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The simultaneous VLA observations of Sgr A* from 90 to 0.7 cm

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Abstract. We present a spectrum of Sgr A* observed simultaneously on June 17, 2003 at wavelengths from 90 to 0.7 cm with the VLA. In the spectrum, we also include the measurements of Sgr A* observed on the same day with the GMRT at 49 cm, the SMA at 0.89 mm and the Keck II at 3.8 μm. The spectrum at the centimeter wavelengths suggests the presence of a break wavelength at λ_b ~3.8 cm (8 GHz). The spectral index is $\alpha = 0.43 \pm 0.03$ ($S \propto \nu^{\alpha}$) at 3.8 cm and shorter wavelengths. The spectrum between λ =3.8 cm and λ =49 cm can be described by a power law with spectral index of $\alpha = 0.10 \pm 0.03$. We detected Sgr A* with 0.22 ± 0.06 Jy at 90 cm, suggesting a sharp decrease in flux density at the wavelengths longer than 49 cm. The best fit to the spectrum at the wavelengths longer than λ_b appears to be consistent with free-free absorption by a screen of ionized gas with a turnover wavelength at $\nu(\tau_{ff} = 1) \sim 100$ cm (300 MHz). This turnover wavelength appears to be three times longer than that of 30 cm (1 GHz) as suggested by Davies et al. (1976) based on the observations in 1994 and 1995. Our analysis suggests that stellar winds from the massive stars near Sgr A* could modulate the flux density at the wavelengths longer than 30 cm (or frequencies below 1 GHz).

1. Introduction

The compact radio source Saggittarius A* (Sgr A*) at the Galactic center (GC) is widely believed to be associated with the supermassive black hole (SMBH) with a mass of $M = 4 \times 10^6 M_\odot$ (Schödel et al. 2002; Ghez et al. 2003). Sgr A* is a prototypical case of low luminosity galactic nuclei. Theoretical models suggest that a model with low efficiency radiative accretion flow might explain the dim nature of Sgr A* based on the observations at the wavelengths of radio sub-millimeter, IR and X-rays. In a recent paper, Loeb (2004) proposed that the stellar wind streams from the young, massive stars may also play an important role in fueling Sgr A* in order to explain the variability in flux densities observed at millimeters/submillimeters. However, the ionized gas of the stellar winds may also attenuate the flux density at longer radio wavelengths. On the other hand, Davies et al. (1976, hereafter DWB) observed Sgr A* at 0.408, 0.96 and 1.66 GHz and only detected at the two higher frequencies. They suggested a low-frequency cutoff at about 1 GHz and suggested that the non-detection at 408 MHz was owing to the free-free absorption. However, detections of significant flux density from Sgr A* at 620 MHz with the GMRT (Roy & Rao 2004a) and at 330 MHz with the VLA (Nord et al. 2004) have raised questions of the early observations and interpretations by Davies et al. (1976).

2. Observations

We carried out simultaneous observations of Sgr A* with the VLA in its A configuration on June 17, 2003, covering a wide frequency range of 90, 20, 6, 3.6, 2, 1.3 and 0.7 cm. The observations at 90 and 20 cm were done in spectral line mode in order to reject RFIs and to minimize the bandwidth smearing effect. Observations at other bands were performed in the VLA standard continuum mode. In this paper, we present the preliminary results from our observations and analysis. The detailed results will be given in An et al. (2004).

3. Results and discussion

3.1. Detection of Sgr A* at 90 cm

We carried out several iterations of phase-only self-calibration to the 90 cm data in order to improve the dynamic range of the image (please see electronic version of the image at 90 cm). The final image is restored with a beam of $10.9'' \times 6.8''$ (PA= $-10°$). The off-source *r.m.s.* noise of ~ 12 mJy/b in the image is estimated. Sgr A East dominates the total flux density at this wavelength. A bump in flux density is observed at the expected location of Sgr A*. The region surrounding Sgr A*, except for the southern extended emission, is significantly absorbed by the ionized gas in Sgr A West. We carried out Gaussian fitting with the intensity slices along the expected major and minor axes to estimate the flux density at 90 cm. The fitted peak brightness is 65±16 mJy/b after subtracting the background confusion, and the deconvolved source size is $14.4'' \times 10.7''$. A total flux density of 220 ± 60 mJy at 90 cm is derived from the model fitting.

3.2. Simultaneous Spectrum at Radio Wavelengths

We also measured the flux densities of Sgr A* at other shorter wavelengths in the IMAGE domain. We use a point-source model (for wavelengths at 6 cm and shorter) or an elliptical Gaussian model (for wavelengths ~20 cm) to fit the data. The spectrum shape around 1 GHz is critical in examination of the low frequency turnover. Thus, we measured the flux density at four discrete frequencies (1.155, 1.300, 1.500 and 1.740 GHz)

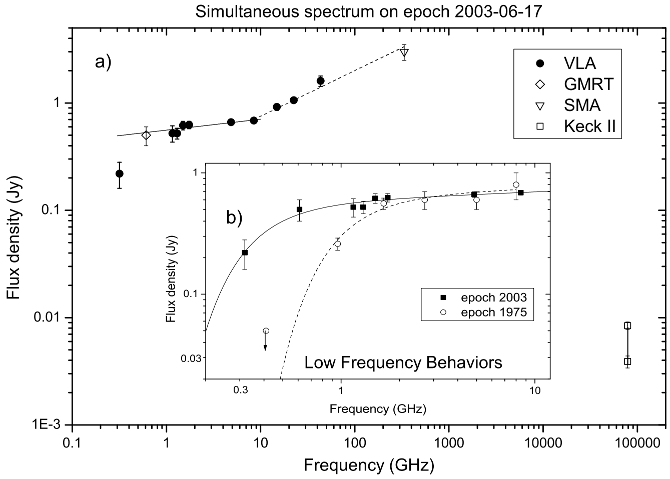

Fig. 1. a) : the observed spectrum of Sgr A* from 90 cm to 3.8μm. *solid circle*: VLA from 90 to 0.7 cm (present paper); *diamond*: GMRT at 610 MHz (Roy & Rao 2004b); *triangle*: SMA at 335 GHz (Zhao et al. 2004) and *square*: Keck II at 3.8μm (Ghez et al. 2004). **b)** : comparison of low frequency free-free fitting between epoch 2003 and epoch 1975. *solid square* : epoch 2003; *open circle* : epoch 1975.

in the 20 cm band. We also measured the flux density on each band in the UV domain. The difference between the flux densities derived from the two procedures was taken as the uncertainty in measurements (ΔS_M). Taking into account of calibration uncertainty (ΔS_C), the inferred 1 σ errors are the quadrature addition of two terms. The uncertainties in a fraction of the flux densities are 27%, 17%, 11%, 9.1%, 7.6%, 5.4%, 4.5%, 7.0%, 5.6% and 11% at the wavelengths between 90, 26, 23, 20, 17, 6, 3.6, 2, 1.3 and 0.7 cm, respectively.

Figure 1a shows the a quasi-simultaneous (within a day) spectrum of Sgr A* from 90 cm to 3.8 μm covering 5 orders of magnitude in the frequency range. A significant break in the cm-band spectrum is seen around $\lambda_b \sim 3.8$ cm (8 GHz). For the wavelengths shorter than λ_b the spectrum can be described by a power-law spectrum: $S_\nu \propto \nu^{0.43\pm0.03}$. The spectrum appears to peak at a millimeter/submillimeter wavelength and the spectral index determined from the flux densities between 0.87 mm and 3.8 νm is $\alpha_{0.87mm/3.8\mu m} = -1.13^{+0.06}_{-0.08}$.

The dashed line represents the fitting between 8 and 335 GHz. The spectrum between 49 cm (620 MHz) to 3.8 cm (8 GHz) is rather flat with a spectral index $\alpha = 0.10 \pm 0.03$. At 318 MHz ($\sim$ 90 cm), the spectrum shows a factor of $\sim$2 decrease in flux density in comparison with the value observed at 49 cm.

3.3. Low frequency behaviors

In Figure 1b, we compare the low-frequency (from 318 MHz to 8.5 GHz) spectrum measured on the epoch of 1975 (DWB; *open circle*) and on the epoch of 2003 (*solid square*). DWB showed an exponential cut-off in flux densities of Sgr A* below 1 GHz and suggested that the cut-off is owing to the free-free absorption by the ionized gas in Sgr A West (the dashed line represents the free-free fitting). However the free-free absorption model appears to confront with the GMRT observation at 49 cm (Roy & Rao 2004b) and our VLA observation at 90 cm in 2003 shown in Fig. 1b. The flux densities of Sgr A* determined from both the GMRT observations at 49 cm and the VLA observations at 90 cm are significantly greater than the values expected from DWB's free-free absorption model. However the measurements from the nearly simultaneous observations using the GMRT and the VLA do show a significant decrease in flux density at 90 cm as is compared to that at 49 cm.

It is unlikely that the flux density variations at the lower frequencies are intrinsic to Sgr A* since the source appears to be quiet at the shorter centimeters based on the monitoring observations (Zhao et al. 2001). If we believe DWB's measurements and free-free absorption model is correct, then the variations in the lower frequencies would suggest that the column density of the free-free absorbing screen is changed over the past 30 years. We can fit DWB's free-free absorption model to the data observed in 2003 in order to assess the change in the column density of the ionized in the front of Sgr A*. The solid line in Figure 1b shows the free-free fit to the 2003 data and the dashed line is the fit to the 1975 data. The discrepancy in free-free fitting between epoch 1975 and 2003 suggests that the critical cut-off frequency ($\nu(\tau_{ff} = 1)$) in free-free absorption must shift from $\sim$1 GHz to $\sim$300 MHz in past 30 years. The inferred shift $\Delta\nu(\tau_{ff} = 1)$ suggests that the free-free optical depth at a given frequency has decreased by a factor of 9. Assuming the electron temperature in the ionized gas did not change in the past 30 years, the inferred decrease in optical depth could be due to a decrease of electron column density in the front of Sgr A*. Such a large-scale variation in the column density of electrons in a time-scale of 30 years was likely taken place in a compact region near Sgr A*. The stellar winds from the orbiting massive stars around Sgr A* within the central 1″could modulate the flux density at low radio frequencies from Sgr A* on a timescale of 10 years (Loeb 2004).

As a synchrotron source, the low frequency behavior of Sgr A* could also be explained by synchrotron self-absorption model (SSA), which is sensitive to the critical cut-off frequency. However, the SSA model requires the strength of the magnetic field much higher than the value that is common accepted.

The Razin suppression effect suggests a cut-off frequency at 10^{1-2} kHz (Davies et al. 1976) which is far below the observed value of $\sim$ 300MHz.

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