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Coordinated mm/sub-mm observations of Sagittarius A* in May 2007

D Kunneriath[1,2], A Eckart[1,2], S Vogel[3], L Sjouwerman[4], H Wiesemeyer[5], R Schödel[6], F K. Baganoff[7], M Morris[8], T Bertram[1], M Dovciak[9], D Downes[10], W J Duschl[11,12], V Karas[9], S König[1,2], T Krichbaum[2], M Krips[13], R-S Lu[2,1], S Markoff[14], J Mauerhan[8], L Meyer[8], J Moultaka[15], K Muzic[1,2], F Najarro[16], K Schuster[10], C Straubmeier[1], C Thum[10], G Witzel[1], M Zamaninasab[1,2] and A Zensus[2]

[1] University of Cologne, Zülpicher Str. 77, D-50937 Cologne, Germany
[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[3] Department of Astronomy, University of Maryland, College Park, MD 20742-2421, USA
[4] National Radio Astronomy Observatory, PO Box 0, Socorro, NM 87801, USA
[5] IRAM, Avenida Divina Pastora, 7, Núcleo Central, E-18012 Granada, Spain
[6] Instituto de Astrofísica de Andalucía, Camino Bajo de Huétor 50, 18008 Granada, Spain
[7] Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA
[8] Department of Physics and Astronomy, University of California, Los Angeles, CA 90095-1547, USA
[9] Astronomical Institute, Academy of Sciences, Boční II, CZ-14131 Prague, Czech Republic
[10] Institut de Radio Astronomie Millimetrique, Domaine Universitaire, 38406 St. Martin d'Heres, France
[11] Institut für Theoretische Physik und Astrophysik, Christian-Albrechts-Universität zu Kiel, Leibnizstr. 15 24118 Kiel, Germany
[12] Steward Observatory, The University of Arizona, 933 N. Cherry Ave. Tucson, AZ 85721, USA
[13] Harvard-Smithsonian Center for Astrophysics, SMA project, 60 Garden Street, MS 78 Cambridge, MA 02138, USA
[14] Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Kruislaan 403, 1098SJ Amsterdam, the Netherlands
[15] Observatoire Midi-Pyrénées, 14, Avenue Edouard Belin, 31400 Toulouse, France
[16] Instituto de Estructura de la Materia, Consejo Superior de Investigaciones Cientificas, CSIC, Serrano 121, 28006 Madrid, Spain

E-mail: `eckart@ph1.uni-koeln.de`

Abstract. At the center of the Milky Way, with a distance of ∼8 kpc, the compact source Sagittarius A* (SgrA*) can be associated with a super massive black hole of $\sim 4\times10^6 M_\odot$. SgrA* shows strong variability from the radio to the X-ray wavelength domains. Here we report on simultaneous NIR/sub-millimeter/X-ray observations from May 2007 that involved the NACO adaptive optics (AO) instrument at the European Southern Observatory's Very Large Telescope, the Australian Telescope Compact Array (ATCA), the US mm-array CARMA, the IRAM 30m mm-telescope, and other telescopes. We concentrate on the time series of mm/sub-mm data from CARMA, ATCA, and the MAMBO bolometer at the IRAM 30m telescope.

1. Introduction

The investigation of the dynamics of stars has provided compelling evidence for the existence of a super-massive black hole (SMBH) at the center of the Milky Way. At a distance of only ∼8 kpc a SMBH of $\sim 4\times10^6 M_\odot$ can convincingly be identified with the compact radio and infrared source Sagittarius A* (Sgr A*) (Eckart & Genzel 1996, Genzel et al. 1997, 2000, Ghez et al. 1998, 2000, 2004ab, 2005, Eckart et al. 2002 , Schödel et al. 2002, 2003, Eisenhauer et al. 2003, 2005). Due to its proximity Sgr A* provides us with a unique opportunity to understand the physics of super massive black holes at the nuclei of galaxies.

Studies of the variable polarized NIR emission and simultaneous radio/NIR/X-ray observations of SgrA* are ideally suited to obtain deep insights into the relativistic physics within 10-100 Schwarzschild radii of the SMBH associated with SgrA*. In the following, we assume for Sgr A* R_s=2R_g=2GM/c$^2\sim$8 μas, with R_s being one Schwarzschild radius and R_g the gravitational radius of the SMBH.

Sgr A* is remarkably faint in all wavebands, challenging current theories of matter accretion and radiation surrounding SMBHs. The feeble emission ($< 10^{-9}$ of the Eddington rate) is due to a combination of a low accretion rate with a low radiation efficiency. Theoretical interpretations at present focus on radiatively inefficient accretion flow and jet models. For a recent summary of accretion models and variable accretion of stellar winds onto Sgr A* see Yuan (2006) and Cuadra & Nayakshin (2006) and the references in these papers.

The first successful simultaneous NIR/X-ray campaigns combined NACO and Chandra as well as mostly quasi-simultaneous mm-data from BIMA, SMA, and VLA (Eckart et al. 2004, 2006a). The NIR/X-ray variability is probably also linked to the variability at radio through sub-millimeter wavelengths showing that variations occur on time scales from hours to years (Bower et al. 2002, Herrnstein et al. 2004, Zhao et al. 2003, 2004, Mauerhan 2005). In various observing campaigns we found simultaneous NIR/X-ray flare variations (Eckart et al. 2008, 2006, 2005, 2004a, Marrone et al. 2008, Yuesf-Zadeh et al. 2008), indications of significant, possibly quasi-periodic, sub-structure within NIR flares (Genzel et al. 2003a, 2003b, Eckart et al. 2006, Ghez 2003b), and highly polarized emission (Eckart et al. 2006).

The 10^{33-34} erg/s flares can be explained with a synchrotron self-Compton (SSC) model involving up-scattered sub-millimeter photons from a compact source component (e.g. Eckart et al. 2004, Eckart et al. 2006a). Inverse Compton scattering of the THz-peaked flare spectrum by the relativistic electrons then accounts for the X-ray emission. This model allows for NIR flux density contributions from both the synchrotron and SSC mechanisms.

The NIR flare emission is polarized with a well defined range over which the position angle of the polarized emission is changing ($60^o\pm20^o$, Eckart et al. 2006b, Meyer et al. 2006ab, 2007). All these observations can be explained in a model of a temporary accretion disk harboring one or several bright orbiting spot(s), possibly in conjunction with a short jet, and suggest a stable orientation of the source geometry over the past few years. Hawley & Balbus (1991) and Balbus (2003) outline a model of an expanding hot spot within an inclined temporary accretion disk. However, the radio/sub-mm/NIR observations also indicate adiabatic expansion within an SSC model (Eckart et al. 2005, 2006, 2008 Yusef-Zadeh et al. 2006ab, 2008, Marrone et al. 2008) and the emission very likely originates from a combination of a temporal accretion disk and a short, low-luminosity jet.

The millimeter/submillimeter wavelength polarization of Sgr A* is variable in both magnitude and position angle on timescales down to a few hours. Marrone et al. (2007) present simultaneous observations made with the Submillimeter Array (SMA) polarimeter at 230 and 350 GHz with sufficient sensitivity to determine the polarization degree and rotation measure within each band. From their measurements they deduce an accretion rate that does not vary by more than 25% and - depending on the equipartition constraints and the magnetic field configuration - amounts to 2×10^{-5} to 2×10^{-7} $M_\odot$ yr^{-1}. The mean intrinsic position angle of the measured polarization is 167°±7° with variations of ∼31° that must originate in the sub-millimeter photosphere of SgrA*.

Here, we present mm- and sub-mm-data that have been obtained using CARMA[1], ATCA[2] and the MAMBO bolometer at the IRAM[3] 30m telescope during a coordinated, multi wavelength observing campaign of SgrA* in May 2007. .

2. Observations and Data Reduction

Interferometric observations in the mm/sub-mm wavelength domain are especially well suited to separate the flux density contribution of SgrA* from the thermal emission of the Circum Nuclear Disk (a ring-like structure of gas and dust surrounding the Galactic Center at a distance of about 1.5-4 pc, see, e.g., Güsten et al. 1987 or Christopher et al. 2005).

In May 2007, global coordinated multi-wavelength observations were carried out in the NIR and mm regimes to study the variability of Sgr A*. We observed the galactic center at 100 and 86 GHz (3 mm wavelength) with the two mm-arrays CARMA and ATCA. In addition we observed with the MAMBO 2 bolometer at the IRAM 30 m-telescope at a wavelength of 1.3 mm. CARMA (Combined Array for Research in mm-wave Astronomy) is located in Cedar Flat, Eastern California, and consists of 15 antennas (6 x 10.4 m and 9 x 6.1 m). The Australia Telescope Compact Array (ATCA), at the Paul Wild Observatory, is an array of 6 22-m telescopes located in Australia, about 25 km west of the town of Narrabri in rural NSW (about 500 km north-west of Sydney). The interferometer data were mapped using the *Miriad* interferometric data reduction package.

The Max-Planck Millimeter Bolometer (MAMBO 2) array is installed at the IRAM 30m telescope on Pico Veleta, Spain. The 37 channel array of the precursor instrument MAMBO has been successfully used by many observers since the end of 1998. Winter 2001/2002 was the first season of the new MAMBO-2 version with 117 pixels. The 37 channel MAMBO is used at the 30 m telescope as a backup system now. Both systems work at 1.2 mm wavelength and have a He-3 fridge to operate the bolometers at a temperature of 300 mK. The bolometer data was reduced using the bolometer array data reduction, analysis, and handling software package, the BoA (Bolometer Data Analysis).

3. Preliminary results of the May 2007 mm-observations

Based on the assigned VLT time we organized a large multi-frequency campaign in May 2007 that included millimeter to MIR observations at single telescopes and interferometers around the world. The main results are: 2 bright NIR flares (16 mJy and 5 mJy) and one CARMA 3mm flare of 0.5 Jy. A 10 day VLBI observing campaign performed with the VLBA at 22, 43 and 86 GHz (1.3cm, 7mm, 3.4mm wavelength) is being reduced. First sub-milliarcsecond resolution VLBI maps are presented by Lu et al. (2008) in this edition.

In order to correct for extended flux contributions in the interferometer data we subtracted the mean visibility trend from each individual visibility. The visibilities had been calibrated via intermittent flux reference observations. We attribute the residual flux density dips/excesses to

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[1] Support for CARMA construction was derived from the states of California, Illinois, and Maryland, the Gordon and Betty Moore Foundation, the Kenneth T. and Eileen L. Norris Foundation, the Associates of the California Institute of Technology, and the National Science Foundation. Ongoing CARMA development and operations are supported by the National Science Foundation under a cooperative agreement, and by the CARMA partner universities.

[2] ATCA is operated by the Australia Telescope National Facility, a division of CSIRO, which also includes the ATNF Headquarters at Marsfield in Sydney, the Parkes Observatory and the Mopra Observatory near Coonabarabran.

[3] The IRAM 30m millimeter telescope is operated by the Institute for Radioastronomy at millimeter wavelengths - Granada, Spain, and Grenoble, France.

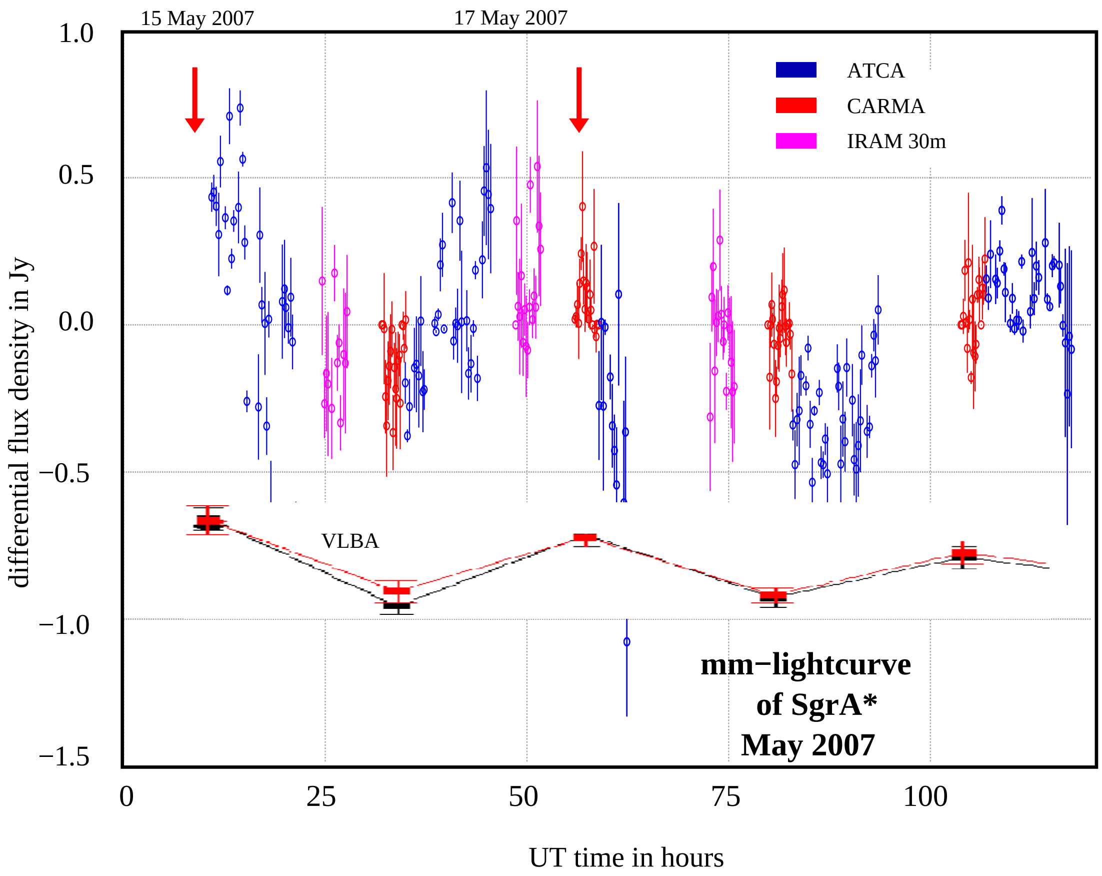

Figure 1. Combined differential light curve of SgrA* in the mm/sub-mm domain for the May 2007 observing run. The MAMBO 2 bolometer at the IRAM 30m-telescope was operated at a central wavelength of 1.2 mm (250 GHz). The CARMA data were centered at 100 GHz and the ATCA data at 86 GHz. We also show the daily 7mm flux density averages of our 2007 VLBA session (black and red symbols represent the signals from the R and L circularly polarized channels). The red vertical arrows mark the peak times of NIR flares observed with NACO. The time axis is labeled with UT hours starting at 00 h on May 15.

variations in the intrinsice flux density of SgrA*. The combined light curve from all telescopes is shown in Fig. 1. Here we can combine the data from different frequencies under the assumption that the spectral index of SgrA* does not change significantly during the flux density variations between 86 and 250 GHz. In this case the flux density variations are frequency independent. The light curve in Fig. 1 shows two peaks, on May 15 and 17 (There is a weaker, third possible peak on May 19). In Fig. 1 we also show the daily flux density averages of the 7 mm VLBA observations that were conducted in parallel. The VLBA data follow the overall shape of the combined CARMA/ATCA/30m lightcurve very well. In Fig. 2 we show residual maps from the four individual tracks obtained with the CARMA array. These maps were computed by subtracting the mean of all 4 maps from the maps of the individual epochs. This procedure clearly reveals the excess flux density detected on May 17.

The first NIR flare detected during the multi-wavelength campaign (see also Eckart et al.

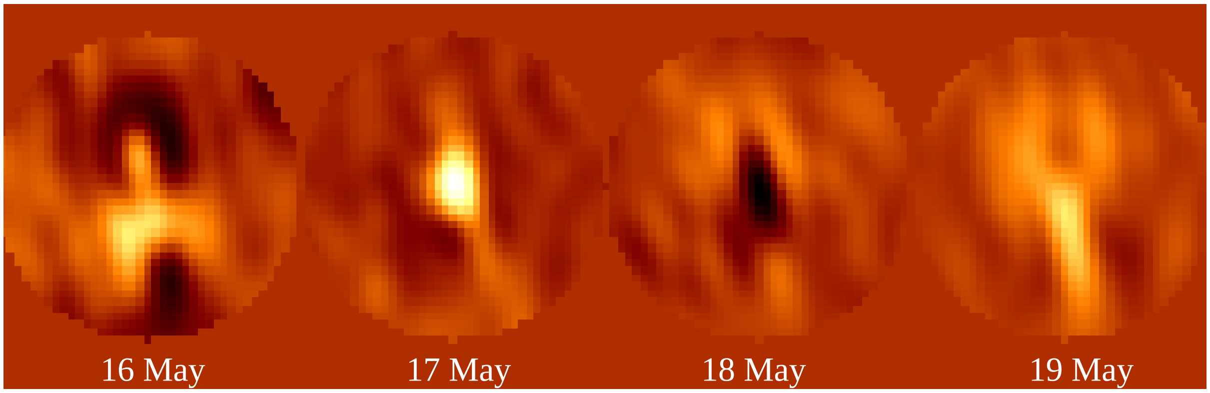

Figure 2. Difference maps at 3 mm of a 40″ diameter region centered on Sgr A*, obtained from the difference between full synthesis maps of the individual days of CAMRMA observations and the full CARMA data set as described in the text. The figure shows that the flux density variations that are evident from the differential light curves (see Fig. 1) can also be seen in the maps constructed from the corresponding data.

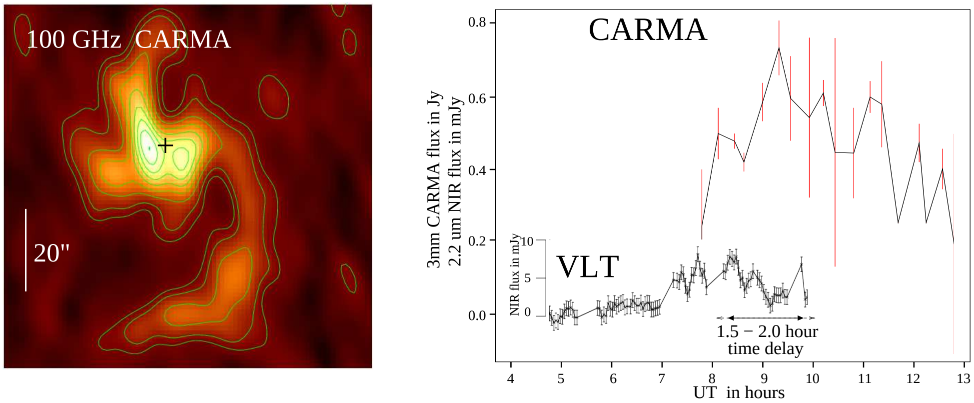

Figure 3. Left: Point source (i.e. SgrA*) subtracted Galactic Center CARMA 100 GHz map composed of the 3 best of 4 full D array coverages (0.05, 0.1, 0.2, ... Jy/beam). The image shows the mini-spiral continuum and demonstrates the high data quality of the 2-3″ resolution map. **Right:** Zooming in on the May 17 CARMA and VLT data. CARMA light curve of SgrA* as derived from visibilities of the two independent baselines between telescopes 3-1 and 14-6 (mean + differences as 1^{st}-order error est.). The **inset** shows the NIR flux density obtained from the VLT at 2.2μm wavelength.

2008) preceeded the combined mm/sub-mm monitoring and the first maximum detected therein. The second NIR flare had overlap with the CARMA observations, which show a 0.5 Jy 3mm flare that is delayed with respect to the NIR flare. In Fig. 3 we show both the VLT NIR and CARMA mm-lightcurve for May 17. The comparison reveals that the NIR flares occured during or just before times of excess mm/sub-mm flux density. For May 15 the details of the NIR flare have been described by Eckart et al. (2008). The observed time difference between the NIR and mm/sub-mm flares can be interpreted in the framework of (adiabatic) expansion of jet or disk synchrotron components - in full support of previous evidence for adiabatic expansion (Eckart et al. 2006a, Yusef-Zadeh et al. 2006). Within the current radio size limits the apparent size of an expanding jet must be small or foreshortened (240 μas at 43 GHz; Bower et al. 2004). However, a plasma component expanding within a relativistic orbit or polarized quasi-periodic emission due to a helical jet structure (Eckart et al. 2004, 2005, 2006a) cannot be fully excluded yet.

Future measurements will concentrate on monitoring the flux density variability of SgrA* in coordinated campaigns (radio/mm/MIR/X-ray) and in polarized radio/NIR emission. NIR telescopes with large aperturtes (VLT, Keck, LBT, TNT) will be best suited to separate SgrA* especially during faint phases from the surrounding high velocity stars. Similarly, mm-interferometers like the PdBI, CARMA, ATCA, and, in future, ALMA can separate SgrA* from the thermal emission of the CND and the mini-spiral. Therefore, the combination of these observing facilities will allow us to study the evolution of expanding synchrotron components.

With near future mm-VLBI at frequencies at and above 230 GHz, the imaging of the central region of SgrA* will become possible, allowing to map out the structure of SgrA* on spatial scales of only a few gravitational radii (Doeleman et al. 2008). By this it should be possible to directly test the hypothesis of spiraling plasmons or density waves in the accretion disk.

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