Modeling polarization signatures of NIR radiation from the Sgr A* black hole environs

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Abstract. The near-infrared (NIR) emission of Sagittarius A* (Sgr A*), the source associated with the supermassive black hole \( (4.4 \times 10^6 M_\odot) \) at the center of our galaxy, is polarized and highly variable. Correlations between intensity and polarimetric parameters of the observed light curves compared with the predicted ones for different configurations, allow us to extract information about the geometry of the radiating region. Here we present the theoretical polarimetric light curves expected in the case of optically thin NIR emission from overdense regions close to the marginal stable orbit. Using a numerical code we track the time evolution of detectable polarization properties produced by synchrotron emission of compact sources in the vicinity of the black hole. We show that the different setups lead to very distinctive patterns in the time profiles of polarized flux and the orientation of the polarization vector and as such may be used for determining the geometry of the accretion flow around Sgr A*.

1. Introduction
At the position of Sgr A*, at the Milky Way’s center, stellar orbits have convincingly proven the existence of a supermassive black hole of mass \( \sim 4.4 \times 10^6 M_\odot \). Sgr A* is a source of variable radio, near-infrared, and X-ray emission. In the NIR, flux-increases of about one order of magnitude and variations in the polarized emission have been observed (e.g., [1, 2, 3]). Some bright NIR and X-ray flares seem to be simultaneous ([4] and references therein), which points to a common physical origin of the observed phenomena. The short time scale variations seen during the NIR and X-ray flares also argue for an emitting region not bigger than about ten Schwarzschild radii \( (r_S = 2GM/c^2 = 2 r_g) \). The nature of this emission is of a non-thermal origin, most likely Synchrotron and/or Synchrotron self-Compton radiation from overdense regions very close to the black hole (see e.g., [4], and also Eckart et al. in this proceedings). The observed flux variations have been interpreted to be due to spots on relativistic orbits close to the inner most marginal stable orbit (ISCO) on an accretion disk ([5, 6, 7, 3]) or as variations in a short jet component([8, 9]).

A number of decades ago it was realized that polarization studies could provide firm clues to the physics of accreting black holes [10]. In strong gravitational field, the observed polarization is affected by light-bending, aberration and Doppler boosting [11]. In the context of the Galactic Center, the polarized NIR emission of SgrA* can be used to constrain the essential parameters
of the system like spin and inclination by fitting the predicted light-curves to the observed ones [12, 13].

In this short paper we summarize results from our modeling of optically thin emission that arise from the close proximity of a black hole and that is a result of two setups: a spot model and an ejected plasmoid. We use a numerical code for our simulations that is able to ray-trace in Kerr metric and track polarization properties of produced synchrotron emission, it handles all relativistic effects present in strong gravity regime not excluding the parallel transport of the polarization vector along the photon trajectory that plays a role in this environment and in this kind of study. We show that the different setups that we are covering here all lead to very distinctive patterns in the time profiles of polarized flux and the orientation of the polarization vector. As such, those patterns can be used for matching the observed variations and can help in determining the geometry of the accretion flow around Sgr A*.

2. Modeling of polarized emission

In the following, we shall compare polarization signatures and their time variations produced by magnetically threaded hot spots/blobs as overdensities in the accretion disk or as ejected plasmoids.

2.1. Orbiting spot

This model has been studied and used in the context of Sgr A* emission by several authors (see e.g. [5, 14, 6, 15, 13]), and we show it here mainly as a reference. We model a single spot/blob as an optically thin 3D-Gaussian with $\sigma = 1 \, r_g$, on an optically thick accretion disk, that is orbiting at radius of $1.1 \times$ ISCO. In this case, we kept the structure of the emitting region not allowing it to deform due to differential rotation in the disk. The orientation of the system is such that the symmetry axis of the disk points towards the north (up) and the observer sees the equatorial plane under inclination of 70 degrees from this axis. Figure 1 presents snapshots from the photon ray-tracing, for the case of a black hole with dimensionless spin parameter $a = 0.5$. The color gradient corresponds to relative flux density (in arbitrary units) and the short lines indicate the orientation of the polarization angle. Figure 2 shows the characteristic light-curve pattern of the orbiting spot for $a = 0.0, 0.5$ and $0.9$ – periodically rising and lowering flux which is the

![Figure 1](image-url)  

*Figure 1.* Snapshot images of $10 \, r_g$ side length taken from the numerical simulation of an orbiting blob for an inclination 70 deg and spin $a = 0.5$. The flux in every snapshot has been normalized to its maximum in order to enhance the low-flux images. The actual flux modulation is presented in the next figure. Color coding corresponds to a linear gradient of the flux emission levels and the green dashes show the polarization (orientation and length of the green lines represent the polarization angle and degree, respectively).
result of relativistic Doppler beaming as well as the gravitational bending as the spot describes one orbit around the black hole. Here we have subtracted the disk emission, and therefore we present only the variable and polarized component. We assumed that a vertical magnetic field is present in the local frame of the spot. Figure 2 also shows the changes in polarization degree (as percentage of the polarization degree at the source) and angle. Such polarized light-curve profile displays the main expected relativistic effects: decrease of polarization degree and rapid change of polarization angle just before the maximum of intensity, though this pattern depends strongly on the local polarization at the source reference frame.

2.2. Blob ejected from the disk
The next example assumes a plasma blob that might be produced by a magnetic loop on the disk corona and is ejected out of the disk surface at $r = 1.3 \times \text{ISCO}$. The plasmoid keeps its orbital motion and shape while moving away. As a first approximation we considered the radial component of the velocity to be zero and assumed the presence of a helical magnetic field with a higher azimuthal component (10 times the vertical one). Figures 3 and 4 illustrate the situation for an observer at 70 degrees with respect to the disk symmetry axis. Figure 3 shows snapshot images in the case of a black hole with spin $a = 0.5$, while Fig. 4 displays the behavior of the intensity, polarization degree and angle for three different spin parameters. The light curve in Fig. 4 covers the evolution of the blob over almost two full orbits and it has two peaks that arise from the Doppler boosting. The intensity modulations are similar to those in the previous
Figure 3. Snapshot images of $20r_g$ side length taken from the numerical simulation of a blob that originates in the accretion disk and is ejected away from it. The inclination of the system is $70\,\text{deg}$ and the black hole spin $a = 0.5$. After the ejection event, the blob material keeps its angular momentum and follows a helical trajectory. Color coding as in Fig. 1.

Figure 4. Time dependence of the total intensity (top), polarization degree (middle) and polarization angle (bottom) over the evolution of the plasmoid (a blob) that is ejected out of the disk surface at a radius $1.3 \times \text{ISCO}$. The colors correspond to different black hole spin parameters: $a = 0.0$ (cyan), $a = 0.5$ (magenta) and $a = 0.9$ (orange). The magnetic field is assumed to be helical with a higher toroidal component. The disk contribution has been subtracted in all cases (disk emission is unpolarized). As in Fig. 2, dashed lines correspond to sections where the total flux is less than $5\%$ of the maximum.

case. Given the assumed magnetic field, the major depolarizations in the light curves coincide with the maxima in flux (compare figures 2 and 4). We can see that this scenario produces a different pattern and could be easily distinguished from the orbiting spot scenario.

3. Conclusions
We have shown preliminary results of two possible models for polarized emission from Sgr A* that can be matched against observational data to better guess what types of processes and geometries could be the sources of the observed NIR flares. Each setup is characterized by a
distinct profile of polarized flux and changes in the angle of the polarization vector. This is a second step on modeling the Sgr A* activity (the first approach has been done using the 2-dimensional KY-code). Further efforts to account for radiative transfer effects in optically thick environments will allow us to describe multiwavelength observations. Ultimately this would lead to constraining the spin of the Sgr A* black hole and its orientation with respect to the galactic plane.

These results can be compared with today’s data as well as with data from future near-infrared polarimetric detectors that will extend our observational capabilities and provide a higher sensibility and resolution than it is available today.

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References
[1] Baganoff F K, Bautz M W, Brandt W N, et al. 2001 *Natur.* **413** 45
[2] Eckart A, Baganoff F K, Morris M, et al. 2004 *A&A* **427** 1
[3] Zamaninasab M, Eckart A, Witzel G, Dovciak M, et al. 2010 *A&A* **510** 3
[4] Eckart A, Garcia-Marin M, Vogel S N, Teuben P, et al. 2012 *A&A* **537** 52
[5] Broderick A E and Loeb A 2005 *MNRAS* **363** 353
[6] Meyer L, Eckart A, Schödel R, et al. 2006 *A&A* **460** 15
[7] Pecháček T and Karas V 2008 *A&A* **487** 815
[8] Falcke H and Markoff S 2008 *A&A* **482** 113
[9] Markoff S, Bower G C and Falcke H 2007 *MNRAS* **379** 1519
[10] Rees M J 1975 *MNRAS* **171** 457
[11] Connors P A, Stark R F and Piran T 1980 *ApJ* **235** 224
[12] Meyer L, Schödel R, Eckart A, Duschl W J, Karas V and Dovciak M 2007 *A&A* **473** 707
[13] Zamaninasab M, Eckart A, Dovciak M, Karas V, et al. 2011 *MNRAS* **413** 322
[14] Dovciak M, Karas V and Matt G 2006 *AN* **327** 993
[15] Noble S C, Leung P K, Gammie C F and Book L G 2007 *CQG* **24** 259