A POWER-LAW BREAK IN THE NEAR-INFRARED POWER SPECTRUM OF THE GALACTIC CENTER BLACK HOLE

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ABSTRACT

Proposed scaling relations of a characteristic timescale in the X-ray power spectral density of galactic and supermassive black holes (BHs) have been used to argue that the accretion process is the same for small and large BHs. Here, we report on the discovery of this timescale in the near-infrared (NIR) radiation of Sgr A*, the 4 × 10⁶ M☉ BH at the center of our Galaxy, which is the most extreme sub-Eddington source accessible to observations. Previous simultaneous monitoring campaigns established a correspondence between the X-ray and NIR regime and thus the variability timescales are likely identical for the two wavelengths. We combined Keck and Very Large Telescope data sets to achieve the necessary dense temporal coverage, and a time baseline of four years allows for a broad temporal frequency range. Comparison with Monte Carlo simulations is used to account for the irregular sampling. We find a characteristic timescale of 154±12 minutes (errors mark the 90% confidence limits) which is inconsistent with a recently proposed scaling relation that uses bolometric luminosity and BH mass as parameters. However, our result fits the expected value if only linear scaling with BH mass is assumed. We suggest that the luminosity–mass–timescale relation applies only to BH systems in the soft state. In the hard state, which is characterized by lower luminosities and accretion rates, there is just linear mass scaling, linking Sgr A* to hard state stellar mass BHs.

Key words: black hole physics – Galaxy: center

1. INTRODUCTION

Cosmic black holes (BHs) show a very wide range of masses: from stellar masses to hundreds of millions of solar masses. An open question has long been whether the accretion and variability processes occurring in the immediate vicinity of the event horizon are the same over this broad mass range. To test this intriguing possibility, investigators identified and studied a characteristic timescale associated with the aperiodic X-ray variability of BH X-ray binaries (BHXRBs) and active galactic nuclei (AGNs; see, e.g., Uttley et al. 2002; Markowitz et al. 2003; Uttley & McHardy 2005). This timescale corresponds to a break in the power spectral density (PSD) at a certain temporal frequency where a power law of slope ρ (with P(f) ∝ f−ρ) breaks to a steeper slope β > ρ.

McHardy et al. (2006) proposed a scaling relationship between the break frequency, the mass of the BH, and the bolometric luminosity of its accretion flow. This extended earlier work which hypothesized that the break timescales of AGN scale linearly with BH mass from the timescales observed in BHXRBs, albeit with some scatter. McHardy et al. (2006) found that this scatter can be explained by introducing the bolometric luminosity as a correction factor. This led them to conclude that AGNs are scaled-up galactic BHs. However, their sample consists of only 10 AGNs and it is therefore desirable to test their scaling relation with newly determined AGN break frequencies. The BH in our own Galactic center (identified with the radio source Sgr A*) is an especially interesting object, as it is the most underluminous BH accretion system observed thus far (with a bolometric luminosity 9 orders of magnitude lower than its Eddington luminosity). It can therefore test the McHardy et al. (2006) relation in so far inaccessible regions of the parameter space.

The existence of a supermassive BH in the center of the Milky Way has been demonstrated beyond reasonable doubt by the proper motion of stars detected in the near-infrared (NIR) waveband (Eckart & Genzel 1996; Ghez et al. 1998, 2000, 2005, 2008; Genzel et al. 2000; Schödel et al. 2002; Gillessen et al. 2009). X-ray and NIR emission associated with Sgr A* has been observable since 2001 and 2003, respectively (Baganoff et al. 2001; Genzel et al. 2003; Ghez et al. 2004), which showed that it is highly variable at both wavelengths (e.g., Eckart et al. 2006a, 2006b; Meyer et al. 2006a, 2006b; Trippe et al. 2007). Simultaneous NIR and X-ray monitoring campaigns revealed that each X-ray flare is accompanied by an NIR flare with zero time lag, which leads to the conclusion that the X-ray photons are being produced by Compton scattering off the relativistic electrons which radiate in the NIR (Eckart et al. 2004, 2006a, 2006b; Meyer et al. 2006a, 2006b; Marrone et al. 2008; Yusef-Zadeh et al. 2006; Hornstein et al. 2007). The fact that the same bunch of electrons is the source for both the NIR and X-ray flux makes it possible to interpret the NIR timing studies reported here in the context of the AGN and BHXRB X-ray results. In fact, since the X-ray background is very high due to the lack of resolving power of X-ray telescopes, coupled with the difficulty of observing individual X-rays, this probably explains the observed fluxes and time lags.

Recent studies of the NIR properties of Sgr A* showed that the variability on timescales of minutes to hours is completely described by an (unbroken) power-law PSD with a slope of −1.6 to −2.5 (Meyer et al. 2008; Do et al. 2009, see also Figure 18 in Eckart et al. 2006b). In this Letter, we extend the time baseline up to years by combining Keck and Very Large Telescope data. We report for the first time the existence of a power-law

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4 We want to note that also in the NIR there might be a background due to unresolved stellar sources at the position of Sgr A*, which has been estimated to contribute up to 30% to the observed flux when Sgr A* is at its lowest flux levels (Do et al. 2009). This low background level is negligible for the purpose of our study.
break frequency in the NIR PSD of Sgr $A^*$, and we show that its deduced range is inconsistent with the McHardy et al. (2006) scaling relation, but fits the expected value when linear scaling with mass is assumed.

2. THE DATA

The NIR adaptive optics instruments at Keck II (NIRC2) and at the VLT UT4 (NACO) have been used for Sgr $A^*$ observations since 2003. A time baseline of years and a sampling timescale of minutes are needed to analyze the broadband PSD of Sgr $A^*$ from minutes to years. Obviously, large gaps in the sampling pattern are unavoidable as the NIR observations have to be carried out during the night and available telescope time limits realistic data sets to a couple of nights each year.

To cover the high-frequency to mid-frequency part of the PSD (meaning timescales of minutes to days in this context), we looked for Keck and VLT data from consecutive nights with individual night observations that are as long as possible. We identified the nights from 2004 July 6–8 (all times UT) as the most suitable. Beginning on July 6, Sgr $A^*$ was observed from 07:50 to 10:35 UT with Keck II, from 23:19 to 04:16 (July 7) with the VLT, then again from 06:35 to 10:30 with Keck II, and finally from 00:53 (July 8) to 06:53 with Keck II, from 23:19 to 04:16 (July 7) with the VLT UT4 (NACO) have been used for Sgr $A^*$ observations since 2003. A time baseline of years and a sampling timescale of minutes are needed to analyze the broadband PSD of Sgr $A^*$ from minutes to years. Obviously, large gaps in the sampling pattern are unavoidable as the NIR observations have to be carried out during the night and available telescope time limits realistic data sets to a couple of nights each year.

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For the coverage of the mid-frequency to low-frequency part of the temporal spectrum (timescales of days to years), we averaged the data of individual nights. This leads to a light curve with irregular sampling of down to one day that covers a time baseline of four years. The details of the whole data set are given in Table 1.

The data reduction was standard, i.e., flat fielding, sky subtraction, and correction for bad/hot pixels. The VLT data have been deconvolved with point-spread functions (PSF) extracted from the individual images (Diolaiti et al. 2000). Aperture photometry was done on each image and the flux was calibrated relative to sources in the field with known flux. See Meyer et al. (2008) for more details. For the Keck data, the individual PSFs have been used to fit sources in the field; see Do et al. (2009) for details. The two photometric techniques lead to indistinguishable results as shown in Meyer et al. (2008).

### Table 1: Summary of the Data

| Date (UT) | Telescope | Filter | Duration (minutes) | Mean Flux (mJy, dereddened) | Reference |
|-----------|-----------|--------|--------------------|-----------------------------|-----------|
| 2004 Jul 6 | Keck      | L'     | 240                | 2.64                        | Hornstein (2007) |
| 2004 Jul 7 | Keck/VLT  | L'/K   | 630                | 4.05                        | Hornstein (2007)/Eckart et al. (2006b) |
| 2004 Jul 8 | VLT       | K      | 479                | 2.00                        | Eckart et al. (2006b) |
| 2004 Jul 26 | Keck     | K      | 27                 | 4.43                        | Ghez et al. (2008) |
| 2005 Jul 31 | VLT/Keck | K      | 591                | 4.01                        | Meyer et al. (2008) |
| 2006 May 3  | Keck      | K      | 140                | 5.53                        | Do et al. (2009) |
| 2006 Jun 20 | Keck      | K      | 125                | 4.57                        | Do et al. (2009) |
| 2006 Jun 21 | Keck      | K      | 164                | 3.62                        | Do et al. (2009) |
| 2006 Jul 17 | Keck      | K      | 189                | 2.86                        | Do et al. (2009) |
| 2007 May 18 | Keck      | K      | 84                 | 5.53                        | Do et al. (2009) |
| 2007 Aug 12 | Keck      | K      | 57                 | 3.05                        | Do et al. (2009) |
| 2008 May 15 | Keck      | K      | 153                | 4.57                        | Unpublished |
| 2008 Jun 2  | Keck      | K      | 160                | 4.00                        | Unpublished |
| 2008 Jul 24 | Keck      | K      | 179                | 3.51                        | Unpublished |

Notes. The first three entries are used for the high- to mid-frequency coverage, see Figure 1.

a Keck means NIRC2 at Keck II; VLT means NACO at VLT (Yepun).

b The fluxes are K-band fluxes. When the L' filter was used, we scaled the flux down to the K-band level using a spectral index of $\alpha = -0.6$ (Hornstein et al. 2007).

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5 More precisely, Keck uses a K' filter ($\lambda = 2.12 \mu$m) and VLT a $K_S$ filter ($\lambda = 2.18 \mu$m). We calibrated both data sets in the same way and thus the difference is negligible.
The irregular sampling with the large gaps makes standard Fourier transform techniques unsuitable for our data set. We therefore employ the first-order structure function (SF), defined as $V(t) = \langle |s(t + \tau) - s(t)|^2 \rangle$ with $s(t)$ being a measurement at time $t$, to look for a break in the power-law PSD (a power law in the PSD translates into a power law in the SF albeit with a different slope; see, e.g., Simonetti et al. 1985; Hughes et al. 1992; Do et al. 2009). The SF for our complete data set is shown in Figure 2. The diamonds represent the high- to mid-frequency data shown in Figure 1, and the crosses show the mid- to low-frequency part. The overlapping region was used to normalize the low-frequency part such that a continuous SF emerges.\(^6\) It shows the superposition of a constant at short lags ($\lesssim 1$ minute) which is the result of uncorrelated measurement noise, a power-law portion between lags of minutes to hours, and a plateau/shallow power law for long time lags ($\gtrsim 1000$ minutes). This plateau at low frequencies points to a break in the power law at shorter lags. To quantify the evidence for the existence of a break frequency and its value, Monte Carlo (MC) simulations are required, as the sampling pattern severely distorts any intrinsic power-law PSD, and introduces the effects of red-noise leak and aliasing (e.g., Uttley et al. 2002).

3. THE SIMULATIONS

We used the following approach for our MC simulations, which is very similar to the PSRESP method by Uttley et al. (2002) and Markowitz et al. (2003): (1) an intrinsic (broken or unbroken) power-law PSD model is assumed and corresponding light curves are generated using the algorithm by Timmer & König (1995). This is done independently for the high-frequency and low-frequency part. These light curves, which are significantly longer and more densely sampled to account for aliasing and leakage, are subsequently resampled according to the sampling function of the real data and uncorrelated measurement

\(^6\) Equivalently, we could renormalize the high-frequency part. The reason why the SF is not automatically continuous goes back to the fact that we average the data of a whole night for the low-frequency part (which reduces the variance), whereas the high-frequency data are not averaged. Contrary to the periodogram (Markowitz et al. 2003), the SF does not have any normalization factor which accounts for that, and thus we use the overlapping region to determine the renormalization factor.

noise is added (see Do et al. 2009, for more details). (2) The SF from the simulated light curves are calculated in the same way as is done for the data (the renormalization is done for each pair of long- and short-term simulations individually). (3) An observed $\chi^2$ value is determined by using the observed SF, the mean simulated SF, and error bars equal to the rms spread of the individual simulated SFs at each time lag (Uttley et al. 2002). (4) The goodness of fit is computed by modeling the $\chi^2$ distribution for each assumed PSD model, i.e., several thousand $\chi^2$ values are calculated using the individual realizations of the simulations instead of the observed data. The probability that the model PSD can be rejected is then given by the percentile of the simulated $\chi^2$ values exceeded by the value of observed $\chi^2$. (5) The steps above are repeated to scan a range of break frequencies and power-law slopes.

For each model PSD, we used 100 simulations for each of the high- and low-frequency part. By combining both sets, we arrived at 10,000 simulations to determine the $\chi^2$-distribution. The class of models we employed as the intrinsic PSD is the singly broken power law:

$$P(f) = \begin{cases} A(f/f_{br})^{-\gamma}, & f \leq f_{br}, \\ A(f/f_{br})^{-\beta}, & f > f_{br}. \end{cases}$$

Here, $f_{br}$ is the break frequency (the characteristic timescale), $A$ is the PSD amplitude at $f_{br}$, $\beta$ is the high-frequency power-law slope, and $\gamma$ is the low-frequency power-law slope with the constraint $\gamma < \beta$. We tested a $\beta$ range of 0.5–3 in increments of 0.1, a $\gamma$ range of 0–1 in increments of 0.1, and a break frequency range of $10^{-6}$ to $3 \times 10^{-2}$ minute$^{-1}$ in multiplicative steps of 1.2. We also tested unbroken power-law models ($P(f) \propto f^{-\beta}$) which are, however, rejected with a likelihood of acceptance of 0% (i.e., none of the 10,000 simulations equaled or exceeded the observed $\chi^2$).

4. RESULTS AND DISCUSSION

The best-fit result with a likelihood of acceptance of 93% can be found at $f_{br} = 6.5^{+5.5}_{-2.9} \times 10^{-3}$ minute$^{-1}$ ($\sim 154^{+124}_{-87}$ minutes), $\gamma = 0.3_{-0.2}^{+0.4}$, and $\beta = 2.1_{-0.5}^{+0.5}$ (errors here are 90% confidence limits). This solution is plotted over the observed SF in Figure 2. In Figure 3, we show the confidence contours in the $\beta$–$f_{br}$ plane at the best-fit value for $\gamma = 0.3$. When the three-dimensional
distribution is marginalized over two parameters, we arrive at the following likeliest values and their 90% confidence limits for the individual parameters: \( P_S = 7.9^{+1.1}_{-1.0} \times 10^{-3} \text{ minute}^{-1} \) (\( \sim 128^{+329}_{-37} \) minute), \( \gamma = 0.6^{+0.4}_{-0.9} \), and \( \beta = 2.1^{+0.8}_{-0.5} \).

The existence of a break in the power-law PSD of Sgr A* can also be inferred by a simple argument: Table 1 reveals that the mean flux of Sgr A* during one night stays roughly the same over the four years of observations. If the power-law PSD extended unbroken over decades, one would expect to observe very different mean fluxes over a time baseline of years. Our detailed MC simulations serve the purpose of quantifying the location of the power-law break. The same simple argument also holds true for the mean X-ray flux of Sgr A*.

Our result of a break frequency at \( -6.5 \times 10^{-3} \text{ minute}^{-1} \) is strikingly different from the prediction of the scaling relation proposed by McHardy et al. (2006). Using a mass of \( M = 4 \times 10^6 M_\odot \) (Ghez et al. 2008) and a bolometric luminosity of \( 2 \times 10^{36} \text{ erg s}^{-1} \) (Narayan et al. 1998), the relation by McHardy et al. (2006) predicts a break frequency at the order of \( 10^{-9} \text{ minute}^{-1} \) for Sgr A*.

Interestingly, if the term with the bolometric luminosity is neglected in the McHardy et al. (2006) relation, i.e., the bolometric index (called “B” in their paper) is set to zero, their relation predicts a break timescale of \( \sim 110 \) minutes for Sgr A*. Also, our deduced break timescale fits the expected value if linear scaling with BH mass is assumed from the typical break timescales observed in the high/soft and low/hard states of Cyg X-1; see Figure 4. This suggests that, while the inclusion of the bolometric luminosity as a free parameter improves the fit in a limited luminosity range, it is in fact not the true physical correction factor that can explain the scatter around the linear mass scaling.

It is, however, uncertain how meaningful a comparison of Sgr A*’s break timescale with the breaks of the much higher luminosity AGN used to derive the mass–luminosity–timescale relation of McHardy et al. (2006) is. These Seyferts are almost certainly in a different accretion state. They have a prominent optically thick accretion disk and much higher accretion rates. The McHardy et al. (2006) relation seems to work well when extrapolated to soft state BHXRBs, which are at comparable Eddington accretion rates to the Seyferts, but for the low-accretion rate hard states the comparison is less obvious. In fact, work by Gierlinski et al. (2008) suggests that in the hard state the high-frequency shape of the PSD is constant despite large changes in luminosity. Therefore, we conclude that the break in the NIR PSD of Sgr A* implies that the McHardy et al. (2006) relation with luminosity scaling applies to soft state AGNs, but that in the hard state there is only mass scaling. Then Sgr A* seems to fit in well with the hard state BHXRBs, consistent with its low luminosity.

Future work will further elucidate the relationship between variability processes across the range of BH masses. Our work presented here extends the set of supermassive BHs with determined break frequencies. The BH in our Galactic center is especially important, as it is the most underluminous source (in terms of Eddington luminosity) accessible to observations, and its mass determination is the most precise for supermassive BHs (Ghez et al. 2008; Gillessen et al. 2009).

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