Polarimetry and strong gravity effects from spots orbiting near a black hole

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We study the modulation of the observed radiation flux and the associated changes in the polarization degree and angle that are predicted by the orbiting spot model for flares from accreting black holes. The geometric shape of the emission region influences the resulting model lightcurves, namely, the emission region of a spiral shape can be distinguished from a simpler geometry of a small orbiting spot. We further explore this scheme for the observed flares from the supermassive black hole in the context of Galactic center (Sgr A*). Our code simulates the lightcurves for a wide range of parameters. The energy dependence of the changing degree and angle of polarization should allow us to discriminate between the cases of a rotating and a non-rotating black hole.

Keywords: Gravitation; Black Holes; Galactic center

1. Introduction

Relativistic corrections to a signal from orbiting spots can lead to large rotation in the plane of observed X-ray polarization. When integrated over an extended surface of the source, this can diminish the observed degree of polarization. Such effects are potentially observable and can be used to distinguish among different models of the source geometry and the radiation mechanisms responsible for the origin of the polarized signal. The idea was originally proposed in the 1970s,[1–3] however, its observational confirmation and practical use in observations are still is a challenging task.

The geometrical effects of strong gravitational fields act on photons independently of their energy. The gravitational field is described by the metric of Kerr black hole[4]

$$ds^2 = -\frac{\Delta}{\Sigma}\Big(dt - a\sin^2\theta\, d\phi\Big)^2 + \frac{\Sigma}{\Delta}\, dr^2 + \Sigma\, d\theta^2 + \frac{\sin^2\theta}{\Sigma}\Big[a\, dt - \big(r^2+a^2\big)\, d\phi\Big]^2 \quad (1)$$

in Boyer-Lindquist (spheroidal) coordinates t, r, θ, ϕ. The metric functions $\Delta(r)$ and $\Sigma(r,\theta)$ are known in an explicit form. The event horizon occurs at the roots of equation $\Delta(r) = 0$; the outer solution is found given by $r = R_+ = 1 + (1-a^2)^{1/2}$.

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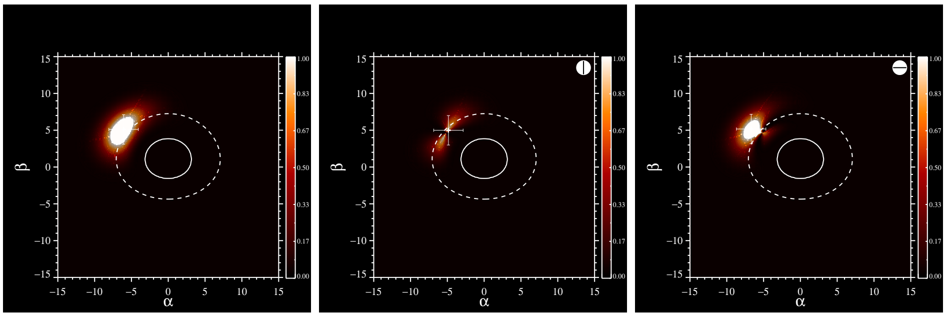

Fig. 1. An exemplary snapshot of a spot orbiting at constant radius just above the marginally stable orbit ($r = 1.1r_{\rm ISCO}$). Left panel: the total intensity image shows the observer plane (α, β) near a non-rotating black hole, as observed at a moderate view angle ($\theta_{\rm o} = 45$ deg). The horizon radius (solid curve) and the ISCO (dashed curve) are indicated. Middle and right panels: The spot emission is assumed to be intrinsically polarized and recorded in two polarization channels, rotated by 90 degrees with respect to each other.[6,7]

Let us note that there are some similarities as well as differences between the expected manifestation of relativistic effects in polarization changes in X-rays and in other spectral bands (NIR). We show these interrelations in the associated poster and point out that the near-infrared polarization measurements of the radiation flares from the immediate vicinity of the horizon have been studied in detail from the Galactic Center (Sagittarius A*) supermassive black hole.[5–7].

2. Polarization from an Orbiting Spot

Within the scheme of the spot scenario the spots are considered to represent regions of enhanced emission on the disc surface rather than massive clumps that would decay due to shearing motion in the disc. The observed signal is modulated by relativistic effects. Doppler and gravitational lensing influence the observed radiation flux and this can be computed by GR ray-tracing. Such an approach has been developed to compute also strong gravity effects acting on polarization properties.[8]

Our code (KY) is publicly available.[8] The current version[a] allows the user to include the polarimetric resolution and to compute the observational consequences of strong-gravity effects from a Kerr black hole accretion disc. Within the XSPEC notation, this polarimetric resolution is encoded by a switch defining which of the four Stokes parameters is returned in the photon count array at the moment of the output from the model evaluation. This way one can test and combine various models, and pass the resulting signal through the response matrices of different instruments. As an illustration, figure 1 shows a single time-frame from a simulation of a spot rotating rigidly at constant radius.

The detected polarization degree is expected to decrease mainly in the part of

[a] http://stronggravity.eu/results/models-and-data/

the orbit where the spot moves close to the region where the photons are emitted perpendicularly to the disc and the polarization angle changes rapidly. The drop of the observed polarization degree occurs also in those parts of the orbit where the magnetic field points approximately along light ray. For the more realistic models the resulting polarization exhibits a very complex behaviour. Among generic features is the peak in polarization degree for the spin parameter $a \to M$ and large inclinations, caused by the lensing effect at a particular position of the spot in the orbit. This effect disappears in the non-rotating $a = 0$ case.

3. Conclusions

We explored the approach based on mapping the Kerr black hole equatorial plane onto the observer's plane at radial infinity. Orbiting spots are projected onto the disc plane (hence imposing the vertically averaged approximation) and then their image is transported towards a distant observer. The strong gravity effects can be seen as the predicted (time-dependent) direction of polarization is changed by light propagation through the curved spacetime. What can be foreseen in the near future is the tracking of the wobbling image centroid that a spot produces. With the polarimetric resolution, this wobbling can provide the evidence of orbiting features. Rotating spots are a viable scenario capable to explain the occurrence about once per day of modulated flares from within a few milli-arcseconds of the Sagittarius A* supermassive black hole.[9,10]

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