INTRADAY VARIABILITY OF SAGITTARIUS A* AT 3 MILLIMETERS

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ABSTRACT

We report observations and analysis of flux monitoring of Sagittarius A* at 3 mm wavelength using the Owens Valley Radio Observatory millimeter interferometer over a period of 8 days (2002 May 23–30). Frequent phase and flux referencing (every 5 minutes) with the nearby calibrator source J1744−312 was employed to control for instrumental and atmospheric effects. Time variations are sought by computing and subtracting, from each visibility in the database, an average visibility obtained from all the data acquired in our monitoring program having similar u-v spacings. This removes the confusing effects of baseline-dependent, correlated flux interference caused by the static, thermal emission from the extended source Sgr A West. Few-day variations up to ~20% and intraday variability of ~20% and in some cases up to ~40% on few-hour timescales emerge from the differenced data on Sgr A*. Power spectra of the residuals indicate the presence of hourly variations on all but 2 of the 8 days. Monte Carlo simulation of red-noise light curves indicates that the hourly variations are well described by a red-noise power spectrum with \( P(f) \propto f^{-1} \). Of particular interest is an ~2.5 hr variation seen prominently on 2 consecutive days. An average power spectrum from all 8 days of data reveals noteworthy power on this timescale. There is some indication that few-hour variations are more pronounced on days when the average daily flux is highest. We briefly discuss the possibility that these few-hour variations are due to the dynamical modulation of accreting gas around the central supermassive black hole as well as the implications for the structure of the Sgr A* photosphere at 3 mm. Finally, these data have enabled us to produce a high-sensitivity 3 mm map of the extended thermal emission surrounding Sgr A*.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: nuclei — Galaxy: center — hydrodynamics

1.INTRODUCTION

It is now widely accepted that the compact radio source Sgr A* is associated with the presence of a black hole of mass \( \sim 4 \times 10^6 \, M_\odot \) located at the dynamical center of the Galaxy (Ghez et al. 2003; Schödel et al. 2003). Although Sgr A* represents a relatively faint galactic nucleus, with \( L \sim 10^{-8.5} L_{\text{GM}} \) (Melia & Falcke 2001), ongoing detections of variability and flares at radio, submillimeter, infrared, and X-ray wavelengths indicate that this is a dynamic object powered by accretion. At centimeter and millimeter wavelengths, persistent variability of Sgr A* has been observed to occur on timescales of weeks, with approximately three active episodes per year, each lasting about a month (Herrnstein et al. 2004; Zhao et al. 2003; Falcke 1999). Furthermore, there appears to be a time-lagged correlation between the centimeter and millimeter fluxes, with variations at shorter wavelengths appearing stronger in amplitude and peaking out before the longer wavelengths (Zhao et al. 2003). This is consistent with a model in which the higher frequency emission originates from smaller spatial scales, closer to the event horizon of the black hole. Short-term variability of Sgr A* at near-infrared (Ghez et al. 2004; Genzel et al. 2003) and X-ray (Baganoff et al. 2004; Baganoff 2003) wavelengths has also been observed recently. Eckart et al. (2004) have reported the first simultaneous detection of an X-ray and near-infrared flare from Sgr A*. Clearly, characterizing the variability timescales at different wavelengths will help elucidate the structure and dynamics of this object.

Also of interest are the effects of radiative transfer on our ability to detect variability on hourly timescales in the radio/submillimeter regime. The size of Sgr A* is dominated by scattering from the turbulent interstellar plasma along the line of sight for \( \lambda \geq 3 \, \text{mm} \) and perhaps also by the optical depth of the plasma flow surrounding the black hole, resulting in a stratification of Sgr A*'s appearance as a function of wavelength (Bower et al. 2004). Owing to the latter, the shortest observed timescales for flux variations at millimeter and submillimeter wavelengths may reveal important information about the structure of the Sgr A* photosphere, since the detectability of flux variations of a given region will depend on whether the variable flux emanates from within or outside the \( \tau = 1 \) surface.

One complication of the interpretation of measurements by interferometer arrays tracking Sgr A* is the nonnegligible flux component contributed by the extended thermal source Sgr A West, which is sampled in a time-varying, baseline-dependent fashion during the observing track. Atmospheric effects must also be controlled. To discriminate true variability from possible atmospheric fluctuations, one must interweave frequent measurements of a nearby phase calibrator with measurements of Sgr A*, especially for interferometers in the northern hemisphere, where Sgr A* is observed at low elevations. Perhaps for these reasons, low-amplitude variability on hourly and subhourly timescales has seldom been claimed with any confidence. The few exceptions have been the report of a 30% intraday flux increase and a 400% flare with an approximately twofold increase on a timescale of 1.5 hr at 2 mm by Miyazaki et al. (2004) and a 10% increase at 15 GHz over a 2 hr period reported by Bower et al. (2002).

In this Letter, we present the results of 8 successive days of observation of Sgr A* at 3 mm using the Caltech Owens Valley Radio Observatory (OVRO) millimeter interferometer. This work was carried out as part of a multiwavelength campaign, including the Chandra X-Ray Observatory, with the goal of observing radio
countertops to X-ray flares, although none occurred while OVRO was observing Sgr A* (F. K. Baganoff 2005, in preparation). Nonetheless, the 8 days of coverage analyzed here have enabled us to detect persistent, low-amplitude variations of Sgr A* on timescales of a few hours and to explore the nature of this intraday variability.

2. OVRO OBSERVATIONS

The Galactic center (Sgr A*) was observed with the OVRO millimeter interferometer in the L configuration at elevations >15° on each of the 8 successive days of the multiwavelength observing campaign (2002 May 23–30). The observing track each day lasted about 6 hr. Data were recorded in both sidebands using two intermediate frequencies (offset from the local oscillator by ±1.5 and ±3 GHz), resulting in a total continuum bandwidth of 4 GHz (νLO = 101.8 GHz during the first 3 days and νLO = 96.3 GHz for the remaining 5 days).

After measuring the fluxes of ~10 potential calibrator sources near Sgr A* in the week prior to the observing run, we chose J1744−312, separated from Sgr A* by only 2°29. Its flux of 0.9 Jy at 100 GHz is adequate for accurate amplitude and phase calibration, and we observed it for 3 minutes after every 5 minute integration on Sgr A*. During each track, absolute flux calibration was done using the planets Uranus and Neptune and was checked by observing secondary calibrators (3C 273, 3C 345, 3C 454.3, 3C 84, NRAO 530).

The data were edited and calibrated with the Caltech millimeter array reduction package MMA. During most of the daily tracks, the weather was exceptional for that time of the year. All 8 days of data were used to construct our model of the source (Fig. 1) and were phase-only self-calibrated in AIPS. To minimize the inclusion of bad data, we deleted all visibilities with coherence <0.8.

Fig. 1.—CLEANed OVRO 3 mm map of Sgr A* and Sgr A West. The familiar structure of the “minispiral” is evident. The beam size is 9.86 × 3.45 with position angle = −62°22. Contour values are 0.02, 0.07, 0.12, 0.17, 0.27, 0.37, and 0.57 Jy beam−1 (black) and 0.77, 1.17, 1.57, and 1.97 Jy beam−1 (white). The map was constructed from all 8 days of data and deconvolved using the AIPS task SCMAP, which performed phase-only self-calibration and CLEANing combined.

In order to discriminate between intrinsic flux variations in the central point source and flux variations due to changes in the spatial frequencies being sampled from Sgr A West (Fig. 1) as the interferometer tracks the source across the sky, it is preferable to analyze the data in the u-v plane. In removing the flux contribution of Sgr A West, we make use of the fact that all visibilities in our data set are the vector sum of components from Sgr A* and Sgr A West. For every visibility Vi, we average the amplitudes and phases of all other visibilities Vj within an averaging kernel of radius ri about Vi. The amplitudes and phases are weighted inversely by their distance drj in the u-v plane, from the central visibility Vi and by their intrinsic weight wi = σi−2 due to system noise (we also experimented with Gaussian kernels, although the resulting difference was negligible). The total weight for each visibility is then given by Wj = wj(1 − drj/rj). We have constructed the size of ri to vary linearly with respect to distance from the u-v plane. This accounts for the decreasing u-v sampling density for the longer baselines, resulting in each averaging kernel having a comparable number of visibilities contributing to the average and thus uniform statistics throughout the entire u-v plane. By choosing an appropriate scaling for ri, we limit the intrakernel phase variations due to source structure to ≤10°, ensuring that all intrakernel visibilities sample the same extended structure component of the source. The final kernel used has a radius range of 0.3–3.0 kλ for the shortest (~4 kλ) to the longest (~40 kλ) baselines. The average phase and amplitude of all remaining visibilities within the kernel are then used to construct a weighted average visibility Vave,i = ∑j Wj/Vj/∑j Wj that represents the global average of the data set (all 8 days of data) in that u-v sector. We then compute a residual visibility Vres,i at each point by subtracting Vave,i from Vi and taking the real part of the difference: Vres,i = Re(Vi − Vave,i). Thus, Vres,i represents the true variability of Sgr A*, since the constant contribution from Sgr A West and the average value of Sgr A* have been subtracted out. Any variations due to atmospheric refraction would be evidenced in the imaginary part of the residuals of Sgr A* (which have been confirmed to be flat) and in the real residuals of the calibrator J1744−312, which was subjected to the same treatment. For flux reference, we assume that the calibrator flux is constant and fix its value at 5 minute
Fig. 3.—Flux residuals for Sgr A* (left panels) and J1744–312 (middle panels) with power spectra for Sgr A* (right panels). The uncertainty for each flux residual represents the relative error and is calculated from the rms variations in J1744–312 within ±8 minutes of each data point. The Lomb power spectra of the data (solid curves) are accompanied by significance levels of 90% (dotted curves) and 99% (dashed curves) determined using 5000 Monte Carlo simulated light curves with an $f^{-1}$ power spectrum.

Figures 2 shows the day-averaged flux residuals of Sgr A* on each day of the campaign. Figure 3 exhibits the intraday variations, showing the real components of the residual visibility vectors of Sgr A* (left panels) and J1744–312 (middle panels) as well as the Lomb-Scargle power spectrum of the residuals (solid curve, right panels). Each residual light curve in Figure 3 is the average of the residuals from all of the baselines. Each separate baseline exhibits residuals that are consistent with the average; i.e., the variations are not dominated by either short or long baselines. Furthermore, we...
checked our result by the more conventional method of restricting our data set to only the longest baselines having u-v spacings >30 kλ and again by calibrating on NRAO 530 and J1744–312 separately. The results of these tests are consistent with those of the analysis method used here.

To characterize the flux variations, we subject the real residual visibilities of Sgr A* to periodic analysis by deriving a Lomb-Scargle power spectrum (Scargle 1982), designed for unevenly sampled time-series data. Our high sampling rate and daily coverage enable us to explore variations on timescales of minutes to hours. Benlloch et al. (2001) illustrate the importance of significance estimation when characterizing time variations in active galactic nuclei. Thus, to estimate the significance of our power spectra, we resort to Monte Carlo simulation. Following an algorithm for generating power-law noise (Timmer & König 1995), we resort to Monte Carlo simulation. Following an algorithm for generating power-law noise (Timmer & König 1995), we produce 5000 artificial red-noise light curves having the same statistical properties (mean and variance) and time sampling as the original data for each day. The artificial curves have power spectra that obey a power law with $P(f) \propto f^{-p}$. Figure 4 is the average of all intraday power spectra of the data (solid curve) and of all simulated light curves with $p$-values of 1.0, 1.5, and 2.0. Figure 4 shows that a power spectrum with $p = 1.0$ is a good fit to the data. Thus, for each frequency bin, we superpose on the power spectra in Figure 3 (right panels) the resulting 90% and 99% upper confidence level envelopes derived from 5000 simulated power spectra using $p = 1.0$.

Figures 3 and 4 show persistent power on timescales of a few hours, both in most of the individual days and in the average power spectrum. Power at long periods on some days (4–6 hr) is likely to represent an overall flux trend for those days. The rise and decay times of the flux residuals generally occur on a timescale of ~1–2 hr, comparable to the timescales observed by previous experiments (Miyazaki et al. 2004; Bower et al. 2002). It is unlikely that variable linear polarization or variable sampling of a constant, linearly polarized source through the fixed, linearly polarized feeds on the OVRO millimeter array can explain the apparent variations in Figure 3, since the linear polarization of Sgr A* at 3 mm has been constrained to be less than 1% (Bower et al. 2003). On several days, notably May 27 and 28, there is strong indication of power on timescales of 1.5–3 hr, some of which appears significant at more than the 99% confidence level derived from our Monte Carlo simulations. This shows up as a peak in the average power spectrum, which rises above the best-fitting red-noise power spectrum with $p = 1$ (Fig. 4). Finally, we note a suggestion of a correlation between the amplitude of few-hour variability and the average flux on a given day (Fig. 2); May 27 and 28, in particular, show the highest mean flux densities. This potential trend clearly needs confirmation.

4. DISCUSSION

The peak at ~2.5–3 hr in the average power spectrum, if confirmed, would suggest that there is a characteristic timescale associated with the 3 mm emission. If we assume that this power spectral peak is due to the dynamical modulation of the emitting gas, we can use the black hole mass to compute a dynamical radius of ~0.8 AU (10R_S). The wavelength dependence of the intrinsic size of Sgr A* taken from Very Long Baseline Array closure-amplitude imaging (Bower et al. 2004) suggests a major-axis size of $6R_S \pm 5R_S$ at 3 mm, which is consistent with the dynamical radius implied by the variability timescale. We speculate that the absence of significant variations on timescales less than 1 hr is owed to the fact that orbital radii with dynamical times less than this are enshrouded in the optically thick regime of the accretion flow at 3 mm. This would also constrain models in which short-term radio variability originates from shocks accompanying a jet (Markoff et al. 2001), if variability of this kind has no preferred timescale.

Future long-term monitoring is critical to accurately assess and characterize the variability of Sgr A* on short timescales. The future Atacama Large Millimeter Array will undoubtedly expand our capabilities and help broaden our understanding of this intriguing source.

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