A 600 MINUTE NEAR-INFRARED LIGHT CURVE OF SAGITTARIUS A*

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ABSTRACT

We present the longest, by a factor of 2, near-infrared light curve from Sgr A*—the supermassive black hole in the Galactic center. Achieved by combining Keck and VLT data from one common night, which fortuitously had simultaneous Chandra and SMA data, this light curve is used to address two outstanding problems. First, a putative quasi-periodicity of ∼20 minutes reported by groups using ESO’s VLT is not confirmed by Keck observations. Second, while the infrared and mm regimes are thought to be related based on reported time lags between light curves from the two wavelength domains, the reported time lag of 20 minutes inferred using the Keck data of this common VLT/Keck night only is at odds with the lag of ∼100 minutes reported earlier. With our long light curve, we find that (1) the simultaneous 1.3 mm observations are in fact consistent with a ∼100 minute time lag, (2) the different methods of NIR photometry used by the VLT and Keck groups lead to consistent results, (3) the Lomb-Scargle periodogram of the whole NIR light curve is featureless and follows a power law with slope −1.6, and (4) scanning the light curve with a sliding window to look for a transient QPO phenomenon reveals for a certain part of the light curve a 25 minute peak in the periodogram. Using Monte Carlo simulations and taking the number of trials into account, we find it to be insignificant.

Subject headings: black hole physics — Galaxy: center

1. INTRODUCTION

The near-infrared (NIR) regime at high angular resolution has proven to be of great value in Galactic center research. The proper motion of stars detected in this wave band demonstrates the existence of a supermassive black hole (BH) at the center of our Galaxy: Sagittarius A* (Sgr A*; see, e.g., Eckart & Genzel 1996; Ghez et al. 1998, 2000, 2005; Genzel et al. 2000; Schödel et al. 2002). In 2003, NIR emission associated with Sgr A* was detected (Genzel et al. 2003; Ghez et al. 2004), which is important since it is the most underluminous BH accretion system observed thus far (with a bolometric luminosity 9 orders of magnitude lower than its Eddington luminosity). The NIR emission is highly variable: intensity changes by factors ≤10, lasting between about 10 and 100 minutes, occur at least 4 times a day, and are highly polarized (e.g., Eckart et al. 2006a, 2006b; Meyer et al. 2006a, 2006b; Do et al. 2008; Trippe et al. 2007). Simultaneous NIR and X-ray observations have revealed that each X-ray flare is accompanied by a NIR flare with zero time lag, but not vice versa (Eckart et al. 2004, 2006a, 2008; Bélangier et al. 2005; Hornstein et al. 2007). Recent campaigns that included mm observations reported a characteristic time lag between the NIR/X-ray and longer wavelengths that has been interpreted in terms of an expanding synchrotron plasmon. The limited overlap between data sets, however, has led to debates over the nature of this time lag (e.g., Eckart et al. 2006a; Yusef-Zadeh et al. 2006, 2008; Marrone et al. 2008).

The characteristics of the NIR emission from Sgr A* is of particular interest given that there have been reports of periodic modulations with a period of ∼20 minutes present in NIR flares detected during VLT observations (Genzel et al. 2003; Eckart et al. 2006b; Meyer et al. 2006a, 2006b; Trippe et al. 2007). In a recent study, however, Do et al. (2008) used robust statistical estimators and found no significant peaks in the periodograms of the Sgr A* light curves observed with the Keck II telescope. Moreover, quasi-periodicities in the X-ray regime claimed to be present by Aschenbach et al. (2004) are not statistically significant (Belanger et al. 2008).

In this Letter, we address the questions of a periodic component in the NIR flux, and the relation of the NIR to the mm regime, by combining for the first time contiguous Keck and VLT data. During that 10 hr session, there was also simultaneous coverage by Chandra and SMA. These observations were published by Marrone et al. (2008) but interpreted taking only the Keck data into account.

2. THE DATA

During the night of 2005 July 30–31, the VLT observed Sgr A* from 23:05 UT to 06:53 UT using the Natural Guide Star Adaptive Optics system and NIR camera NACO on UT4.2 Since these observations have not been published before, the observational details are given here. The detector integration time was 15 s, and four images were co-added before the data were recorded: the effective resolution is ∼1 image/80 s. Dithering was used to minimize the effects of dead pixels. The atmospheric seeing conditions ranged between 1′′–2.5′′ (as determined by the differential image motion monitor) during the

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first two hours, and 0.5″–1.25″ afterward (the average Strehl ratio of the VLT data is 17%).

At 07:00 UT, the Keck II telescope started its monitoring campaign using the NIRC2 camera in combination with Laser Guide Star AO. The Keck observations were made by cycling through the H-K-L wavelength filters (see Hornstein et al. 2007 for details). Since the VLT observations were carried out in $K$ band, we consider only the $K$-band subset of the Keck data.

Both data sets were reduced in the same standard way, i.e., sky subtracted, flat-fielded, and corrected for bad pixels. Images with a Strehl ratio less than 10% were removed (13 out of 266 VLT images). For every individual image, the point-spread function (PSF) was extracted with the code StarFinder by Diodati et al. (2000). Each exposure was deconvolved with a Lucy-Richard deconvolution and restored with a Gaussian beam. The flux of Sgr A* and other compact sources in the field were obtained via aperture photometry on the diffraction limited images with a circular aperture of radius 0.03″. The background flux density was determined as the mean flux measured with apertures of the same size at five different positions in a field located 1″ northwest of Sgr A* that shows no individual stars. Photometric calibration was done relative to stars in the field with known flux. For the extinction correction we assumed $A_K = 2.8$ mag (Eisenhauer et al. 2005). Estimates of uncertainties were obtained from the standard deviation of fluxes of nearby constant sources.

It is noteworthy that this is the first time that Galactic center VLT and Keck data have been reduced homogeneously. While the VLT groups mainly use deconvolution and aperture photometry, the Keck group uses PSF fitting without deconvolution. The Keck part of the light curve presented in the next section is similar to that reported by Hornstein et al. (2007) where the PSF fitting technique was applied. After rescaling the light curve by a multiplicative factor to account for a different dereddening factor and slightly different calibration values used by Hornstein et al. (2007) the average difference per data point between both methods is only 0.031 mJy (dereddened), well within our 1 σ error bar of 0.18 mJy. Both data reduction methods are consistent with each other, and no large systematic errors are introduced by choosing either one.

3. RESULTS

3.1. The NIR Properties of Sgr A*

Figure 1 (left panel) shows the 2005 July 30–31 dereddened light curve. The first 450 minutes are the VLT data, and the following 130 minutes are the Keck data. Note that the error bars are smaller for the Keck data due to better seeing conditions at Mauna Kea that night. The corresponding Lomb-Scargle periodogram for the entire light curve is presented in the right panel of Figure 1. It is consistent with the finding of Do et al. (2008) that the NIR emission of Sgr A* is described by a single stochastic process (other than additive measurement noise) that has a power-law spectrum, $P \propto f^{-\alpha}$, very similar to the X-ray emission of AGNs. The Lomb-Scargle periodogram in Figure 1 is a single realization of this process and therefore fluctuates around the spectrum. We determine the probability density function (PDF) of these fluctuations around the spectrum at a given frequency empirically with Monte Carlo simulations. With the PDF at hand, we can assess the likelihood that peaks in the periodogram are not due to a fluctuation but rather have a physical cause intrinsic to the source.

We used two different Monte Carlo based analyses recently developed by Do et al. (2008) and Belanger et al. (2008) to look for significant peaks in the periodogram. These analyses are carried out by first determining the power-law index of the spectrum of the stochastic process, and then generating light curves (realizations of this process; Timmer & König 1995) with a sampling function matching those of the data set. Finally, the significance of each observed periodogram peak is derived from the large simulated reference data set.

An accurate determination of the power-law index $\alpha$ of the underlying stochastic process is important in this approach. Belanger et al. (2008) do this by first performing several estimates of $\alpha$ by fitting a power law to the periodogram made from the light curve binned with successively larger bin times, and then carrying out simulations with the same count rate and sampling to find the matching curve of $\alpha$ versus bin time. Do et al. (2008) also use MC simulations, but determine the power-law index using the structure function, which also takes the sampling into account. Both methods lead to a spectral index of $\alpha = 1.6 \pm 0.05$ (formal fitting error). Note that the length
of the light curve allows us to sample frequencies $<10^{-4}$ Hz (0.006 minute$^{-1}$) for the first time, showing that the power law extends to this regime. Unfortunately, we cannot fully exclude the possibility of spectral leakage from a process with a spectral index steeper than $-1.6$. However, our main conclusions in this Letter also hold true for steeper power-law indices. We plan to use more sophisticated spectral estimators elsewhere.

The periodogram in the right panel of Figure 1 clearly shows no outlying peaks above the underlying spectrum of the power-law process. However, the featurelessness of the periodogram of the whole light curve does not rule out the presence of a periodic component in parts of it, as the mechanism giving rise to such a component may be transient and short lived. We therefore did a search for periodicities over a restricted range of frequencies by scanning the light curve using a sliding window method where window here means a subspan of the time series. This consists of constructing a periodogram for the data subset corresponding to each window, and assigning a significance to each point based on the probability density functions derived from the simulations of the whole light curve described above.

Figure 2 shows the result of such a scan using a 60 minute window with 5 minute steps. The probability that the most significant peak in each periodogram is due to a statistical fluctuation around the power-law spectrum is plotted against the start time of the sliding window. The most significant peak overall (the one with the lowest probability to be due to a fluctuation) is found in the window starting at minute 385, and we thus looked at this window subset in more detail. Indeed, the flux between 385 and 445 minutes looks very similar to the “subflare” phenomenology reported by Genzel et al. (2003), Eckart et al. (2006a, 2006b), and Meyer et al. (2006b). These subflares are flux peaks superimposed on broader, longer lasting flux excursions and are thought to be the manifestation of the claimed quasi-periodicity. Meyer et al. (2006a, 2006b) and Eckart et al. (2008) showed that they can be interpreted in terms of a relativistically orbiting spot whose emission adds to the emission of the accretion flow. The NIR flux can therefore be described as $F(t) = A(t) + M(t) + S(t)$ with $A(t)$ a stochastic process with a power-law spectrum as above, $M(t)$ uncorrelated measurement noise, and $S(t)$ the deterministic flux of an (evolving) orbiting spot leading to a (quasi-)periodicity. Our MC simulations include $A(t)$ and $M(t)$ so that a possible quasi-periodic component can be identified as significant in the periodogram.

Figure 2 shows that there is a peak in the periodogram corresponding to the 385–445 minute subset which has a false alarm probability of only $2 \times 10^{-5}$ (this corresponds to 4.2 $\sigma$ in Gaussian equivalent terms, but note that the PDF is not Gaussian). This peak occurs at a frequency of 0.04 minute$^{-1}$ (25 minutes). However, we have to ask how likely it is that a periodogram peak is such a low probability occurs not only in this window, but in any window. After all, there is a priori nothing special about this certain subspan of the light curve. We therefore count how often a peak with probability $\leq 2 \times 10^{-5}$ occurs in our simulations in any window: for a fixed window length of 60 minutes, we find 3120 occurrences for 30,000 simulations. This implies that the overall false alarm probability of the peak in the 385–445 minute subset is 0.104 (corresponding to 1.6 $\sigma$). Furthermore, we have to take into account the trials with windows of different lengths in scanning the data: this immediately yields a final significance of $\leq 1 \sigma$.

Hence, we conclude that the whole light curve is consistent with a pure power-law process and no periodic component is needed. It is important to point out, however, that if we had observed (or analyzed) only the part of the data between 385 and 445 minutes, our result would have been interpreted as a 4 $\sigma$ detection of a 25 minute QPO. This points to an explanation of the contradictory results of Genzel et al. (2003), Eckart et al. (2006a, 2006b), and Meyer et al. (2006b) on the one hand, and Do et al. (2008) on the other. Our results here seem to favor the finding of Do et al. (2008) where no periodicity was detected.

It is interesting to note that the 25 minute periodogram peak is most significant for a 60 minute sliding window, implying that only the first two of the four “subflares” between 380 and 460 minutes are sampled. The reason for this is probably that the period—if present—is evolving over the four cycles resulting in a periodogram peak which is too wide to be identified as a significant periodic component. This, however, does not exclude the presence of an evolving, inward-spiraling bright spot or more complicated hydrodynamic instabilities in the accretion flow around Sgr A* (e.g., Falanga et al. 2007).

3.2. The Connection to the Millimeter Regime

The Chandra X-Ray Observatory and the SMA observed Sgr A* simultaneously to this new NIR light curve as reported by Hornstein et al. (2007) and Marrone et al. (2008). Chandra started its observations at 20:00 UT (30 July) and stopped at 08:30 UT (31 July), so that there are simultaneous X-ray data for the entire NIR light curve seen in Figure 1. No X-ray flare occurred during the overlap time (23:05–09:00 UT) (see Fig. 6 in Hornstein et al. 2007) despite the activity in the NIR with flares which are somewhat stronger than average. This may be due to the higher X-ray background caused by the steady Bondi-Hoyle accretion flow within 1" around Sgr A* or/and a large surface area of the flaring region that leads to a low synchrotron self-Compton luminosity (see also Marrone et al. 2008).

In contrast to the X-ray light curve, the SMA 1.3 mm observations, which started at 05:28 UT, show some variability (see Fig. 3). In particular, they show one flare at 08:20 UT,
In this Letter we report on a 600 minute NIR light curve of Sgr A* that combines Keck II and VLT data. We showed that the Lomb-Scargle periodogram of the overall light curve is featureless, and is statistically consistent with a single stochastic process that has a power-law spectrum of index $-1.6$. A certain subset of the data has a prominent peak in its corresponding periodogram which, however, is not significant when analyzed in the context of the whole light curve. This points to the following dilemma in Sgr A* research: if a periodic component exists, it is clearly a weak and transient phenomenon that persists over very few cycles, and probably has an evolving period. As we have shown, certain parts of longer pure red noise light curves can easily mimic such a behavior. To be able to distinguish between both scenarios, many light curves are needed and the range of frequencies under consideration must be narrowed down, e.g., to 0.04–0.07 minute$^{-1}$ if a noticeable peak continues to occur in this range only.

We furthermore showed the difficulty with establishing the simple expanding plasma model frequently proposed to relate NIR and mm flares. Sgr A* is such an active source in the NIR (and maybe not every NIR flare has a millimeter counterpart) that very long simultaneous observations are needed for a meaningful cross-correlation analysis.

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References: VLT:Yepun(NACO), Keck:II(NIRC2), SMA

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