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Intra-Day Variability of Sagittarius A* at Multi-Wavelengths

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Abstract. This paper reviews the recent progress in the study of the intra-day variability (IDV) of Sagittarius A* (Sgr A*), the best known supermassive black hole candidates with a dark mass concentration of $4\times10^6 M_\odot$ at the center of our galaxy.

Key words. Galaxy: center—galaxies: individual (Sagittarius A*)—techniques: interferometric.

1. Introduction

The observations of stellar orbits in the proximity of Sagittarius A* (Sgr A*), the compact radio source located in the dynamical center of our galaxy, as well as the VLBI observations of proper motion of Sgr A* itself, have established that it is a supermassive black hole with a mass of $4\times10^6 M_\odot$ (Bower *et al.* 2004; Shen *et al.* 2005; Reid & Brunthaler 2004; Doeleman *et al.* 2008; Ghez *et al.* 2008; Gillessen *et al.* 2009). Its bolometric luminosity is only about $3\times10^9 L_{\rm Edd}$ (Melia & Falcke 2001). As the nearest supermassive black hole to us, it provides the best opportunity to study the geometry and physics of black hole accretion. Since Sgr A* is embedded in a thick thermal material, it is particularly difficult to observe its intrinsic structure. Observations of intra-day variability (IDV) thus provide a powerful and alternate tool to probe information of hot plasma in the vicinity of the black hole. Over the past few years, a number of observations have been carried out to study the IDV of Sgr A* and flaring emission have been detected at radio through X-ray wavelengths. Simultaneous observations at multi-wavelengths are also carried out to investigate the relationship of variability behaviour at different wavelengths, as well as the emission mechanisms of the flaring emission.

2. Variability of Sgr A*

2.1 *Radio to mm, sub-mm wavelengths*

Sgr A* was known to be a variable radio source at a level of 20–40% with time scales ranging from years to days since 1982 (Brown & Lo 1982). Significant IDV was not detected until the 21st century by Bower *et al.* (2002), who reported a ∼20% change in the total intensity and fractional circular polarization on a time scale of 1 hr at 15 GHz. Similar, but less prominent changes were apparent at 8.4 and 4.8 GHz. Later, Miyazaki *et al.* (2004) reported an IDV event at short mm wavelengths with the NMA. The flux density at the peak of the flares increased from 3.5 to 4.7 Jy in 30 minutes at 140 GHz. The two-fold increase in time scale of the flare is estimated to be about 1.5 hr at 140 GHz. This short time scale variability suggests that the physical size of the emitting region is smaller than 12 AU. Subsequent OVRO and SMA observations not only confirmed the existence of IDV at mm and sub-mm wavelengths, but also detected IDV in linear polarization (Mauerhan *et al.* 2005; Marrone *et al.* 2006).

Monitoring observations of Sgr A* from the northern hemisphere have been strictly limited to a short observing window (<7 hr/day) for the galactic center region. We have performed monitoring observations of the 3-mm flux density towards Sgr A* with the ATCA since 2005 October (Li *et al.* 2009; Miyazaki *et al.* 2009). The ATCA is an interferometer consisting of five 22-m radio telescopes at Narrabri, Australia where Sgr A* passes almost overhead, allowing a much longer observing window ($>$ 8 hr at elevation angles above 40°). Several IDV events were detected. On 12 August 2006, Sgr A* exhibited a 33% fractional variation in about 2.5 hr. On 13 August 2006, two peaks separated by about 4 hr, with a maximum variation of 21% within 2 hr, were seen (see Fig. 3 of Li *et al.* 2009).

Recently, Yusef-Zadeh *et al.* (2010) investigated the variability of Sgr A* and found evidence for sub-minute time scale variability at radio wavelengths, which constrains the size of the emitting region to be less than 0.1 AU. The nature of such short time scale variable emission or quiescent variability is unclear and it could result from fluctuations in the accretion flow of Sgr A*.

2.2 *NIR/IR wavelength*

The confusion emission from stellar clusters and dust makes it extremely difficult to detect the weak counterpart of Sgr A* at NIR/IR wavelength. Genzel *et al.* (2003) reported several flares observed with VLT for the first time. They observed a powerful flaring by a factor of 5, which lasted for 30 min. Two flares exhibited a 17-min quasi-periodic variability (QPO). Ghez *et al.* (2004) also reported the detection of a variable point source with significant flux density changes on time scales as short as 40 min in the galactic center with Keck II telescope. Subsequent VLT observations have resulted in a number of QPO detections with characteristic time scales of 15–25 min, which has been interpreted as the signature of the orbital motion of the heated electrons (Meyer *et al.* 2006; Trippe *et al.* 2007). However, the reality of QPO activity is still hotly debated mainly because of the low signal-noise ratio (Meyer *et al.* 2008; Do *et al.* 2009). Flares occur frequently at NIR/IR wavelength, about four times per day on average (Eckart *et al.* 2006a; Dodds-Eden *et al.* 2009).

The high degree of linear polarization of the flaring emission at NIR/IR wavelength points to a synchrotron origin (Eckart *et al.* 2006b; Trippe *et al.* 2007).

2.3 *X-ray band*

The X-ray flaring emission of Sgr A* was firstly detected with Chandra in October 2000 (Baganoff *et al.* 2001). The flare has a duration of about 10 ks, with flare peaks L(2–10 keV)$=1.0\pm0.1\times10^{35}$ erg s^{-1}, about 45 times the quiescent state. Later on several other flares were detected by XMM–Newton (e.g., Goldwurm *et al.* 2003; Porquet *et al.* 2003, 2008; Bélanger *et al.* 2005) and Chandra (e.g., Baganoff *et al.* 2003; Eckart *et al.* 2004). The brightest flare with a flux amplitude of about 160 was observed in October 2002 (Porquet *et al.* 2003). The duration of the flare is shorter than one hour ($\sim$2.7 ks). The light curve of the X-ray flares can exhibit short but deep drops close to the flare maximum, indicating that the X-ray emission is emitted from a region as small as $7R_s$. The occurrence of X-ray flare is less frequent compared with the NIR band, $\sim$1 per day on average (e.g., Baganoff 2003; Bélanger *et al.* 2005). The emission mechanism responsible for the X-ray flare remains unclear yet. The synchrotron self-Compton scattering is favoured, and synchrotron emission scenario from an electron distribution with a cooling break is also proposed to explain a bright X-ray flare (Dodds-Eden *et al.* 2009).

2.4 *Simultaneous observations at multi-wavelengths*

The first successful attempt of simultaneous observation showed that X-ray flares happened simultaneously to the NIR flares and they evolved on the same time scale (Eckart *et al.* 2004). Many NIR flares have been observed to show X-ray counterparts (e.g., Eckart *et al.* 2006a). There is no evidence of time delay between the peaks of detected flares, indicating that both NIR and X-ray emission are optically thin (Yusef-Zadeh *et al.* 2009). At radio wavelengths, time delay of about 30 min has been detected for flaring emission at 7 and 13 mm wavelengths (Yusef-Zadeh *et al.* 2006, 2008). The sub-mm flare was also observed to follow the NIR and X-ray flares with a delay of about 100 min (e.g., Eckart *et al.* 2008; Marrone *et al.* 2008). The relationship between radio and NIR/X-ray flaring emission remains unclear due to the limited simultaneous time coverage between radio, infrared and X-ray telescopes (Yusef-Zadeh *et al.* 2009).

We observed Sgr A* at 3 and 7 mm wavelengths with ATCA on 3 October 2008 (Fig. 1a). The positive peak in DCF result suggests that 3 mm emission lead 7 mm emission by 1 ± 0.5 hr, which is consistent with Yusef-Zadeh *et al.* (2009). An expanding plasma model of van der Laan (1966) was invoked to explain the observed time delay (e.g., Yusef-Zadeh *et al.* 2006; Eckart *et al.* 2008; Li *et al.* 2009). 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. We found that the 3 and 7 mm light curves could be fitted simultaneously with the expanding plasmon model (Fig. 1b). The fitting results indicate that the observed variation of Sgr A* at two wavelengths on 3 October 2008 is consistent with the expanding plasmon model.

Table 1 summarizes the IDV characteristics of Sgr A*.

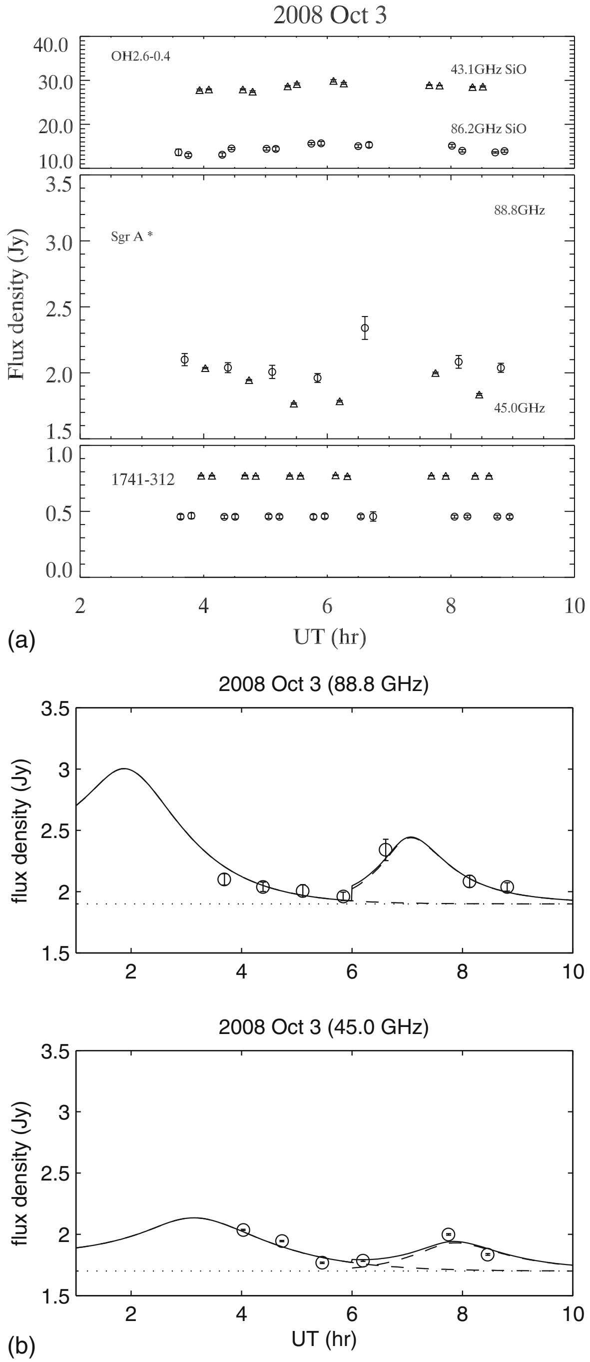

Figure 1. (**a**) ATCA 3 (○) and 7 mm (△) light curves of Sgr A* and calibrator OH2.6-0.4 (top panel) and PKS 1741-312 (bottom panel) on 3 October 2008; (**b**) The solid line represents the expanding plasmon model fitting to the observed 3 mm (upper panel) and 7 mm (bottom panel) light curves on 3 October 2008. The quiescent flux were supposed to be 1.9 and 1.7 Jy at 3 and 7 mm, respectively. Two blobs are used to fit the flaring emission.

Table 1. IDV characteristics of Sgr A*.

Band	Telescope	Max. Amp.	Typical time scale	Correlation with other bands
cm	ATCA/VLA	20%[a]	$>$1 hr[a]	–
mm/sub-mm	ATCA/BIMA CSO/NMA OVRO/SMA VLA	40%[b]	2 hr[c]	7 mm lead 13 mm by $\sim$30 min[d]
NIR/IR	Keck II/VLT	$\sim$10 times[e]	40 min[f] (17 min[g] ?)	Simultaneous with X-ray[h], lead sub-mm by 90 min[i]
X-ray	Chandra/XMM	160 times[j]	10 min[k]	Simultaneous with NIR, lead sub-mm by 100 min[l]

[a] Bower *et al.* (2002); [b] Mauerhan *et al.* (2006); [c] Li *et al.* (2009); [d] Yusef-Zadeh *et al.* (2006); [e] Trippe *et al.* (2007); [f] Ghez *et al.* (2004); [g] Genzel *et al.* (2003); [h] Eckart *et al.* (2004); [i] Eckart *et al.* (2008); [j] Porquet *et al.* (2003); [k] Porquet *et al.* (2008); [l] Yusef-Zadeh *et al.* (2008).

3. Prospect

The variability of the total flux density would be accompanied by the structural change and flux density monitoring combined with high resolution VLBI observations would be critical to explore the origin of the flaring emission from Sgr A* (Shen 2005). From the VLBA observations at 3 frequencies (22, 42, 86 GHz), a tendency for the sizes of the minor axis to increase with total flux is seen, which points towards a source intrinsic origin (Lu *et al.* 2011). Future short wavelength VLBI observations are expected to sensitively monitor the changing morphology of Sgr A* using non-imaging techniques with time resolutions of tens of seconds and powerfully constrain the flaring models of Sgr A* (Doeleman *et al.* 2009; Fish *et al.* 2009).

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