A polarized infrared flare from Sagittarius A* and the signatures of orbiting plasma hotspots

S. Trippe,1† T. Paumard,1‡ T. Ott,1 S. Gillessen,1 F. Eisenhauer,1 F. Martins1 and R. Genzel1,2
1Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany
2Department of Physics, University of California, Berkeley, CA 94720, USA

ABSTRACT
In this article we summarize and discuss the infrared, radio and X-ray emission from the supermassive black hole in the Galactic Centre, SgrA*. We include new results from near-infrared polarimetric imaging observations obtained on 2006 May 31. In that night, a strong flare in Ks band (2.08 μm) reaching top fluxes of ~16 mJy could be observed. This flare was highly polarized (up to ~40 per cent) and showed clear substructure on a time-scale of 15 min, including a swing in the polarization angle of about 70°. For the first time we were able to observe both polarized flux and short-time variability, with high significance in the same flare event. This result adds decisive information to the puzzle of the SgrA* activity. The observed polarization angle during the flare peak is the same as observed in two events in 2004 and 2005. Our observations strongly support the dynamical emission model of a decaying plasma hotspot orbiting SgrA* on a relativistic orbit. The observed polarization parameters and their variability with time might allow to constrain the orientation of accretion disc and spin axis with respect to the Galaxy.

Key words: accretion, accretion discs – black hole physics – Galaxy: centre.

1 INTRODUCTION
The centre of our Milky Way hosts the 3.6 × 10⁶ M☉ supermassive black hole (SMBH) and radio source SgrA*. This BH is generally invisible in near-infrared (NIR) wavelengths and was not detected in this spectral range before 2002 when diffraction-limited observations at 8-m-class telescopes became possible (Genzel et al. 2003; Ghez et al. 2004).

Since then, several NIR flares, which appear on time-scales of few events per day, have been observed photometrically (Ghez et al. 2005; Eckart et al. 2006a), spectroscopically (Eisenhauer et al. 2005) and polarimetrically (Eckart et al. 2006b). Such flares last typically for about 60–120 min. These observations gave information on the colours and spectral indices of flares (Eisenhauer et al. 2005; Ghez et al. 2005; Gillessen et al. 2006; Krabbe et al. 2006). They included the detection of polarized flux and quasi-periodic substructures on time-scales of 15–20 min (Genzel et al. 2003; Eckart et al. 2006b).

In recent years, variable and flaring emission from SgrA* has been observed in a variety of wavelength bands, especially in the radio (Aitken et al. 2000; Melia & Falcke 2001 [and references therein], Bower et al. 1999a; Bower, Falcke & Backer 1999b; Bower et al. 2003; Miyazaki, Tsutsui & Tsuboi 2004; Marrone et al. 2006) and X-ray (Baganoff et al. 2001, 2003; Goldwurm et al. 2003; Aschenbach et al. 2004; Bélanger et al. 2005, 2006)) regimes. Substructure on minute time-scales was also detected in X-ray flares (Aschenbach et al. 2004; Bélanger et al. 2006). Additionally, variable polarized flux from SgrA* was found in submm to mm radio bands (Bower et al. 2005; Macquart et al. 2006; Marrone et al. 2006).

In this article we discuss the physics behind the emission from SgrA* taking into account new results of polarimetric imaging observations obtained in 2006 May. In Section 2 we describe the observations and the data reduction, in Section 3 we present the observational results. In Section 4 these data are placed into the context of earlier results, and in Section 5 they are discussed and interpreted.

2 OBSERVATIONS AND DATA REDUCTION
We have repeatedly carried out observations on the 8.2-m-UT4 (Yepun) of the ESO-VLT on Cerro Paranal, Chile, using the detector system NAOS/CONICA (NACO for short) consisting of the AO system NAOS (Lenzen et al. 2003) and the 1024 × 1024-pixel NIR camera CONICA (Lenzen et al. 2003).

On 2006 May 31, in total 240 min of polarimetric Ks band (λ_centre = 2.08 μm) imaging data of the Galactic Centre were obtained. The Wollaston prism mode of NACO made it possible to...
simultaneously observe two orthogonal polarization angles (corresponding to the ordinary and the extraordinary beam of the prism, respectively) per image. In order to cover a sufficient number of polarimetric channels, the observed angles were switched using a half-wave retarder plate.

The images were obtained alternately covering the polarization angles 0°/90° and 45°/135°, respectively. Each cycle took no more than about 150 s. The spatial resolution of the data is around 60 mas at mediocre Strehl ratios. All frames have a pixel scale of 13.27 mas pixel⁻¹.

All images were sky-subtracted, bad-pixel- and flat-field-corrected. To extract the fluxes of SgrA* and two comparison stars, we applied aperture photometry. Eight bright and isolated stars in the field of view served as calibrator sources. As SgrA* was confused with a weak star, S17, at the observation epoch, this star’s flux contribution of 2.5 mJy was subtracted from the flare data.

As always two pairs of polarization channels were observed alternately, for each source sets of four flux values (for the four angles per time bin) were obtained. In order to extract the polarimetric parameters—degree of polarization $p$, angle of polarization $q$—from a given data set, this data set was first normalized by dividing all four values by their average. Due to this, the average of the data set is set to 1. The amplitude of variations around the average level due to polarized flux is limited to the range from 0 to 1. As we use the convention that the degree of polarization is the ratio of polarized flux versus total flux, this amplitude corresponds to the degree of polarization. We compute the polarized flux as the product of the degree of polarization and the total source flux. One should note that throughout this article ‘polarization’ and ‘polarimetry’ refer to linear polarization.

As described above, in each image source fluxes are calibrated by dividing the target source count rates by the count rates of calibration stars taken from the same image (photometric calibration). This means that a possible average polarization of the calibrator stars is erased. As indeed the stars of the observed Galactic Centre region show an average polarization of 4 per cent at an angle of 25°, due to foreground extinction by dust (Eckart et al. 1995; Ott, Eckart & Genzel 1999), this has to be corrected. This correction was done by multiplying the four flux values of a data set with the function

$$f(\phi) = 1 + 0.04 \sin(2(\phi + 25^\circ)), \quad \phi = 0^\circ, 45^\circ, 90^\circ, 135^\circ. \quad (1)$$

(polarimetric calibration). The factor of 2 in the argument of the sine is due to the convention that polarization angles are limited to the range [0°, 180°]. After this, each normalized data set was fit with a sine curve with a period of 180°. This delivers the degree of polarization (the sine curve’s amplitude) and the angle of polarization (the sine curve’s phase).

In our definition, a polarization angle of 0° corresponds to a pointing to the north and the angle is counted east of north. In both the polarimetric calibration and the fitting, a global rotation of the polarization vector with respect to the sky of 36° was taken into account. This rotation was found using polarimetric NACO Wollaston data of the calibrator star IRS21 obtained in 2005 July. Comparing the parameters extracted from this data set with results found with different instruments and reported earlier (14 per cent and 14°; Eckart et al. 1995; Ott et al. 1999) leads to a rotation of 34°. This rotation might be caused by a known shift (the abovementioned 36°) in the zero position of the half-wave plate, although this shift is assumed to be corrected in the instrument set-up (N. Ageorges, private communication; NACO HWP commissioning report). Given the numerical agreement (better than 2°) we believe that at least in this data set a correction was not applied.

The sine fitting procedure described above is demonstrated in Fig. 1 for four different time bins. Here the connection between $p$ and $q$ on the one side and amplitude and phase of the flux data on the other side is obvious. This figure already indicates some evolution of the polarization parameters with time; details will be discussed below.

Data sets, for which the values were consistent with being identical within the errors (corresponding to a $\chi^2_{\text{reduced}} < 0.789$ in case of three degrees of freedom) were not fit in order not to apply a systematically incorrect model. Another effect to be taken into account was the bias caused by the non-zero errors of the flux values. Bias can lead to a systematic overestimation of polarization fraction and polarized flux especially in cases of low fluxes. In order to check this, we calculated $p$ and polarized flux using analytical expressions for the Stokes parameters $I$, $Q$ and $U$ corrected for the bias terms. The results are presented in Fig. 2. In no case the deviation exceeded 3 per cent (in $p$; average deviation: 1.15 ± 1.34 per cent) respectively.
are minutes after 00:00 UT of the observation day, the first data point are present. All times mentioned here and elsewhere in this article of S17. In all light curves gaps due to intermediate sky observations to the foreground extinction screen and before subtracting the flux values are the observed fluxes before polarimetric calibration relative to the extinction screen polarization and subtraction of half of the total source flux. These values are the observed fluxes, before calibrating relative to the extinction screen polarization and subtraction of the flux variations in the order of 7 mJy or 40 per cent within 10 min time.

### 3 RESULTS

The light curves for SgrA* and two comparison stars, S2 and S7, are presented in Fig. 3 (top panel). In this figure the light curves are shown for each polarization channel separately. The presented values are the observed fluxes before polarimetric calibration relative to the foreground extinction screen and before subtracting the flux of S17. In all light curves gaps due to intermediate sky observations are present. All times mentioned here and elsewhere in this article are minutes after 00:00 UT of the observation day, the first data point obtained is located at \( t = 399 \) min.

From these light curves one can see a strong and fast variability of the flare. Especially interesting is its double peak, which shows flux variations in the order of 7 mJy or 40 per cent within 10 min time.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Observed total and polarized fluxes of SgrA* and the comparison stars S2 and S7. Top panel: light curves of SgrA*, S2 and S7 separated into the four polarimetric channels. Due to the splitting of the light into one ordinary and one extraordinary beam, each channel in average contains one half of the total source flux. These values are the observed fluxes, before calibrating relative to the extinction screen polarization and subtraction of the confusing star S17. S2 and S7 are shifted along the flux axis. The fast variability of SgrA* and its strong polarization can be seen clearly, especially in comparison to S2 and S7. Bottom panel: polarized flux of SgrA*. The two main maxima in the polarized flux correspond to the maxima in the light curve. In all figures the central gap in the data is due to sky observations, around a time \( t = 480 \) min the flare fades out. Where data points are missing, no parameters were computed (see Section 2 for details).

The two maxima of the double peak are separate in time by only 15 min. Additionally, the different fluxes in the polarimetric channels point towards significant polarization. This is demonstrated more directly in Fig. 4, where the difference of two channels is mapped and compared to a sum image of the vicinity of SgrA*. It is important to note that those differences in the polarimetric channels are not visible in the light curves of the comparison stars. This holds for both flux levels corresponding to the peaks of the flare (S2) and for fluxes corresponding to the end of the flare (S7).

The amount of observed polarized flux from SgrA* is shown in the bottom panel of Fig. 3. The polarized flux shows two maxima at times 405 respectively 420 reaching up to around 2 mJy; these maxima correspond to the double peak in the light curves. During the entire flare the polarized flux is never lower than \( \sim 0.6 \) mJy.

The evolution of the parameters degree and angle of polarization is presented in Fig. 5. The degree of polarization is about 15 per cent at the beginning of the observation and increases after the second main maximum (\( t > 430 \)) up to roughly 40 per cent. This can be seen also in Fig. 1, were two examples for the fluxes in the four polarimetric channels are given for time bins corresponding to the first peak (\( t = 404 \)) and the second peak (\( t = 476 \)). The increase is a direct consequence of the fact that the polarized flux level remains roughly constant while the overall flux is decreasing with time after the double peak.

Inspecting Figs 3 and 5, it might not be obvious that for times \( t < 430 \) the polarized flux is variable and the degree of polarization is not. To check this, we computed the reduced \( \chi^2 \) for each data set using the assumption that the data do not vary with time. We find a \( \chi^2_{\text{red}} = 2.12 \) for the polarized flux, whereas for the degree of polarization we find \( \chi^2_{\text{red}} = 0.88 \). Thus we conclude that indeed only the polarized flux varies for \( t < 430 \), whereas the degree of polarization remains constant within the errors.

The polarization angle remains at a constant level around \( 80^\circ \) during the time of the double peak, that is, \( t \leq 430 \). The first two data points indicate that the angle could have been even larger before the first peak; but as this signal is only marginally significant (1–1.5\( \sigma \)), this is completely speculative. Beginning at \( t \sim 430 \), \( \phi \) swings by about \( 70^\circ \) within 15 min, reaching values down to \( \sim 10^\circ \). This is (within the errors) close to the angle of the foreground polarization (\( \sim 25^\circ \)).

When discussing the angle of polarization, one has to keep in mind possible calibration artefacts. As described in Section 2, our data are calibrated so that an intrinsically unpolarized source shows...
a signal corresponding to $p = 4$ per cent and $q = 25^\circ$. Therefore it is in general possible to observe a source composed of two superposed flux components, a polarized one and a non-polarized one. As long as both components are significantly bright, one would measure the polarization parameters of the polarized source flux. But when the polarized component fades away, the observed $p$ and $q$ would move towards the foreground level.

To assure that we are not mislead by such an effect, the comparison to a source with a brightness similar to SgrA* (plus S17) at the very end of the flare ($t = 470–480$) without applying any polarimetric calibration becomes important. Indeed this is what is shown in Fig. 3, where the photometric light curves of SgrA* and S7 are compared. As one can see, even at the very end of the flare SgrA* is clearly polarized intrinsically, whereas S7 is not at all. Additionally, we repeated the fitting of the polarization parameters without re-introducing the foreground polarization into the data. The results turned out to be identical within the errors compared to those shown in Figs 3 and 5. Thus we are confident that the description above is valid.

Morphologically, the flare shows two phases. In the first phase, covering times $t \lesssim 430$, the double peak occurs, the polarized flux changes rapidly and traces the overall emission, and both degree and angle of polarization remain constant.

In the second phase ($t > 430$) the overall flare slowly fades away while the polarized flux remains on a roughly constant level, leading to an increase in the degree of polarization. Additionally the swing in polarization angle occurs.

Following the evolution of the flare with time, one has to note that it is highly dynamic on a typical time-scale of 15 min, which expresses itself in all parameters: the overall flux (double peak), polarized flux, polarization angle and degree of polarization.

4 CONTEXT

The SgrA* activity described above for the first time combines several separately observed properties on high significance levels: (1) strong, variable NIR activity with an overall duration of more than 80 min, (2) substructure on a time-scale of 15 min and (3) clear, variable polarization.

These signatures allow a deeper understanding of the physical emission mechanisms of SgrA*. This is especially obvious in the long-term context of observed infrared, radio and X-ray activity. For this reason the overall properties of SgrA* flares are discussed and compared here.

Since 2002 we have observed the NIR emission of SgrA* using the ESO Very Large Telescope on Cerro Paranal, Chile. Photometric and polarimetric imaging data were collected with NACO in $H$, $K$ and $L$ bands (1.3–4.1 $\mu$m; Genzel et al. 2003; Trippe 2004; Eckart et al. 2006a,b).

Infrared spectra were obtained using SINFONI, a combination of the integral field spectrometer SPIFFI (Eisenhauer et al. 2003a,b) and the adaptive optics (AO) system MACAO (Bonnet et al. 2003, 2004), at VLT-UT4. The data covered the $K$ band from 1.95 to 2.45 $\mu$m with a spectral resolution of $R = 4500$ (Eisenhauer et al. 2005; Gillessen et al. 2006). The properties of 16 observed infrared flares are given in Table 1.

Additional to our work, infrared observations of SgrA* were obtained by Ghez et al. (2004, 2005) in $K$, $L$ and $M$ bands using the Keck II telescope on Hawaii. Emission in $L$ and $M$ bands observed with NACO was also reported by Clénet et al. (2004, 2005). Yusef-Zadeh et al. (2006) used the Hubble Space Telescope to monitor flares in the range 1.60–1.90 $\mu$m. Recently, Krabbe et al. (2006) collected spectroimaging data of a $K$ band flare using the integral field spectrometer OSIRIS at the Keck II telescope.

In radio wavelengths (submm to cm) SgrA* was discovered by Balick & Brown (1974) and has since then been monitored extensively (recently e.g. Bower et al. 1999a,b; Aitken et al. 2000; Melia & Falcke 2001; Bower et al. 2003; Miyazaki et al. 2004; Bower et al. 2005; Macquart et al. 2006; Marrone et al. 2006) photometrically, spectroscopically and polarimetrically using a large ensemble of telescope facilities.

In X-ray wavelengths (few keV) SgrA* flares have been observed photometrically and spectroscopically since 1999 using the NASA Chandra and the ESA XMM–Newton space telescopes (Baganoff et al. 2001, 2003; Goldwurm et al. 2003; Aschenbach et al. 2004; Bélanger et al. 2005, 2006; Eckart et al. 2006a).

This view over many separate observations in several wavelength regimes allows some general statements.

(i) SgrA* emission is flaring. In NIR and X-ray wavelengths it is regularly detected in form of outbursts. In both bands flares correspond to an increase of flux by factors of up to $\sim$10 from the background level within some 10 min. The typical length of a flare is

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Evolution of degree and angle of polarization for SgrA* and S2 during the flare. Top panel: degree of polarization. During the flare ($t < 480$) it never sinks below 10 per cent, reaching top levels of $\sim$40 per cent. Bottom panel: angle of polarization. Of special interest is the strong swing of $\sim 40^\circ$ occurring in the time range 430–445 min, that is, within 15 min. In both panels the results for S2 mirror the calibration. Where data points are missing, no parameters were computed (see Section 2 for details).
in the range of 1–3 h. The flare event rate (i.e. the number of flares per time) is in the order of few events per day. For the 16 cases listed in Table 1 the flare rate is 2.5 events per day; including some flares covered by poor quality data increases this number to about 3.3 NIR events per day. In four cases NIR and X-ray flares were observed to be simultaneous within the available time resolutions (few minutes). Inspecting Table 1 shows (within the limits of low-number statistics) a general trend: flares are the more seldom, the more luminous they are. In contrast to this, changes in the radio flux are limited to variations of <50 per cent within hours to days.

The flaring character of SgrA* is illustrated by the light curves presented in Fig. 3. Here the emission drops down to (and remains) zero (within the errors) in both total flux and polarized flux, after a phase of strong activity. Another example is given in Fig. 6. This figure presents an H-band flare observed in 2004 April. In this case, after more than 1 h of zero emission from the position of the BH, strong emission raises up to 9 mJy within about 20 min. In both cases the observations are inconsistent with a permanent, variable NIR source. An equivalent behaviour could be observed at several other occasions in both NIR and X-ray bands. Thus the classification of SgrA* emission as ‘flaring’ is justified.

(ii) SgrA* emission is polarized. Linear polarization in the order of few to few per cent was detected in radio and NIR bands. In NIR, this polarization is observed in flares as described in Sections 2 and 3. For three NIR flares so far observed polarimetrically (flares 6, 13 and 15 in Table 1) we found polarization degrees of 15–20 per cent and angles of ~80° on sky at times of maximum fluxes. The polarization fractions of flares 6 and 13 do not show significant variations with time. In contrast to the flare described in Section 3, there are no distinct peak/decay phases. Unfortunately, these statements are weakened by the larger relative errors caused by lower peak fluxes (5 and 8 mJy in contrast to 16 mJy) of the flares 6 and 13.

Concerning the observed polarization angle, it is important to note that this angle was found repeatedly in three measurements covering a time span of two years. This strongly suggests that the geometry of the emission region is stable in time.

In comparison to this, the continuous radio flux was found to be polarized with $p \approx 2–8$ per cent and $q \approx 135–165^\circ$ (at 880 μm). The radio polarization is variable (typically within the ranges given before) on time-scales of few hours. Interestingly, Macquart et al. (2006) find the intrinsic angle of polarization to be about 165°. This would be close (~25°) to our result for the decay phase of the flare described in Section 2 (modulo 180°). Such an agreement could indicate that at least in some phases of activity NIR and radio observations are tracing emission from the same region around SgrA*.

Additional information has been found in the circularly polarized radio emission. This was originally reported by Bower et al. (1999b). Based on a re-analysis of older VLA data, Bower (2003) finds a constancy of the sign of the circular polarization for about 20 yr. This would – again – point towards a fixed B field orientation in the emission region.

(iii) SgrA* flares show a quasi-periodic substructure on time-scales of minutes. Examples for this are given in Fig. 7 (left-hand column) where the light curves of five $K_s$-band flares observed from 2003 to 2005 are presented. The first four (from top) panels show fluxes versus time, the fifth panel shows the polarized flux of the flare described by Eckart et al. (2006b).

All flare light curves (especially panels 1, 2, 4) show characteristic structures: an overall profile (rise, maximum, decay) lasting about 1–2 h is repeatedly modulated in cycles of 15–25 min. In the right-hand column of Fig. 7 Scargle periodograms (Scargle 1982) of the respective light curves are shown to visualize periodicities. The Scargle periodogram is defined as

$$ P_X(\omega) = \frac{1}{2} \frac{\left( \sum_j X_j \cos \omega t_j \right)^2}{\sum_j \cos^2 \omega t_j} + \frac{\left( \sum_j X_j \sin \omega t_j \right)^2}{\sum_j \sin^2 \omega t_j}, $$

Here $\omega$ is the angular frequency, $t_j$ the time of data point $j$, $X_j$ is the value measured at time $t_j$ and $P$ the power.

**Table 1.** Properties of infrared flares observed since 2002. Observations were obtained in photometric (‘phot’), polarimetric (‘pol’) and spectroscopic (‘spec’) modes. $\alpha$ is the colour index (defined as $\nu L_\nu \propto \nu^\alpha$), $p$ the degree of polarization and $q$ the angle of polarization. Parameters marked ‘–’ were not measured. Typical uncertainties are for fluxes: 1 mJy ($L'$ band: 3 mJy); time: 2 min; $\alpha$: 1; $p$: 5 per cent; $q$: $10^\circ$.

| No. | Epoch (yr) | Mode of observation | Band | Peak flux (mJy) | Duration of flare (min) | Time-scale of substructure (min) | $\alpha$ | $p$ (per cent) | $q$ (°) |
|-----|------------|---------------------|------|---------------|------------------------|--------------------------------|--------|-------------|----------|
| 1   | 2002.66    | phot                | $L'$ | 30            | >15                    | –                               | –      | –           | –        |
| 2   | 2003.35    | phot                | $H$  | 16            | 30                     | –                               | –      | –           | –        |
| 3   | 2003.45    | phot                | $K_s$| 13            | 80                     | 20                              | –      | –           | –        |
| 4   | 2003.45    | phot                | $K_s$| 9             | 85                     | 17                              | –      | –           | –        |
| 5   | 2003.32    | phot                | $H$  | 9             | >15                    | –                               | –      | –           | –        |
| 6   | 2004.45    | pol                 | $K_s$| 5             | 35                     | –                               | –      | 20          | 80       |
| 7   | 2004.51    | phot                | $K_s$| 8             | >250                   | 25                              | –      | –           | –        |
| 8   | 2004.52    | phot                | $K_s$| 3             | 85                     | 13                              | –      | –           | –        |
| 9   | 2004.54    | spec                | $K$  | 3             | 60                     | –                               | -2.2  | –           | –        |
| 10  | 2004.54    | spec                | $K$  | 3             | 60                     | –                               | -3.5  | –           | –        |
| 11  | 2005.27    | phot                | $K_s$| 3             | >20                    | –                               | –      | –           | –        |
| 12  | 2005.46    | spec                | $K$  | 8             | >150                   | 20                              | -3 to +2 | –           | –        |
| 13  | 2005.57    | pol                 | $K_s$| 8             | 100                    | 20                              | –      | 15          | 75       |
| 14  | 2006.40    | phot                | $L'$ | 25            | 110                    | –                               | –      | –           | –        |
| 15  | 2006.41    | phot                | $K_s$| 16            | >80                    | 15                              | –      | 15–40       | 80–10    |
| 16  | 2006.42    | phot                | $L'$ | 23            | >150                   | –                               | –      | –           | –        |

*Very uncertain due to poor data quality. Variations within the same flare and correlation with source flux. Variations within the same flare with time.
Emission from Sagittarius A∗

769

Figure 6. A beginning H-band flare observed on 2004 April 28, with NACO. Top panel: light curve of the event. The flare begins after \( t \approx 85 \) min. Before this time, no flux is detected at the position of SgrA∗. For \( t < 85 \) min the upper limits for source flux are given. Gaps are due to sky observations and a short breakdown of the AO system. Bottom panels: images showing SgrA∗ before and after beginning of the flare. The left-hand image is an average of 20 frames obtained in the time range \( t = 45–60 \) min. The position of SgrA∗ is free of any excess emission. The right-hand image is an average of the last five frames obtained. Here SgrA∗ is clearly visible. This example data set illustrates the flaring character of SgrA∗: the BH does not show any detectable activity for at least 1.5 h, then a flare raises from zero level within minutes.

In order to illustrate the signatures presented in Fig. 7, Fig. 8 gives a simple model in form of an artificial light curve. Please note that this model is an illustration only, not a simulation or reconstruction of a flare. The artificial flare is composed of four additive components (in arbitrary units): (i) a sine half wave with length 100 and amplitude 10 as overall profile, (ii) a sine wave with amplitude 1.2 and period 18 as periodic modulation, (iii) random Gaussian noise with \( \sigma = 1 \) and (iv) a constant background of height 1. The sum of these four components forms the artificial flare. For each of the three non-constant components on the one hand and the final synthesized flare light curve on the other hand we computed the respective periodograms.

Comparing Figs 7 and 8 allows to disentangle the features in the flare periodograms. These are: strong peaks at frequencies \( \nu < 0.02 \) 1 min\(^{-1}\) due to the overall flare profiles; secondary maxima at \( \nu \approx 0.04–0.08 \) 1 min\(^{-1}\) due to the (quasi-)periodic substructure; and noise signals over the entire spectra.

Including this work, quasi-periodic signals in NIR flares have now been found in the range of 13–30 min. This substructure is generally quite weak – indeed the ‘double peak’ of the flare described in Sections 2 and 3 is the strongest case seen so far – and detected only in a part of all observed flares. This statement is true also for the X-ray activity of SgrA∗, where quasi-periodic substructure with periods of about 5–22 min was reported for some flares.

5 DISCUSSION

With all these elements at hand, we can start drawing fairly robust conclusions on the nature of the flares. However, at this point we...
do not conclude that we can derive reliable quantitative parameters of SgrA∗. Many parameters would still highly depend on the model assumptions made by the author. Therefore such a quantitative statement would necessarily suffer from oversimplification. The important physical facts or hints are better obtained through qualitative discussion.

5.1 Nature of the flares

First of all, we know from imaging observations that flares occur always at the same location, consistent within a few mas (a few 100 Schwarzschild radii, RS) with the gravitational centre of the nuclear starcluster and the radio source SgrA∗ (Genzel et al. 2003; Ghez et al. 2004; Eisenhauer et al. 2005). But more importantly, the light curves of several NIR and X-ray flares observed so far show significant variations on the time-scale of 15 min. This demonstrates that the region involved in these substructures is smaller than ∼10RS. Furthermore, the typical time-scale in the light curves is consistent across these flares, ranging from 13 to 30 (±2) min.

This time-scale is within the range of the innermost stable circular orbit (ISCO; Bardeen, Press & Teukolsky 1974) orbital periods allowed for Kerr BHs of 3–4 × 10⁸ M⊙ and various spin parameters. Many authors (Genzel et al. 2003; Liu, Petrosian & Melia 2004; Yuan, Quataert & Narayan 2004; Broderick & Loeb 2006; Paumard et al., in preparation) have studied the possibility that the flare emission may actually come from matter orbiting the BH close to the ISCO. The scatter in the observed periods is not a concern: in the context of this ‘orbiting blob scenario’, it would simply indicate that the outbursts do not always occur exactly on the ISCO, but that a range of orbital radii is allowed. Orbits inside the ISCO are unstable. Since flares last for more than one orbital period (typically more than four), we can assume that flares occur outside this orbit. For this reason, the shortest period ever measured (13 ± 2 min; Fig. 7 and Table 1) sets a lower limit to the spin parameter a of the BH: using M_SgrA∗ = 3.6 ± 0.3 × 10⁸ M⊙ (Eisenhauer et al. 2005), this leads to a ≥ 0.70 ± 0.11 (following Bardeen et al. 1974).

The presence of this quasi-periodic substructure imposes serious limits on alternative emission scenario. Bow shock fronts caused by stars moving through the accretion disc material (Nayakshin, Cuadra & Sunyaev 2003) should not show such modulation.

In case of jet emission (Falcke & Markoff 2000; Markoff et al. 2001; Yuan, Markoff & Falcke 2002) such modulations would be imprinted on the jet if the jet nozzle was located in the accretion disc, orbiting the BH. Indeed, the jet model by Falcke & Markoff (2000) requires a nozzle with a radius of ~4 RS and a height of ~8 RS. This extension would be small enough to allow for the observed short-time variability. On the other hand, Gillessen et al. (2006) analyse the cooling time-scales of orbiting hot spots and find a limit on the extension of the emission region of 0.3 RS. As this would be one order of magnitude smaller than the size of the model jet nozzle, the emission in the early phases of a flare probably cannot be explained by a ‘pure’ jet emission model. This does not exclude the presence of a jet but makes it unlikely that a jet is responsible for a significant part of the observed NIR emission. In the end or decay phase of a flare, when a substantial shearing and broadening of the emission region is expected from the hotspot model, a growing contribution from respectively evolution into a jet is thinkable; we will pay attention to this again later.

Additionally, the observations also do not a priori exclude the possibility of spiral density waves propagating in the accretion disc. Those oscillations have been discussed in the context of stellar BH systems in order to explain high-frequency (kHz range) QPOs (e.g. Kato 2001; Petri 2006, and references therein). A rotating two-arm structure could double the orbital time-scale and thus loose the constraints on the BH spin. But those structures are expected to have life times which are shorter than the time of a single orbital revolution (Schnittman, Krolik & Hawley 2006); this does not agree with the observations of flares lasting for several orbital periods (up to hours).

Our description might be somewhat challenged by X-ray observations for which quasi-periodicities as short as 5 min have been claimed (Aschenbach et al. 2004; Aschenbach 2006). Using the dynamical picture described above, such a short period would require a spin of about a = 0.99. Indeed Aschenbach et al. (2004) claim the detection of several, resonant frequencies in the same flares. They interpret this as a signature of oscillations in the accretion disc, leading to a spin of a = 0.996 and a mass of M_SgrA∗ = 3.3 × 10⁸ M⊙ (Aschenbach 2006). However, Béland et al. (2006) find one periodicity of 22 min and no additional signals in the same data sets. They developed a rigorous statistical method that excludes other (quasi-)periods being present to a statistically significant level in the data. This 22-min-period falls in the range of the periods observed in NIR flares. From now on, we implicitly assume that the flare emission comes from matter orbiting the BH.

The fact that the flare emission is polarized nicely confirms the synchrotron radiation nature of the emitted light. This was already suspected from the overall spectral energy distribution, NIR and X-ray colour indices and the occasional occurrence of simultaneous NIR and X-ray flares (Zylka & Mezger 1988; Zylka, Mezger & Lesch 1992; Baganoff et al. 2001; Baganoff et al. 2003; Liu et al. 2004; Yuan et al. 2004; Eckart et al. 2006a). In this context, the polarization parameter curves (Figs 3 and 5) convey information about the geometry of the magnetic field. The remarkable permanence of the polarization parameters, in particular polarization angle, across

Figure 8. An artificial flare light curve as illustration of substructure signatures. All units are arbitrary, but numerical values were selected thus that a comparison to Fig. 7 is straightforward. Top left-hand panel: the additive components of the artificial flare: an overall profile (sine half-wave) with amplitude 10 and duration 100; a sine wave modulation with amplitude 1.2 and period 18; and Gaussian noise with σ = 1. Top right-hand panel: Scargle periodograms for each of the three components shown in the top left-hand panel. Bottom left-hand panel: the synthesized flare light curve. This is the sum of the three components shown in the top left-hand panel plus a constant background of height 1. To ease a comparison to real data, all data points are plotted with error bars with the length of the noise’s σ. Bottom right-hand panel: Scargle periodogram of the light curve shown in the bottom left-hand panel.
three NIR flares observed over 2 yr (Eckart et al. 2006b, this work) indicates that the magnetic field geometry as well as the orbital plane remained the same for all three events. This shows that the flaring material has enough time to settle in the BH’s equatorial plane before the occurrence of the flare, and speaks in favour of a somewhat permanent accretion disc experiencing energetic events rather than temporary structures building up randomly for each flare.

5.2 Geometry of the system

When comparing our data to the models by Broderick & Loeb (2006), the non-detection of variations in the polarization angle during the peak phase strongly suggests that the accretion disc is seen (within few degrees) edge-on. The non-detection of variations in the polarization fraction also speaks for an edge-on view of the disc. This parameter is not exactly constant, but it would show only a short dip (∼2 min) that our time sampling would not allow detecting. Additionally, the constancy of the polarization fraction (about 15 per cent during the peak phase) speaks against the picture of (i) a dominating, slow component of the light curves (e.g. emission from the disc itself) on top of which (ii) the periodic signal due to a second component is seen. Such a second component would be unlikely to be subject to the same magnetic field as the bright spot itself. On the contrary, the mechanism proposed by Paumard et al. (in preparation) by which this slow component is due to shearing of the hotspot, evolving into a ring, fits this observational result well.

There are basically two possible geometries for the magnetic field in the orbiting spot scenario: poloidal (perpendicular to the orbital plane) and toroidal (tangential to the orbit). The poloidal field is more natural in the absence of matter or outside of the disc. On the other end, the field inside the disc is most likely frozen and dragged by the matter. Due to shear, this naturally leads to a toroidal field (De Villiers, Hawley & Krolik 2003; Broderick & Loeb 2006). A transition region above the disc and at its inner edge must exist, in which the magnetic field is somewhat disorganized. This explains the fairly low observed polarization fraction (∼15 per cent; in a perfectly organized field, the polarization fraction of synchrotron emission is of order 75 per cent, Pacholczyk 1970). The question remains which component of the field is dominant; we will come back to this later.

The decay part of the flare reported here (Sections 2 and 3) shows a dramatic change in both polarization fraction (from 15 per cent to 40 per cent) and polarization angle (from 80° to 10°). It follows that the magnetic field seen by the electrons also changes dramatically. It becomes much more organized, leading to an increased polarization fraction, and rotates by ∼70°. There are two options to explain this change: either the field changes where the electrons are, or the electrons move to region with a different field geometry. We will explore both possibilities below.

Let us first assume the flaring material remains on the orbital plane: in this case, a change in the magnetic field could be due to the fact that the accretion disc vanishes, letting the magnetic field relax into its matterless state, which is poloidal. This means that the field was mostly toroidal during the peak phase. The same conclusion is reached if the matter leaves the disc from its inner edge, falling onto the BH.

The other possibility is that the material moves out of the accretion disc. Since the flares are magnetically driven, it seems natural to assume that this matter would follow the field lines, perhaps into a jet. Here again, the final magnetic field is likely poloidal, hence the initial field is toroidal.

In these two schemes, the field is toroidal during the peak phase and poloidal during the decay phase. We now assume that this is the case. A toroidal field in the peak phase is yet another hint that the material has settled into a disc and been able to drag the field before the occurrence of the flare.

The orientation of the magnetic field with respect to the Galactic plane, which is located at +27°, contains additional information. Indeed the peak phase polarization angle is roughly perpendicular to the Galactic plane (to within ∼30°), whereas the decay phase polarization angle is mostly in the Galactic plane (to within ∼10°).

We therefore see here an indication that the accretion disc of SgrA* lies essentially in the plane of the Galaxy, and that its spin axis is essentially aligned with that of the Galaxy. But as long as there are no stricter constraints on the polarized NIR emission from SgrA*, it is possible that future observations revise this picture.

5.3 Proposed model

Given together, we state that our data support the following model: SgrA* is a fairly rapidly (perhaps maximally) rotating BH. Its spin axis is essentially aligned with that of the Galaxy. It is surrounded by a somewhat permanent accretion disc, with an inner edge close to the ISCO, in which the magnetic field is toroidal. Outside of this disc, the field is poloidal. Occasionally, shear will bend the magnetic field so much that a magnetic reconnection is warranted. This is most likely to occur near the inner edge of the disc, where shear is most effective. The magnetic reconnection heats a fraction of the electrons to a hot temperature (∼10^7 K). The region affected is localized, smaller than the constraint imposed by cooling-time arguments in Gillessen et al. (2006): R < 0.3R_S. These electrons swirl in the toroidal magnetic field and emit synchrotron emission. The emitting region orbits the BH, giving rise to the periodic signal we observe. Shear as well as magnetic forces make the region extend along the orbit. Since it spans only a small range in distance from the BH, the shear is not extremely fast and allows the periodic signal to be discernable for several periods. Nevertheless, within a few orbital periods, the entire ISCO glows in synchrotron emission, and this emission is responsible for the dominating, slow part of the light curves (Paumard et al., in preparation). After some time, the magnetic reconnection is over, removing the heating mechanism from the picture. The electron population cools down, and at the same time extend outside of the disc, perhaps into a jet. The dominating field then becomes poloidal.

6 SUMMARY

On 2006 May 31, we observed a K_s-band flare from SgrA* which shows

(i) a high level of total flux, up to ∼16 mJy;
(ii) strong, variable polarization, with p = 15–40 per cent;
(iii) a polarization angle between ∼80° (during the peak phase) and ∼10° (in the decay phase), swinging within about 15 min;
(iv) repeated substructure (double peak in total and polarized flux) on a time-scale of 15 min.

Using this as well as information gathered during the last years from radio, NIR and X-ray observations, we see strong indication that the flare emission in SgrA* is the synchrotron emission from material orbiting the BH. We also find indication that some of this material eventually makes it into a jet, reconciling the ‘orbiting spot scenario’ tenants with the jet hypothesis literature (Markoff et al. 2001; Yuan et al. 2002).
Finally, we might have observed the first pieces of evidence that a SMBH spin axis is aligned with that of its host galaxy.

ACKNOWLEDGMENTS

Special thanks to N. Ageorges, ESO, for helpful discussions on NACO. We are grateful to the ESO instrument scientists and engineers who made possible this successful work. FM acknowledges support from the Alexander von Humboldt Foundation. We also would like to thank the anonymous reviewer whose comments helped to improve the quality of this article.

REFERENCES

Aitken D. K., Greaves J., Chrysostomou A., Jenness T., Holland W., Hough J. H., Pierce-Price D., Richer J., 2000, ApJ, 534, L173
Aschenbach B., 2006, ChJAS, 6, 221
Aschenbach B., Grosso N., Porquet D., Predehl P., 2004, A&A, 417, 71
Baganoff F. K. et al., 2001, Nat, 413, 45
Baganoff F. K. et al., 2003, ApJ, 591, 891
Balick B., Brown R. L., 1974, ApJ, 194, 265
Bardeen J. M., Press W. H., Teukolsky S. A., 1974, ApJ, 194, 265
Bélinger G., Goldwurm A., Melia F., Ferrando P., Grosso N., Porquet D., Warwick R., Yusef-Zadeh F., 2005, ApJ, 635, 1095
Bélinger G., Terrier R., De Jager O., Goldwurm A., Melia F., 2006, ApJ, in press
Bonnet H. et al., 2003, SPIE, 4839, 329
Bonnet H., Abuter R., Baker A., Bornemann W., Brown A., Castillo R., Conzelmann R., Danzter R., 2004, The ESO Messenger, 117, 17
Bower G. C., 2003, Ap&SS, 288, 69
Bower G. C., Backer D. C., Zhao J. H., Goss M., Falcke H., 1999a, ApJ, 521, 582
Bower G. C., Falcke H., Backer D. C., 1999b, ApJ, 523, L29
Bower G. C., Wright M. C., Falcke H., Backer D. C., 2003, ApJ, 588, 331
Bower G. C., Falcke H., Wright M. C., Backer D. C., 2005, ApJ, 618, L29
Broderick A. E., Loeb A., 2006, MNRAS, 367, 905
Clénet Y. et al., 2004, A&A, 424, L21
Clénet Y., Rouan D., Gratadour D., Marco O., Léna P., Ageorges N., Gendron E., 2005, A&A, 439, L9
De Villiers J.-P., Hawley J. F., Krolik J. H., 2003, ApJ, 599, 1238
Eckart A., Genzel R., Hofmann R., Sams B. J., Tacconi-Garman L. E., 1995, ApJ, 445, L23
Eckart A. et al., 2006a, A&A, 450, 535
Eckart A., Schödel R., Meyer L., Trippe S., Ott T., Genzel R., 2006b, A&A, 455, 1
Eisenhauer F., Abuter R., Bickert K., Biaucat-Marchet F., Bonnet H., Brynnel J., Conzelmann R. D., Delabre B., 2003a, SPIE, 4841, 1548
Eisenhauer F., Tecza M., Thalte N., Genzel R., Abuter R., Iserlohe C., Schreiber J., Huber S., 2003b, The ESO Messenger, 113, 17
Eisenhauer F. et al., 2005, ApJ, 628, 246
Falcke H., Markoff S., 2000, A&A, 362, 113
Genzel R., Schödel R., Ott T., Eckart A., Alexander T., Lacombe F., Rouan D., Aschenbach B., 2003, Nat, 425, 934
Ghez A. et al., 2004, ApJ, 601, L159
Ghez A. et al., 2005, ApJ, 635, 1087
Gillet S. et al., 2006, ApJ, 640, L163
Goldwurm A., Brion E., Goldoni P., Ferrando P., Daigne F., Decourchelle A., Warwick R. S., Predehl P., 2003, ApJ, 584, 751
Kato S., 2001, PASJ, 53, 1
Krabbe A., Iserlohe C., Larkin J. E., Barczys M., McElwain M., Weiss J., Wright S. A., Quirrenbach A., 2006, ApJ, 642, L145
Lenzen R. et al., 2003, SPIE, 4841, 944
Liu S., Petrosian V., Melia F., 2004, ApJ, L101, 2004
Macquart J.-P., Bower G. C., Wright M. C. H., Backer D. C., Falcke H., 2006, ApJ, 646, L111
Markoff S., Falcke H., Yuan F., Biermann P. L., 2001, A&A, 379, L13
Marrone D. P., Moran J. M., Zhao J. H., Rao R., 2006, ApJ, 640, 308
Melia F., Falcke H., 2001, ARA&A, 39, 309
Miyazaki A., Tsutsuji T., Tsuboi M., 2004, ApJ, 611, L97
Nayakshin S., Cuadra J., Sunyaev R., 2003, A&A, 413, 173
Ott T., Eckart A., Genzel R., 1999, ApJ, 523, 248
Pacholczyk A. G., 1970, Radio Astrophysics. Freeman & Co., San Francisco, ISBN 0-7167-0329-7
Pétri J., 2006, Ap&SS, 302, 117
Rousset G., Lacombe F., Puget P., Hubin N. N., Gendron E., Fusco T., Arsenault R., Charton J., 2003, SPIE, 4839, 140
Scargle J. D., 1982, ApJ, 263, 835
Schnittman J. D., Krolik J. H., Hawley J. F., 2006, ApJ, 651, 1031
Trippe S., 2004, Master thesis (Diplomarbeit), Ludwig-Maximilians-Universität München
Yuan F., Markoff S., Falcke H., 2002, 383, 854
Yuan F., Quataert E., Narayan R., 2004, ApJ, 606, 894
Yusef-Zadeh F. et al., 2006, ApJ, 644, 198
Zylka R., Mezger P. G., 1988, A&A, 190, L25
Zylka R., Mezger P. G., Lesch H., 1992, A&A, 261, 119

This paper has been typeset from a TEX/LATEX file prepared by the author.