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Constraining spherically symmetric metrics by the gap between photon rings

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Gravitational lensing of luminous matter that surrounds a black hole or some other sufficiently compact object produces an infinite sequence of images. Besides the direct (or primary) image, it comprises demagnified and deformed replicas of the original known as photon rings which are progressively nearing the boundary of the socalled shadow.

We present analytical approximation formulas for higher-order photon rings for an asymptotically flat, static, spherically symmetric spacetime that admits a photon sphere. We consider an emission ring in the equatorial plane and an observer at arbitrary inclination far away from the center. Fixing the emission radius and leveraging the strong deflection limit, which provides an analytical logarithmic approximation for the deflection angle, we find the deformed shape of higher-order photon rings in the form of a polar equation on the observer's screen.

In particular, we use the relative separation between two neighboring photon rings, which we call "gap parameter", for characterizing the underlying spacetime. We obtain an analytical expression for the gap parameter of higher-order photon rings for metrics of the considered class that may depend on multiple parameters.

The advantage of using this quantity is in the fact that, to within the assumed approximations, it is independent of the mass of the central object (or of some other characteristic parameter if the mass is zero) and of the distance of the observer. Measurements of the gap parameter, which may become possible in the near future, will restrict the spacetime models that are in agreement with the observations. Even without knowledge of the emission radius, it will conclusively rule out some metrics. We exemplify our calculations of the gap parameter with the Schwarzschild, Reissner-Nordstrom, Janis-Newman-Winicour and Ellis wormhole metrics.

Primary authors: ARATORE, Fabio (Università degli studi di Salerno); Dr TSUPKO, Oleg (ZARM, Bremen University, Germany); PERLICK, Volker

Presenter: ARATORE, Fabio (Università degli studi di Salerno)

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