Variations in the spectral slope of Sgr A* during a NIR flare

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Abstract. We have observed a bright flare of Sgr A* in the near infrared with the adaptive optics assisted integral field spectrometer SINFONI. Within the uncertainties, the observed spectrum is featureless and can be described by a power law. The associated power law index is subject to systematic effects, namely the determination of the background level. We explore these effects and can show that while the absolute value of the spectral power law index is relatively uncertain, our data nevertheless suggest that the spectral index is correlated with the instantaneous flux. Both quantities experience significant changes within less than one hour. We argue that the near infrared flares from Sgr A* are due to synchrotron emission of transiently heated electrons, the emission being affected by orbital dynamics and synchrotron cooling, both acting on timescales of $\approx 20$ minutes.

1. Introduction
The detection of stellar orbits [1, 2, 3, 4] close to Sgr A* has proven that the center of our Galaxy hosts a massive black hole (MBH) with a mass of $(3.6 \pm 0.2) \times 10^6 M_\odot$. Sgr A* appears rather dim at all wavelengths, which is explained by accretion flow models [5, 6, 7, 8]. In the near infrared (NIR) it was detected after diffraction limited observations at the 8-m class telescopes had become possible [9, 10]. In the near infrared (NIR) it was detected after diffraction limited observations at the 8-m class telescopes had become possible [9, 10]. Usually the emission is not detectable. However, every few hours Sgr A* flares in the NIR for 60 to 90 minutes, reaching up to $K \approx 15$ mag. During these flares the lightcurves show characteristic quasi-periodic oscillations [9] with a timescale of $\approx 17$ min. The position of the flares coincides with the dynamical center of the stellar orbits.

Recent progress in understanding the Galactic Center (GC) has been made by integral field spectroscopy using the 2004 commissioned instrument SINFONI at the VLT [11, 12]. One main result [2] is the finding that the S-stars visibly orbiting Sgr A* are mostly B dwarfs, intensifying the so-called “paradox of youth” [13]. Furthermore, using SINFONI it becomes possible to determine radial velocities for these stars on a regular basis. Also, a first flare spectrum was obtained by [2], showing a featureless, red spectrum (power law index in $\nu S_\nu \sim \nu^\beta$ of $\beta \approx -3$).
The basic consensus model which explains the overall, multiwavelength spectral energy distribution (SED) of Sgr A* is that the mm-IR emission from Sgr A* is synchrotron emission from relativistic electrons close to the last stable orbit (LSO) [14, 15, 16, 17]. Radiatively inefficient accretion flow (RIAF) models with a thermal electron population ($T_e \approx 10^{11}$ K) produce the observed peak in the submm but fail to produce enough flux at 2 $\mu$m. The NIR emission requires transiently heated or accelerated electrons as proposed by [18]. If a few % of the electrons are heated up to $\approx 10^{12}$ K significant NIR flux emerges. This basic scenario is illustrated in Fig. 1.

![Figure 1. Basic scenario for the spectral energy distribution of Sgr A*](image)

2. New observations

We observed the GC region on 2005 June 18 from 2:40 to 7:15 UT with SINFONI. The field of view was 0.8” × 0.8” for individual exposures, mapped onto 64×32 spatial pixels. We observed in K-band, spectrally dispersed at a resolution of FWHM 0.5 nm. The first 12 integrations lasted 5 min each. During those we noticed NIR activity of Sgr A* (see Fig. 2) and we switched to 4 minute exposures. We followed Sgr A* for another 32 exposures. In total we interleaved nine integrations on a specifically chosen off field (712” W, 406” N of Sgr A*). The seeing was $\approx 0.5$” and the optical coherence time $\approx 3$ ms, some short-time deteriorations excluded. The AO was locked on the closest optical guide star ($m_R = 14.65$, 10.8” E, 18.8” N of Sgr A*), yielding a spatial resolution of $\approx 80$ mas FWHM, close to the diffraction limit of UT4 in K-band ($\approx 60$ mas).

Our detection triggered immediate follow-up observations with VISIR, a mid-infrared (MIR) instrument mounted at the ESO-VLT unit telescope Melipal (UT3). From 5:25 UT onwards VISIR was pointing to the GC. At the position of Sgr A* no significant flux was seen. A conservative upper limit of 40 mJy (not dereddened) at 8.59 $\mu$m is reported.

The reduction of the SINFONI data followed the standard steps: From all source data we subtracted the respective sky frames to correct for instrumental and atmospheric background. We applied flatfielding, bad pixel correction, a search for cosmic ray hits, and a correction for the optical distortions of SINFONI. We calibrated the wavelength dimension with line emission...
lamps and tuned on the atmospheric OH-lines of the raw frames. Finally we assembled the data into cubes with a spatial grid of 12.5 mas/pix.

3. Analysis

3.1. Flux determination

For all 44 cubes we extracted a collapsed image (median in spectral dimension) of a rectangular region (0.25” × 0.5”) centered on Sgr A* and containing the three S-stars S2, S13, and S17. We determined the flux of Sgr A* from a fit with five Gaussians to each of these images. Four Gaussians with a common width describe the four sources. The fifth Gaussian (with a width 3.5× wider, typical for the halo from the imperfect AO correction) accounts for the halo of the brightest star S2 ($K \approx 14$ mag). The halos of the weaker sources (all $K < 15$ mag) could be neglected for the flux measurement. We fixed the positions of all sources (known a-priori from a combined cube) and the amplitude ratios for the stars. Five parameters were left free: an overall amplitude, the background, the width, the flux ratio halo/S2, and $F$, the flux ratio Sgr A*/S2. This procedure disentangles real variability from variations in the background, the Strehl ratio, and the seeing.

As a crosscheck we determined $F$ in a second way for all images; for both Sgr A* and S2 we measured the flux difference between a signal region centered on source and a reasonable, symmetric background region. The such determined values agreed very well with the fits. For further analysis we used the fitted ratios and included the difference between the two estimates in the errors.

3.2. Determination of the spectral slope

The procedure adopted to obtain the spectral power law $\beta$ index for a given cube was as follows:

(i) Extract the spectrum of Sgr A* from the signal region, namely a ring with radius 3 pixels centered on source.
(ii) Extract the spectrum of the background from the background region. For its choice see the following subsection.

(iii) The raw spectrum is obtained as the difference of signal and background spectrum

(iv) Repeat the same steps for S2, using identically chosen signal and background regions

(v) Divide the raw spectrum by the S2 spectrum in order to correct for instrumental effects and interstellar extinction

(vi) Multiply the result with \( \nu S_\nu \) of a black body with the temperature of S2 (T=25000 K)

(vii) Clean and rebin the such obtained spectrum into 60 bins

(viii) Fit the result with a power law \( \alpha \cdot \nu^\beta \).

(ix) In order to estimate the error of the result, repeat the determination of \( \beta \) for a sample of slightly differently chosen signal and background regions.

While the definition of the signal region is straight forward, it is less clear how a proper estimate of the background can be achieved, as the background flux is varying spatially due to the bright neighbouring S-stars and temporally due to variable AO correction. The value of the spectral power law index \( \beta \) crucially depends on the background subtraction. Subtracting too much light would artificially make the signal look redder than it is, underestimating the background would make Sgr A* artificially too blue.

3.3. Choice of the background

For a reasonable choice of the background region the nearby sources S2 and S17 have to be excluded explicitly. Furthermore, the background flux is varying spatially. Actually Sgr A* lies close to a saddle point in the background light distribution, caused by S2 and S17 (see Fig. 1). In the East-West direction the background has a maximum close to Sgr A*, in the North-South direction it has a minimum near the position of Sgr A*. A proper estimate of the background can be achieved in two ways: a) working with small enough, symmetric apertures, and b) subtracting from the signal an off state obtained at the position of Sgr A* from cubes in which no emission is seen. We used the first method as well as two variants of the second.

Small apertures: The local background at a position \( \vec{x} \) can be estimated by averaging over a small, symmetric region centered on \( \vec{x} \). Given the background geometry we have chosen a ring with inner radius 3 pix and outer radius 7 pix. The circular symmetry was only broken since we explicitly excluded those pixels with a distance to S17 and S2 smaller than 3 and 7 pixels respectively. Unfavorable for this method is that the local background is only approximated, since a sufficiently large region has to be declared as signal region. 

Off state subtraction: Another way to estimate the local background is to extract it from cubes in which no signal is seen. Since the seeing conditions change from cube to cube, one still has to correct for the varying amount of stray light in the signal region. We estimate this variation by measuring the difference spectrum between signal and off cube in a stray light region. The latter must not contain any field stars and should be as far away from the nearby sources as Sgr A*. We used two stray light regions to the left and to the right of Sgr A*, between 5 and 10 pixels away. The disadvantage of this method is that one needs a suitable off state. The latter point is critical for our data. Even though Sgr A* has not been detected directly in the first three cubes, the light at its position appears redder than the local background\(^1\). Assuming that this light is due to a very dim, red state of Sgr A*, we would subtract too much red light and artificially make the flare too blue. In this sense, this method strictly speaking yields an upper limit for \( \beta \).

Constant subtraction: The off state method can be varied to obtain a lower limit for \( \beta \).

\(^1\) Inspecting older (non-flare) SINFONI data we found cases similar to the new data and other cases in which the light was identical to the local background emission. This is consistent with the L-band observations by [10, 22].
Assuming that the true off state spectrum has the color of S2, one can demand that it is flat after division by S2. In our data, the S2 divided off state spectrum is rising towards longer wavelengths. Hence, in this third method we estimate the background at blue wavelengths and use that constant as background for all spectral bins.

![Image of graphs showing lightcurve and variation of the spectral power law index \( \beta \) during the flare. Time is counted from 2:40 UT. Top: Flux ratio flare/S2. Thin dots are exposures affected by bad seeing. Middle/top: \( \beta \) using the small apertures background. Middle/bottom: \( \beta \) using the off state subtraction background. Bottom: \( \beta \) using the constant subtraction background.]

### 4. Results

We observed a strong (flux density up to 8 mJy or \( \nu L_\nu \approx 10^{35} \) ergs/s), long (more than 3 hours) flare which showed significant brightness variations on timescales as short as 10 minutes (Fig. 3, top). While the data is not optimal for a periodicity search (poorer sampling than our previous imaging data), it is worth noting that the highest peak in the periodogram (significance of \( \approx 2 \sigma \)) lies at a period of \( \approx 18 \) min. This is also the timescale found by [9], who identify the quasi-periodicity with the orbital time close to the LSO of the MBH.

We divided the data into three groups: a) the cubes of the first peak near \( t = 50 \) min ("pre-flare"), b) the cubes at \( t > 100 \) min with \( \mathcal{F} < 0.25 \) ("dim state"), and c) the cubes at \( t > 100 \) min with \( \mathcal{F} > 0.25 \) ("bright state"). For the three sets we created combined cubes in which we determined \( \beta \) using all three background estimates. In all cases we obtained the correct spectral index \( 2.9 \pm 0.5 \) for S17 (a star with a spectrum similar to S2 but a flux comparable to Sgr A*).
For Sgr A* we get:

\[
\begin{array}{|c|ccc|}
\hline
\beta & \text{preflare} & \text{dim state} & \text{bright state} \\
\hline
\text{off state subtr.} & -1.4 \pm 0.4 & -0.7 \pm 0.4 & +0.4 \pm 0.2 \\
\text{small apertures} & -1.8 \pm 0.3 & -1.7 \pm 0.4 & -0.1 \pm 0.3 \\
\text{constant subtr.} & -3.4 \pm 0.4 & -2.3 \pm 0.3 & -0.3 \pm 0.2 \\
\hline
\end{array}
\]

The values obtained from the small apertures lie between the values from the other two methods, consistent with the idea that they yield upper and lower limits. The absolute values for \( \beta \) vary systematically according to the chosen background method. However, independent from that, it is clear that the preflare is redder than the dim state which in turn is redder than the bright state. An obvious question then is whether there is an instantaneous correlation between flux and \( \beta \).

Hence, we applied the spectral analysis to the individual cubes. We kept the data in which Sgr A* is detected, the error \( \Delta \beta < 1.5 \) and the spectral index for S17 does not deviate more than 1.5 from the expected value. The resulting spectral indices appear to be correlated with the flux (Fig. 3, 4). The values match the results in [2] and [22]. Bright flares are indeed bluer than weak flares, as suspected by [22] and consistent with the earlier multi-band observations of [9]. Our key new result is that this even holds within a single event.

For all three background methods it is clear that the main event was preceded by a weak, red event. For the small apertures and the constant subtraction method instantaneous flux and spectral index are correlated. For the off state subtraction method one could instead group the data into a preflare at the beginning and a bluer, brighter main event.

We checked our data for contamination effects. If stray light would affect the flare signal, \( \beta \) should be correlated with the seeing (measured by the width from the multiple fits). Since we did not find such a correlation, we exclude significant contamination.

![Figure 4](image_url)

**Figure 4.** Correlation plots between the flare flux and the spectral index \( \beta \). Points with error bars represent the flare, blue dots are \( \beta_{S17} \). Thick black dots mark the points with an error \( \Delta \beta < 1 \), red triangles mark the data with good seeing (FWHM < 75 mas). The line is a fit to the thick black dots. Open circles denote the data from [2] - near 2 mJy - and [22] - near 7 mJy. Left: Small apertures method; middle: off state subtraction method; right: constant subtraction method.

5. Interpretation

A conservative interpretation of our data is suggested by Fig. 4, middle. There was a weak, red event before, and possibly independent from, the main flare which was a much bluer event.
Plausibly the preflare is then due to the high-energetic tail of the submm peak [9]. The main flare requires nevertheless a population of heated electrons.

A more progressive interpretation follows from the instantaneous correlation between flux and $\beta$ (Fig. 4, left & right). Then our data suggest that we observed a single event and that the NIR variability is caused by the combination of transient heating with subsequent cooling and orbital dynamics of relativistic electrons. In the following subsection we will exploit this idea.

5.1. Synchrotron emission

In the absence of continued energy injection, synchrotron cooling will suppress the high energy part of the electron distribution function. This results in a strong cutoff in the NIR spectrum with a cutoff frequency decreasing with time. At a fixed band one expects that the light becomes redder as the flux decreases. This can cause the correlation between flux and $\beta$. The observed flare apparently needs several heating and cooling events. In Fig. 5 we show variants of our thermal synchrotron model that demonstrate explicitly that suitable electron distribution functions exist: One can reproduce the fluxes and spectral slopes of Sgr A* in the NIR without violating any other observation, namely in the MIR and submm regime.

![Figure 5](image-url)

**Figure 5.** Measured fluxes of Sgr A* from the submm to the NIR and synchrotron models. The submm data and MIR upper limits are the same as in Fig. 1. The upper limit at 8.6 $\mu$m is from the simultaneous VISIR observation (dereddened). Our NIR data are shown as short bars for typical flux density values of 1.5, 3.5, and 7 mJy. Solid black line: Thermal synchrotron model for an emitting sphere with $R = R_S$, $B = 30$ G, $n_e = 2 \times 10^7$ cm$^{-3}$ and $T_e = 1.5 \times 10^{11}$ K. Dashed black line: 1% of the electrons are heated up to $T_e = 2 \times 10^{12}$ K. This model can account for the bright state but a parameter set that reproduces the dim state requires a large electron density, yielding high MIR- and FIR fluxes (blue line). Red lines: The effect of synchrotron cooling of the heated electrons, assuming 4-minute exposures taken 4 minutes (solid) and 16 minutes (dashed) after the heating event. The observed range of spectral indices can be reproduced, but larger flux variations than observed are predicted. Green: A variation of the cooling model that mildly increases $T$, $B$ and $n_e$ while the electrons cool for 8 minutes. This model seems more likely given its lower flux predictions for the MIR, FIR and submm.
The synchrotron cooling time is comparable to the observed timescale of decaying flanks as in Fig. 3 (top) or [9]. In a RIAF model [23] the magnetic field $B$ is related to the accretion rate $\dot{M}$. For disk models with $\dot{M} \approx 10^{-8} M_\odot/\text{yr}$ [24, 25] one has $B \approx 30 \text{ G}$ at a radial distance of $3.5 R_s$ (Schwarzschild radii). The cooling time for electrons emitting at $\lambda = 2 \mu\text{m}$ for $B = 30 \text{ B}_{30} \text{ G}$ is

$$t_{\text{cool}} \approx 8 B_{30}^{-3/2} \lambda_2^{1/2} \text{ min} .$$

This is similar to the orbital timescale, making it difficult to disentangle flux variations due to heating and cooling from dynamical effects due to the orbital motion.

5.2. Orbital dynamics

The timescale of $\approx 20$ minutes for the observed variations suggests orbital motion close to the LSO as one possible cause. Any radiation produced propagates through strongly curved spacetime. Beaming, multiple images, and Doppler shifts have to be considered [26, 27]. Recent progress has been made in simulating these effects when observing a spatially limited emission region orbiting the MBH [28, 29, 30, 31].

That the emission region is small compared to the accretion disk can be deduced from X-ray observations [32, 33, 34]. In order to explain the X-ray luminosity the emission region has to be a small spot.

For such a small emitting region the Doppler effect can lead to a time-dependent variation of the spectral slope. In this dynamical model the observed light corresponds to different rest frame frequencies depending on the orbital phase. If the source spectrum is curved, flux and spectral index appear correlated. Following this interpretation, the emission during the brightest part originates from a rest-frequency with larger $\beta$ than the dimmer state emitted at shorter wavelengths. Note that such a concavely curved spectrum is naturally expected from the synchrotron models.

6. Conclusions

The observation of a long, bright flare from Sgr A* with adaptive optics assisted integral field spectroscopy at the VLT allowed us to measure for the first time the temporal evolution of the spectral power law index of the emission. While the absolute values of the index have a large systematic uncertainty caused by the difficulty to establish a clean background estimate in the crowded region, it is clear that the index changes with time. We adopted three different background estimates and found consistently that the spectral index is correlated with the instantaneous flux of Sgr A*. This can be interpreted in terms of synchrotron emission models as well as in purely dynamical models. Most probably the observed flux and power law index are affected by both phenomena.

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