHT images, we need to think carefully about how to initially construct and keep track of the changing spot. We construct a shearing spot as an assembly of smaller non-shearing spots arranged in equal mass shells that approximate the density structure of the non-shearing spot. These mini-spots serve as Lagrangian control points for calculating the local density in a way similar to smoothed particle hydrodynamics methods.

To be able to propagate the mini-spots through jet velocity field, we need a set of coordinates $\xi$ that co-move with each mini-spot.

$$\xi_1^\mu = \epsilon^{\mu \alpha \beta \gamma} t_\alpha z_\beta u_\gamma$$  \hspace{1cm} (1)

$$\xi_2^\mu = \epsilon^{\mu \alpha \beta \gamma} t_\alpha \xi_\beta u_\gamma$$  \hspace{1cm} (2)

$$\xi_3^\mu = \epsilon^{\mu \alpha \beta \gamma} \xi_\alpha z_\beta u_\gamma,$$ \hspace{1cm} (3)

where $\epsilon^{\mu \alpha \beta \gamma}$ is the 4th-dimensional Levi-Civita symbol, $t_\alpha$ is the lab frame time-like Killing vector, $z_\beta$ is the lab frame vertical spatial unit vector, and $u_\gamma$ is the lab frame velocity. Once these $\xi$ are normalized, they serve as a space-like orthonormal triad that is also orthogonal to the lab frame vertical; together they form a complete spacetime basis.

We divide our non-shearing density profile into radial, azimuthal, and polar shells evenly distributed by mass. From our
co-moving cartesian basis we then construct the initial mini-spot distribution in Boyer-Lindquist coordinates $x^\mu_{ijk}$ where each $i$, $j$, and $k$ index corresponds to a single mini-spot shell.

$$
x^\mu_{ijk} = \rho_i \sin(\vartheta_j) \cos(\varphi_k) \xi^\mu_1 + \rho_i \sin(\vartheta_j) \sin(\varphi_k) \xi^\mu_2 + \rho_i \cos(\vartheta_j) \xi^\mu_3 + r^\mu,
$$

where $\rho$, $\vartheta$ and $\varphi$ are the shell indices for each mini-spot, and $r^\mu$ is the initial spot center position in the lab frame. Every mini-spot appears simultaneously in the frame co-moving with the spot center, but will appear at different Boyer-Lindquist times in the lab frame.

To find the mini-spot positions at later times, we calculate each mini-spot trajectory $dx^\mu_{ijk}/dt$ using the value of the velocity field $u^\mu_{ijk}$ at the mini-spot,

$$
\frac{dx^\mu_{ijk}}{dt} = \frac{u^\mu_{ijk}}{u^\nu_{ijk}}.
$$

We use a 4th/5th order Cash-Karp Runge-Kutta method to integrate along these trajectories, with adaptive step sizes determined by the error of the 4th order calculation (Press et al. 2007). We first integrate backwards from our initial Boyer-Lindquist time to make sure we have mini-spot trajectories for every mini-spot in the lab frame, then integrate forward along the trajectories from the initial time to far enough in the future to travel significantly up the jet. At each step in these integrations, we record the new lab frame positions of the mini-spots in a table.

We can calculate the density at any point by adding up the density contribution from all the mini-spots nearby:

$$
n_s = \rho_0 \frac{r_s^3}{N_s} \sum_j \frac{\exp \left( - \frac{1}{2} \Delta r_j r_s^{-1} \Delta r_j \right)}{\sqrt{|l_j^1|}},
$$

Our total density $n_s$ is made up of $j$ mini-spots with individual number densities normalized by the correlated distance between one mini-spot and its nearest neighbors. Here, $\rho_0$ is the
Figure 7. Late time evolution of shearing spots launched at $\phi = 270^\circ$. From left to right, the columns correspond to spots with initial cylindrical radii at $0.5\rho_{\text{crit}}$, $0.75\rho_{\text{crit}}$, $\rho_{\text{crit}}$, $1.25\rho_{\text{crit}}$, and $1.5\rho_{\text{crit}}$. The first row is $31t_g$ (11 days) after the spot was launched, and the second row is $21t_g$ (8 days) after the spot was launched. A clear arc structure is apparent in all interior spots, but is suppressed or non-existent in exterior spots.

Figure 8. Light curves of a shearing spot launched at $\phi = 270^\circ$. The spot was launched at $0.5\rho_{\text{crit}}$ (blue solid), $0.75\rho_{\text{crit}}$ (red dash), $\rho_{\text{crit}}$ (green long dash), $1.25\rho_{\text{crit}}$ (teal dash-dot), and $1.5\rho_{\text{crit}}$ (orange dot). Interior spots exhibit much higher initial intensities, but decay much faster than spots launched further away. Vertical dashed lines correspond to the same times as those in the previous figure.

The sum in Equations (7 – 10) are over the mini-spot nearest neighbors to the central $(i,j,k)$ mini-spot where we want to calculate the density. The nearest neighbor spots are relative the their shell coordinates; the nearest $r$ neighbors live in the $i+1$ and $i-1$ shells, the nearest $\phi$ neighbors live in the $j+1$ and $j-1$ shells, and the nearest $\theta$ neighbors live in the $k+1$ and $k-1$ shells. The BC function is a function that makes sure we calculate the shortest distance between two $\phi$ shells.

We only consider the covariance of nearest neighbors in the $r-r$, $\phi-\phi$, $\theta-\theta$, and $r-\theta$ directions because we do not expect much shearing in the $\theta-\phi$ or $r-\phi$ directions. Indeed, it is apparent in Figure 2 that this is the case, with the most significant shearing occurs in the radial and poloidal directions.
the proper density is given by $n_s/u_t$.

Black hole driven spots should have a much more extended density profile than a non-shearing gaussian spot launched with the same initial conditions. This is readily evident in Figure 3, which shows the shearing spot with an extended tail feature forward of the spot central density, and a much more extended density region in general. Shearing spots launched at different launch radii should also develop different density profiles, demonstrated on Figure 4 since the velocity field structure changes significantly outside the critical field surface.

Even though spots might only differ in initial radial launch distance by less than $5r_g$ they exhibit substantially different density profiles after even a few gravitational time steps. A black hole driven spot will experience a much stronger velocity gradient than an wind driven spot, and should be distinguishable in much the same way a non-shearing gaussian spot is distinguishable from a shearing spot.

3. Exploration of Imaging

3.1. Radiative Transfer

The primary emission mechanism near the black hole is synchrotron radiation from thermal and non-thermal electrons. The thermal component is modeled using the emissivity de-
Figure 10. Late time evolution of a spot launched at $\rho = 0.5 \rho_{\text{crit}}$ at cylindrical angles $\phi$ of $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$. The first row is $31 t_g$ (11 days) after the spot was launched, and the second row is $21 t_g$ (8 days) after the spot was launched. Black hole launched spots like these shear enough to fully wrap around the jet axis by these late times.

Figure 11. Light curves of a shearing spot launched at $0.5 \rho_{\text{crit}}$. The spot was launched at $\phi = 90^\circ$ (red dashed), $180^\circ$ (green long dash), $270^\circ$ (orange dash-dot), and $0^\circ$ (blue solid). Spots launched at $\phi = 270^\circ$ exhibit the highest maximum intensities, and spots launched at $\phi = 90^\circ$ the lowest maximum intensities.

The non-thermal emission is assumed to follow a power-law distribution which cuts off below some critical Lorentz factor, as described by Jones & Odell (1977). The cut-off is fit to match M87’s observed millimeter spectrum (Broderick & Loeb 2009), and the absorption coefficients are determined directly from Kirchoff’s law (Broderick & Blandford 2004).

The image generation process can always produce black hole shadows, but for most cases the images generated are of a much larger physical scale; the typical image size is 650 by 400 µas. At this scale, the black hole shadow is relatively small, and our choice of intensity scaling can wash out the shadow by over-saturating the emission very near the shadow.

3.2. Shearing v. Non-Shearing Spots

The distributed density profile of the shearing spots is easily distinguishable from the gaussian spot in the imaging space as well. It is readily apparent that the shearing spot has a much more extended intensity profile. This Figure 5 is a snapshot at $25 GM/c^3$ (about 225 hours or 9.4 days) after the initial launch, and the shearing spot exhibits a complex structure. The spot has sheared out enough to wrap up on itself at least once, creating a distinct arc over the bright jet emission near the black
Figure 12. Horizon scale images of a spot launched at \( \rho = 1.0 \rho_{\text{crit}} \) with \( \phi \) angles of 0°, 90°, 180°, and 270°. The top row is \( 7 t_g \) (2.5 days) after the spot launch and the bottom row is \( 3 t_g \) (1 day) after the spot launch. Changing the azimuthal launch parameter still produces significant differences in image intensity, with spots launched at low angles contributing to a much lower image intensity than spots launched at large angles.

This hole. The bright line down the center of the image is not a high density region, but emission from the low-density tail of the shearing spot that is strongly beamed towards the observer. The black hole shadow is represented by the dashed circle in these images, and is always located at the origin with respect to the coordinates of the image.

3.3. Shearing Spots, Changing Radius

We have demonstrated the shearing spot is substantially different from the gaussian spot in both its density profile and in the image domain. Our next task is to compare shearing spots at different launch positions. M87 has a large spin, which means photons from our spots can be strongly beamed towards or away from us when the spot is near the black hole, in addition to beaming associated with the acceleration from the jet itself. The geometry of the velocity field in the jet will also lead to different shearing morphologies, depending on whether the spot was launched inside or outside the jet critical surface.

Zooming into the immediate region around the black hole at early times, we can still see differences in image structure when we change the spot launch radius. Even though the spot is very bright at early times, we can see in Figure 6 that black hole-driven spots shear away much faster than wind-driven spots. We can also see how spots starting at the critical radius initially look very much like black hole-driven spots, but shear into a longer and more diffuse version of a wind-driven spot at later times.

Spot densities for wind-driven spots remain relatively compact, as seen above in Figure 4. Even after \( 30 t_g \) (11 days), wind-driven spots are only slightly more extended compared to their launch size. Nevertheless, propagation time delays smear the spots on the image plane. While this happens for black hole-driven spots as well, this phenomenon is easiest to see in wind-driven spots, where the spot both shears and travels much more slowly.

If we zoom out and look at the spot for longer, as we do in Figure 7, the same conclusions still apply: azimuthal shearing is most significant inside the critical surface (about \( 9.5 r_g \)), which is responsible for low surface brightness arcs. Outside the critical surface, azimuthal shearing is significantly suppressed, and the spot slowly expands and flows outward, generating an extended arm in the last column.

Figure 7 demonstrates that spots launched inside the jet critical surface exhibit sheared structures that distinguish them from spots launched outside the critical surface. The spot launched at \( \rho = 0.5 \rho_{\text{crit}} \) (first column) looks much different than the spot launched at \( \rho = 1.5 \rho_{\text{crit}} \) (last column). The black hole-driven spot has an arc structure in the second row from the bottom, \( 10 t_g \) (90 hr) after the spot was launched. The arc becomes even more pronounced in each successive row, whereas the exterior spot just has a more extended emission region coming straight out of the bright jet region. Structure in the image perpendicular to the jet axis like arcs and sickles appear in all interior spots, even for spots launched at the critical surface. Spots launched outside the critical surface exhibit much dimmer arcs, and disappear entirely for spots launched only \( 4 r_g \) (\( \rho = 1.5 \rho_{\text{crit}} \)) away from the critical surface.

Without a spot, the jet electron density is set such that the total intensity for a quiescent jet is approximately 1 Jy. For a fixed spot electron density, the maximum intensity in the image depends strongly on the initial radial launch position. The maximum intensity exceeds the quiescent jet by well over an order of magnitude for spots launched inside the jet critical surface, dropping below and order of magnitude only for spots launched well outside the jet critical surface. While the launch position dramatically changes the maximum intensity of the image, the intensity decay rate is just as diagnostic for differentiating spot launch positions. Black hole-driven spots have very fast
Figure 13. Late time evolution of a spot launched at $\rho = \rho_{\text{crit}}$ for $\phi$ angles of $0^\circ$, $90^\circ$, $180^\circ$, and $270^\circ$. The top row is $31t_g$ after the spot launch and the bottom row is $21t_g$ after the spot launch. These critical spots experience less extended emission starting from low angles of $\phi$ than at higher angles of $\phi$.

Figure 14. Light curves of a shearing spot launched at $1.0r_{\text{jet}}$. The spot was launched at $\phi = 90^\circ$ (green long dashed), $180^\circ$ (red dashed), $270^\circ$ (orange dot-dashed), and $0^\circ$ (blue solid). The spot launched at $\phi = 270^\circ$ has by far the highest maximum intensity. Wind-driven spots exhibit much slower intensity decay, but also much lower maximum intensities. When the spot is only $4r_{\text{jet}}$ away from the critical surface, as shown by the green line in Figure 8, the maximum intensity of the image only reaches six times the quiescent level, but decays to half-maximum approximately 100 hr later. Lower maximum intensities from interior spots can be attributed to significantly less beaming and slower velocities outside the jet, which also means the spot experiences less aggressive shearing. This keeps the spot relatively compact, lengthening the time the spot dominates the emission.
3.4. Changing Launch Azimuth

Fixing the radial launch position to 50% the critical surface but varying the azimuthal launch angle around the jet dramatically alters the structure of intensity in the image. These dramatic differences can be attributed to different projections of the shearing spot as it shears around the jet, and there is qualitatively no structural differences between these different launch positions. The spot in each of these cases shears in the same way and in the same amount of time, as we can see in Figure 9. At late enough times, e.g., Figure 10, there exists an additional bright region between the main arc of the sheared spot and the bright stationary jet. This region is the tail of the spot re-entering the region of the jet that provides the strongest beaming. Even though the spot tail has very low density, the beaming in this region of the jet is strong enough to make the tail of comparable brightness to the main spot arc.

The maximum intensity of the image changes by about a factor of four for black hole-driven spots as the azimuthal launch position changes. These light curves help serve as a probe for beaming. Spots starting at a launch position of $\phi = 90^\circ$ have the lowest maximum intensity, which also roughly correlates to the region in the jet where emission is most strongly beamed away from the line of sight. Similarly, the spot launched at $\phi = 270^\circ$ has the highest maximum intensity, which is in the region of the jet where emission is most strongly beamed towards the line of sight. These differences in launch position only lead to quantitative differences in the total intensity; the rate of decay of the intensity is roughly similar for all azimuthal launch positions. The image intensity decays from maximum to half-max in roughly 50 hr for each launch position. While the difference in intensity between launch positions is certainly dramatic, the decay of the image intensity is a much better diagnostic for determining the radial launch position of shearing spots.

The images of interior shearing spots shows the development of secondary bright regions corresponding to the spot tail re-entering a region of high beaming. This “echo” shows up in at least one of the light curves. The light curve for spot position $\phi = 0^\circ$ in Figure 11 immediately decays without reaching a peak intensity, then has a bump between 100 hr and 150 hr. This bump represents the tail of the spot shearing all the way around the jet, additively contributing to emission from the center of the spot as it reaches the side of the jet with the largest beaming towards our line of sight.

Similar to black hole-driven spots, launching spots on the critical surface at different azimuthal positions leads to substantially different emission structures in the image at later times, as seen in Figure 12. Even so, these different structures can be explained as different projections of the same spot arc around the jet. Arcs in these images stay relatively compact and bright compared to arcs associated with black hole-driven spots and there are no echoes at late times from the spot tail re-entering the region of highest beaming, as demonstrated in Figure 13. Spots on the critical surface shear less than spots inside the critical surface and no spot on the critical surface shears completely around in the simulated time.

Also similar to black hole-driven spots, fixing the radial launch position to the critical surface but changing the azimuthal launch position changes the maximum intensity of the light curve by an order of magnitude around the jet, as we can see in Figure 14. The spot launched on the side with the highest beaming, $\phi = 270^\circ$, reaches a tremendous maximum intensity of approximately 15 Jy. The spot launched on the side of the jet with the lowest beaming, $\phi = 90^\circ$ barely impacts the intensity of the image at all. The intensity decay from maximum is still roughly the same for each different launch position, approximately 100 hr from maximum intensity to half-maximum. While the value of the maximum intensity strongly depends on
Figure 16. Late time evolution of a spot launched at \( \rho = 1.5 \rho_{\text{crit}} \) for \( \phi \) angles of 0\(^\circ\), 90\(^\circ\), 180\(^\circ\), and 270\(^\circ\). The top panel is 31\( t_g \) (11 days) after the spot launched while the bottom panel is 1\( t_g \) (9 hours) after the spot launched. Wind launched spots maintain their initial shape for much longer, and do not generate arcs perpendicular to the jet axis.

As mentioned earlier, the consequences of slow light can best be seen in images of wind-driven spots. We can see in Figures 15 and 16 that as the azimuthal launch position around the jet changes, the line-of-sight angle with respect to the observer also changes. When this angle is relatively large, e.g., in the images for \( \phi = 180^\circ \), the image of the spot better traces the physical structure of the spot. At other positions, the image of the spot stretches into an extended, diffuse arm even though the spot itself remains relatively spherical.

Wind-driven spots have very low maximum intensities even on the bright, approaching side relative to interior or critical spots. While these spots may not be as bright as other spots, they persist in the light curve for much longer. We can see in Figure 17 that the time from maximum intensity to half-max is approximately 150 hr, nearly a week long. Just as in the other cases, the maximum intensity strongly depends on the azimuthal launch position. Light curves for spots launched away from the bright side barely exceed the flux associated with the quiescent jet.

3.5. Critical Spots, Changing Height

Fixing the radial and azimuthal launch positions but altering the launch height is approximately degenerate with changing the observer time of the spot image. Spots that start at a higher position look structurally very similar to late-time im-

the azimuthal launch position, the rate of decay of intensity serves as a strong diagnostic for the radial launch position.
Figure 18. Altering the launch height of spots launched at $\rho = \rho_{\text{crit}}$. The first column is a spot launched with a height of $6r_g$ and the second column is a spot launched with a height of $24r_g$. Time flows from the bottom row to the top row in steps of $10t_g$ (4 days). Spots starting at lower jet heights appear brighter, and experience stronger shearing than a spot launched further up the jet. Early time spots at high launch heights look qualitatively like late time spots with low launch heights.

Figure 19. Light curves of a shearing spot launched at $1.0\rho_{\text{crit}}$. The spot was launched at $270^\circ$, at heights of $z = 6r_g$ (blue solid), $z = 12r_g$ (red dashed), and $z = 24r_g$ (green long dashed). Spots that start higher up the jet appear much dimmer than lower spots, and spots that start lower than $12r_g$ experience a full rise, peak, and fall in their light curve ages of spots launched at lower heights. For example, the spot launched at $12r_g$ and seen about 180 hr after launch looks very much like a spot launched at $6r_g$ imaged 270 hr after launch (Figure 18).

The light curves for spots launched at different heights changes as one would expect (Figure 19). Spots starting lower in the jet experience much larger accelerations and shearing, but remain optically thick for longer. The combination of a large, optically thick spot and high accelerations leads to a tremendous increase in maximum intensity, easily beating other spots. Even so, the intensity decay seems to be independent of height. Combined with the previous explorations, the intensity decay time remains the strongest image diagnostic for measuring the radial launch position.

3.6. Exploration of Light Curves

The total averaged image intensity is an easily accessible and measurable quantity. Here we discuss in more detail how the total image intensity changes with spot azimuthal launch position, and how changing the spot launch radius drastically changes the image intensity decay time outside the jet.

The light curves for spots launched at fixed radial positions but changing azimuthal positions have maximum intensities that vary by at least a factor of 5. Starting at $\phi = 240^\circ$ and going to $\phi = 350^\circ$ in increments of $10^\circ$, we see in Figure 20 that for a spot launched on the critical surface with an initial height of $12r_g$, the azimuthal launch position with the highest intensity is actually $\phi = 300^\circ$. The jet is inclined towards the line of sight, so the beaming component of the jet biases the region of highest intensity to be slightly ahead of where the beaming from the black hole spin would maximize the intensity if we looked directly down the jet axis.

The region of azimuthal parameter space where beaming boosts the image intensity to large multiples of the quiescent jet only occurs between $\phi = 260^\circ$ and $\phi = 340^\circ$, less than a quarter of the total azimuthal parameter space. Outside this region, the maximum intensity quickly drops to within a few factors or less of the quiescent jet. If these energetic spot events occur on a yearly basis, we may still have difficulty detecting them with imaging methods because they launch away from the side of the jet with significant beaming.
Ideally, to identify and analyze these energetic events, the spot must persist long enough to be seen in at least two observations during the EHT observing window. The time it takes for a spot to evolve from its maximum intensity to half the maximum is a useful quantity for characterizing the spot lifecycle. For a spot starting on the critical radius, the half-life is largest when the spot starts on the dim side of the jet ($\phi = 90^\circ$), as seen in Figure 21. Here, the spot half-life is approximately 60 hr, but drops to between 30 hr and 40 hr when the spot should be brightest ($\phi = 300^\circ$). This arises because when the spot has its highest maximum intensity, it begins on the side of the jet with the highest beaming towards our line of sight. Thus the combined effects of shearing and moving out of our line of sight decreases the spot lifetime.

The systematically shallow light curves exhibited by spots launched outside the jet relative to those launched inside the jet appears in the spot half-life. This is shown for various launch positions in Figure 22, for which the wind-drive spots generally have longer half-lives than black hole driven spots. That is, wind-driven spots last at least four times longer than black hole-driven spots for 75% of the azimuthal launch parameter space. The half-life for a wind driven spot drops substantially in the last quarter, just exceeding that for black hole-driven spots for $\phi = 0^\circ$; nevertheless, it remains longer at all launch orientations.

While wind-driven and black-hole driven spots are easy to distinguish, Figure 22 demonstrates that differentiating between slightly different black hole-driven spots may be more difficult. Spots that start on the critical surface have half-lives that are different by a factor of two compared to spots at half the critical surface. Figure 23 shows that for black hole-driven spots for $\phi = 0^\circ$, the half-life for a spot launched on the critical surface has a half-life longer than the black hole driven spot by approximately a factor of two.
The emission from compact spots near the base of M87’s jet is strongly shaped by the velocity field of the jet. Material originating inside or on the jet velocity critical surface experiences significant shear forces on timescales easily probed by the Event Horizon Telescope. These spots are sheared into complex arcs perpendicular to the jet axis that should be readily apparent in reconstructed images of the black hole region of M87. Material originating outside the velocity critical surface experiences much less shear, producing no arcs in reconstructed images, and are thus distinguishable from interior spots.

The evolution of structure in these spots is almost uniquely dependent on the radial launch position of the material. While the azimuthal launch position of the spot dramatically alters the maximum intensity of the reconstructed image, the sheared structure remains qualitatively the same for fixed launch radii. The shape of the light curve depends most strongly on radial launch position of the spot. Interior spots exhibit high maximum intensities but fall to quiescent jet intensities within a couple of days. Exterior spots exhibit lower maximum intensities, but persist in the light curve for well over a week. Changing the azimuthal launch position of a spot can alter the maximum intensity by well over an order of magnitude due to differences in beaming around the jet. Even so the decay in intensity due to expansion, shearing, and beaming remains the same for any spot with the same radial launch coordinate.

Wind-driven jets should populate themselves with material far from the jet axis, which we model by launching spots outside the jet critical surface. Similarly, black hole driven jets should populate themselves close to the jet axis, which we model by launching spots inside the jet critical surface. Using both reconstructed images and well-resolved light curves, it is possible to distinguish between black-hole driven and wind driven relativistic jets.

These distinctions persist in the visibility data, which may be used to probe jet launching physics without using image reconstruction. In a future publication we explore how visibility data can also help distinguish between black hole driven and wind driven relativistic jets.

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