Multi-wavelength and polarimetric observations of Sagittarius A*

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Abstract. We summarize the results of some of the latest NIR/sub-millimeter/X-ray observing campaigns. Those include the latest simultaneous observations as well as the most recent results from VLT NACO observations of polarized NIR flare emission of Sgr A*. We interpret the new NIR polarimetry results using a model in which spots are on relativistic orbits around Sgr A*, which is associated with the massive 3.6 million solar mass black hole at the Galactic Center. In the NIR the observations have been carried out using the NACO adaptive optics (AO) instrument at the European Southern Observatory’s Very Large Telescope. In the X-ray and radio domains we used the ACIS-I instrument aboard the Chandra X-ray Observatory and the Submillimeter Array on Mauna Kea, Hawaii, as well as the Very Large Array in New Mexico, respectively.

1. Introduction

The compact radio source Sagittarius A* (Sgr A*) has been convincingly identified in the radio and infrared with a massive black hole (MBH) of mass 3.6±0.3×10^6 M⊙ at the center of our Galaxy (Schödel et al. 2003; Ghez et al. 2005; Eisenhauer et al. 2005) at a distance of only 7.6±0.3 kpc (Eckart & Genzel 1996, Genzel et al. 1997, 2000, Ghez et al. 1998, 2000, 2003a, 2003b, 2005, Eckart et al. 2002, Schödel et al. 2002, 2003, Eisenhauer 2003, 2005). Especially in the case of the center of the Milky Way, progress has been made through the investigation of stellar dynamics (see references above). Sgr A* is the nearest supermassive black hole. It is about one hundred times closer than the nucleus of the nearest similar galaxy in M31*. It therefore provides us with a unique opportunity to understand the physics and possibly the evolution of these objects.

1 Based on observations with CHANDRA and ESO VLT observations 271.B-5019(A) and 271.B-5019(A).
Compelling evidence for a massive black hole at the position of Sgr A* is also provided by the observation of variable emission from that position both in the X-ray and recently in the near-infrared (Baganoff et al. 2001, 2003, Eckart et al. 2004, 2006a, Porquet et al. 2003, Goldwurm et al. 2003, Genzel et al. 2003, Ghez et al. 2004a, Eisenhauer et al. 2005, Belanger et al. 2005, and Yusef-Zadeh et al. 2006a). The temporal correlation between rapid variability of the near-infrared (NIR) and X-ray emission (Eckart et al. 2004, Eckart et al. 2006a) suggests that the emission showing $10^{33-34}$ erg/s flares arises from a compact source within a few ten Schwarzschild radii ($R_S$) of the MBH. This fact points to a common physical origin of the observed phenomena and is probably linked to the variability at radio through sub-millimeter wavelengths (Herrnstein et al. 2004, Mauerhan et al. 2005 and references therein). For a black hole of its size, Sgr A* is extremely underluminous, at about $10^{-9-10} L_{\text{Edd}}$. This surprisingly low luminosity has motivated many theoretical and observational efforts to explain the processes that are at work in the immediate vicinity of Sgr A*.

2. **Simultaneous NIR/X-ray Observations of Sgr A***

Simultaneous observations of Sgr A* from the radio to the X-ray regime are an ideal tool to learn about the emission mechanisms responsible for the radiation from the immediate vicinity of the central black hole. The first successful experiment during which simultaneous X-ray and near-infrared flare emission has been detected was presented by Eckart et al. (2004). They detected a weak $6 \times 10^{33}$ erg/s X-ray flare and covered its decaying flank in the NIR. The flux density variability of Sgr A* at radio through submillimeter wavelengths has been studied extensively, showing that variations occur on time scales from hours to years (e.g. Bower et al. 2002, Herrnstein et al. 2004, Zhao et al. 2003). Some of the radio variability is probably due to interstellar scintillation. So far the connection to variability at NIR and X-ray wavelengths had not been clearly elucidated. Zhao et al. (2004) showed that there is a probable link between the brightest X-ray flare ever observed and flux density at mm- and short cm-wavelengths on a timescale of less than 24 hours (see also Mauerhan et al. 2005).
New simultaneous NIR/sub-millimeter/X-ray observations of the Sgr A* counterpart were recently presented by Eckart et al. (2006a). The authors closely investigate the physical processes that may be responsible for the variable emission from Sgr A*. The observations were carried out using the NACO adaptive optics (AO) instrument at the European Southern Observatory’s Very Large Telescope and the ACIS-I instrument aboard the Chandra X-ray Observatory as well as the Submillimeter Array on Mauna Kea, Hawaii, and the Very Large Array in New Mexico. Eckart et al. (2006a) detected one moderately bright flare event in the X-ray domain and 5 events at infrared wavelengths. At 2 - 8 keV the X-ray flare had an excess luminosity of about $33 \times 10^{33}$ erg/s. For its entire duration the flare was covered in the X-ray domain and was detected as a simultaneous NIR event with no time lag larger than an upper limit of $\leq 10$ minutes - which is mainly given by the required binning width of the X-ray data.

The time-lag between the NIR and X-ray flare emission is very small and in agreement with a synchronous evolution (see Fig.1). This is indicated by all flares covered simultaneously in 2003 and 2004. Cross-correlation shows that the time lag between the flares at different wavelengths is less than 10 minutes and therefore consistent with zero. There was no extensive overlap between radio and the NIR/X-ray measurements in 2004 resulting in no simultaneous flare detections between the NIR/X-ray data and the VLA and SMA data. However, the excess flux densities detected in the radio and sub-millimeter domain may indeed be linked with the flare activity observed at shorter wavelengths. Combined with the information that the NIR flare spectra are very red with variable spectral indices (Eisenhauer et al. 2005, Hornstein et al., this issue and Ghez et al. private communication) we can successfully describe the flares by a SSC model in which a substantial fraction of the NIR emission is due to a truncated synchrotron spectrum. The flaring state can be explained with a synchrotron self-Compton (SSC) model involving...
Figure 3. Comparison between model results of an orbiting spot model (red lines) for July 2005 and the measured total flux density (left) and polarization angle (right). The thin dashed lines in the right panel indicate the \( \pm 3\sigma \) uncertainties of the data. The vertical dashed lines indicate the times at which sub-flares occurred. For details see Eckart et al. (2006b). The model is shown in red. The model calculations show the compatibility of the orbiting spot model with the NIR polarization data.

There are a number of detailed items linked to the variability and the overall spectrum of Sgr A* that have to be mentioned. They are a direct consequence of the model described above and the most recent MIR/NIR measurements.

The NIR flares may contain both synchrotron and SSC flux density contributions: The total number of detectable flares can be obtained by integrating over the amplitude dependent flare rate. The model presented by Eckart et al. (2006a) suggests that in the NIR domain the observed flares can be produced by a mixture of both synchrotron and SSC emission. Here we can assume that the X-ray flares are predominantly produced by SSC emission rather than synchrotron emission. As a consequence - and in good agreement with the observations - the total number of detected X-ray flares is smaller than that in the NIR. However, the NIR flares may have contributions from both the synchrotron and the SSC part of the flare spectrum. The contribution of the latter depends on the properties of the relativistic electron spectrum reflected in parameters like the spectral index of the optically thin radio continuum and the exact location of the high and low energy cutoff frequencies of the scattered SSC spectrum. Therefore it may be difficult to discriminate between the SSC and synchrotron dominated flare activity. It appears to be plausible that the SSC dominated NIR flares are bluer than the synchrotron dominated ones.

The NIR flare power spectrum: The description of the flare activity as a power-law under the assumption of a characteristic flare time implies that the 'NIR quiescent phase' of Sgr A* can be regarded as a sequence of frequent low amplitude flares of Sgr A*. Such models have been shown by Eckart et al. (2004) and have been described in detail in Eckart et al. (2006a). The observed flares may be the consequence of a clumpy or turbulent accretion and the flare
power spectrum may be coupled to the power spectrum of accreted clumps or turbulence in the accretion flow. In addition - as a consequence of the possible IR turn over of the synchrotron spectrum (see Eckart et al. 2006a) - the flare rates at longer IR wavelengths may be higher than at shorter NIR wavelengths.

The linkage to radio variability: The radio and submillimeter data show clear indications for variability that appear to occur on somewhat longer timescales than the X-ray and IR variations. The exact relation between the radio/sub-mm domain and the NIR/X-ray domain still remains uncertain, due to the lack of sufficient simultaneous coverage. However, the amplitudes and time scales indicated are consistent with a model in which the emitting material is expanding and cooling adiabatically (see also the recent work by Yusef-Zadeh et al. 2006b and the recent interferometric measurements of variable 340 GHz linear polarization in Sagittarius A* by Marrone et al. 2006).

A dust component close to the line of sight toward Sgr A*: Finally Eckart et al. (2006a) have shown that most of the MIR flux density seen towards the position of Sgr A* is due to dust emission (see Fig.5). Ghez et al. (2005) as well as Eckart et al. (2006b) have shown the existence of a dust component close to the line of sight toward Sgr A*. This component may be part of the mini-spiral material, is likely located behind Sgr A* and the blue high velocity stars and may account for as much as 10^{-2} M_\odot in gas and dust. In case the material is not typical of the mini-spiral and if the dust temperature is substantially higher than material associated with the mini-spiral (i.e. higher than \sim200-400 K) then the overall mass of this component can be considerably smaller (see also Ghez et al. 2005). This implies that the overall spectral shape of Sgr A* is likely to be significantly less peaked in the FIR wavelength domain, as suggested by the the upper limits that are usually inferred. Combined with the results from the SSC modeling one can expect that the intrinsic spectrum of Sgr A* is peaked at frequencies of a few THz.

3. The Polarized NIR Flare Emission from Sgr A*

Using the NACO adaptive optics (AO) instrument at the ESO VLT Eckart et al. (2006b) have obtained new polarization data of the variable NIR emission of the Sgr A* counterpart. The authors find that the variable NIR emission of Sgr A* consists of a contribution of a non- or weakly polarized main flare with highly polarized sub-flares (see Fig.2). The flare activity shows a quasi-periodicity of 20\pm3 minutes consistent with previous observations (Genzel et al. 2003). The highly variable and polarized emission clearly shows that the NIR emission is of non-thermal origin.

In Fig.3 we compare the model results of an orbiting spot model (red lines) for July 2005 with the measured total flux density (top) and polarization angle (bottom). As a demonstration of the consistence between the model and the data we have chosen a solution that gives a satisfactory representation of the total flux density. For the chosen inclination of 55° the position angle of the E-vector resulting from the model and interstellar polarization does not wrap over 2\pi and agrees with the measurements to within \pm3 times the mean 1\sigma uncertainties of the measurements - as indicated by the thin dashed lines. This solution has to be compared to scenarii with different inclinations as shown in the model results by Eckart et al. (2006b). Details of the modeling are given in Dovciak, Karas & Yaqoob (2004). The calculations show the compatibility of the orbiting spot model with the NIR polarization data. Within the measurement uncertainties the model represents the observed light curve reasonably well. Regarding the fact that we neglected possible tilts and warps of the accretion disk (e.g. Bardeen & Petterson 1975, Lubow, Ogilvie & Pringle 2002) and used a highly idealized and therefore somewhat unphysical intrinsic polarization model, the discrepancy of the polarization angle in detail is not surprising. Currently the observations cannot discriminate between a jet or a model of a temporarily existing
Figure 4. Left: High pass filtered L'-band image. In addition to sharp features in the mini-spiral there are the linear NIR feature (LF) and in the inset the X-ray feature XF (Morris et al. 2004) pointing approximately into the direction of Sgr A*. Right: An image of the central 0.5×0.5 pc$^2$ of the Galactic Center at $\lambda=3.8\mu$m (see Moulitaka et al. 2004, 2005; Viehmann et al. 2005, 2006). The two lines centered on the position of Sgr A* limit the range over which the polarization angle varied on the sky. For more details see Eckart et al. (2005, 2006b).

or temporarily bright disk (see Fig.3). In the disk model the quasi-periodic flux density variations can be explained due to polarized spots on relativistic orbits around the central MBH. In the jet model the variable polarization could also be due to a helical magnetic field along a short jet and the variable sub-flare emission could be explained by temporal instabilities in the jet (see elongated features in the NIR and X-ray that are possible - but unlikely jet candidates in Fig.4). However, near the last stable orbit (LSO) a short (possibly only of the order of a few Schwarzschild radii) jet emerging from a disk may look almost indistinguishable from a case involving a pure disk or orbiting spots (see also Fig.4 in Bower et al. 2004). Recent model calculations by Meyer et al. (submitted to A&A) show that the current data indicate spin parameters $a>0.5$, inclinations of $50^0<i<70^0$ and orbital radii slightly larger that that of the last stable orbit. The observed rapid variability - be it related to the jet or the disk model - suggests now that alternative explanations for the high central mass concentration involving boson or fermion balls are increasingly unlikely.

4. Summary and discussion

Our investigation also shows that the NIR K-band is the ideal wavelength band to study the flare emission from Sgr A*. In combination with adaptive optics systems it provides the highest angular resolution at the lowest amount of contamination by dust emission. At wavelengths shorter than the K-band, little emission is found because most flares are expected to be red (Eisenhauer et al. 2005). At longer wavelengths the angular resolution is lower and the dust contamination is high. Observations in the K-band are - in the framework of the presented physical model - ideally suited to observe both synchrotron and SSC flare emission. In addition the model also gives us the opportunity to perform polarization measurements that could provide additional information to study the relevant emission mechanisms.
Figure 5. The dust component close to the line of sight toward Sgr A*. On the left we show a portion of an L-band image of the vicinity of Sgr A*. On the right point sources S1, S2, S17, and S0-20 have been subtracted. In both images we show a single resolution element of 104 mas diameter. The scale of 0.5 arcsec corresponds to 19.5 mpc or 4017 AU. More details are given in Eckart et al. 2006a. See also Ghez et al. 2005.

Future progress will mainly depend on further successful simultaneous observing campaigns, especially between the NIR and (sub)mm-domains to see whether flares are related to extending plasma components. Here extensive simultaneous data are not available so far. Further polarization data from the NIR to the radio as well as (sub-)mm-VLBI and NIR interferometric experiments are also highly desirable to study the details of the accretion process in Sgr A*.

A strong emphasis will also be put on measurements of the Galactic Center using the Large Binocular Telescope (LBT) and the Very Large Telescope Interferometer (VLTI). High angular resolution interferometric observations of the Galactic Center in the NIR/MIR will provide key information on the central massive black hole and the stellar cluster it is embedded in. These observations have already started by observing the luminous dust enshrouded star IRS3 using MIDI at the VLTI (Pott et al. 2005a, 2005b). As a future NIR wide field interferometric imager offering an angular resolution of about 10 milliarcseconds LINC/NIRVANA at the Large Binocular Telescope will be an ideal instrument for imaging galactic nuclei including the center of the Milky Way.

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