Polarimetric features from spots orbiting near a black hole – II.

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Correlations between the modulation of the observed radiation flux and the changes in the polarization degree and angle are expected in the orbiting spot scenario for X-ray/NIR flares from accreting black holes. We update our model (based on the KY code) and we confirm that the geometric shape of the emission region plays a significant role in the amplitudes and profiles of the model light curves. The emission regions of spiral wave can be distinguished from a simpler geometry of an orbiting spot provided that the S/N is sufficiently good. We discuss the relevance of this model for the observed flares from the supermassive black hole in the Galactic center. Despite the fact that the hot spot scenario represents a phenomenological scheme to the flare origin, it is a useful test bed that helps to examine the role of model geometry. The KY code allows us to simulate the lightcurves for a wide range of parameters. The energy dependence of the changing degree and angle of polarization then allows, *in principle*, to discriminate between the cases of a rotating vs. non-rotating black hole.

Introduction

We have been developing further our code for time-dependent analysis of relativistic spectral features originating in black-hole accretion flows; see ref. [1], Paper I. Detailed tracking of time-dependent spectral features, including the polarization effects, is particularly pertinent for the modelling and interpretation of Sgr A* flares [2], Paper II. Practical implementation of the idea (originally proposed in the late 1970s for Cygnus X-1 accreting black hole) is a challenging task because the polarimetric investigations need a high signal-to-noise ratio. In this respect the Galactic Center seems to be currently the most promising target to reveal the strong-gravity effects acting on polarization; and near infrared spectral band seems to be appropriate domain from the view point of present-day technology.

We adopt the Kerr metric to describe the gravitational field and the geometrical optics to calculate propagation of light through it. Apart from energy shifts, the wave fronts of light propagating near a rotating black hole exhibit the frame dragging effect. On the other hand, the wave fronts do not depend on polarization. Therefore, the impact of strong gravity on observed polarization comes in a somewhat complicated manner, through the interplay of light-bending and beaming.

Polarization and strong gravity effects

We assume the geometry of a radiating and orbiting spot, in which a substantial degree of intrinsic polarization is expected as a result of the synchrotron mechanism or of Compton scattering. Relativistic effects are even more prominent (and unique) if the spot occurs close to the observer–black hole line. In that case one needs to include the higher-order, gravitationally bent light rays. The 'spot' represents a blob of gas or kind of phenomenological inhomogeneity in our terminology.

The model of an orbiting blob has been fairly successful in explaining the observed modulation of various types of accreting black hole sources. Not all variability patterns can be explained in this way, however, the scheme is general enough to be able to capture also the effects of spiral waves and similar kind of transient phenomena that are expected to occur in a magnetized accretion disc [3], Paper III. Our spot is supposed to be intrinsically polarized. It represents a rotating surface feature which shares the bulk Keplerian motion of the underlying medium at sufficiently large radii above the innermost stable orbit (ISCO), gradually decaying due to the differential rotation of the disc.

We have applied different prescriptions for the local polarization [4]. For example, one set of models assumes the local emission to be polarized either in the direction normal to the disc plane, or perpendicular to the toroidal magnetic field. In the case of partial local polarization the observed polarization signal will be diluted by an unpolarized fraction, and so the polarization degree of the final signal will be proportionally diminished. In another set of models we assumed a lamp-post illuminated spot as the source of spot polarization by reflection. For the spot shape we first assumed that the spot does not change its shape during its orbit, but then we also consider the spot decaying with time. The relativistic effects can be clearly identified and understood with these simple toy models, as they produce visible signatures in the observed lightcurves and in polarization properties.

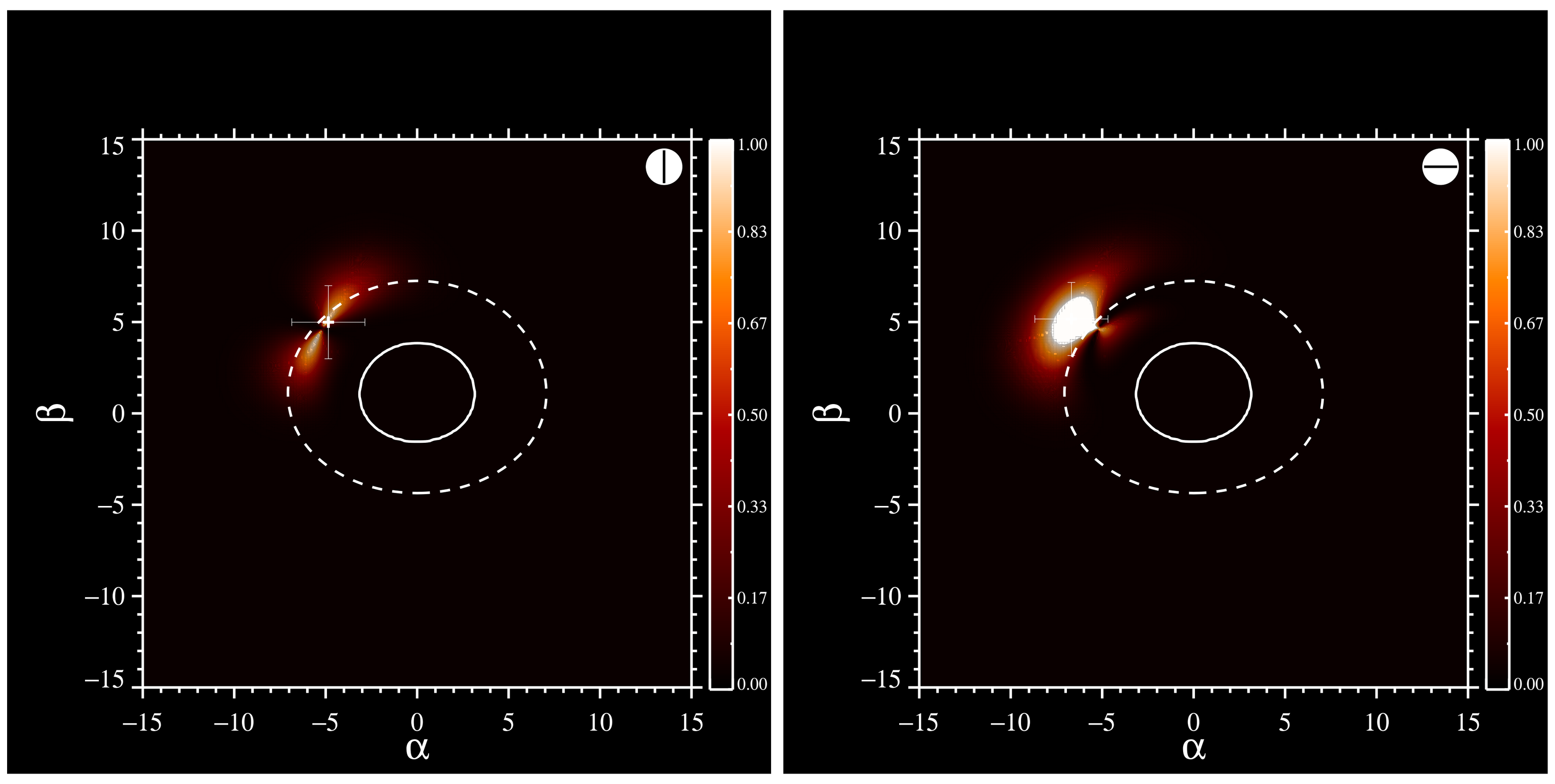

Fig. 1: A snapshot of a spot orbiting at constant radius $r = 1.1r_{\rm ISCO}$. The image is produced by the spot emission that is assumed to be intrinsically polarized and recorded in two polarization channels, rotated by 90 degrees with respect to each other [4]. The image is shown in the observer plane (α, β), for a non-rotating black hole observed at a moderate view angle, $\theta_o = 45$ deg. The horizon radius (solid curve) and the ISCO (dashed curve) are shown for the reference. Orientation of the polarziation filter is indicated in the top-right corner of the plot.

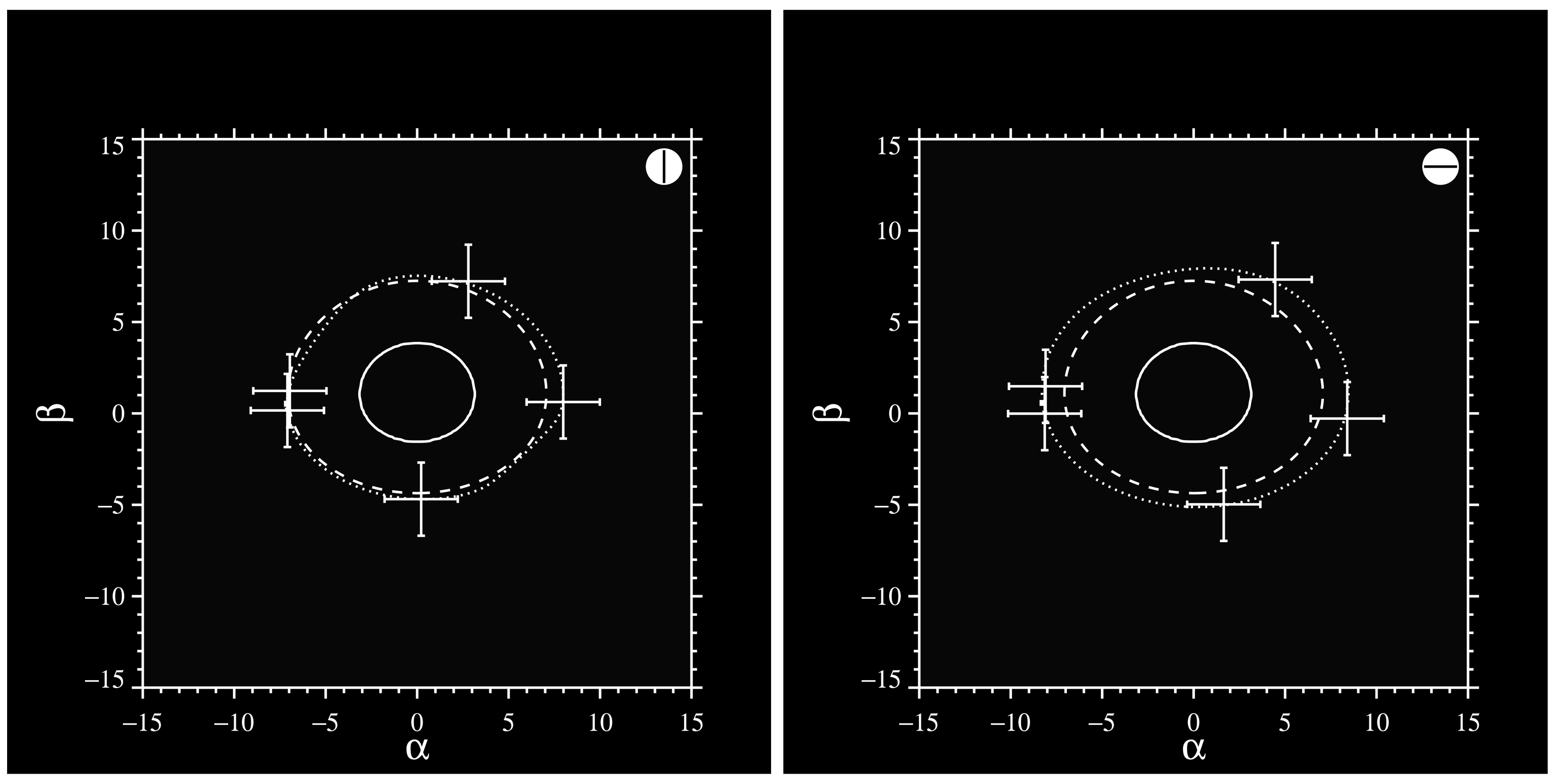

Fig. 2: Trajectory of the image centroid during one revolution of the spot corresponding to the previous figure. The centroid position was computed from the total observed flux distribution in the observer plane. The wobbling position of the image centroid is indicated by crosses at different moments along the image track (dotted curve).

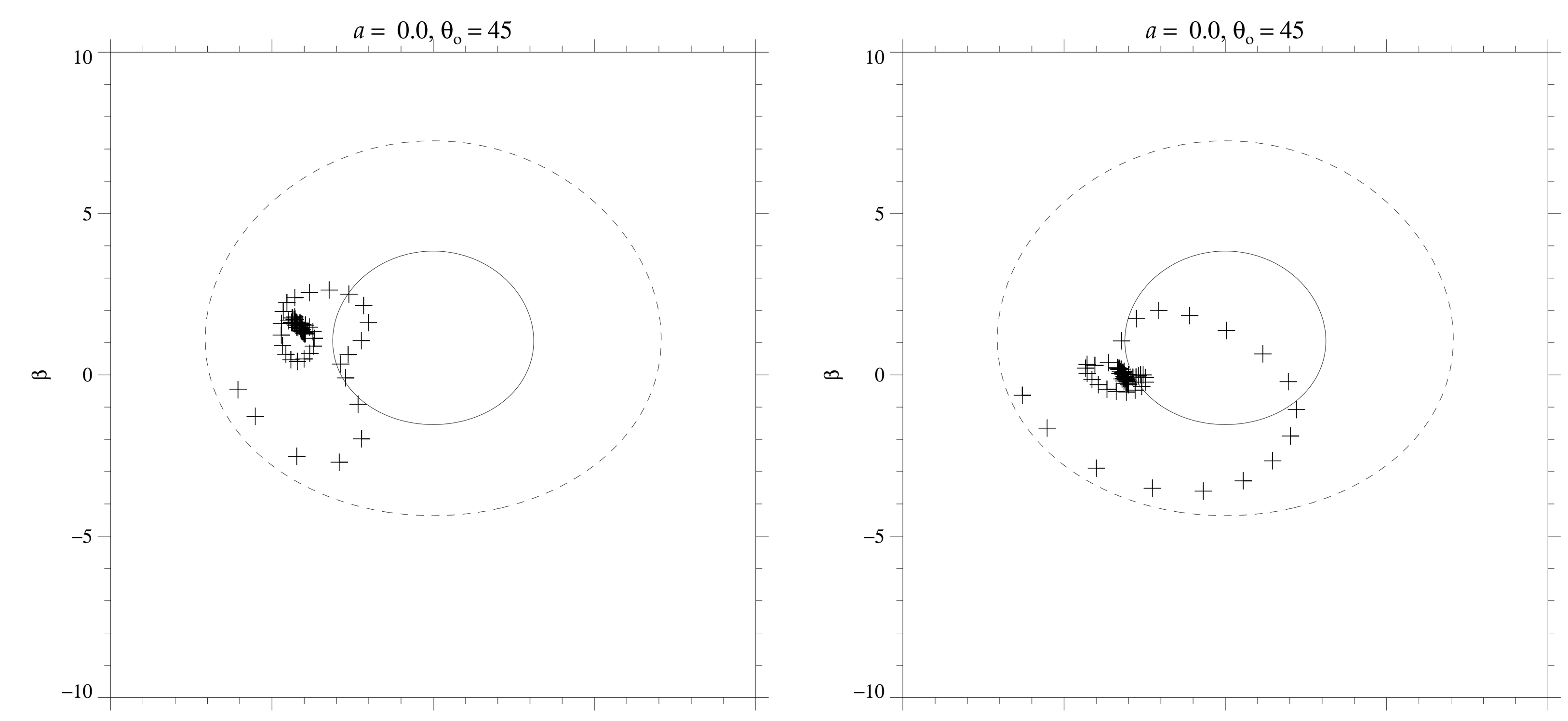

Fig. 3: The image centroid motion similar to Fig. 2, but now the spot is supposed to become elongated and eventually destroyed due to the shearing motion in the accretion disc. The disc itself also contributes to part of the emitted radiation in this example. The case of a rotating black hole, $a = 0.5M$, seen at $\theta_o = 45$ deg. The final track of the centroid image was extracted, taking into account both the spot and the underlying disc contributions. As a result of this model set-up, the centroid wobbles slightly off the geometrical center of the system, and the centroid motion evolves as the spot gradually disappears. Each orbit remains just above the ISCO and the image of the corresponding track settles down within one or two full orbits.

References

[1] Dovčiak M., Karas V., Yaqoob T., 2004, ApJS, 153, 205; Paper I

[2] Eckart A. et al., 2008, A&A, 492, 337, Paper II

[3] Karas V., Dovčiak M., Eckart A., Meyer L., 2007, in Black Holes and Neutron Stars, eds. S. Hledík & Z. Stuchlík (Silesian University, Opava), pp. 99–108 (arXiv:0709.3836); Paper III

[4] **Karas V., Zajaček M., Kunneriath D., Dovčiak M., 2022, Advances in Space Research, 69, 448**

Paper I

Paper II

Paper III

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