A two component hot spot/ring model for the NIR flares of Sagittarius A∗

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Abstract. The supermassive black hole at the Galactic Center, Sgr A∗, shows frequent radiation outbursts, so-called flares. In the near-infrared some of these flares were reported to show intrinsic quasi-periodicities of 18 ± 3 min. In 2005, we have carried out polarimetric observations of these QPOs in the K-band. These observations allow for a detailed investigation of Sgr A∗ within the hot spot model. In this model, inhomogeneities in the accretion flow are represented as confined orbiting material. By simultaneous fitting of the lightcurve fluctuations and the time-variable polarization angle, we address the question whether these changes are consistent with the hot spot model, in which the interplay of relativistic effects plays the major role. We consider all general relativistic effects that imprint on the polarization lightcurves. As the synchrotron mechanism is most likely responsible for the intrinsic polarization, we consider two different magnetic field configurations as approximations to the complex structure of the magnetic field in the accretion flow. Considering the quality of the fit, we think that the spot model is favoured. Finally, our confidence contours give constraints to the spin parameter and the inclination of the supermassive black hole associated with Sgr A∗.

1. Introduction

The compact radio, infrared and X-ray source Sagittarius A* (Sgr A*) is the manifestation of a massive (M = 3.6 × 10⁶M⊙) black hole (MBH) at the center of the Milky Way (e.g. [26], [17], [14]). With Eddington luminosities of L_{Edd} = 10^{-9} – 10^{-10}, it is the most extreme sub-Eddington source accessible to observations. Sgr A* shows the feature of so-called ’flares’, short bursts of increased radiation that last for about 60-100 min. These flares were first discovered at X-ray wavelengths, where the flux of Sgr A* may rise by factors up to ~100 during such an event (e.g. [2], [25], [111]). At near-infrared (NIR) wavelengths, the flares show very similar timescales, but the flux varies only by factors of ≤ 10, see [16]. Although the exact cause of the flares is still unclear, it is generally accepted that they are caused by synchrotron and synchrotron self-Compton emission processes within ≲ 10 Schwarzschild radii (R_S) of the black hole [12, 18].

The most intriguing feature related to these flares is the presence of quasi-periodic oscillations (QPOs) with a period of 17-22 min, which have been detected in several of these events [16, 4, 13, 22]; see also Bélanger et al., this volume. The quasi-periodicity manifests itself in the lightcurve as sub-flares superimposed on the underlying main flare. It is not clear yet, how these quasi-periodicities are created. The timescale of the lightcurve variations and the rather small volume around Sgr A*, where these
variations originate, indicate that rapid motion in strong gravity is involved. Also, frequencies in microquasar QPOs scale with the inverse mass of the BH, and the frequency of the QPOs in Sgr A* indicates that an extrapolation from the stellar-mass BH case in microquasars to the MBH case is applicable [1, 21, 23].

However, these QPOs of Sgr A* have only been observed unambiguously in a few cases, which has raised some doubts about their nature, in particular whether they may just be related to a red-noise-like process in the source. This aspect is discussed extensively in Meyer et al. [22] for the flare that shows the clearest evidence of quasi-periodicities. They conclude that the ∼17 min periodicity reported by Genzel et al. [16] is most probably not due to red noise. The discovery by Eckart et al. [13] that periodicities can show up in NIR polarized light, while at the same time being hardly visible in the total flux, raises the possibility that such periodicities may be present in most flares.

Variations of the degree and angle of polarization can carry valuable information on relativistic effects (e.g. [8], [5], [10]). Here, we apply the relativistic ray-tracing code by Dovciak et al. [10] to a combined orbiting spot/ring model to fit the recent NIR polarimetric observations by Eckart et al. [13].

2. The model of an orbiting blob
In our model the broad underlying flare is caused by some kind of non-axisymmetric accretion disk instability of a truncated disk/ring, see [22]. The sub-flares are due to a compact, confined emission region on a relativistic orbit around the MBH. Such ‘hot spots’ can be created in reconnection events and/or at shocks, in which thermal electrons are accelerated into a broken power law [29]. Due to the proximity of the BH horizon, general relativistic effects imprint on the synchrotron radiation of such inhomogeneities [6, 5, 10, 20, 21, 7, 15, 24]. Redshifts, lensing, time delay, change in emission angle and change in polarization angle belong to these. The code by Dovciak et al. [10] takes these special and general relativistic effects into account by using the concept of a transfer function, first utilized in [9]. A transfer function relates the flux as seen by a local observer comoving with an accretion disk to the flux as seen by an observer at infinity. This transfer of photons is numerically computed by integration of the geodesic equation. For the change of polarization angle the method of Connors & Stark [8] has been used.

The disk/ring’s time behavior was assumed to be Gaussian and to account for the main flare. The spot is orbiting within the disk and the equatorial plane of a Kerr BH. Its intrinsic luminosity follows roughly a two-dimensional normal distribution with σ ∼ 1.5R_S (R_S = 2GM/c^2), which is jolted in the radial direction so that the azimuthal extent is larger. As the periodicity reported by Eckart et al. [13] is ∼ 19min, the spot follows a circular trajectory in the case a_* ≥ 0.5. Note that the radius for the corresponding orbit is spin dependent [3] if it is chosen such that this observed periodicity is matched. In the case a_* ≤ 0.5 the spot is freely falling, i.e. plunging towards the horizon.

To investigate the parameters of Sgr A*, we have fitted for the inclination angle, the dimensionless spin parameter a_*, the brightness excess of the spot with respect to the disk, the initial phase of the spot on the orbit, the orientation of the equatorial plane on the sky and the polarization degree of the disk (constrained to ≤ 15%) and the spot (≤ 70%). From these, only the spin parameter and the inclination are needed for the ray-tracing computation. For these two parameters we have chosen a discrete grid with 0 ≤ a_* ≤ 1 and steps of 0.1, and an inclination angle 10° ≤ i ≤ 70° with steps of 5°; i = 0°: face-on. For i > 70° multiple images could become important, which are not included in our treatment. The special geometries, where strong lensing – and therefore higher order images – is important, are all characterized by viewing angles very close to edge on.

The observational data include the effects of foreground polarization, so they have to be taken into account in the modeling calculations, too. Following the calibration of Eckart et al. [13], we fix it to be 3.4% at 25°. The geometry of the magnetic field of the spot is completely unknown. As a first order approximation, the fits are done for two different simple field configurations [24]. The first configuration is such that the resulting projected E-Vector is always perpendicular to the equatorial plane. Such preferred orientation could result from perturbations in the disk similar to sunspots (see also
Figure 1. The solution with the least $\chi^2$ values (in red) for the constant $E$-vector scenario. Shown is the flux (top), polarization angle (middle), and degree of linear polarization (bottom). The parameters of the model are inclination $= 70^\circ$, $a_\star \approx 1$, an orientation of the projection of the disk on the sky of $0^\circ$ (east of north) and a polarization degree of the disk (spot) of 9% (60%). The spot is confined during its three revolutions and shearing is not taken into account. As there is no simple physical model for the evolution of the spot within the accretion flow, the changes of its intrinsic luminosity are incorporated in a discontinuous way.

Shakura & Sunyaev [27]). As a second configuration, we have chosen a global azimuthal magnetic field. This behaviour may be caused by the magneto-rotational instability and is motivated by global MHD simulations (Hirose et al. [19]). In this case, the $E$-vector would rotate along the orbit, if relativistic effects were switched off.

3. Results
Figure 1 shows the fit with the least reduced-$\chi^2$ value within the discrete grid discussed in the last section. High inclination and high spin give the best solutions. The case of the azimuthal magnetic field leads to slightly higher $\chi^2$ values, i.e. worse fits. There, high inclination and medium spin is preferred. Regarding
Figure 2. The confidence contours for the constant $E$-vector (top) and the azimuthal magnetic field case (bottom). The red (green) line is chosen such that the projection onto one of the parameter axes gives the $1\sigma$ ($3\sigma$) limit for this parameter. The values for the dimensionless spin parameter are constrained to the physical region $0 \leq a_\ast \leq 1$. We constrained the inclination to $\leq 70^\circ$, because multiple images are not incorporated in our approach.

The confidence contours shown in figure 2 reveal that for both magnetic field cases the spin parameter $a_\ast$ cannot be well constrained from the current data due to the relatively large error bars. However, within the $3\sigma$ limit, $a_\ast$ can be inferred to lie in the range $0.4 \leq a_\ast \leq 1$. This is in agreement with previous observations [16, 4]. The range of the inclination is higher for the scenario of the azimuthal magnetic field. Since the $\chi^2$-minimum is lower for the constant $E$-vector, this case should be given more weight. That means the inclination is $\geq 35^\circ$ on a $3\sigma$ level.

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