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THE SIMULTANEOUS SPECTRUM OF SGR A* FROM λ20CM TO λ1MM AND THE NATURE OF THE MM-EXCESS

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ABSTRACT

We report results from a multiwavelength campaign to measure the simultaneous spectrum of the super-massive black hole candidate Sgr A* in the Galactic Center from cm to mm-wavelengths using the VLA, BIMA, the Nobeyama 45m, and the IRAM 30m telescopes. The observations confirm that the previously detected mm-excess is an intrinsic feature of the spectrum of Sgr A*. The excess can be interpreted as due to the presence of an ultra-compact component of relativistic plasma with a size of a few Schwarzschild radii near the black hole. If so, Sgr A* might offer the unique possibility to image the putative black hole against the background of this component with future mm-VLBI experiments.

Subject headings: galaxies: nuclei—Galaxy: Center—black hole physics

1. INTRODUCTION

It is now almost certain that the Galaxy hosts a dark mass of $2.6 \cdot 10^6 M_\odot$ in its very center. This has been demonstrated most convincingly by high-resolution near-infrared speckle imaging of the central star cluster (Eckart & Genzel 1996) where proper motions of stars yield velocities of up to $\sim$ 2000 km/sec near the compact radio source Sgr A*. Its location within the optical frame has now been determined with high accuracy by Menten et al. (1996). To explain the nature of Sgr A* various models have been proposed, such as an advection dominated accretion flow (Narayan et al. 1995), Bondi-Hoyle accretion (Melia 1994), and a jet outflow (Falcke et al. 1993; Falcke 1996a)—all involving a supermassive black hole.

And indeed, the gravitational potential required to explain the run of stellar velocities around Sgr A* is that of a point source within $\sim$ 0.01 pc, implying a central dark mass density of $> 10^{12} M_\odot \mathrm{pc}^{-3}$. Such a mass density is too high to be explained by a cluster of stellar remnants and therefore strongly supports the presence of a black hole (Maoz 1997) in the Milky Way. Nevertheless, a definite and direct proof for the existence of black holes in general and in the Galactic Center in particular is still missing, because the scales probed by NIR imaging are still large compared to the the event horizon, the defining characteristic of a black hole.

However, since the black hole is most certainly associated with the non-thermal radio source Sgr A* (e.g. Eckart et al. 1993, Backer 1996), interferometric observations at mm-wavelengths might eventually have the resolution to reach even those extreme scales. Hence the mm-spectrum of Sgr A* is of considerable interest. Early mm-observations of Sgr A* suggested the presence of a mm-excess due to a sub-mm bump (Zylka et al. 1992 & 1995) in the spectrum, possibly caused by an ultra-compact region in Sgr A* (Falcke et al. 1993; Falcke 1996b). The existence of this bump was, however, uncertain due to the variability of Sgr A*. In order to determine the reality of this crucial feature in the spectrum, we have conducted an experiment to measure the spectrum of Sgr A* simultaneously from λ20cm to λ1mm.

The Galactic Center (GC) was observed on three consecutive days on 25-27 October 1996 with four different telescopes (VLA, BIMA, Nobeyama 45 m, & IRAM 30 m) on three continents. The campaign was set up with redundancies in wavelengths and time coverage. The observations were prepared, performed, and reduced independently by four different groups and will be described in Section 2. The results are presented in Sec. 3, and their implications are discussed in Sec. 4. For a discussion of the overall spectrum of Sgr A* and a comparison to model predictions, we refer the reader to the recent work by Serabyn et al. (1997). Here we will solely focus on the mm-excess and its implications.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *VLA A-configuration*

Observations of Sgr A* with the VLA in its A-configuration were scheduled for 2 hrs on each of three successive days on 25-27 October 1996. Sgr A* was observed at 43.3 GHz for the entire run on each of the dates using the thirteen antennas mounted with the λ7mm receivers. The rest of the array was used to observe Sgr A* at 22.5, 14.9, 8.45, 4.85, 1.64, 1.44, and 1.36 GHz in snapshot mode ($\sim$10 min observing time on the target source at each frequency). The weather was cloudy during the observations. On October 25th all data were lost due to strong wind and on the 26th data at 5 and 1.67 GHz were lost due to setup problems.

The flux density scale was determined using the primary calibrator 3C 286 assuming flux densities of 1.45, 2.50, 3.43, 5.18, 7.48, 13.8, 14.7, and 15.0 Jy for the frequencies given above (from 43.3 to 1.36 GHz). Both 1730–130 and 1741–312 were used to check the phases and amplitudes. At 43 GHz the AIPS task ELINT was used to correct for elevation-dependent antenna gains. The data were further self-calibrated for the phase only,

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images were reconstructed, and flux densities were measured in the image domain. Uncertainties (1 σ) of the flux densities were estimated including the r.m.s. and the uncertainties in the flux density calibration.

2.2. *BIMA C-configuration*

BIMA observed the GC in its C-configuration on all three days under good weather conditions throughout. Uranus was initially used as the primary flux calibrator. The observing sequence followed a triangular pattern including Sgr A*, NRAO 530 (1730-130), and OH 5.89–0.39 (at 17 57 26.7 -24 03 54 (B1950), a luminous compact H II region), with 5 min, 2.5 min and 1.7 min integration times respectively. The total observing time each day was 1.5 - 2 hours.

Since the data was decorrelated at the long baselines, NRAO 530 was not a suitable calibrator. Instead we used OH 5.89–0.39 as a phase and amplitude calibrator for Sgr A* which is only $\sim 7°$ away. The flux density of OH5.89–0.39 was taken to be 8.5 Jy at λ3mm as determined by the Nobeyama single dish.

Since OH 5.89–0.39 is slightly resolved at the longest baselines (disk of $\sim 5''$, e.g. Zijlstra et al. 1990) we only used baselines shortwards of 10 Kλ. A cleaned map was restored with a beam of $17'' \times 16''$and background subtraction was done, using the scaled 2cm VLA map, as described for the Nobeyama 45 m telescope below.

2.3. *Nobeyama 45m*

The Nobeyama 45 m single dish observed the GC at two epochs using SIS receiver at 40 and 100 GHz bands, and the Nobeyama bolometer array (NOBA – a seven element bolometer array; Kuno et al. 1993) at 150GHz. Except for the 150 GHz observations, the sources were observed with cross scans and beam switching was used, which gives a beam throw of $6'$. In addition to Sgr A* we observed Uranus (as primary flux density calibrator), NRAO 530, and OH 5.89-0.39.

For May 24-28, 1996 we calibrated our flux densities against Uranus (11.0Jy, 130K) for the 107 GHz and NGC 7027 (5.4 Jy) for the 43 GHz observations. The zenith optical depth was 0.1-0.2. Beam sizes were $15.2'' \times 16.2''$ at 107 GHz, and $36.5'' \times 40.7''$ 43 GHz. The relative uncertainty of each observation is 0.2 Jy and during this observing run we did not see any change in flux density of Sgr A* above the 10% level. We estimated the thermal contribution to the flux density within our beam from the 15 GHz VLA data used by Zylka & Mezger (1988). The VLA data was scaled to the respective frequencies, using a spectral index of -0.1 for free-free emission, and convolved with a beam corresponding to the single dish observations.

For 25-30 Oct 1997 day-to-day variations of Sgr A* were less than 15% of the total flux density at 95 GHz and less than 20% at 150 GHz, hence we only present flux densities averaged over several days (27, 29, & 30 Oct for 95 GHz, and 25 & 29 Oct for 150 GHz data). Beam sizes for NOBA at 150 GHz are $12''$ with separations of $16''$ and bridge readout technique was incorporated (Kuno et al. 1993). The flux densities of the observed sources are given in Table 1.

2.4. *IRAM 30 m*

We observed Sgr A* during the campaign with the IRAM 30 m single dish antenna simultaneously with 3 receivers at 106.3, 152.3, and 235.6 GHz and with beamsizes of $23''$, $15''.7$, and $10''.2$ respectively. We had relatively bad weather on 26 October 1996, usable conditions on 25, and very good weather on 27 October 1996 with an optical depth of $\tau = 0.2$ at 235.6 GHz. Chopping was used (beam throw of $60''$). To account for the effects of anomalous refraction, each scan was shifted to the center position of fitted Gaussians with shifts up to $3''$. The contribution from thermal free-free emission, as derived from the 15 GHz VLA map used in Zylka & Mezger (1988), was fitted to the wings of each scan and subtracted. A statistical error of the measurement was derived from the standard deviation of the combined scans. Flux densities and errors for Sgr A* are given in Table 2.

3. RESULTS

Despite several lost datasets we were able to obtain a spectrum of Sgr A* which covers the range from 1.36 to 232 GHz. The individual flux densities are summarized in Table 2.

3.1. *cm-Spectrum*

The spectrum at lower frequencies between 1.36 and 43 GHz was successfully measured on two days by the VLA and is described by two power laws with spectral indices $\alpha = 0.17$ ($S_\nu \propto \nu^\alpha$) below and $\alpha = 0.30$ above 10 GHz, while there is a marked break between 8.5 and 15 GHz with $\alpha = 0.77$ (Fig. 1). We did not find any variability at and below 8.5 GHz between the two days (at the 1% level for 8.5GHz). We find an increase by $\sim$15% in flux at 15 GHz between 26 & 27 Oct. 1996, however, in addition to the statistical errors given in Tab. 2, we may have a systematic error of up to $\sim$10% at frequencies 15 GHz and higher in the observations on 26 Oct 1996 due to possible improper correction of different air masses. Thus we cannot claim any significant intra-day variability of Sgr A* from our data at cm wavelengths.

3.2. *mm-Spectrum*

The errors of the mm-telescopes are much larger than those of the VLA and comparison of various data-sets indicate that the variability at λ3 & 2mm is not larger than 20% over a period of three days during the campaign at all frequencies below 150 GHz (see also Gwinn et al. 1991). We therefore first combined all available data for each telescope to obtain an average flux density measurement of Sgr A* over the campaign period. Due to the different sampling of the datasets, the mean of the average flux density will differ by $\pm$1 day between the telescopes and in general is skewed towards the end of the campaign period. In light of the limits of variability for Sgr A*, we find that such an uncertainty is tolerable for the compilation of a simultaneous, broad-band spectrum.

Since the individual flux densites from the three mm-telescopes agree within the errors with each other we then combined the flux density measurements from the different telescopes at λ3 & 2mm and compared it with the time-averaged VLA flux densities (Table 2, Fig. 1).

First of all we notice that the λ3mm flux density is only slightly above the extrapolation from the VLA observations which is reassuring concerning the possible systematic uncertainties in the thermal background subtraction. Hence, the fact that the λ2mm flux density — measured by the same telescopes — lies substantially (0.8Jy, $\sim 4\sigma$) above the extrapolation from the VLA cm data becomes even more significant. If we only consider λ7, 3, & 2mm we find that the spectral index of Sgr A* increases to $\alpha = 0.52$ in the mm-range, while the λ3-to-2mm spectral index even becomes $\alpha = 0.76$, hence *we conclude that there is a significant mm-excess in the spectrum of Sgr A **. The

λ1.3mm measurement is consistent with such an excess but, because of the large errors, has no significance for this discussion.

4. SUMMARY & DISCUSSION

A major problem in discussing the spectrum of Sgr A* and the reality of the mm-excess has been the non-simultaneity of the measurements and the comparison of array (low frequencies) and single dish (high frequencies) flux densities. Our simultaneous observations now show a smooth transition from the VLA to the mm-telescopes and an upturn in the spectrum of Sgr A* between λ3mm and λ2mm in the single dish observations alone. The results of all telescopes were consistent with each other and we conclude that the observed mm-excess is not due to variability or technical artifacts.

A concern that needs to be addressed in more detailed when studying the spectrum of Sgr A * is, however, confusion by other sources. The diffuse free-free emission in the GC obviously is a major source of confusion for single dish observations of Sgr A* and subtraction of this component was taken care of as discussed in Section 2. Optically thick thermal emission, e.g. from cold dust, on a scale of a few arcseconds and beyond seems to be negligible in the mm-regime (Zylka et al. 1995) and comparison of single-dish and high-resolution interferometer flux density measurements (with OVRO) do not indicate the presence of such components at smaller scales as discussed by Serabyn et al. (1992[7], 1997).

Finally, a major contribution of a yet unknown non-variable point source in the very vicinity of Sgr A* can also be ruled out. Based on high resolution VLA images with a resolution of $0\overset{''}{.}1$ at λ13 and λ7 mm, the peak flux density for such a hypothetical source is below 5 mJy at λ7mm. The brightest regions near Sgr A* are IRS 13 ($3''$ SW to Sgr A*) which contributes 100 mJy (integrated within a $3''\times3''$ area) and IRS 2 (1-$2''$ south to IRS 13) which contributes 85 mJy (within a $2''\times2''$area)—the spectra of these sources are consistent with optically thin free-free emission. From the upper limits at lower frequencies it follows that any source which might be confused with Sgr A* would contribute negligibly to the total flux density of Sgr A* at mm-wavelengths. For a source with optically thick, thermal emission, for example, the contribution has to be less than 50 mJy at λ2mm in order to be below the upper limits at λ7mm. We therefore conclude that the mm-excess is indeed an intrinsic feature of Sgr A*.

The sub-mm bump causing this excess is, in fact, very well explained by assuming the presence of a compact, self-absorbed synchrotron component in Sgr A*. As outlined in Falcke (1996b; see also Beckert & Duschl 1997) this sub-mm component can be described in its most simple minded form by four parameters: magnetic field B, electron density n, electron Lorentz factor $\gamma_{\rm e}$, and radius R. These input parameters correspond to three measured quantities: synchrotron self-absorption (i.e. upturn) frequency $\nu_{\rm ssa}$, peak flux density $S_{\nu_{\rm max}}$, and peak frequency $\nu_{\rm max}$. With an equipartition parameter k which is assumed to be of order unity (but does not enter strongly) and a distance to the GC of 8.5 kpc, we find that the radius of this emitting region is then given by

$$R \sim 1.5\cdot 10^{12}{\rm cm}\quad k^{-1/17}\left(\frac{S_{\nu_{\rm max}}}{3.5{\rm Jy}}\right)^{8/17}$$
$$\left(\frac{\nu_{\rm max}}{10^{12}{\rm Hz}}\right)^{-16/51}\left(\frac{\nu_{\rm ssa}}{100{\rm GHz}}\right)^{-35/51}. \qquad (1)$$

This size is consistent with the upper limits ($\sim$1 AU) from VLBI (Rogers et al. 1994) and lower limits ($\sim 10^{12}$cm) from scintillation experiments (Gwinn et al. 1991). In comparison we also note that the Schwarzschild radius ($R_{\rm S}$) of the putative $2.6\cdot10^6 M_\odot$ black hole in the GC is already $R_{\rm S}=0.77\cdot10^{12}$ cm and thus the compact sub-mm component should correspond to a region in the very vicinity of the black hole. Most interesting is the possibility that this region is directly affected by general relativistic effects, and could for example be gravitationally amplified if the radiation is intriniscially anisotropic (e.g. similar to Cunningham 1975).

Finally, a compact component with the parameters as in Eq. 1 would be very interesting for mm-VLBI, since, if this is not just a spot near the black hole horizon, the black hole horizon could be imaged against the background of this sub-mm emission. As Bardeen (1973, his Fig. 6) has shown, a black hole in such a configuration would appear as a dark disk with a diameter of 4.5 $R_{\rm S}$, (i.e. $3.45\cdot10^{12}$ cm, or 27μas). Since the extrapolated scattering size of Sgr A* at 215 GHz is also $\sim$27μas (e.g. Yusef-Zadeh et al. 1994)—similar to the expected resolution of future mm-VLBI experiments (e.g. Wright & Bower 1997), direct imaging of the putative black hole in the GC might be in reach within the next decade.

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TABLE 1
NOBEYAMA FLUX DENSITIES

Source	107 GHz	43 GHz	150 GHz	95 GHz
NRAO 530	13.2 ± 0.4 Jy	16.0 ± 0.5 Jy	12.0 ± 1.2 Jy	12.6 ± 0.7 Jy
OH 5.89–0.39	8.5 ± 0.3 Jy	9.0 ± 0.3 Jy	8.8 ± 0.9 Jy	8.0 ± 0.5 Jy
Sgr A*+thermal	5.5 ± 0.2 Jy	11.0 ± 0.3 Jy	4.0 ± 0.4 Jy	5.1 ± 0.3 Jy
Sgr A*	2.7 ± 0.4 Jy	1.9 ± 0.6 Jy	3.1 ± 0.4 Jy	2.0 ± 0.4 Jy

NOTE.—Flux densities and 1 σ errors for Galactic Center sources obtained with the Nobeyama 45m antenna. 107 and 43 GHz flux densites are from 24-28 May 1996, and 150 and 95 GHz flux densities are from 25-30 Oct. 1996.

TABLE 2
MEASURED FLUX DENSITIES FOR SGR A*

telescope	ν [GHz]	26 Oct 1996 S_ν [Jy]	26 Oct 1996 err.	27 Oct 1996 S_ν [Jy]	27 Oct 1996 err.	All days S_ν [Jy]	All days err.
IRAM	235.6					2.8	±0.9
IRAM	152.3					2.9	±0.25
IRAM+Nobeyama	151.					2.9	±0.21
Nobeyama	150.					3.1	±0.4
IRAM	106.3					2.4	±0.35
IRAM†+Nobeyama+BIMA	95.0					2.1	±0.23
Nobeyama	95.					2.0	±0.4
BIMA	93.					1.9	±0.5
VLA	43.3	1.4	±0.2	1.50	±0.05	1.3	±0.14
VLA	22.5	1.0	±0.1	1.20	±0.07	1.1	±0.05
VLA	14.9	0.95	±0.06	1.10	±0.03	1.03	±0.03
VLA	8.45	0.72	±0.01	0.71	±0.01	0.72	±0.01
VLA	4.85			0.64	±0.01	0.64	±0.01
VLA	1.64			0.55	±0.03	0.55	±0.03
VLA	1.44	0.54	±0.04	0.52	±0.02	0.53	±0.02
VLA	1.36	0.53	±0.04	0.52	±0.02	0.53	±0.02

NOTE.—Description of columns: (1) – telescope or combination of telescope involved to derive the flux density, (2) – frequency (average if multiple telescopes), (3) – VLA flux density on 26 Oct. 1996, (4) – one σ error, (5) – VLA flux density on 27 Oct. 1996, (6) – one σ error, (7) – flux density averaged over the available data from all three days (linear average of columns 3 & 5 for VLA data else weighted by error), (8) – combined one σ error. Additional note: † calculated from 106.3 GHz assuming a spectral index of $\alpha = 0.76$.

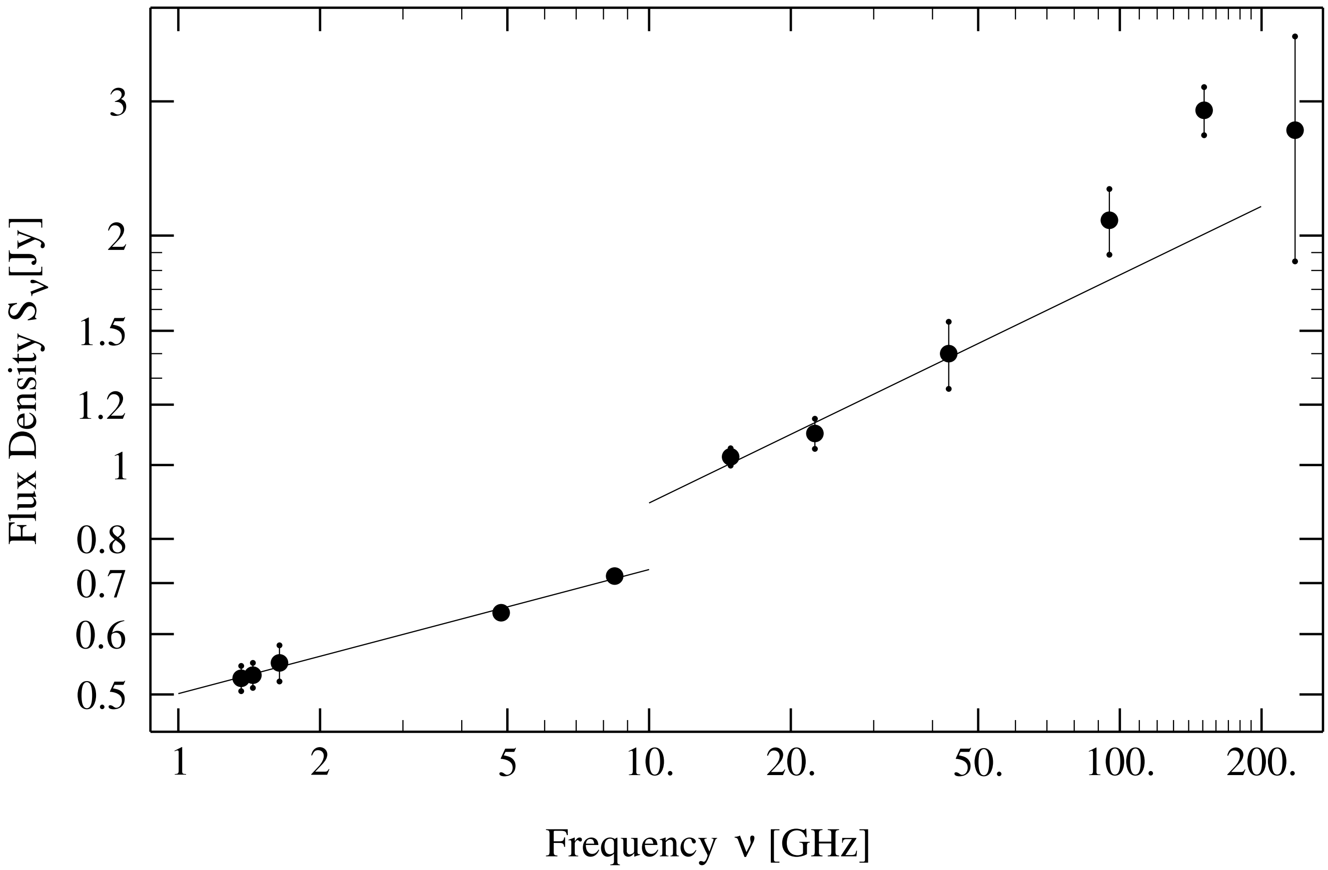

FIG. 1.— Spectrum of Sgr A* plotted as the logarithm of the flux density vs. the logarithm of the frequency. Shown are the data averaged over the campaign period; flux densities at neighboring frequencies were also combined from the different mm-telescopes. Solid lines represent power law fits to the low- and high-frequency VLA data.