Abstract. We have performed monitoring observations of the 3-millimeter flux density toward the Galactic center compact radio source Sgr A* with the Australia Telescope Compact Array (ATCA) since 2005 October. Careful calibrations of both elevation-dependent and time-dependent gains have been done to establish the variability behavior of Sgr A*. It has been found that during several observing epochs Sgr A* was quite active, showing significant intraday variation. We report a detected intraday event. On 2006 August 13, Sgr A* exhibits a maximum variation of 22% within 2 hrs, and two peaks with a separation of 4 hrs are seen. We discuss two possible scenarios, the orbiting hotspot model and the expanding plasmon model.

1. Introduction
There is compelling evidence that Sagittarius A* (Sgr A*), the extremely compact radio source at the dynamical center of the Galaxy, is associated with a massive black hole of $4 \times 10^6 M_\odot$. Since its discovery in 1974, Sgr A* has been extensively observed with radio telescopes in the northern hemisphere, and temporal flux variations at millimeter wavelengths were reported. Yusef-Zadeh et al. [20, 22] carried out VLA observations at 7- and 13-mm. They detected an increase of flux at a level of 7% ($\Delta S / S$) and 4.5% at 7- and 13-mm respectively, with a duration of about 2 hrs. The peak of flare emission at 7-mm led the 13-mm peak by 20-40 minutes. Mauheran et al. [12] detected intra-day variability (IDV) of 20% and in some cases up to $\sim$40% using the Owens Valley Radio Observatory (OVRO) at 3-mm. The rise and decay of the flux generally occur on a timescale of 1-2 hrs. At 2-mm, Miyazaki et al. [13] reported a 30% flare with an approximately twofold increase on a timescale of about 1.5 hrs observed by the Nobeyama Millimeter Array (NMA). On the other hand, flares with violent intensity increases during very short timescales have also been detected at X-ray and infrared wavelengths [1, 9], inferring that these emissions from Sgr A* originate within just a very vicinity to the central massive black
hole. This is further strengthened by the simultaneous detection of X-ray, infrared and sub-mm flares [5, 6, 7, 21, 22, 11]. Since Sgr A* is embedded in thick thermal material, it is particularly difficult to observe its structure, thus observations of IDV can give indirect constraints on the source emission geometry and emission mechanism. However, previous monitoring of Sgr A* from the northern hemisphere has been tightly constrained to within a short observing window (≪ 7 hrs/day) for the Galactic Center region. We have performed monitoring observations of flux density toward Sgr A* at 3-mm since 2005 October when the Australia Telescope Compact Array (ATCA) of the Australia Telescope National Facility (ATNF) was available at 3-mm for the first time. The ATCA is an interferometer consisting of five 22-m antennas at Narrabri, Australia where Sgr A* passes almost overhead, allowing a much longer observing window (≫ 8 hrs with elevation angle > 40°). Thus, the ATCA calibrations and flux measurements of Sgr A* are expected to be more accurate.

Here we present our effort to search for IDV. We describe the ATCA observations, the data reduction and present the detected one IDV event in Section 2. We discuss two possible scenarios that can account for the detected flux density variation of Sgr A* in Section 3 and finally summarize the results in Section 4.

2. Observations, Data Reduction and Results

So far, we have performed 3-mm ATCA flux density monitoring of Sgr A* over 95 hrs in the following days: 2005 October 18, 2006 June 9, August 9-13, 2007 October 19-21 and 2008 June 1, 3 and 4. The primary beam of the ATCA is ≈ 36′ (FWHM) at 3-mm. We used dual (linear) polarization double sideband (DSB) HEMT receivers in the 3-mm band as the front-ends. On 2005 October 18, the data were obtained from simultaneous observations of both the lower (93.504 GHz) and upper sidebands (95.552 GHz), separated by ≈ 2 GHz, with 32 channels and a total bandwidth of 128 MHz. In the observation in 2006 and later, the data were obtained in a dual mode: the lower sideband (86.243 GHz) was set to the frequency accorded with the SiO J=2-1 v=1 line with 256 channels and a total bandwidth of 32 MHz, the upper sideband (88.986 GHz) was used as a wideband channel with again 32 channels and a total bandwidth of 128 MHz. Since the continuum data of the lower sideband with narrow bandwidth have low signal to noise ratio, we use only the upper sideband data for Sgr A* and other continuum sources.

In June and August 2006, we observed Sgr A* in 6 days with a careful design of calibration. Four secondary calibrators (control sources) including SiO maser source OH2:6-0.4 and continuum sources PKS 1921-293, PKS 1710-269 and PKS 1730-130 were used to check the consistency of the gain calibrations. The observations usually lasted for 10 hrs at elevations larger than 20°. Primary calibrator Uranus was observed for about 10 minutes at the end of each observation. PKS 1253-055 was observed to calibrate bandpass instrumental gain. The pointing accuracy was checked by observing VX Sgr, a known strong SiO maser source, every half an hour. The instrumental gain and phase were calibrated by alternating observations of Sgr A* and secondary calibrators.

In 2007 October, we carried out three new 3-mm ATCA observations. This time, we used a closer source, PKS 1741-312, which separated from Sgr A* by only 2.3″, as well as OH2:6-0.4 and PKS 1730-130 as control sources. Just in June 2008, we carried out our first ATCA quasi-simultaneous 3- and 7-mm observation of Sgr A*, with frequencies alternated between 3- and 7-mm every half hour.

All the data processing was conducted using the ATNF MIRIAD package [16]. At millimeter wavelengths, the atmosphere can no longer be approximately transparent. The opacity effect is included in an effective system temperature - the so-called “above atmosphere” system temperature [18] for the ATCA measurements at 3-mm wavelength. The bandpass corrections were made using the strong ATCA calibrator PKS 1253-055. For the amplitude calibration,
we first applied the nominal elevation-dependent gains and then used calibrators to determine the additional corrections. The flux density scale was derived from observations of the primary calibrator Uranus except in August 2006 when the observational data on Uranus were corrupted due to the bad weather. Then, PKS 1921-293 was used with a reported flux density of 8.44 Jy during our observations from the ATCA calibrator list on web. We expect an accuracy of 20% for the absolute amplitude calibration in these observations. After the phase self-calibration, the data were averaged in 5 minutes bin to search for shorter timescale variability. The flux measurements of Sgr A* were estimated by fitting a point source model to visibilities on the projected baselines longer than 25kλ (or 85 m at 3-mm) to suppress the contamination from the surrounding extended components \[13, 12\]. Both the fitting error reported by MIRIAD and the rms of the residual visibilities were used to get the error estimate.

It is known that antenna efficiency varies with the elevation mainly due to the gravitational distortion of the dishes. Though nominal elevation-dependent gains can be done routinely in MIRIAD, this effect seems hard to be fully compensated as evidenced by spikes at elevation about 60° and 90°. Close calibrator is needed to make further correction, otherwise significant elevation effect (e.g., peaks at about 60°) will be shown up in the light-curves, which often indicate problem in amplitude calibration. To inspect this problem we have plotted flux density as a function of elevation angle (Fig. 2) as well as time.

Figure 1 shows our preliminary results of Sgr A* 3-mm light curves (2005-2008) observed with the ATCA. On 2006 August 13, the light-curves of Sgr A* and control sources are shown in Figure 2. The flux density of Sgr A* first increased from 1.9 Jy to 2.1 Jy. After the first peak, it decreased to 1.8 Jy in 1.6 hrs. Then it increased to the second peak 2.24 Jy in 1.8 hrs. After that it decreased to 1.95 Jy in 1.6 hrs. The maximum fractional variation \(\frac{\Delta S}{S}\) is \(\sim 22\%\) with a timescale of about 2 hrs. The timescales for the rise and fall are consistent with the previous observations at 3-mm \[12, 20\]. Moreover, two peaks with a separation of 4 hrs are seen, which is also seen in Mauerhan et al. \[12\].

3. Discussions
The timescales for the rise and fall on 2006 August 13 are much shorter than synchrotron cooling timescale, suggesting the existence of some other mechanisms responsible for the variation. Several models have been invoked to explain the flaring activity of Sgr A*, such as the orbiting hotspot model and expanding plasmon model.

An orbiting hotspot model can be used to explain the short-term NIR and X-ray variability \[3, 4, 14, 15, 17, 6, 7\]. The hotspot is modeled by an over-density of non-thermal electrons centered at a point orbiting at the Keplerian velocity. This situation may arise in the case of magnetic reconnection event similar to the solar flare. Due to the Doppler shift and relativistic
beaming the approaching portion of the hotspot orbit appears considerably brighter than the receding portion. This model is successful in explaining the NIR $\sim 17$ minutes quasi-periodic oscillation (QPO). The hotspot model is applied to radio band by taking into account the effects of disk opacity for a typical radiatively inefficient accretion-flow model [4]. In previous studies [3, 4, 14, 15, 17, 6, 7], the hotspot always locates near the inner last stable orbit, thus the NIR $\sim 17$ minutes QPO can be produced. Since the creation of such kind of spot is still under discussion, we can not exclude the possibility that such kind of spot may appear somewhere away from the inner last stable orbit and thus produce quasi-periodic oscillation with a longer timescale. In the following we fit our detected IDV events with a simple hotspot model.

According to Bardeen et al. [2], for a spinning black hole

$$T \doteq 110(r^{3/2} + a_+) \frac{M}{3.6 \times 10^6 M_\odot} [sec]$$

where $a_+$ is the black hole dimensionless spin parameter ($-1 \leq a_+ \leq 1$), and $r$ is a circumferential radius within the equatorial plane given in units of gravitational radius $r_g (\frac{GM}{c^2})$. In the hotspot model, the different time-scale of variability in the total flux is caused by the different location of the hot spots. If our observed IDV events were caused by an orbiting hotspot, the estimated orbital radius around a central Schwarzschild black hole was about $25 r_g$ on August 13.

Though hotspot model can interpret some observations, especially the QPOs in the NIR and X-ray bands, it fails to explain the observed time delay in Sgr A* at 43 and 22 GHz [20, 21, 22]. Expanding plasmon model [19] was then invoked. In this model, rather than the synchrotron cooling, the adiabatic cooling associated with expansion of the emitting plasma is responsible for the decline of flare. Flaring at a given frequency is produced through the adiabatic expansion of an initially optically thick blob of synchrotron-emitting relativistic electrons. The initial rise of the flux is produced by the increase in the blob’s surface area while it still remains optically
thick; the curve turns over once the blob becomes optically thin because of the reduction in magnetic field, the adiabatic cooling of the electrons, and the reduced column density as the blob expands.

Our observed IDVs with different amplitudes and timescales seem also consistent with the expanding plasmon model in the context of jet or outflow. The amplitudes and timescales vary with the relativistic particle energy distribution, expanding velocity and size of the blob. The expanding plasmon model can also be used to interpret the 2000 March 7 NMA short millimeter flare reported by Miyazaki et al. [13]. In their observation, the positive spectral index between 134 and 146 GHz during the flare peak is clear, the peak flux density at the 140 GHz is apparently larger than that at the 100 GHz. The spectral variation suggests that the energy injection to photons occurred in the higher frequency regime and the emitting frequency was shifted to the millimeter-wavelength regime with time. This is well consistent with the scenario predicted by expanding plasmon model.

Trippe et al.[17] observed the NIR emission of Sgr A* using the ESO Very Large Telescope since 2002 and obtained 16 flares, 7 of which show a quasi-periodic sub-structure on time scales of minutes. A pure hotspot or expanding plasmon model is hard to explain all the observations, and the real image may be a combination of these two components. As far as our observation is concerned, both the expanding plasmon model and the orbiting hotspot model seem to be possible explanations. The time delay between different frequencies in flare emission can help distinguish these two models.

4. Summary
We presented the the ATCA flux density monitoring of Sgr A* at 3-mm, with emphasis on a pronounced IDV event. Two peaks with a separation of 4 hrs are seen on 2006 August 13. It exhibits a maximum variation of 22% within 2 hrs. The short timescale indicates the existence of some other mechanisms rather than synchrotron cooling that should be responsible for the variation. The expanding plasmon model and the orbiting hotspot model that can account for flux density variation of Sgr A* were discussed. It seems that both of them can be used to interpret our detected IDV events. Future simultaneous multi-wavelength monitoring is expected to discriminate them.

Acknowledgments
The Australia Telescope Compact Array is part of the Australia Telescope which is founded by the Commonwealth of Australia for operation as a National Facility managed by the CSIRO.

This work has been partially supported by the National Natural Science Foundation of China (grants 10573029, 10625314 and 10633010) and the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No. KJCX2-YW-T03), and sponsored by the Program of Shanghai Subject Chief Scientist (06XD14024) and the National Key Basic Research Development Program of China (No. 2007CB815405).

ZQS acknowledges the support by the One-Hundred-Talent Program of the Chinese Academy of Sciences.

References
[1] Baganoff FK et al. 2001 Nature 413 45
[2] Bardeen JM, Press WH, Teukolsky SA 1972 ApJ 178 347
[3] Broderick A E and Loeb A 2005 MNRAS 363 353
[4] Broderick A E and Loeb A 2006 MNRAS 367 905
[5] Eckart A, Baganoff FK, Morris M et al. 2004 A&A 427 1
[6] Eckart A, Baganoff, F K, Schödel R et al. 2006 A&A 450 535
[7] Eckart A, Baganoff FK, Zamaninasab M et al. 2008 A&A 479 625
[8] Falcke H 1999 ASP Conf. Ser. 186 113
[9] Genzel R et al. 2003 *Nature* **425** 934
[10] Herrnstein RM, Zhao JH, Bower GC, and Goss WM 2004 *AJ* **127** 339
[11] Marrone DP, Baganoff M, Morris M et al 2007 astro-ph/07122887
[12] Mauerhan JC, Morris M, Walter F and Baganoff F 2005 *ApJ* **623** L25
[13] Miyazaki A, Tsutsumi T and Tsuboi M 2004 *ApJ* **611** L97
[14] Meyer L, Schoödel R, Eckart A et al 2006a *A&A* **458** 25
[15] Meyer L, Eckart A, Schoödel R et al 2006b *A&A* **460** 15
[16] Sault RJ, Teuben PJ, and Wright MCH 1995 *ASP Conference Series* **77** 433
[17] Trippe S, Paumard T, Ott T, Gillessen S, Eisenhauer F, Martins F and Genzel R 2007 *MNRAS* **375** 764
[18] Ulich BL 1980 Astrophys. *Letters* **21** 21
[19] van der Laan H 1966 *Nature* **211** 1131
[20] Yusef-Zadeh F, Bushouse H, Dowell CD et al. 2006a *ApJ* **644** 198
[21] Yusef-Zadeh F, Roberts D, Wardle M, Heinke C, and Bower GC 2006b *ApJ* **650** 189
[22] Yusef-Zadeh F, Wardle M, Heinke C et al. 2007 astro-ph/07122882