Mem. S.A.It. Vol. 79, 1054

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# Flares of Sgr A*: from X-ray to mm

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**Abstract.** Here we report on the results of our recent coordinated mm/sub-mm/NIR observations of Sagittarius A* (Sgr A*) in May 2007. The observations revealed several flare events in all wavelength domains. These flare emissions can be described with a combination of a synchrotron self-Compton model (SSC) followed by an adiabatic expansion of the source. The NIR observations can be interpreted in a model involving a temporary disk with a short jet. In the disk component the quasiperiodic flux variations can be explained due to the spots on relativistic orbits around the central supermassive black hole (SMBH). The 15 May 2007 NIR flare shows the highest subflare contrast observed until now. It shows also evidence for a variation of the profile of consecutive subflares. This profile variation could be successfully modeled through the variation of the spot structure due to differential rotation within the accretion disk.
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**Key words.** black hole physics, X-rays: general, infrared: general, accretion, accretion disks, Galaxy: center, Galaxy: nucleus

## 1. Introduction

Compelling evidence for a massive black hole at the position of Sgr A* is provided by observations of stellar dynamics (Eckart et al. 1996; Genzel et al. 1997; Ghez et al. 1998; Eckart et al. 2002; Schödel et al. 2002, 2003; Eisenhauer et al. 2005), and variable emission from that position (Baganoff et al. 2001; Eckart et al. 2004; Genzel 2003; Yusef-Zadeh et al. 2006). The close temporal correlation between rapid variability of the near infrared (NIR) and X-ray emission suggests that the emission with $10^{33-34}\,erg\,s^{-1}$ flares arises from a compact source within a few tens Schwarzschild radii ($R_s = 2R_g = 2GM/c^2 \sim 8\ \mu$as) of the black hole. This points to a common physical origin of the phenomena and may be linked to the

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variability at radio through submillimeter wavelengths.

The flares can be explained with a synchrotron self-Compton (SSC) model involving up-scattered submillimeter photons from a compact source component (Eckart et al. 2004, 2006). Inverse Compton scattering of the THz-peaked flare spectrum by the relativistic electrons then accounts for the X-ray emission. This model allows for NIR flux density contributions from both the synchrotron and SSC mechanisms.

There is also evidence for a 17±3 minute quasiperiodic modulation of the NIR and X-ray emission (Genzel 2003; Eckart et al. 2006; Meyer et al. 2006,?; Belanger et al. 2006; Aschenbach et al. 2004; Aschenbach 2004). In the following we refer to this phenomenon as QPO: quasi periodic oscillation. The NIR flare emission is polarized with a well defined range over which the position angle of the polarized emission is changing (60º ± 20º; Eckart et al. 2006b; Meyer et al. 2006a,b,2007). All these observations can be explained in a model of a temporary accretion disk harboring a bright orbiting spot possibly in conjunction with a short jet (Eckart et al. 2006, 2008; Meyer et al. 2006,?, 2007), suggesting a stable orientation of the source geometry over the past few years. On the other hand, radio/sub-mm/NIR observations also indicate adiabatic expansion within a SSC model (Eckart et al. 2006, 2008; Yusef-Zadeh et al. 2006) and the emission very likely originates from a combination of a temporal accretion disk and a short, low-luminosity jet.

Here we present the most recent NIR measurements that we obtained using the VLT[1] and the results of our relativistic hot-spot modeling which includes the effects of rotational shearing inside the accretion disk. To show the possible link of this activity to mm and sub-mm flares we present data obtained with CARMA (Combined Array for Research in mm-wave Astronomy), ATCA (Australia Telescope Compact Array) and MAMBO 2 (Max-Planck Millimeter Bolometer) at the IRAM 30m telescope during a coordinated, multi wavelength observing campaign of Sgr A* in May 2007.

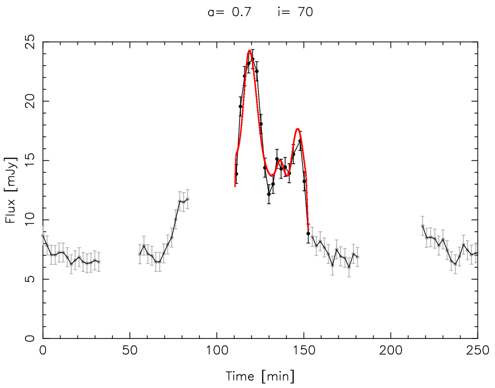


**Fig. 1.** The best fit achieved by a spot model including the rotational shearing for the 15 May 2007 NIR flare. The fit prefers high inclination angle and spin parameter ($i$ = 70º & $a$ = 0.7).

## 2. Observations and data reduction

As part of a large observing campaign, Sgr A* was observed in May 2007 using the VLT. The observations of Sgr A* were carried out in the NIR $K_S$-band (2.0-2.36$\mu$m) using the NIR camera CONICA and the adaptive optics (AO) module NAOS on the European Southern Observatory's Very Large Telescope UT4 on Paranal, Chile, during the nights between 14 and 15 May 2007.

Furthermore, we observed the Galactic Center at 100 and 86 GHz (3 mm wavelength) with the two mm-arrays CARMA and ATCA. In addition we observed with the MAMBO 2 bolometer at the IRAM 30 m-telescope at a wavelength of 1.3 mm. The flux monitoring was accompanied by VLBI imaging performed in parallel on 10 consecutive days with the VLBA at 22, 43 and 86 GHz. The interferometric data were analysed using AIPS and MIRIAD. The data from the bolometer array were analyzed using BoA (IRAM bolometer data analysis package).

[1] Based on observations at the Very Large Telescope (VLT) of the European Southern Observatory (ESO) on Paranal in Chile; Program: 079.B-0084 May 2007.

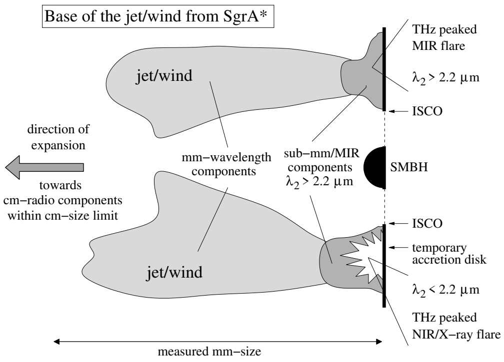


**Fig. 2.** A possible source structure for the accretion disk around the SMBH associated with Sgr A*. In this sketch the disk is shown as a vertical thick line to the right. Extending to the left, we show one side above the disk. Higher energy flare emission (lower part) is responsible for the observed NIR/X-ray flare emission. Lower energy flare emission (upper part) may be peaked in the THz domain and may substantially contribute to long wavelength infrared emission. Here we have assumed that their NIR/X-ray contributions are negligible (see more details and model description in Eckart et al. 2008). In addition to the expansion towards and beyond the the mm-source size, radial and azimuthal expansion within the disk may occur. Here $\lambda_2$ is the wavelength corresponding to the upper synchrotron cutoff frequency.

## 3. Modeling and discussion

We interpret the polarized infrared flare events via the emission of spots on relativistic orbits around the central SMBH in a temporary disk (Eckart et al. 2006b, Meyer et al. 2006ab, 2007). The model calculations are based on the KY-code by Dovciak, Karas, & Yaqoob (2004) and are usually done for a single spot orbiting close to the corresponding last stable orbit. This allows us to fit the model parameters to the actual data. The procedure was first demonstrated by Meyer et al. (2006ab, the authors also discuss in detail the differences with other modeling efforts, e.g. Broderick & Loeb 2006a,b). This procedure implies that the dimensionless spin parameter exceeds a minimum value of 0.5 (Fig. 1, see also Eckart et al. 2004; Meyer et al. 2006a,b).

A combination of this SSC hot spot model and an adiabatically expanding model could successfully fit the data from X-ray/NIR to the sub-mm and mm domain (Fig. 2, Eckart et al., private communication). Fig. 3 shows the combined light-curve from all telescopes. Data from different frequencies combined under the assumption that the spectral index of Sgr A* does not change significantly during the flux density variations between 86 and 250 GHz. Fig. 3 shows two peaks, on May 15 and 17 (there is a weaker, third possible peak on May 19). The comparison reveals that the NIR flares occurred during or just before times of excess mm/sub-mm flux density. For May 15 the details of the NIR flare have been described by Eckart et al. (2008). The observed time difference between the NIR and mm/sub-mm flares can be interpreted in the framework of (adiabatic) expansion of jet or disk synchrotron components - in full support of previous evidence for adiabatic expansion (Eckart et al. 2006; Yusef-Zadeh et al. 2006). Future measurements will concentrate on monitoring the flux density variability of Sgr A* in coordinated campaigns (radio/mm/MIR/X-ray) and in polarized radio/NIR emission. NIR telescopes with large aperturtes (VLT, Keck, LBT, TNT) will be best suited to separate Sgr A* from the surrounding high velocity stars, especially during faint phases. Similarly mm-interferometers like the PdBI, CARMA, ATCA and in future ALMA can separate Sgr A* from the thermal emission of the CND and the mini-spiral. Therefore, the combination of these observing facilities will allow us to study the evolution of expanding synchrotron components.

With near future mm-VLBI at frequencies at and above 230 GHz, the imaging of the central region of Sgr A* will become possible, allowing to map out the structure of Sgr A* on spatial scales of only a few gravitational radii. By this it should be possible to directly test the hypothesis of spiraling plasmons or density waves in the accretion disk.

*Acknowledgements.* Part of this work was supported by the German *Deutsche Forschungsgemeinschaft, DFG* via grant SFB 494. M. Zamaninasab, D. Kunneriath and R.-S. Lu are members of the International Max Planck Research School

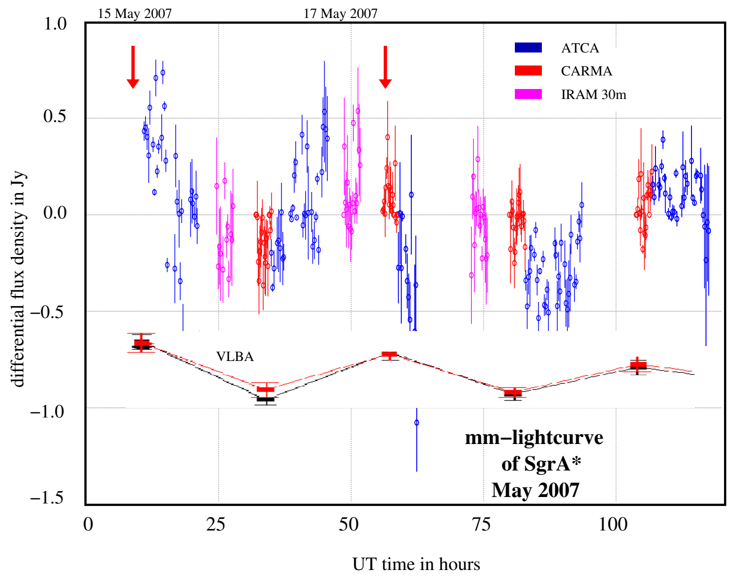


**Fig. 3.** Combined differential light curve of SgrA* in the mm/sub-mm domain for the May 2007 observing run. The MAMBO 2 bolometer at the IRAM 30m-telescope was operated at a central wavelength of 1.2 mm (250 GHz). The CARMA data were centered at 100 GHz and the ATCA data at 86 GHz. We also show the daily 7mm flux density averages of our 2007 VLBA session (black and red symbols represent the signals from the R and L circularly polarized channels). The red vertical arrows mark the peak times of NIR flares observed with NACO. The time axis is labeled with UT hours starting at 00 h on May 15.

(IMPRS) for Astronomy and Astrophysics at the MPIfR and the Universities of Bonn and Cologne. R.S. acknowledges support by the Ramón y Cajal programme by the Ministerio de Ciencia e Innovación of the government of Spain.

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