Diffraction Limited Imaging Spectroscopy of a Sgr A* Flare with OSIRIS

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Abstract. We present diffraction limited K-band integral field spectroscopy of a flare associated with SgrA*. From the spectrum we determined the K-band spectral index of the pure flare emission to be $(F(\nu) \propto \nu^{\alpha})$ of $\alpha = -2.6 \pm 0.9$. If we do not subtract the quiet state emission of SgrA*, then our spectral index is consistent with earlier observations of Ghez et al. 2005 [8]. We compare our observations with other data already published and discuss the implications.

1. Introduction
The infrared variability or flaring of SgrA*, first reported by [5] and [7], has become an important observable to investigate the physics in the immediate vicinity of the black hole in the center of our Galaxy. Flares are fairly frequent and they are also readily observable with adaptive optics at 8-10m class telescopes [2, 8]. The infrared variability is closely linked with the X-ray variability detected a few years earlier [1, 16, 10]. In fact, flares are related multiwavelength phenomena [4]. The reported short timescales of the variability of a few minutes imply that the emission arises from an environment close to the Schwarzschild radius. Flares thus have become a key in our understanding of mass accretion processes towards the Galactic Center black hole and the related relativistic and high energy phenomena. In particular, the spectral indices of flare emissions and their possible variations from flare to flare and during a single flare hold important clues about the emission processes involved [19, 15]. We observed SgrA* with OSIRIS, the new Keck NIR integral field spectrometer during commissioning of the instrument. These data are the first laser guide star (LGS) assisted spectra ever taken of the Galactic Center region.

2. Observations and Data Reduction
The OSIRIS (OH Suppressing InfraRed Imaging Spectrograph) instrument is a new facility near infrared (NIR) integral field spectrograph designed for the Keck Observatory’s Adaptive Optics (AO) system. It utilizes an array of microlenses and a HAWAII-2 detector (2048\times2048 pixels) to simultaneously obtain about 1020 full IR band spectra at a spectral resolution of $R = 3700$ over a rectangular field of view with about $16\times64$ spatial positions. More information about OSIRIS can be found in [14, 17, 20].
Figure 1. These wavelength collapsed K-band images centered on SgrA* were obtained with OSIRIS on Keck II. The left data set shows SgrA* at the beginning of a flare still at a low level of activity. The image on the right was obtained 5 minutes later and shows a typical flare at the location of SgrA*. Two field stars are labeled. The rectangles indicate the pixels used for extracting the on-source and background spectra on S2 and SgrA*.

We observed the Galactic Center on April 29, 2005 at Keck II during the first deployment of OSIRIS with the LGS AO system (Wizinowich et al., in prep.). Two consecutive K-band frames, each with 300 s integration time were obtained at an airmass of 1.65 with SgrA* in the field of view (FOV). Overhead between the frames was about 37 s. A sky field was observed immediately after the 2nd frame.

The data was reduced using the dedicated OSIRIS data reduction pipeline, described in more detail in [12, 11]. After sky subtraction, individual spectra in each frame were straightened and corrected for crosstalk from adjacent spectra. Arc line spectra were used for wavelength calibration. Atmospheric differential dispersion effects were also corrected by tracing the peak emission of the stellar continuum point spread function (PSF) through the wavelength slices of the cube. Telluric and instrumental transmission, and also the foreground extinction to the Galactic Center were corrected by dividing all spectra by the average spectrum of star S2 and multiplying them by a 30,000K black-body, representing S2 of type O8V or B0V [6]. Due to the low signal/noise we did not attempt to model the stellar Br\textsubscript{γ} absorption line at 2.166 \( \mu \)m. For the same reason, OH residuals have been ignored in the spectra.

3. Results

Basic results have been published in [13]. A more detailed view on SgrA* is presented in Figure 1, which shows the vicinity of SgrA* including the stars S2 and S17 (according to [3]) and excludes the rest of OSIRIS' field of view. The angular resolution on the sky is 60 mas and both images have been obtained at a pixel scale of 20 mas. The angular resolution achieved is lower than the diffraction limit of 46 mas at 2.18 \( \mu \)m, probably due to the low telescope elevation. The two panels display the images produced by collapsing all of the wavelength channels from 2.02 \( \mu \)m through 2.38 \( \mu \)m. The left image, obtained first, shows SgrA* close to its quiet state (pre-flare). The right image shows clear indication of a flare at the position of SgrA* (flare).

The flare at the position of SgrA* is located 145±5 mas south and 22±5 mas west of S2 at the epoch of the observations. Inspecting the identical position in the pre-flare frame reveals a weaker but still notable emission at the location of SgrA*. The spectrum of SgrA* was determined from the flare frame using a 5 × 4 pixel\(^2\) box centered on the position of the flare. The general background was determined by measuring the average pixel value in the 22 pixels that form a circumference around the 5×4 aperture, also indicated in Figure 1. The spectrum of S2, used for calibration as described in the previous section, was determined in an identical fashion from the same frame. An identical procedure was applied to the pre-flare frame. Assuming that the flare is unresolved in our data, the extraction regions for SgrA* and star S2 cover the same fraction of the PSF for each source.
The resulting spectra are shown in Figure 2. The lowest spectrum represents the pre-flare emission. The middle spectrum, shifted up by one unit, is the extracted spectrum of the flare. The upper spectrum, shifted up by 4 units, is the difference between the flare spectrum and the pre-flare spectrum, and we will refer to this as the pure-flare spectrum. All three of the spectra have been smoothed by a 30 pixel wide boxcar filter and were then fitted with a power law \((F(\lambda) \propto \lambda^m)\). The resulting fits and slopes \(m\) are indicated in Figure 2 along with \(1\sigma\) errors. These slopes were converted into a frequency power law index \(\alpha\) \((F(\nu) \propto \nu^\alpha)\) listed in Table 1. We note here that the spectral index of the flare is quite red \((\alpha = -2.6 \pm 0.9)\).

4. Discussion
From the spectral fits, the K-band flux of the flare and the pre-flare were determined (Table 1) assuming that S2 has a magnitude of \(m_K = 13.9\) mag \((24\ mJy)\) [6]. The flux in the flare spectrum is 9.6 mJy, which is 6.1 mJy stronger than the pre-flare and corresponds to an increase of the K-band flux by a factor of 2.8 within 5.6 minutes. Photometric K-band data by [4] indicate that the lowest activity level of SgrA* can be 12 times fainter than S2 corresponding to a K-band flux density of 2 mJy. Comparing this factor with Table 1 suggests that the K-band emission in the pre-flare frame is within a factor of 2 of the lowest activity level measured. Our observations thus very likely record the beginning of a flare brightening up to a typical level of activity. We also conclude that the intrinsic K-band flux of the flare is probably best represented by the difference between the peak value of 9.6 mJy and the lowest background of 2 mJy, yielding \((7.6 \pm 34\%)\) mJy. This value has been used in Figure 3 (see below).

[3] were first to report measurements of the spectral index of the emission of SgrA* in the NIR. Their spectral indices \(\alpha\) for the flux density \(F(\nu)\) lie in the range between -3.3 and -4.8, with an averaged index of \(\alpha_E = -4 \pm 1\) for fluxes < 2 mJy. Their value has been obtained in a similar fashion to ours, in that two spectra of different activity levels were subtracted from each other. However, their result is different from our value of \(\alpha_K = -2.6 \pm 0.9\) (see Table 1 and Figure 3).

Figure 3 summarizes all published spectral indices for SgrA*’s K-band flares as a function of their 2 \(\mu\)m flux density. In a recent paper, [8] report spectral indices based on K’ and L’ imaging. Their method of determining \(\alpha\) is directly based on K’-L’ PSF fitting photometry.
Figure 3. SgrA*’s K-band spectral index ($\alpha$, where $F(\nu) \sim \nu^\alpha$) as a function of its 2 $\mu$m flux density. The results of [3], [8], and [9] are indicated. The result of this work is denoted by the triangles. The open triangle marks the spectral index and flux density derived from the flare-spectrum (Figure 2 middle), the filled triangle represents the spectral index of the pure-flare spectrum (Figure 2 top). For the arrows see text. The rage of data points obtained by [9] is indicated by the shaded area between the two boundary lines.

However, different from our result and from [3], their result does not account for flux from the source during its quiet phase. Thus their value of $\alpha = -0.5$ has a different meaning than our flare index. It is more correctly compared to the slope of the flare spectrum in Figure 2 (middle) which includes the local background and has an index of $\alpha = -0.6 \pm 0.4$. We find that our value for the spectral slope is in fact very consistent with the observations by [8]. In addition, their K-band flux densities are close to our results, especially if we correct for the difference between K’ and K bands (as indicated by the arrow). Using their spectral index value of $\alpha = -0.5$ and K’ flux density of 7.2 mJy, we calculate a K-band flux density of 9.2 mJy, again very comparable to our measurement of 9.6 mJy for frame 2.

We thus confirm the findings of [8] for the slope of the flare plus local background within the 1 $\sigma$ errors. It is interesting to note that both spectral indices were obtained by very different techniques and using different wavebands: K’ and L’ versus K band only. The spectral indices reported by [3] are clearly different but were also taken at a significantly lower level of activity. Our data and the data by [3] imply a dependency of the spectral index on the flare intensity, another suggestion first made by [8].

However, new observations by Ghez et al. (private communication and this volume), let them conclude that they do not find any significant dependence of the flare spectral index on the flare intensity. Such finding is not only inconsistent with [3] but does also contradict the conclusion reached in a recent paper by [9] based on near infrared spectra taken with the SINFONI instrument at the VLT. More observations are clearly needed to clarify the possible dependence of the flare spectral index on its (K-band) flux.

To further complicate the picture there also is an interesting twist with the observations by [9]. Although their version of Figure 3 covers a range of K-band flare flux densities which look statistically significant, their distribution of values in the diagram does not comply well with the data published by [8] and by us [13]. In order to illustrate this, Figure 3 also shows the [9] range of data values indicated by the shaded area between the boundaries. Here, since [9] assumes the S2 flux to be 19 mJy instead of 24 mJy (this paper), we already accounted for the different calibration in order to be able to directly compare the results. The reason for the discrepancy...
Table 1.

| Target                   | $F_\nu$ [mJy] | $\alpha$ |
|--------------------------|---------------|----------|
| Star S2 (both frames)    | 24            |          |
| SgrA* (pre-flare)        | 3.5 ± 20%     | 2.7 ± 1.3|
| SgrA* (frame 2)          | 9.6 ± 20%     | -0.6 ± 0.4|
| SgrA* flare              | 6.1 ± 34%     | -2.6 ± 0.9|

between [9] and our results or those by [8] remains unclear.

The argument has been made that the flare’s spectral index as presented by [13] might need to be corrected slightly. Since they have subtracted a strong flare from a weak flare (see above), they might have subtracted two flares with different spectral indices. The intrinsic spectral index of the strong flare could thus be different from the value they determined. This argument can easily be checked by adopting the spectral indices determined by [3] in Figure 3 and by assuming that the weak 1.5 mJy flare included in our pre-flare observation might have a spectral index as low as $\alpha = -4.5$. Adding such a spectrum to the pure-flare spectrum in Figure 2 would slightly pull the spectral index of the resulting pure-flare spectrum towards more negative values. Such possible correction would rather increase the discrepancy between our data and the observations by [9].

Both the infrared and the X-ray variability are probably due to transiently heated relativistic plasma accelerated at ~10 times the Schwarzschild radius [15, 18]. The synchrotron emission from the high-energy electrons within this plasma can account for the observed X-ray flares. The models can also be tuned to explain the infrared flux, its variability, and also the range of spectral indices [15, 19]. If the flare spectral index is indeed a function of the flare activity level, stronger flares involve more energetic electrons, making the infrared spectrum bluer. Such a finding would considerably narrow the range of process parameters describing the origin of the flares.

References

[1] Baganoff, F.K., et al. 2001, Nature, 413, 45
[2] Clénet Y., Rouan D., Gratadour, D., Marco, O., Léna, P., et al. 2005, A&A, 439, L9
[3] Eisenhauer, F., Genzel, R., Alexander, T., Abuter, R., Paumard, T., et al. 2005, ApJ, 628, 246
[4] Eckart, A., Baganoff, F.K., Morris, M., Bautz, M.W., Brandt, W.N., et al. 2004, A&A, 427, 1
[5] Genzel R., Schödel, R., Ott T., Eckart, A., Alexander, T., et al. 2003, Nature, 425, 934
[6] Ghez, A.M., Duchêne, G., Matthews, K., Hornstein, S.D., Tanner A., et al. 2003, ApJ, 586, L127
[7] Ghez, A.M., Wright, S.A., Matthews, K., Thompson, D., Le Mignant, D., et al. 2004, ApJ, 601, L159
[8] Ghez, A.M., Hornstein, S.D., Lu, J., Bouchez, A., Le Mignant, et al. 2005, ApJ, 635, in print
[9] Gillessen, S., Eisenhauer, F., Quataert, E., Genzel, R., Paumard, et al. 2006, ApJ, 640, L163
[10] Goldwurm, A., Brion, E., Goldoni, P., Ferrando, P., Daigne, F., et al. 2003, ApJ, 584, 751
[11] Krabbe, A., Gasaway T., Weiss J., Larkin J., Barczys M., et al. 2002, SPIE, 4847, 448
[12] Krabbe, A., Gasaway T., Song, I., Iserlohe, C., Weiss, J., et al. 2004, SPIE, 5492, 1403
[13] Krabbe, A., Barczys, M., Larkin, J.E., LaFreniere, D., Quirrenbach, A., et al. 2006, ApJL, 642, L145
[14] Larkin, J.E., Quirrenbach, A., Krabbe, A., Aliado, T., Barczys, M., et al. 2003, SPIE, 4841, 1600
[15] Liu, S., Petrosian, V., & Melia F. 2004, ApJ, 611, L101
[16] Porquet, D., Predehl, P., Aschenbach, B., Grosso, N., Goldwurm, A., et al. 2003, A&A, 407, L17
[17] Quirrenbach, A., Larkin, J.E., Krabbe, A., Barczys, M., & LaFreniere, D. 2003, SPIE, 4841, 1493
[18] Yuan, F., Quataert, E., & Narayan R. 2003, ApJ, 598,301
[19] Yuan, F., Quataert, E., & Narayan R. 2004, ApJ, 606, 894
[20] Weiss, J., Barczys, M., Larkin, J.E., LaFreniere, D., Quirrenbach, A., et al. 2002, SPIE, 4848, 519