

# Observational Signatures of Traversable Wormholes\*

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**Abstract:** In this paper, we study the observational signatures of traversable Simpson-Visser wormholes illuminated by luminous celestial spheres and orbiting hot spots. We demonstrate that when light sources and observers are on the same side of the wormholes, the images of the wormholes mimic those of black holes. However, when the light sources are positioned on the opposite side from observers, photons traversing the wormhole throat generate distinct observational signatures. Specifically, unlike black hole images, the wormhole images are confined within the critical curve, resulting in smaller centroid variations. Furthermore, the light curve of hot spots can exhibit additional peaks.

**Keywords:** gravitational lensing, wormhole, astrometry

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## I. INTRODUCTION

The groundbreaking images of the supermassive black holes candidates M87\* and Sgr A\*, captured by the Event Horizon Telescope (EHT) collaboration, have opened new avenues for understanding the nature in the strong field regime [1–14]. These images reveal a characteristic feature: a dark interior region surrounded by a bright ring, which is in good agreement with theoretical predictions for Kerr black holes. This feature emerges from the strong gravitational lensing of light near light rings (or photon spheres in spherically symmetric black holes) [15–22]. As a result, black hole images encode valuable information of the black hole geometry and have spurred extensive research [23–43].

However, the finite resolution of the EHT observations allows alternative explanations beyond black holes. Certain horizonless Ultra-Compact Objects (UCOs) can exhibit light rings (or photon spheres) similar to black holes, mimicking their behavior in observational simulations [44–47]. Therefore, distinguishing these UCOs from black holes is a crucial topic. For example, various studies have proposed echo signals in late-time waveforms as a potential discriminant, arising from the presence of a reflective surface or an extra photon sphere in specific UCO models [48–58]. Moreover, the general relativistic Poynting-Robertson effect and epicyclic fre-

quencies can be employed as tools to investigate the potential existence of wormholes [59, 60]. Additionally, asymmetric thin-shell wormholes with two photon spheres have been found to exhibit double shadows and an extra photon ring in their images [61–65]. However, the existence of multiple photon spheres outside the event horizon has also been reported for a class of hairy black holes within certain parameter spaces [66–70]. These multiple photon spheres in black holes can introduce features similar to those observed in wormholes, including echo signals [71], double shadows [70] and extra photon rings [72, 73]. These findings highlight the ongoing challenge of differentiating between wormholes and black holes, necessitating the development of further discriminatory methods for UCOs and black holes.

Recent observations of flaring activity near black holes, particularly the recurrent detections close to Sgr A\* [74–76], have garnered significant attention. While the underlying mechanism remains unclear, it is generally believed to be attributed to magnetic reconnection within magnetized accretion disks [77–79]. Nevertheless, orbital hot spots have been employed to understand the observational signatures of these flares [80–83]. Research on the observational signatures of hot spots has been extended to hairy black holes [84] and various UCOs [85–87] to differentiate between black holes and UCOs.

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This paper investigates a static, spherically symmetric regular spacetime proposed by Simpson and Visser [88]. This spacetime interpolates between black holes, black-bounces and wormholes through a parameter denoted by  $a$ . Previous studies have shown that for  $0 < a < 3M$ , the regular spacetime exhibits the same shadow as a Schwarzschild black hole with identical mass and distance [89–91]. Notably, based on observations of the M87 galaxy's center by the EHT, the parameter is estimated to be  $a \approx 4.2M$  [92]. Simultaneously, a rotating generalization of the Simpson-Visser metric within a specific region of the parameter space can effectively model the observed size and deviation from circularity of M87's shadow [93]. These imply that the wormhole can closely mimic the observational behavior of black holes. However, prior research has solely considered scenarios where the light source and observer reside on the same side of the wormhole. It is both natural and necessary to investigate scenarios where the light source and the observer are located on different sides of the wormhole. Intuitively, such a scenario would yield significantly different observational results, potentially aiding in the distinction between wormholes and black holes.

Our work focuses on the optical appearances of traversable Simpson-Visser wormholes illuminated by luminous celestial spheres and the hot spots. In Section II, we review the Simpson-Visser spacetime and discuss circular orbits for both massless and massive particles. Sections III and IV present our numerical simulations for the celestial sphere and the hot spot, respectively. Finally, we summarize our key findings in Section V. Throughout the paper, we adopt the convention  $G = c = 1$ .

## II. SET UP

The Simpson-Visser spacetime can be described by the line element presented in [88],

$$ds^2 = -f(r)dt^2 + \frac{1}{f(r)}dr^2 + (r^2 + a^2)(d\theta^2 + \sin^2\theta d\phi^2),$$

$$f(r) = 1 - \frac{2M}{\sqrt{r^2 + a^2}}, \quad (1)$$

where  $M$  is the ADM mass, and  $a$  is a parameter to regularize the spacetime. The spacetime can transition from a Schwarzschild black hole to a traversable wormhole by increasing  $a$  from 0. Specifically, the cases with  $a = 0$  and  $a > 2M$  correspond to a Schwarzschild black hole and a traversable wormhole, respectively. Additionally, intermediate states exist, including a black-bounce for  $0 < a < 2M$  and a one-way wormhole for  $a = 2M$ . In this paper, we focus on traversable wormholes with  $a > 2M$ . Note that traversable wormholes possess two distinct spacetimes, described by  $r > 0$  and  $r < 0$ , respectively. These two spacetimes are connected at the throat, located

at  $r = 0$ .

The motion of test particles in the spacetime is governed by the geodesic equations,

$$\frac{dx^\mu}{d\lambda} = p^\mu, \quad \frac{dp^\mu}{d\lambda} = -\Gamma_{\rho\sigma}^\mu p^\rho p^\sigma, \quad (2)$$

where  $\lambda$  is an affine parameter, and  $\Gamma_{\rho\sigma}^\mu$  is the Christoffel symbol. Due to the spherically symmetric and static nature of the spacetime, three conserved quantities arise that characterize the geodesics,

$$E = -p_t, \quad L_z = p_\phi, \quad L^2 = p_\theta^2 + L_z^2 \csc^2\theta. \quad (3)$$

For a massless particle,  $E$ ,  $L_z$  and  $L$  represent the total energy, the angular momentum along the symmetry axis, and the total angular momentum, respectively. For a massive particle, these quantities describe the corresponding values per unit mass. Besides, the Hamiltonian constraint,  $\mathcal{H} = g_{\mu\nu} p^\mu p^\nu / 2 = \epsilon / 2$ , introduces a fourth constant. This constant takes the value  $\epsilon = 0$  and  $-1$  for massless and massive particles, respectively. In spherically symmetric spacetimes, the trajectories of test particles are uniquely characterized by the impact parameter  $b \equiv L/E$  and the constant  $\epsilon$ . According to the Hamiltonian constraint and eqns. (2) and (3), the radial geodesic equation can be expressed as

$$\left(\frac{dr}{d\lambda}\right)^2 + V_{\text{eff}}(r) = b^{-2}, \quad (4)$$

where the effective potential is defined as

$$V_{\text{eff}}(r) = \left(-\frac{\epsilon}{L^2} + \frac{1}{r^2 + a^2}\right) \left(1 - \frac{2M}{\sqrt{r^2 + a^2}}\right). \quad (5)$$

In the case of photons, we consider unstable circular orbits of radius  $r_{\text{ph}}$ , which correspond to the maximum of the effective potential,

$$V_{\text{eff}}(r_{\text{ph}}) = b_{\text{ph}}^{-2}, \quad V'_{\text{eff}}(r_{\text{ph}}) = 0, \quad V''_{\text{eff}}(r_{\text{ph}}) < 0. \quad (6)$$

These unstable circular orbits form a photon sphere at  $r_{\text{ph}}$ , which has a significant impact on observations. Depending on the value of  $a$ , the wormhole may possess either one or two photon spheres. Specifically, when  $a \geq 3M$ , the wormhole has a single photon sphere at  $r_{\text{ph}} = 0$ , and when  $2M < a < 3M$ , the wormhole has two photon spheres at  $r_{\text{ph}}^\pm = \pm \sqrt{9M^2 - a^2}$ . Moreover, when  $2M < a < 3M$ , the effective potential exhibits a minimum at the wormhole throat ( $r = 0$ ) due to the  $Z_2$ -symmetry of the wormhole. This potential minimum corresponds to an

“anti-photon sphere” [94], also referred to in some literature as a stable photon sphere. However, photons trapped within the potential well surrounding the anti-photon sphere cannot escape to reach distant observers, rendering it negligible in the optical appearance of wormholes. Therefore, this study focuses exclusively on photon spheres associated with potential maxima, which are critical for gravitational lensing and optical observations. To illustrate the effects of different numbers of photon spheres on observational phenomena, we will take the wormhole of  $a = 5M$  with a single photon sphere and the wormhole of  $a = 2.1M$  with two photon spheres as examples. The effective potentials for these two cases are shown in Fig. 1.

For massive particles, their stable circular orbits can exist within a certain region. The inner edge of this region corresponds to an innermost stable circular orbit (ISCO), satisfying the following conditions

$$V_{\text{eff}}(r_e) = b_e^{-2}, \quad V'_{\text{eff}}(r_e) = 0, \quad V''_{\text{eff}}(r_e) = 0. \quad (7)$$

When  $2M < a < 6M$ , the ISCOs are located at  $r_e^\pm = \pm \sqrt{36M^2 - a^2}$ . If we consider a hot spot orbiting the wormhole at the ISCO on the equatorial plane, its energy and angular momentum per unit mass are given by  $E_e = \sqrt{8/15}M$  and  $L_e = 6M/\sqrt{5}$ , respectively. Consequently, the corresponding angular velocity and period are  $\Omega_e = M^{-1}/6\sqrt{6}$  and  $T_e = 12\sqrt{6}\pi M$ , respectively.

To obtain the images of some light sources, we use the backward ray-tracing method to numerically compute light rays from observers to light sources. In the local frame of a static observer at  $(t_o, r_o, \theta_o, \phi_o)$ , the photon's

local 4-momentum  $p^{(\mu)}$  can be expressed by the initial 4-momentum  $p_o^\mu$ ,

$$\begin{aligned} p^{(t)} &= \frac{p_o^t}{f(r_o)}, & p^{(r)} &= f(r_o)p_o^r, & p^{(\theta)} &= \sqrt{r_o^2 + a^2}p_o^\theta, \\ p^{(\phi)} &= \sqrt{r_o^2 + a^2}|\sin\theta_o|p_o^\phi. \end{aligned} \quad (8)$$

Furthermore, considering the observation angles  $\alpha$  and  $\beta$  as defined in [95], the components of the local 4-momentum become

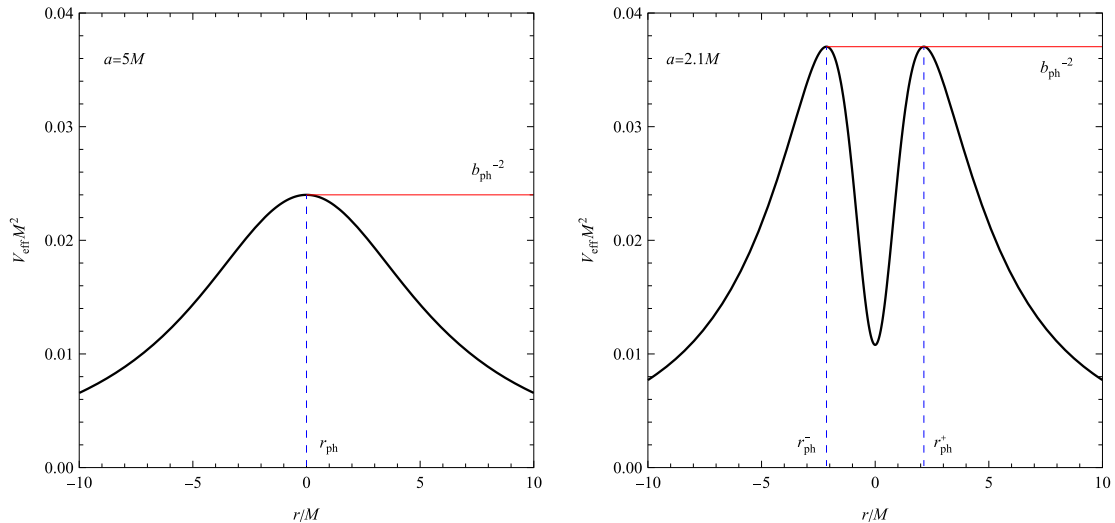
$$p^{(r)} = p^{(t)} \cos\alpha \cos\beta, \quad p^{(\theta)} = p^{(t)} \sin\alpha, \quad p^{(\phi)} = p^{(t)} \cos\alpha \sin\beta. \quad (9)$$

These relationships (8) and (9) connect the initial conditions for light rays to the observation angles. In the image plane, we define the Cartesian coordinates as

$$x \equiv -r_o\beta, \quad y \equiv r_o\alpha. \quad (10)$$

### III. CELESTIAL SPHERE

This section investigates observations of traversable wormholes illuminated by a celestial sphere. This model simulates the optical appearance of the universe as lensed by the wormholes. To illustrate the image of the celestial sphere, we position a luminous celestial sphere at  $r_{\text{cs}} = 50M$  or  $-50M$ , while a static observer is situated at  $r_o = 10M$ ,  $\theta_o = \pi/2$  and  $\phi_o = \pi$ . The celestial sphere is di-



**Fig. 1.** (color online) The effective potentials for photons. **Left Panel:** The traversable wormhole with  $a = 5M$  possesses a single photon sphere located at  $r = 0$ , corresponding to the critical impact parameter  $b_{\text{ph}} = 5\sqrt{5/3}M$ . **Right Panel:** The traversable wormhole with  $a = 2.1M$  possesses two photon spheres located at  $r_{\text{ph}}^+ = 3\sqrt{51}M/10$  and  $r_{\text{ph}}^- = -3\sqrt{51}M/10$ , corresponding to the same critical impact parameter  $b_{\text{ph}} = 3\sqrt{3}M$ .

vided into four quadrants (colored green, red, blue and yellow) corresponding to the upper left, upper right, lower left and lower right regions relative to the observer. Additionally, a grid of black lines is overlaid, representing lines of constant longitude and latitude, where adjacent lines are separated by  $\pi/18$ . For a more detailed discussion on the external view of the celestial sphere, refer to [96–98]. To generate a simulated image, we vary the observation angles and numerically integrate the trajectories of  $2000 \times 2000$  photons until they intersect with the celestial sphere or reach the cutoff radius at  $|r| = 50M$ .

We first investigate the scenario where the observer is situated on the same side as the celestial sphere (e.g.,  $r_{\text{cs}} = 50M$ ). The observed images are presented in Fig. 2. When the impact parameter is smaller than the critical impact parameter, light rays originating from the celestial sphere will inevitably pass through the throat into the other spacetime, making them undetectable to the observer. Consequently, the images exhibit a dark region confined by the critical curve, which resembles black hole images. Additionally, the left panel displays a larger dark region due to its larger critical impact parameter. Moreover, a series of compressed higher-order celestial sphere images exist outside the critical curve, asymptotically approaching it. Interestingly, wormholes with two photon spheres exhibit similar observational appearance to those with one, as the observed photons are solely influenced by the photon sphere at  $r = r_{\text{ph}}^+$ .

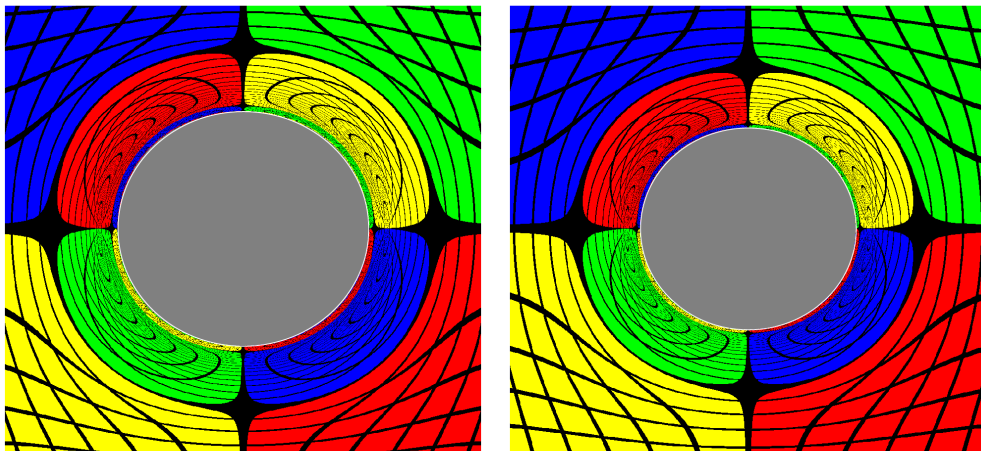
To investigate the optical appearance of the celestial sphere on the other side of the wormhole, we extend our analysis to scenarios where the celestial sphere is located at  $r_{\text{cs}} = -50M$ . The left and right panels of Fig. 3 display the corresponding image of wormholes with one and two photon spheres, respectively. Photons emitted from the celestial sphere in the other spacetime can traverse the throat and be observed, forming celestial sphere images

within the critical curve. Furthermore, the wormhole with two photon spheres exhibits a greater number of compressed higher-order celestial sphere images compared to the single-photon sphere case. This phenomenon occurs because, in the two-photon sphere wormhole, photons emitted from the celestial sphere traverses both photon spheres at  $r = r_{\text{ph}}^-$  and  $r = r_{\text{ph}}^+$  before reaching the observer. As the impact parameter approaches the critical value, the increased light deflection due to the double effect of the photon spheres results in more compressed higher-order celestial sphere images.

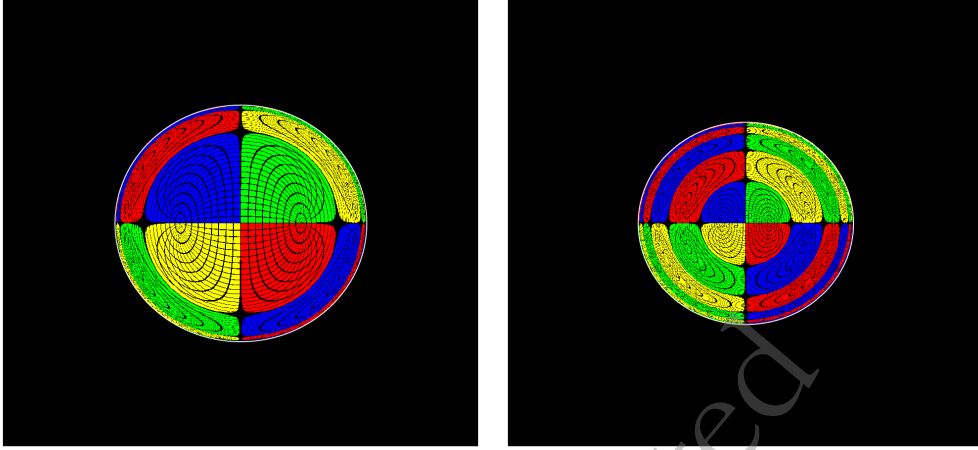
Our analysis reveals that the relative positioning between the celestial sphere and the observer has a significant influence on the observed image. When the celestial sphere is located on the same side as the observer, light rays are primarily affected by one photon sphere, resulting in an image similar to that of a Schwarzschild black hole. However, when the celestial sphere and the observer are on different sides, the observed images are within the critical curve. In this scenario, the presence of two photon spheres leads to more compressed higher-order celestial sphere images.

#### IV. HOT SPOT

This section explores observable signatures of hot spots orbiting around traversable wormholes. To simplify the analysis, we consider the hot spot as an isotropically emitting sphere with a radius of  $0.25M$ , following a counterclockwise path on the ISCO. As found in [99, 100], observers with large inclination angles perceive more significant Doppler effects during the hot spot motion, which can provide more information about spacetime properties. Therefore, the observers in this section are placed at  $(r_o, \varphi_o, \theta_o) = (100M, \pi, 80^\circ)$ . To achieve optimal precision and efficiency, we simulate the hot spot



**Fig. 2.** (color online) The images of wormholes illuminated by the celestial sphere on the same side as the observer. The left panel shows the wormhole with a single photon sphere ( $a = 5M$ ), while the right panel illustrates the case with two photon spheres ( $a = 2.1M$ ). The white curve denotes the critical curve, which is generated by light rays escaping the photon spheres.



**Fig. 3.** (color online) The images of wormholes illuminated by the celestial sphere on the opposite side from the observer. The left panel shows the wormhole with a single photon sphere ( $a = 5M$ ), while the right panel illustrates the case with two photon spheres ( $a = 2.1M$ ). Since photons emitted from the celestial sphere must traverse the throat before reaching the observer, the observed images are bounded by the critical curve. Compared to the single photon sphere case, the image of the double-photon sphere wormhole exhibits more compressed higher-order images. The critical curve, outlined in white, is traced by light rays escaping the photon spheres.

image using a  $1000 \times 1000$  pixel grid for each snapshot and generate 500 snapshots for a complete orbit. Light rays are traced backward from the observer to the hot spot at each time  $t_k$  to determine the intensity  $I_{klm}$  assigned to each pixel. To provide valuable insights into the characteristics and evolution of hot spot images within a single orbital period, our analysis focuses on the following image properties [86, 101–104]:

- **Time-integrated image:** This image captures the complete trajectory of the hot spot in one period by integrating the intensity over all snapshots. Mathematically, each pixel is assigned an integrated intensity,

$$\langle I \rangle_{lm} = \sum_k I_{klm}. \quad (11)$$

- **Light curve:** The light curve depicts the variation in the magnitude over time. The flux at each snapshot is calculated using the following formula,

$$F_k = \sum_l \sum_m \Delta\Omega I_{klm}. \quad (12)$$

The magnitude is then derived from the flux as follows,

$$m_k = -2.5 \lg[F_k / \min(F_k)]. \quad (13)$$

- **Centroid motion:** The centroid motion tracks the movement of the hot spot image. In each snapshot, the centroid is obtained by calculating the intensity-weighted

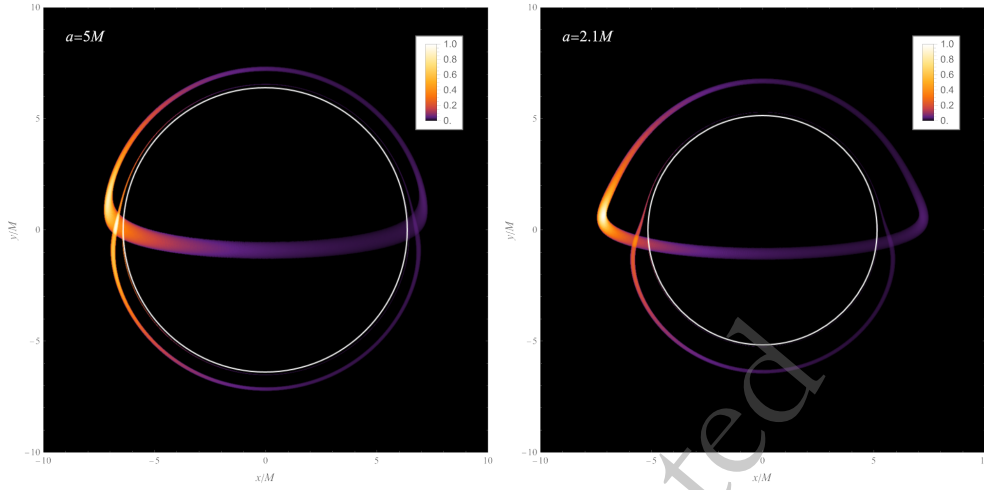
average position of all pixels, normalized by the total flux,

$$\vec{c}_k = F_k^{-1} \sum_l \sum_m \Delta\Omega I_{klm} \vec{r}_{lm}. \quad (14)$$

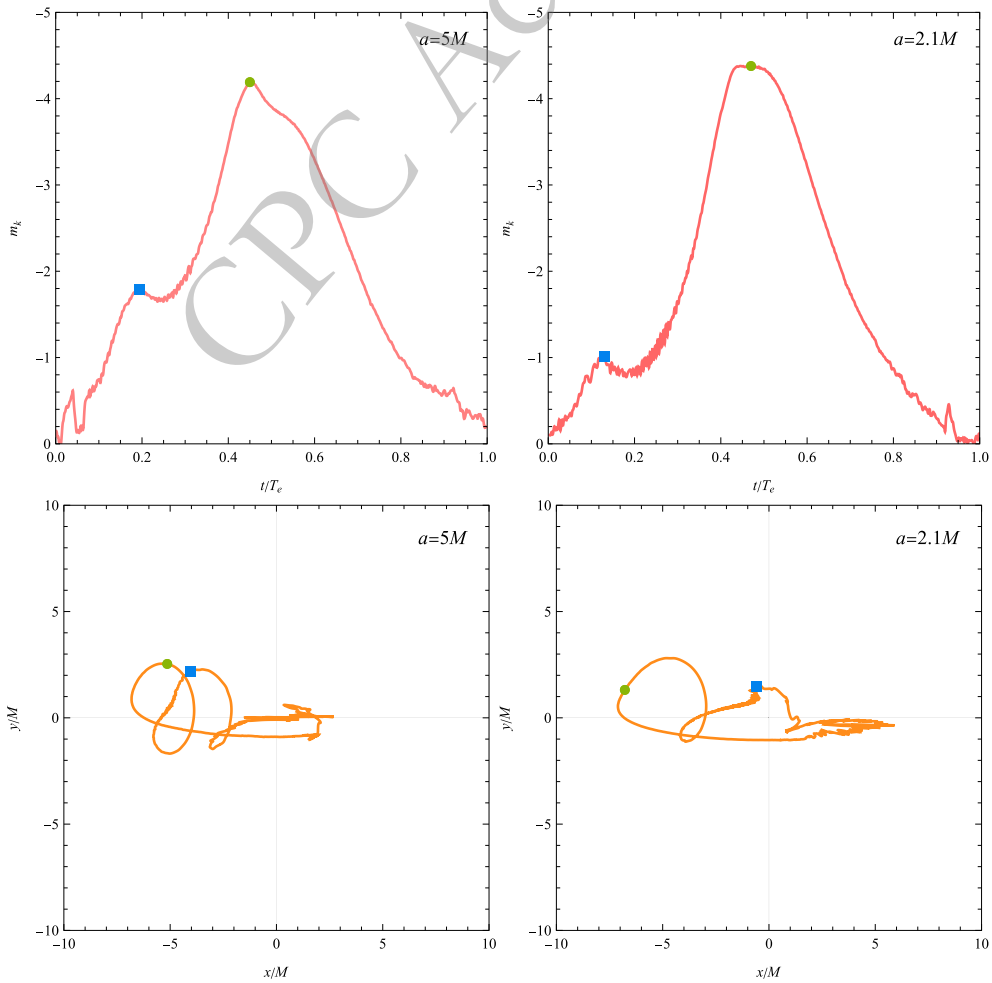
Here,  $\Delta\Omega$  is the solid angle per pixel, and  $\vec{r}_{lm}$  is the position of the pixel relative to the image center.

**Fig. 4** presents time-integrated images of the hot spot moving on the same side as the observer. Similar to observations in black holes [84, 86], both single-photon sphere and double-photon sphere wormholes exhibit two distinct image tracks. Additionally, the two image tracks in the left panel are closer to the critical curve, as the corresponding wormhole with a larger  $a$  has a larger critical curve. To decipher the origin of these tracks, we introduce a numerical count,  $n$ , representing the number of equatorial plane crossings a light ray undergoes during its trajectory. This numerical count characterizes light rays and the resulting image tracks. Consequently, the semicircular track corresponds to the primary image with  $n = 0$ , while the other one corresponds to the secondary image with  $n = 1$ . Furthermore, when the hot spot travels in front of the wormhole, its primary image forms the lower section of the semicircle track, and its secondary image forms the upper section closer to the critical curve. Conversely, if the hot spot moves behind the wormhole, the positions of the primary and secondary images are reversed.

The light curve and centroid motion of the hot spot images are depicted in the top and bottom rows of **Fig. 5**, respectively. As expected, both single-photon sphere and double-photon sphere wormholes exhibit light curve and centroid motion characteristics similar to those observed



**Fig. 4.** (color online) The time-integrated images of the hot spot orbiting wormholes on the same side as the observer. The observer is positioned at an inclination angle of  $\theta_o = 80^\circ$ . Pixel intensities are normalized to the maximum value for comparison. The white curve represents the critical curve, which is generated by light rays with the critical impact parameter. Both the images of the single-photon sphere (**Left Panel**) and double-photon sphere (**Right Panel**) wormholes show two distinct image tracks, closely resembling the Schwarzschild black hole case.



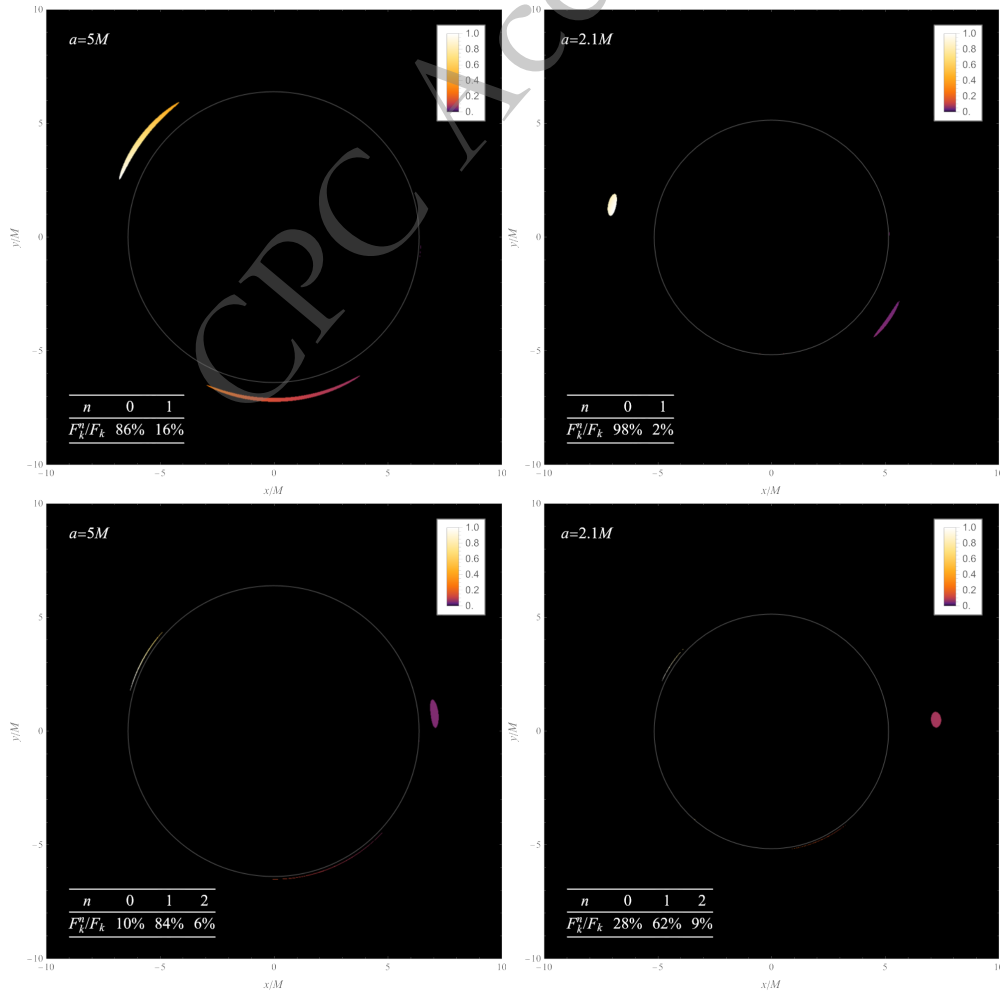
**Fig. 5.** (color online) The light curve (**Top Row**) and the centroid motion (**Bottom Row**) for the hot spot that moves on the same side as the observer. The left and right columns correspond to the wormholes with a single and double photon spheres, respectively. Green dots and blue squares denote the highest and second-highest peaks of the light curve, respectively.

in Schwarzschild black holes. Specifically, the light curve displays a prominent peak (denoted by green dots) and a secondary, fainter peak (denoted by blue squares). The Doppler effect displaces the centroid towards the left within the field of view, and the centroid motion appears irregular due to the presence of higher-order images. These findings suggest that, when hot spots and observers are on the same side, the appearance of traversable wormholes can mimic that of Schwarzschild black holes. Additionally, the snapshot of the highest and second-highest light curve peaks are presented in Fig. 6. These figures reveal that the primary ( $n=0$ ) and secondary ( $n=1$ ) images dominate the highest and second-highest peaks, respectively.

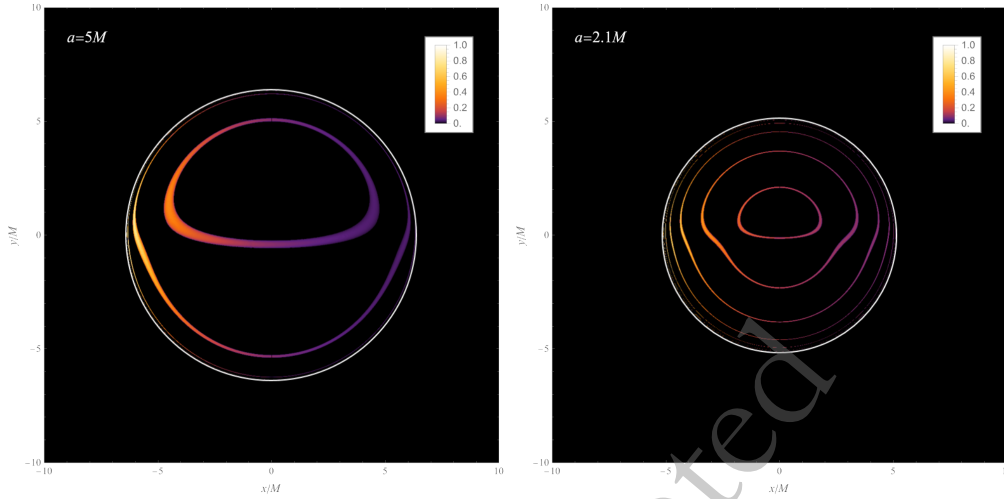
We now consider the scenario in which the hot spot is located on the opposite side of the observer. Specifically, the hot spot orbits the wormholes along the ISCO at  $r=r_e^-$ . Time-integrated images for this scenario are

presented in Fig. 7. Only photons with impact parameters less than the critical value,  $b < b_{\text{ph}}$ , can overcome the potential peak(s) and traverse the wormhole. Consequently, the images are confined within the critical curve. For the single-photon sphere wormhole, the hot spot image exhibits two distinct tracks. The inner and outer tracks correspond to the  $n=1$  and  $n=2$  images, respectively. Note that photons traversing the wormhole throat always cross the equatorial plane once, resulting in the absence of the  $n=0$  image. On the other hand, the double-photon sphere wormhole presents a markedly different observation image compared to the single-photon case. Since emitted photons need to traverse two photon spheres to reach the observer, stronger light deflections occur, which manifests as four distinct tracks in the integrated image. From the innermost outward, these tracks correspond to images with  $n=1, 2, 3$  and 4, respectively.

The corresponding light curve and centroid motion of



**Fig. 6.** (color online) Snapshots of the same-side hot spot for the single-photon sphere (Left Column) and double-photon sphere (Right Column) wormholes, captured at the light curve peaks. The upper and lower rows depict the snapshots corresponding to the highest and second-highest peaks, respectively. The relative contribution of the  $n^{\text{th}}$ -order image to the total flux  $F_k$  is given by  $F_k^n/F_k$ , where  $F_k^n$  denotes the flux of the  $n^{\text{th}}$ -order image at  $t=t_k$ .



**Fig. 7.** (color online) The time-integrated images of the hot spot orbiting wormholes on the side opposite to the observer. The critical curve is depicted as white curves. **Left Panel:** The image of the single-photon sphere wormhole exhibits two distinct image tracks within the critical curve. **Right Panel:** The image of the double-photon sphere wormhole shows four distinct image tracks within the critical curve. Traversing an additional photon sphere results in the emergence of two more image tracks.

the hot spot are presented in the top and bottom rows of Fig. 8, respectively. Similar to the same-side case, the single-photon sphere wormhole exhibits a light curve with a prominent peak and a secondary peak. Consistent with this, the snapshots in the left panel of Fig. 9 reveals that the highest and second-highest peaks are dominated by the  $n = 1$  and  $n = 2$  images, respectively. Furthermore, due to the confinement of the images within the critical curve, the centroid motion is restricted to a smaller range. Intriguingly, the hot spot orbiting the double-photon sphere wormhole displays three distinct peaks of comparable heights in the light curve, as shown in the upper-right panel of Fig. 8. The corresponding snapshots in the right panels of Fig. 9 reveal that the highest peak is dominated by a combination of  $n = 2$  and 3 images, the second-highest peak by  $n = 1$  and 2 images, and the third-highest peak by  $n = 3$  and 4 images. Consequently, the presence of more higher-order images leads to a more irregular centroid motion in this case.

These observations of the different-side hot spot offer potential avenues for distinguishing wormholes from black holes. Notably, wormholes exhibit a more restricted range of central motion compared to black holes. Additionally, the three-peaked light curve of the double-photon sphere wormhole provides a unique signature for differentiating it from the single-photon sphere counterpart.

## V. CONCLUSIONS

This paper investigates the images of traversable wormholes illuminated by celestial spheres and hot spots. Two spacetimes are connected at the wormhole throat, which allows light rays to travel from one side to the other

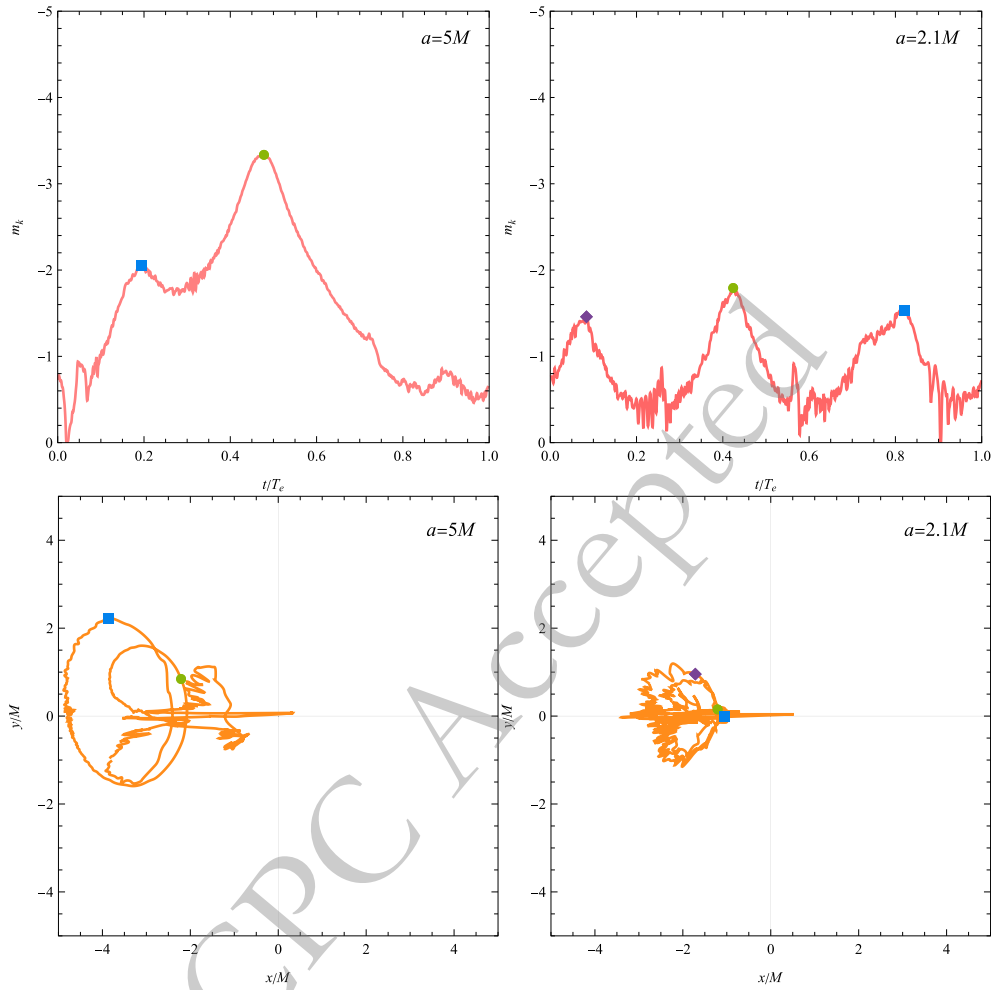
one. When the celestial sphere and hot spot reside on the same side as the observer, their images closely resemble those of a black hole. However, significant differences arise when the light sources are positioned on the different side from the observer. Specifically, we found that

- Same-side scenario: The celestial sphere forms images outside the critical curve, with a sequence of compressed celestial sphere images asymptotically approaching the critical curve. The hot spot exhibits two distinct image tracks with asymmetric brightness when observed at an inclination angle of  $\theta_o = 80^\circ$ . These two tracks lead to two peaks in the light curve.

- Different-side scenario: The celestial sphere always forms images within the critical curve, with compressed higher-order images asymptotically approaching the critical curve. The hot spot manifests as two distinct image tracks for the single-photon sphere case, while the double-photon sphere case exhibits four distinct image tracks. In the single-photon sphere case, the two tracks again lead to two peaks in the light curve. Conversely, the four tracks in the double-photon case result in three peaks in the light curve.

By analyzing these image characteristics, we can gain valuable insights into the optical signatures of light sources near wormholes. This understanding has the potential to not only differentiate between wormholes and black holes but also discriminate between single-photon sphere and double-photon sphere wormholes. While observing images from the other side of the wormhole presents an intriguing prospect, it also poses greater challenges. Therefore, higher resolution instruments, such as





**Fig. 8.** (color online) The light curve (**Top Row**) and the centroid motion (**Bottom Row**) for hot spots orbiting wormholes on the side opposite to the observer. The left and right columns correspond to the wormholes with a single and double photon spheres, respectively. The light curve in the single-photon sphere case exhibit two peaks, while three peaks of comparable heights appear in the double-photon sphere case.

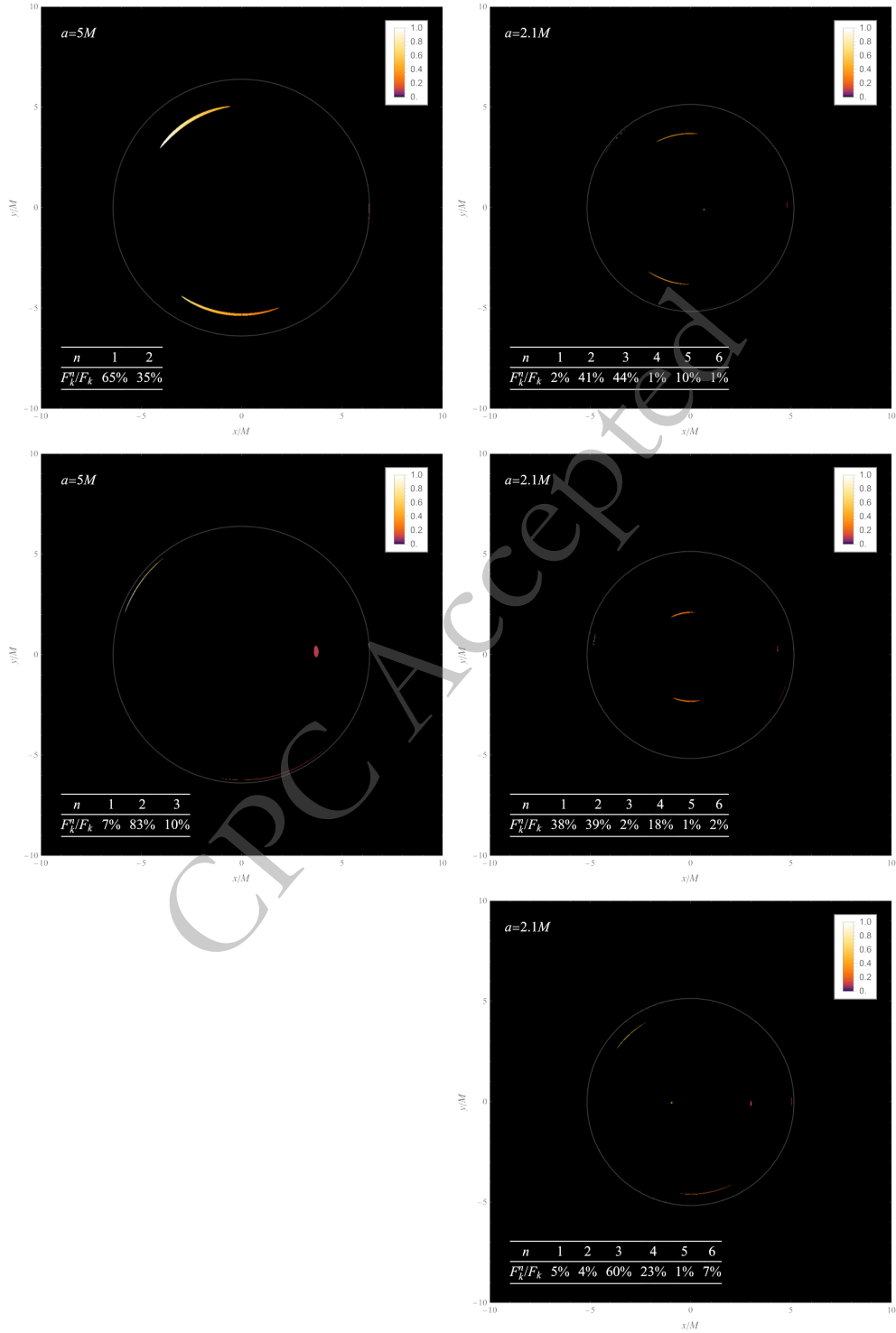
the next-generation Very Long Baseline Interferometry, are also keenly expected.

Finally, a crucial aspect of distinguishing wormhole signatures from those of other astrophysical objects, such as distant normal stars, merits further discussion. While both distant stars and wormholes illuminated by light sources on the opposite side of the observer can both produce images near their centers, stars are generally not compact enough to support photon spheres. As a result, light rays emitted by stars do not undergo strong gravitational lensing, leading to the absence of higher-order images. In contrast, the photon spheres of wormholes can lead to the formation of multiple, highly distorted images of the background light source, often appearing as rings or arcs surrounding the central image. Therefore, with

sufficiently high angular resolution, the detection of these higher-order images would serve as a distinct signature of a wormhole with a background light source. Although a single central image might be indistinguishable from that of a distant star, the presence of these additional, strongly lensed images offers a clear method for differentiating wormholes from normal stars. Future observational efforts with advanced telescopes capable of achieving the necessary resolution may reveal these characteristic signatures, potentially providing evidence for the existence of traversable wormholes.

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**Fig. 9.** Snapshots of the hot spot orbiting wormholes on the side opposite to the observer, for wormholes with a single (**Left Column**) and double (**Right Column**) photon spheres. The snapshots are captured at the highest (**Top Row**), second-highest (**Middle Row**) and third-highest (**Bottom Row**) magnitude peaks.

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