On the orientation of the crescent image of M87*

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ABSTRACT

The first image of the black hole (BH) M87* obtained by the Event Horizon Telescope (EHT) has the shape of a crescent extending from the E to SWW position angles, while the observed direction of the large-scale jet is NWW. Images based on numerical simulations of BH accretion flows suggest that on average the projected BH spin axis should be oriented SSE - SSW. Alternatively, if the spin axis is matched with the jet direction, emission from the SEE sector of the photon ring would be difficult to account for. We explore highly simplified toy models for geometric distribution and kinematics of emitting regions in the Kerr metric, and perform ray tracing to calculate the corresponding images. We strictly assume that (1) the BH spin vector is fixed to the jet axis, (2) the emitting regions are stationary and symmetric with respect to the BH spin, (3) the emissivities are isotropic in the local rest frames. Emission from the crescent sector SSE - SSW can be readily explained in terms of an equatorial ring with either circular or plunging geodesic flows, regardless of the value of BH spin. In the case of plane-symmetric polar caps with plunging geodesic flows, the dominant image of the cap located behind the BH is sensitive to the angular momentum of the emitter. Within the constraints of our model, we have not found a viable explanation for the observed brightness of the SEE sector. The SEE ‘hotspot’ might have been produced by a non-stationary localised perturbation in the inner accretion flow. Alternatively, it could result from locally anisotropic synchrotron emissivities. Polarimetric and multi-epoch results from the EHT will be essential to verify the theoretically expected alignment of the BH spin with the large-scale jet.

Key words: Black hole physics — Galaxies: active — Galaxies: individual: M87 — Gravitation — Relativistic processes

1. Introduction

The EHT Collaboration presented the first resolved image of a photon ring surrounding the supermassive BH dubbed M87* (EHT Collaboration 2019a). The image obtained at the wavelength of $\lambda = 1.3$ mm and the angular resolution of $\sim 20$ $\mu$as can be best described as an asymmetric crescent of diameter $\sim 42$ $\mu$as with brightness enhanced on the southern side (EHT Collaboration 2019f), more precisely for position angles in the range PA $\in [70^\circ : 270^\circ]$ (NEE - W) (EHT Collaboration 2019d, Fig. 27). On the other hand, interferometric observations at longer wavelengths reveal a well-known relativistic jet: at $3.5$ mm wavelength the jet collimation and acceleration zone can be probed up to $\sim 1$ mas (Hada et al. 2016; Kim et al. 2018); at $7$ mm wavelength mildly superluminal motions can be traced up to $\sim 6$ mas (Mertens et al. 2016; Walker et al. 2018). The jet is directed at the mean position angle of PA$_{\text{jet}} \approx 288^\circ$ (NWW), and this projected direction has been stable over decades of observations.

The EHT image of M87* has been compared with ray-traced images obtained from an extensive library of general relativistic magnetohydrodynamical (GRMHD) simulations of geometrically thick accretion onto BHs of various spins (EHT Collaboration 2019e). The enhanced brightness on the southern side of the ring has been interpreted as resulting from Doppler beaming of mildly relativistic plasma flow that is approaching the observer. A sense of rotation for the BH (rather than for the large-scale accretion flow) can be deduced from this as counter-clockwise (CCW; corresponding to the observer inclination angle with respect to the BH spin $i > 90^\circ$). However, the projected orientations of the BH spin vectors — obtained by rotating the simulated images to minimise the difference from the observed image — were found to span a range of PA$_{\text{BH}} \approx 150^\circ : 280^\circ$, with the mean value of $\approx 205^\circ$ and standard deviation of $\approx 55^\circ$ (SSE - W; top panels of Fig. 9 in EHT Collaboration 2019e). The mean offset from PA$_{\text{jet}}$ is $\approx 80^\circ$ clockwise (CW), which is equivalent to $\sim 1.5\sigma$. The predictions of GRMHD simulations specifically tailored to the case of M87 are that the major axis of the bright part of the ring should be oriented parallel to the projected jet axis (Dexter et al. 2012; Mościbrodzka et al. 2016; Davelaar et al. 2019).

There are strong arguments to support the assumption that relativistic jets should be directed along the BH spin axis — the leading scenario for launching jets is the Blandford-Znajek mechanism (Blandford & Znajek 1977), numerical simulations demonstrated the robustness of jet alignment even for flipping BH spins (McKinney et al. 2013), and there is no evidence for jet precession in the particular case of M87 (see Section 7.3.(2) in EHT Collaboration 2019e).

In the GRMHD simulations of accretion-jet systems (EHT Collaboration 2019e), the synchrotron emission is produced mainly in the accreting torus or in the outer jet funnel, but not in the polar jet regions. Emission from the polar regions requires additional physical mechanisms of energy dissipation beyond the regime of ideal magnetohydrodynamics (MHD). In particular, these regions could be related to particle-starved gaps in the BH magnetospheres suggested as the sites of very-high-energy gamma
ray emission (e.g., Levinson & Rieger 2011, Broderick & Tchekhovskoy 2015, Katsoulakos & Rieger 2018) that has actually been observed in M87 and found to be variable on the time scale of days (e.g., Aharanian et al. 2006; Abramowski et al. 2012). The polar regions could also be related to the lamppost model for the origin of hard X-ray emission in AGNs and X-ray binaries (e.g., Martocchia, & Matt 1996; Miniutti, & Fabian 2004). The first kinetic simulations of BH magnetospheres with pair creation demonstrate the formation of charge gaps at intermediate latitudes for low enough rate of particle supply (Parfrey et al. 2019). For these reasons, we find it particularly important to include in our study a simplified case of polar caps. In this letter, we consider highly simplified (stationary, axisymmetric) toy models for the distribution of emitting regions around the BH M87*, and we ray-trace the corresponding images in the Kerr metric in the limit of optically thin emission with uniform fluid-frame emissivity. We find that our model can naturally explain a section of the crescent image that extends between SSE and SWW position angles, however, it cannot explain emission observed in the SEE sector.

2. Methods

We perform ray tracing of scalar radiation in the Kerr metric for BH mass $M$ and spin $a$ $(G = 1 = c)$, using the Boyer-Lindquist coordinates $x^\mu = (t, r, \theta, \phi)$, employing a newly developed numerical code. We integrate the null geodesics $x^\mu (\lambda)$ over the affine parameter $d\lambda = dt/p^t$, with the 4-momentum $p^\mu = dx^\mu/d\lambda$, starting from a stationary observer of position $x^\mu_\text{obs} = (t_\text{obs}, r_\text{obs} = 100M, \theta_\text{obs} = 0^\circ, \phi_\text{obs} = 0)$ and 4-velocity $u^\mu_\text{obs} = u^t_\text{obs}(1, 0, 0, 0)$. We perform first-order explicit integration backward in time, with an adaptive time step $dt \propto r$. The integration involves 4 constants: asymptotic energy $E$, asymptotic angular momentum $L$, Carter constant $Q$, and square of the 4-momentum $p_\mu p^\mu = 0$ (e.g., Bardeen et al. 1972; Sikora 1979). Integration is interrupted either when the photon falls onto the BH $(p^t \geq 10^5)$ or when the photon escapes $(r > r_{\text{obs}})$.

The emitting regions are assumed to be optically thin with uniform isotropic emissivities with power-law spectrum $J_\nu (\nu \text{cm}) \propto \nu^{-\alpha}$ of spectral index $\alpha$ in their local rest frames. We adopt a spectral index $\alpha = 0.5$, and we checked that varying $\alpha$ has little effect on the resulting image. The emission mechanism is not specified, and no absorption of radiation is considered. The emitters are allowed to be in motion relative to the local stationary observers with radial velocities $\beta_r = dr/dt$ and angular velocities $\Omega_r = d\phi/dt$, hence their 4-velocities are $u^\mu_\text{em} = u^t_\text{em}(1, \beta_r, 0, 0)$. From the covariant radiative transfer equation $dI_\nu/\nu^2 = j_\nu/\nu^2$ (e.g., Mościbrodzka & Gammie 2018), for every geodesic $\mathcal{G}$ that intersects an emitting region $S$, the observed intensity is integrated as being proportional to $I_{\nu, \text{obs}} \propto \int_{\mathcal{G} \cap S} d\lambda g^{2+\alpha}$, where $g = |p_\mu(x_\text{obs})u^\mu_\text{obs}/[p_\mu(x_\text{em})u^\mu_\text{em}]|$ is the factor that combines gravitational redshift with the Doppler boost due to the motion of the emitter. The obtained images are scaled in the units of $\theta_g = \arcsin(M/r_{\text{obs}})$, Gaussian-smoothed (using the scipy.ndimage.gaussian_filter tool) with the angular resolution of $5.38\theta_g \approx 20\mu as$, and normalised to the peak flux density of the EHT image. The centring of the EHT image relative to the simulated images is approximate.

We consider very simple geometries for stationary emitting regions that are axisymmetric with respect to the BH spin axis and plane-symmetric with respect to the BH equatorial plane. As such, they can be defined by the location of their boundaries in the coordinates $r, \theta$. In particular, we consider regions defined by $r \leq r_{\text{max}}$ and $0 \leq \theta_\text{min} \leq \theta \leq \theta_{\text{max}}$ or $\pi/2$, and for plane symmetry we also include the mirror regions that satisfy $\theta_\text{min} \leq (\pi - \theta) \leq \theta_{\text{max}}$. In our calculations we adopt an outer radius $r_{\text{max}} = 6R_g$, since lower values of $r_{\text{max}}$ result in images that are too compact.

3. Results

Fig. 1 shows our rendering of the EHT image of M87* for 2017 April 11, adapted from Fig. 3 in EHT Collaboration (2019a), that we use for reference. The peak flux density in terms of brightness temperature is $5.7 \times 10^9 K$.

We first study the effect of location of the emitting regions in the $\theta$ space, considering the following four cases: (TH1) $\theta_\text{min} = 0$ and $\theta_{\text{max}} = 30^\circ$ (polar caps); (TH2) $\theta_\text{min} = 30^\circ$ and $\theta_{\text{max}} = 45^\circ$; (TH3) $\theta_\text{min} = 45^\circ$ and $\theta_{\text{max}} = 75^\circ$; (TH4) $\theta_\text{min} = 75^\circ$ and $\theta_{\text{max}} = 90^\circ$ (equatorial ring). The results are shown in Fig. 2 for two extreme values of BH spin: $a = 0$ and $a = 0.9$. We note that there is only a mild effect of BH spin on the images produced with $r_{\text{max}} = 6M$.

In the case of polar caps (TH1), the image is dominated by a single compact hot spot slightly offset from the image centre along the jet direction, coinciding with the middle...
Fig. 2. A series of simulated images for source regions limited to the radial coordinate values $r \leq r_{\text{max}} = 6M$ and to different values of the polar coordinate (models TH1-4, from left to right) for two values of BH spin. In these cases, the local emitter is assumed to be stationary ($\beta_r = 0 = \Omega$), and the spectral index is $\alpha = 0.5$. The simulated images are shown with colour shading and grey contours, while the EHT image of M87* is shown with solid white contours. The contour levels correspond to brightness temperature values of $(2.5, 3.5, 4.5, 5.5) \times 10^9 \text{K}$, both for the simulated images and for the EHT image. The dashed white circle indicates a photon ring of radius $21 \mu\text{as} \approx 5.5\theta_g$ (best-fit estimate by EHT). The dashed white line indicates the position angle $\text{PA}_{\text{jet}} = 288^\circ$ of the large-scale jet.

Fig. 3. The case of polar caps (TH1) for $a = 0.5$, showing the effect of Doppler beaming due to radial infall of the emitting fluid with fixed radial velocity $\beta_r$. See Fig. 2 for more description.

Fig. 4. The case of polar caps (TH1) for $a = 0.5$ with fixed values of conserved energy $E$ and angular momentum $L$. See Fig. 2 for more description.
of the shadow observed by the EHT. This is an image of the front polar cap, while the image of the back polar cap is smeared roughly uniformly along the photon ring. In the case TH2, the image of the front cap becomes extended, but remains centrally peaked. In the case TH3, the image morphology turns into a ring of radius $\sim 4R_g$ without a deep shadow on top of a roughly uniform image of the back ring spanning the entire photon ring. Finally, in the case of equatorial ring (TH4), the size of the simulated image becomes consistent with the size of the EHT image, but the brightness distribution along the ring is fairly uniform.

The effect of BH spin is that for $a = 0$ the brightest sector of the ring is that opposite to the jet direction, while for $a = 0.9$ it is rotated towards the southern side (CW in the case of TH2 and CCW in the case of TH3). Without additional Doppler beaming, there is too much emission from the northern part of the ring.

We now consider the effect of Doppler beaming due to the motion of the emitting plasma. First, in the case of polar caps (TH1), we study the effect of radial infall with fixed coordinate velocity $\beta_r$. Fig. 3 shows that the image of the front cap is strongly suppressed for the radial velocity of $\beta_r \geq 0.4$, and we see the image of the back cap magnified into a ring that is slightly brighter on the southern side. This illustrates the basic fact that kinematics of emitting fluid, which involves mildly relativistic motions, has a very strong effect on the appearance of BH environments.

However, the case of fixed radial velocity, including that of static emitter fluid, is physically unrealistic. Hence, as the next level of approximation, we consider plunging ($\beta_r < 0$) timelike geodesic flows that conserve energy $E$ and angular momentum $L$. We neglect the poloidal 4-velocity components $u^\theta = 0$. Since the 4-velocity components $u^t$ and $u^\phi$ can be calculated explicitly from $E$ and $L$, we can then calculate the radial component $u^r$ from $u^t = -1$. We consider the fluid to be constricted to regions where $(u^r)^2 \geq 0$.

Fig. 4 presents the case of polar caps (TH1) for the BH spin value of $a = 0.5$ and fixed asymptotic energy $E = 1$, showing the effect of moderate angular momentum $0 \leq L \leq 0.6$. The case of $L = 0$ is very similar to the case of $\beta_r = -0.4$ — it is a fairly uniform ring with maximum brightness in the SE sector. Introducing non-zero $L$ has a very strong effect for decreasing the brightness along the northern side of the ring, turning it into a crescent already for $L = 0.2$, although the N-S contrast is still too low, and the second-brightest contour of the crescent is rotated CCW with respect to the observed image. Higher values of $L$ make the image too compact, centred in the S sector.

In the case of equatorial rings (TH4), we consider either the plunging geodesic flows with conserved $E$ and $L$, or quasi-Keplerian circular motions with $\beta_r = 0$ and angular velocity $\Omega = \Omega_{\text{circ}}$, with the rings limited from the inside by the ISCO (innermost stable circular orbit; Bardeen et al. 1972) and from the outside by $r_{\text{max}} = 6M$ (we only consider prograde disks for $a > 0$, for which $R_{\text{ISCO}} < 6M$).

Fig. 5 compares the images calculated in these two scenarios for two values of BH spin $a = 0.5, 0.9$. It is notable that these images are very similar to each other, with most of the emission concentrated along the southern side of the photon ring. Our models for plunging flows with fixed $E$ and $L$ provide very natural match with the observed emission in the SSE-SWW sector. On the other hand, emission from the SEE sector is very weak in all cases. It should be stressed that these results are not very sensitive to the choice of $E$ and $L$ values, since the images are very similar for $0.94 \leq E \leq 1.3$ and for $2 \leq L \leq 3.9$. Most of these values of $E$ and $L$ allow for flows plunging onto the BH horizon.

4. Discussion and conclusions

The EHT image of M87* BH could be interpreted either as a single crescent extending from the E to SWW sectors of the photon ring, or as a combination of a short crescent in the SSE-SWW sector and a compact SEE ‘hotspot’. The GRMHD simulations of geometrically thick accretion onto BHs tend to produce images of crescents that are roughly parallel to the projected jet axis (Dexter et al. 2012; Moscibrodzka et al. 2016; Dave et al. 2019). Hence, these simulations can explain emission from the SSE-SWW sector as naturally as our simplified toy models. This qualitative consistency of results suggests that the SEE emission might require a distinct origin.

In our models of polar caps (TH1), the image of the front polar cap is expected to coincide with the observed position of the BH shadow. In Fig. 3, we demonstrate that radial infall with velocity of $\beta_r \sim 0.4$ is able to suppress the image of the front cap, at the same time enhancing the extended image of the back cap. In turn, Fig. 4 shows that the image of the back cap is sensitive to the angular momentum of the plunging flow, with $L \approx 0.4$ it is possible to reproduce the required north-south contrast, however, emission from the SEE sector is insufficient to explain the EHT observations.

Our models of equatorial rings (TH4) with $r_{\text{max}} \approx 6R_g$ (Fig. 5) produce crescent images that typically extend from
SSR to W position angles, with only weak emission in the SEE sector, almost independently of the adopted kinematic model for the emitter fluid. We considered stable equatorial orbits limited from the inside by ISCO (prograde orbits for $a > 0$) and plunging flows with conserved energy and angular momentum, and in no case were we able to extend the crescent towards the SEE sector. The EHT image of M87* does not allow to significantly constrain the value of BH spin due to the fact that the radius of the photon ring is not sensitive to the spin value (EHT Collaboration 2019d), and the photon ring departs substantially from circularity only for $a \geq 0.95$ (Bambi et al. 2019). Stronger constraints can be put from the requirement for production of sufficiently powerful jets, which essentially eliminates the values $|a| < 0.4$ (Nokhrina et al. 2019; Nemmen 2019). We find that considering extreme spin values of $a = 0$ and $a = 0.9$ does not qualitatively affect the obtained images for $r_{\text{max}} = 6R_g$. This effect would be much greater for smaller values of $r_{\text{max}}$ (e.g., 3), which would however result in significantly smaller images (for the same value of BH mass). On the other hand, Dokuchaev, & Nazarova (2019) argued that the relative orientation of the BH shadow and the brightness centre of the crescent constraints the spin value to $a \approx 0.75 \pm 0.15$. That result was obtained by ray tracing emission from plunging geodesic flows with conserved $E$ and $L$ in an optically thin equatorial disk limited to within the ISCO radius. That study suggests that the SEE ‘hotspot’ coincides with the brightest point of the accretion flow, oriented roughly perpendicularly to the BH spin, which is however not consistent with the direction of the large-scale jet. Our models were calculated under strict assumptions of azimuthal and planar symmetry of the emitting regions. The easiest way to obtain a crescent image of correct orientation is to relax the assumption of azimuthal symmetry, adding an $m = 1$ mode to the local emissivity. However, from such relaxed models we cannot draw any meaningful constraints on the geometry and velocity fields of the underlying plasma flows. In particular, emission in the SEE sector could be explained by a localised and temporary perturbation in the accretion flow. One possibility for such perturbations are filaments resulting from the interchange instability operating in the magnetically arrested disks (MAD) (McKinney et al. 2012). Any such temporary effects should not persist in the subsequent EHT observations. Short-term variations of the EHT images of M87* are at the level of $\lesssim 15\%$ over the time range of 6 days, equivalent to $16R_g/c$ (EHT Collaboration 2019d, Fig. 33).

It has been suggested that synchrotron self-absorption may have a significant effect on the image of M87* at the 1.3 mm wavelength if observed eventually in a higher flux state (Kawashima et al. 2019). A potentially more important factor could be anisotropic rest-frame emissivity due to the synchrotron process operating in ordered magnetic fields. While GRMHD simulations are likely to produce realistic distributions of magnetic fields, they typically treat the emitting particles as locally isotropic. On the other hand, it has been argued in the context of relativistic AGN jets that the momenta of energetic electrons could be strongly concentrated along the local magnetic field lines (e.g., Sobacchi & Lyubarsky 2019). Global kinetic numerical simulations or improved subgrid MHD models may be required to incorporate such effects.

The origin of emission observed by the EHT in the SEE sector of the photon ring in M87* cannot be explained using strictly stationary and axisymmetric models – whether equatorial rings or polar caps – that assume the theoretically expected alignment of the BH spin with the large-scale jet. A solution to this problem may be enabled by the highly anticipated polarimetric results from the EHT.

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