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Sgr A* in the Near Infrared

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Abstract. The massive black hole Sgr A* in the center of the Milky Way is a source of highly variable X-ray and infrared radiation, best described as individual flares that happen every few hours and last for roughly one hour. Flares are extremely interesting in itself, the emission mechanism being synchrotron radiation in the infrared and Inverse Compton scattering in the X-ray domain. Naturally, one needs simultaneously large optical telescopes and X-ray satellites to study the physics of these flares. Furthermore and independent from the exact emission mechanism, flares can be used as a probe for the gravitational field in which they occur - the strongly curved space-time around a rotating black hole of 4 million solar masses. To measure the dynamics of flares near-infrared interferometry seems to be suited best. I discuss both aspects of future observations of Sgr A*, with some emphasis on interferometry which has the potential to ultimately test general relativity in its strong field regime.

Key words. blackhole physics — Galaxy: center — infrared: stars — techniques: interferometric

1. Introduction

Sgr A* is the black hole candidate in the Galactic Center (GC). It was discovered first in the radio regime (Balick & Brown 1974). Today the source can be observed in the radio, submm, NIR and X-ray regime. While at the longer wavelengths it is a rather steady source, Sgr A* shows strong flux variations in the NIR and X-ray domain.

The NIR has been particularly important in proving the nature of Sgr A* as a massive black hole. Other than at radio and submm wavelengths the NIR allows to observe stars which can be used as clean test particles for the gravitational potential of the much heavier black hole. The GC is a region with an extremely high density of stars. Therefore, historically, the clue has been the development of high angular resolution techniques. The main obstacle is Earth's atmosphere, blurring all images to $\sim 1''$, much worse than the diffraction limit of the telescopes used in the NIR.

In 1992 the first useful diffraction-limited images from the GC have been obtained using Speckle techniques at ESO's 3.6m NTT, leading to the detection of very high proper motions (Eckart & Genzel 1996). The 10m Keck telescope started Speckle observations in 1995, resulting in the detection of accelerations (Ghez et al. 2000). The next major step for-

Send offprint requests to: Stefan Gillessen ward was the use of adaptive optics at the 8.2m VLT in 2002 which immediately led to the determination of the first stellar orbit around SgrA* (Schödel et al. 2002). These measurements finally established the nature of Sgr A* as a massive black hole of $4 \times 10^6 M_\odot$.

In the same year, the VLT also discovered Sgr A* for the first time in the NIR (Genzel et al. 2003). A spurious NIR source was observed at the position where the previously derived point mass hasd to to reside, also coincident with the radio source Sgr A*.

2. Characteristics of Sgr A* in the NIR

Sgr A* is extremely dim, it typically emits only at $10^{-10} \times L_{\rm Eddington}$. The bulk of energy is released in the submm. In the NIR most of the time it is too faint to be detected in the highly confused steller field around it. Typically once per night, however, it shines up and reaches K-band (2.2μm) magnitudes of $m_K = 14$ (corresponding to $\nu L_\nu \approx 2 \times 10^{34}$erg/s), comparable to the stars for which orbits have been determined. These flares last around 90 minutes. The light from Sgr A* is notably redder than that of the stars. For reasonably bright flares one finds a power law index of $\beta \approx 1$ in $\nu L_\nu \sim \nu^\beta$, while the faintest states of Sgr A* seem to be even redder (Eisenhauer et al. 2005a; Gillessen et al. 2006), $\beta \approx -3$. The submm emission of SgrA* can be unterstood in terms of radiatively inefficient accretion flow models (Yuan, Quataert & Narayan 2003, 2004), in which the submm emission is explained by the synchrotron light of a population of thermal electrons with $T \approx 10^{11}$K. However, such models fail to predict any significant NIR flux. The NIR flares require that a small fraction (few %) of the electrons is heated to $T \approx 10^{12}$K.

Another striking feature of the NIR flares is the quasi-periodicity in the light curves. Essentially in all flares observed at the VLT so far under good conditions the power spectra of the light curves showed excess power in the region around 17 - 22 minutes (Genzel et al. 2003; Trippe et al. 2007). The variations have been seen in the H-, K- and L-band, thus from 1.4μm to 4μm. This has been interpreted as signature of the orbital motion of the heated electrons (Genzel et al. 2003). Since the shortest possible period for a $4 \times 10^6 M_\odot$ black hole at the innermost stable circular orbit is ≈ 30 minutes, the shorter periods observed put a lower limit of $a \gtrsim 0.5$ for the spin of Sgr A*.

In 2004 VLT observations have shown that the NIR emission of Sgr A* can be strongly (up to 40%) polarized (Eckart et al. 2006; Trippe et al. 2007). Since then polarization has been measured for several flares. The angle on-sky of the linear polarization has been found to be the same for all these flares. This strongly suggests a stable geometry of the source, as expected for instance for an accretion disk. The angle coincides within the errors with the orientation of the galactic plane. One possible geometry could be a toroidal magnetic field in the accretion disk which in turn is then roughly aligned with the galactic plane. Moreover, in one case even a swing of the angle away from the usual value at the end of the flare has been observed (Trippe et al. 2007).

3. Simultaneous NIR and X-ray observations

Also in the X-ray domain Sgr A* is a variable source, its emission can be described also in the X-ray regime as flares. Therefore it was obvious to try simultaneous observations in the two wavebands. The first successful attempt (Eckart et al. 2004) already showed two extremely interesting findings: The X-ray flares happen simultaneously to the NIR flares and they evolve on the same time scale. These findings support the idea that the X-ray emission is due to the Inverse Compton (IC) radiation of the transiently heated electrons that create the NIR emission. In this picture both the simultaneity and the coevolution of the NIR and X-ray emission are natural. In contrast, if the X-ray emission were due to synchrotron emission, the cooling time of the electrons would be much shorter than the observed X-ray variations.

From the IC picture one can derive an estimate for the size of the flaring region. The brightness ratio of synchrotron to IC flux is a function of the source size and the magnetic

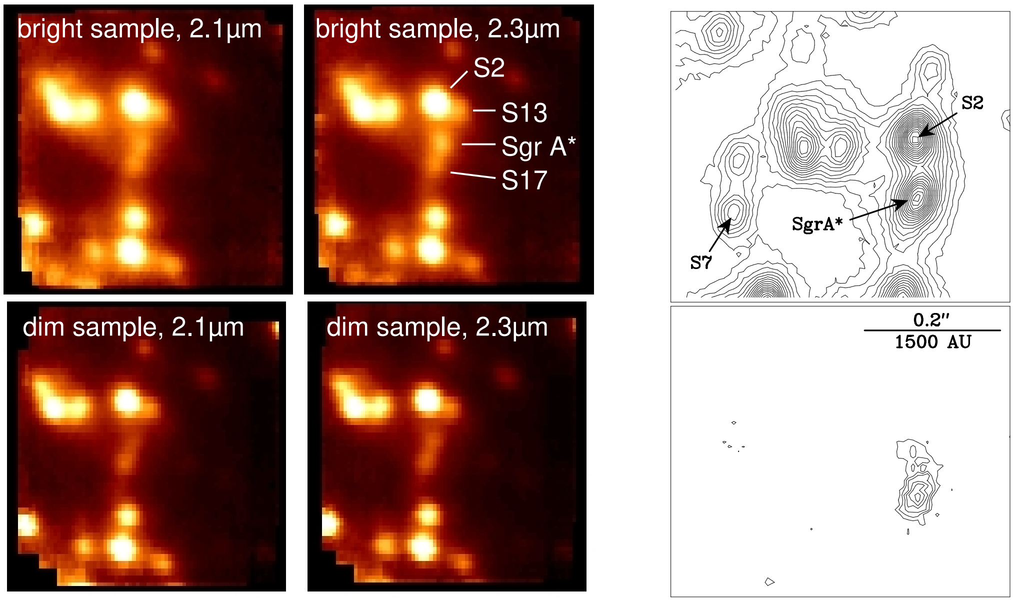


Fig. 1. Left (4 panels): A flare from Sgr A* as seen with the NIR integral field spectrograph SINFONI at the VLT. The channel maps from a bright state and a dim state sample of exposures. Sgr A* is brighter in the longer wavelength maps, indicating that it is is redder than the field stars. Furthermore, the effect is more pronounced in the dim sample, meaning that Sgr A* is redder therein than in the bright sample. Right (2 panels): Another flare from Sgr A* observed with the NIR image NACO at the VLT in polarimetric mode. The top panel shows the sum of the two polarization states, the bottom one the difference. Clearly Sgr A* is the only polarised source in the field.

field strength. Assuming the canonical value of $B = 30$G (Yuan, Quataert & Narayan 2004) and taking the observed range of brightness ratios $X/IR \approx 0.1-1$ one finds that the size of the emitter is roughly 0.3 Schwarzschild radii and thus is small compared to size of the accretion disk. This confirms the idea that flares are due to orbiting hot spots.

In April 2007 another bright, simultaneous NIR and X-ray flare has been observed with the VLT and XMM/Newton. The data both in the NIR and the X-ray is of exquisit detail. The analysis is ongoing and further constraints on the emission mechanism can be expected.

4. Future observations of Sgr A*

The future research on flares of Sgr A* can be divided into two categories:

1. Better understand the physics of the emission mechanism
2. Use the emission as a probe for relativistic dynamics close to an event horizon

The first category essentially is a refinement of research being done today already. The number of well-covered flares still is relatively low, and some of the NIR properties of Sgr A* are not yet fully accepted in the community. In particular the significance of the quasi-periodic oscillations is discussed as well as the NIR color of the fainter flares. Furthermore, in the MIR (10μm) the spectral energy distribution of Sgr A* is only relatively weakly constrained by current upper limits. Clearly, a further understanding of the emission from Sgr A* will rely on simultaneous multi-wavelength campaigns. In particular it would be important to measure simultaneously the spectral index in the NIR and X-ray domain, which has never been achieved so far. Ideally such a measurement would allow to follow the evolution of

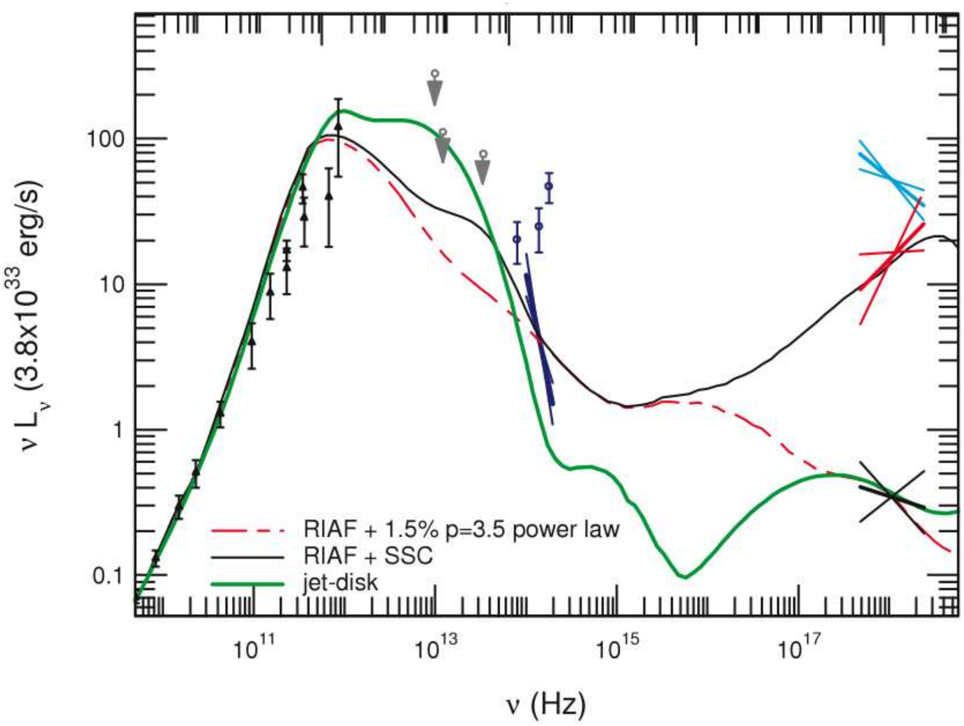


Fig. 2. Compilation of observations and models for Sgr A* from the radio to the X-ray regime (Eisenhauer et al. 2005a).

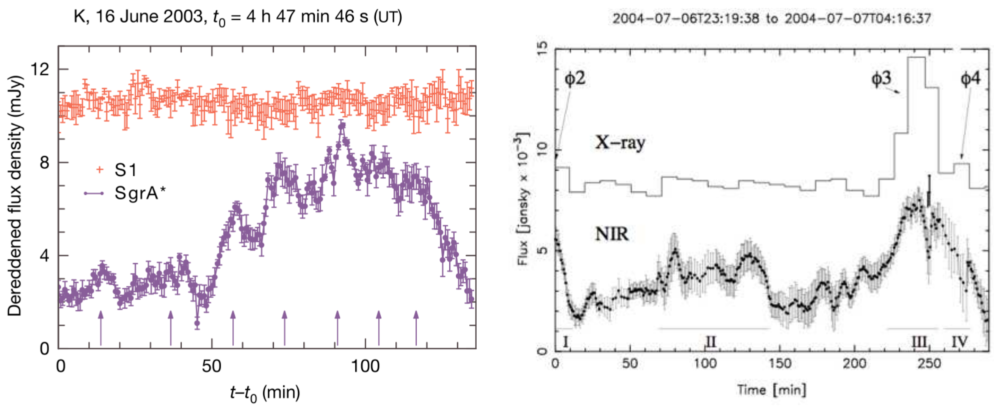
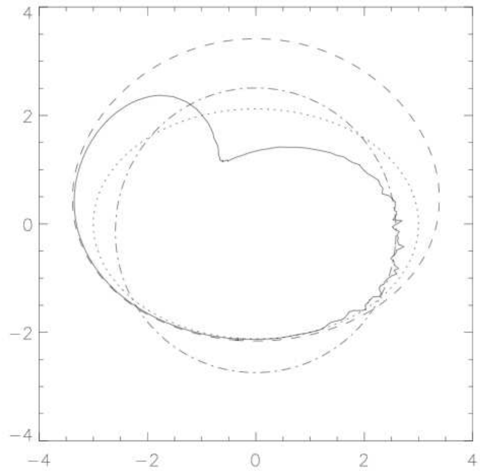


Fig. 3. Left: A light curve from a NIR flare of Sgr A*. The most striking feature is the quasiperiodic oscillation on a timescale of ≈ 20min. Right: Simultaneous light curves from Sgr A* in the NIR and X-ray (Eckart et al. 2004). Clearly the two wavebands coevolve.

flux and color of Sgr A* in the two wavebands in parallel during flare events. This would allow to test in detail the theoretical models for Sgr A*.



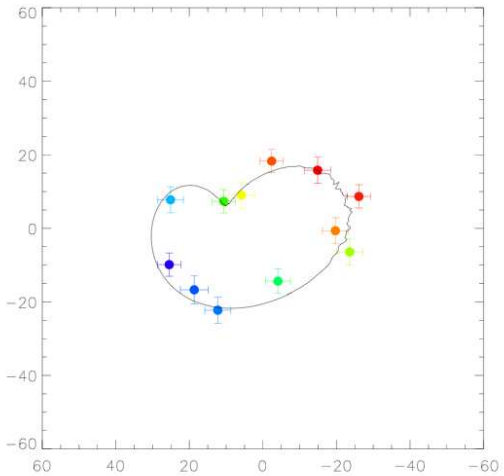


Fig. 4. Left: Strong relativistic effects around a black hole: A compact source orbits the black hole. Multiple images occur. The unresolved centroid moves along the solid line and can be used to trace the relativistic effects. The units are Schwarschil radii. Right: Simulated observations of an orbiting hot spot. Ten flares have been coadded, assuming an astrometric accuracy of 10 μas. Further it was assumed that every 3 minutes an exposure was possible. The units are microarcseconds.

The second category aims at a different physics. Since the flares are originating from a localized source close to the event horizon of Sgr A*, they are probes of the dynamics and light propagation properties of the gravitational field. Such an observation program would ultimately aim at testing gravity in its strong field limit.

Interestingly, the corresponding observations seem feasible. The angular diameter of the event horizon of Sgr A* on sky is 10 μas. Scaling the astrometric accuracy from existing imaging systems shows that an interferometer with a baseline of $B \approx 100$m allows to measure positions relative to a phase reference source with 10 μas accuracy. This has been demonstrated recently for the Palomar testbed interferometer (Lane & Muterspaugh 2004). For accessing Sgr A*, the telescope apertures have to be much larger and adaptive optics has to be used. Hence, the ideal facility for an experiment aiming at resolving the motions around Sgr A* is the VLTI.

Current dynamic models which are based on relativistic ray tracing of an orbiting plasma hot spot need in addition to the compact source also a somewhat extended component in order not to overpredict the contrast in the light curves. These models can be used to predict the motion of the light centroid of the flares. Typical values are several tens of microarcseconds per orbital revolution. VLTI observations should therefore be a strong tool for testing gravity induced orbits around Sgr A*. The first step would be to establish the orbital motion in contrast to for example a linear motion. This should be possible with one flare only. If several flares can be coadded, the relativistic effects (like multiple images) would become apparent. This would be probing a completely untested regime of gravity. Unfortunately the current VLTI misses these goals. No 4-telescope beam combiner is available today, the sensitivity of the current instruments is too low and NIR adaptive optics is not available for all four telescopes. Also the upcoming PRIMA facility should reach regularly only 100 μas astrometry. Therefore MPE (Garching) together with the French PHASE collaboration, the Max-Planck-Institute for astronomy (Heidelberg) and the University of Cologne, is currently proposing a 4-telescope beam combiner instrument called GRAVITY that would bring VLTI to its full power (Eisenhauer et al. 2005). The main components ar NIR adaptive optics and a fringe tracking system. Particularly important is the fact that in the GC extreme narrow angle astrometry can be performed. In other words, a suitable phase reference is within the interferometric field of view of VLTI (2”). This essentially means, that the light from the phase reference and Sgr A* will travel on exactly the same beam path, thereby reducing the systematic errors that limit for instance PRIMA by another order of magnitude.

In 2007 the feasibility study for GRAVITY was finished, the proposed schedule foresees installation at the VLTI during 2012.

References

Balick, B. & Brown, R.L. 1974, ApJ, 194, 265

Eckart, A. & Genzel, R. 1996, Nature, 383, 415

Eckart, A.; Baganoff, F. K.; Morris, M.; Bautz, M. W.; Brandt, W. N.; Garmire, G. P.; Genzel, R. & 7 coauthors 2004, A&A, 427, 1

Eckart, A.; Schdel, R.; Meyer, L.; Trippe, S.; Ott, T.; Genzel, R. 2006, A&A, 455, 1

Eisenhauer, F.; Perrin, G.; Rabien, S.; Eckart, A.; Lena, P.; Genzel, R.; Abuter, R.; Paumard, T. 2005, AN, 326, 561

Eisenhauer, F.; Genzel, R.; Alexander, T.; Abuter, R.; Paumard, T.; Ott, T.; Gilbert, A.; Gillessen, S.; Horrobin, M.; Trippe, S.& 11 coauthors 2005, ApJ, 628, 246

Genzel, R.; Schödel, R.; Ott, T.; Eckart, A.; Alexander, T.; Lacombe, F.; Rouan, D.; Aschenbach, B. 2003, Nature, 425, 934

Ghez, A.; Morris, M.; Becklin, E. E.; Tanner, A.; Kremenek, T. 2000 Nature, 407, 349

Gillessen, S.; Eisenhauer, F.; Quataert, E.; Genzel, R.; Paumard, T.; Trippe, S.; Ott, T.; Abuter, R. & 5 coauthors 2006, ApJ, 640, L163

Lane, B. F. & Muterspaugh, M. W. 2004, ApJ, 601, 1129

Schödel, R.; Ott, T.; Genzel, R.; Hofmann, R. & 19 coauthors 2002, Nature, 419, 649

Trippe, S.; Paumard, T.; Ott, T.; Gillessen, S.; Eisenhauer, F.; Martins, F.; Genzel, R. 2007, MNRAS, 375, 764

Yuan, F.; Quataert, E.; Narayan, R. 2003, ApJ, 598, 301

Yuan, F.; Quataert, E.; Narayan, R. 2004, ApJ, 606, 894