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High-frequency VLBI Imaging of Sgr A* and VX Sgr

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VLBI observations at millimeter wavelengths provide unprecedented high angular resolution and allow to image regions, which are self-absorbed at longer wavelengths. Here we present new results from a multi-frequency VLBA monitoring of Sgr A* at 22, 43, and 86 GHz performed on 10 consecutive days in May 2007. We discuss the source structure of Sgr A* through the analysis of the closure phase and closure amplitude, of which the latter improves the calibration accuracy and shows indications of a non-Gaussian brightness distribution at the highest frequency. We also present preliminary maps of the maser emission lines (v=1, J=1-0, and J=2-1) in the circumstellar SiO maser of VX Sgr. This will put new constraints on the kinematics and the pumping mechanisms of SiO masers.

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1. Introduction

VLBI observations at millimeter wavelengths offer a number of advantages over VLBI observations at centimeter wavelengths. First and foremost, the higher angular resolution allows detailed imaging of compact galactic and extragalactic radio sources with angular resolutions of a few 10 μas. For nearby objects (like Sgr A*) or very massive objects (like M 87) these angular scales translate into spatial scales of only a few to a few ten Schwarzschild radii around the central super massive black hole (SMBH). In addition, mm-VLBI provides a deeper/clearer look into the core region of compact radio sources, much less affected by source intrinsic opacity, Faraday depolarization, and interstellar scattering effects (in the case of Sgr A*). Therefore VLBI observations at short millimeter wavelengths are a very complementary observing technique, which adds new insights to the inferences drawn from the lower frequency observations. At 43, 86 and 129 GHz, mm-VLBI allows to access SiO maser transitions with sub-mas resolution, opening a new window on their study. Here we discuss some preliminary results on Sgr A*, and the SiO maser in VX Sgr.

2. Observations and data reduction

During a global multiwavelength observing campaign on Sgr A* performed in 2007, the target source and some calibrators (VX Sgr, NRAO 530 and some other AGN) were observed in frequency switch mode with the VLBA on 10 consecutive days from May 15 to 24 at 22, 43, and 86 GHz [1],[2]. The SiO maser in VX Sgr (v = 1, J = 1-0 and J = 2-1) was observed in interleaved short VLBI scans to assist the amplitude calibration of Sgr A* at 43 and 86 GHz.

3. Results

3.1 Does Sgr A* has substructure?

The compact radio source Sgr A* is believed to be the emission counterpart of a 4 million $M_\odot$ BH. Its relative proximity makes it the most promising candidate for a detailed investigation of a BH with VLBI on scales of a few Schwarzschild radii (R_s, 1 $R_s \approx 0.1$ AU $\approx 10\,\mu$as for Sgr A*). VLBI observations of Sgr A* have been driven to short millimeter wavelengths where scattering effects induced by the ISM vanish and the underlying intrinsic source structure becomes visible. A data analysis which uses hybrid imaging and Gaussian modelfits with the closure quantities (closure phase and amplitude) allows to reduce the calibration errors to less than 10-20 % and by this reliably constrain the emission structure of Sgr A*. Here we present some new results of the inter-day VLBI monitoring program of May 2007. In the context of the orbiting hot spot model

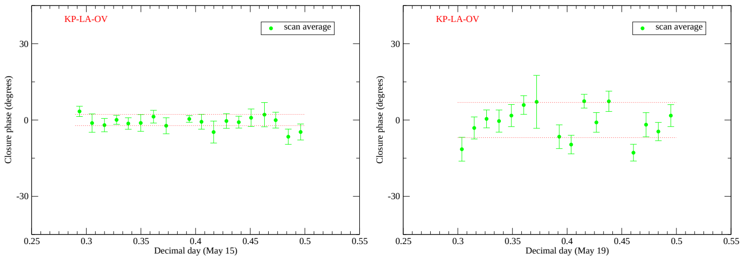

Figure 1: Plot of a typical closure phase versus time for the KP-LA-OV triangle at 86 GHz on May 15 (left) and 19 (right), 2007. The dotted lines indicates the 1 σ range of the mean closure averaged over the full data train.

[3], short-timescale asymmetric structures, and thus quasi-periodic deviations of the closure phase from zero, would be expected. Such effects would be more prominent and easier to detect at higher frequencies due to the smaller beam size and lower source-intrinsic opacity. We analyzed the closure phase for our data on a triangle by triangle basis. In Figure 1, we show two typical examples of the closure phase. Through χ^2 test, we conclude that the closure phases are zero within

the measurement errors, suggesting that the source structure is indeed point like or symmetric and not variable within a given day and also on time scales of several days [1].

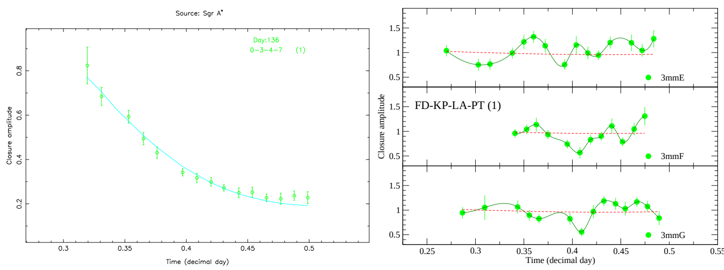

Figure 2: Left: Closure amplitudes of the quadrangle BR-KP-LA-OV at 43 GHz on May 16, 2007. The solid line delineates a best-fit model (see text). Right: Closure amplitudes for the FD-KP-LA-PT quadrangle at 86 GHz (May 19, 20, 21, 2007, from top to bottom). Spline interpolations are shown as solid lines and the dashed lines are for the 10 day averaged Gaussian source model [1].

For the analysis of the closure amplitudes, we performed, for each scan, an incoherent average of the 10 s (coherently) averaged visibility amplitudes, including a noise bias correction (e.g., [4]). Closure amplitudes were then formed for the incoherently averaged amplitudes. We limit ourselves to high SNR visibilities with a SNR cutoff of 5 to avoid closure amplitude bias. We fitted the closure amplitudes with a single elliptical Gaussian component in a 3-D parameter space (angular size along the major and minor axis, and P.A. of the major axis). In Figure 2 (left) we show as an example the Gaussian model fitting to the closure amplitudes at 43 GHz. For the source structure we obtained the following parameters: $\theta_{\rm major} = 0.70^{+0.01}_{-0.01}$ mas, $\theta_{\rm minor} = 0.37^{+0.06}_{-0.07}$ mas, and P.A. = $82.6^{+3.0}_{-3.2}$ degree with a $\chi^2_\nu = 1.7$. The errors are at 3 σ level and are derived from the projection of the χ^2 confidence contours onto the parameter axis for the case of 3 parameters. At 22 and 43GHz, a single Gaussian component fits the source structure very well. At 86 GHz, however, a direct fitting of the closure amplitudes does not converge. We notice that the closure amplitudes are formed mainly using visibility data of the inner 5 VLBA antennas (FD, KP, LA, OV, PT). In this case only 5 independent closure amplitudes are available. Furthermore, the large scatter of the data indicates that a single Gaussian component may be only a first order approximation to the true source structure. As an example we show the FD-KP-LA-PT quadrangle at 86 GHz for the three experiments on May 19, 20, and 21 along with an elliptical Gaussian model in Figure 2 (right). Reduced chi-square (χ^2_ν) values of the fitting to the 5 closure amplitudes of 3.3 (May 19), 3.8 (May 20), 4.1 (May 21) indicate a poor fit for such a single Gaussian model. The data therefore suggest some non-Gaussianity of the source structure.

3.2 Mapping the circumstellar SiO maser emission in VX Sgr

SiO maser emission around asymptotic giant branch (AGB) stars is a good probe of the physical conditions and motions in the innermost shells of circumstellar envelopes. Since the knotty emission is very bright and compact, it is an ideal target for multi-frequency VLBI studies of the maser emitting regions. Previous research showed that the SiO emission often originates in the inner radius of the dust shell of a few stellar radii from the central star. VLBI observations have shown that the masers exhibit ring-like or elliptical morphology, and reveal a complex gas kinematics in these inner shells, for instance, contraction, e.g., [4], expansion, e.g., [5], and even rotation, e.g., [6].

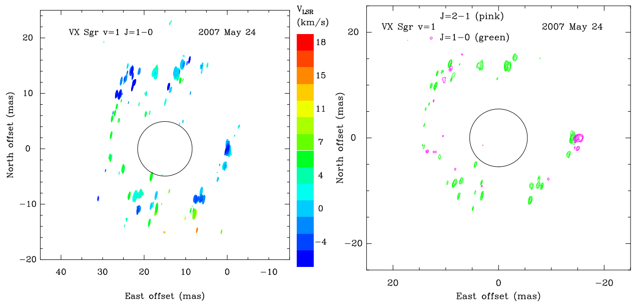

Figure 3: SiO maser images towards VX Sgr. Left: Line-of-sight velocity structure image of the v=1,J=1-0 emission showing a ring-like morphology. Right: Velocity-integrated total intensity VLBI image of the 43.1 GHz v =1, J= 1-0 (green) and the 86.2 GHz v=1, J=2-1 (pink) SiO emission toward VX Sgr. In both images, the circle outlines a uniform stellar disk with a diameter of 8.7 mas [7].

VX Sgr is a M-type supergiant and is a source of strong OH, H_2O, and SiO maser emission. Our preliminary results from the analysis of the 2007 data show in detail the very complex SiO maser emission in the circumstellar envelope of VX Sgr. Fig 3 (left) shows the velocity structure of the J=1-0 maser emission establishing its ring-like structure. Our monitoring observations also allow us to study the time evolution of the two transitions on a daily time scales. Shown in Fig 3 (right) is a composite image of the velocity-integrated total intensity maps for both transitions. The frequency dependence of the two transitions is of great importance for the testing of the maser emission models, and provides information on physical conditions of matter and radiation field near the star. A proper registration of the emission distribution from the two transitions puts constrains on the maser pumping schemes, either radiative, [8, 9] or collisional, [10], or hybrids of these scenarios [11].

4. Summary

Closure phase analysis confirmed the apparent symmetric structure of Sgr A*. We did not detect significant variations of the closure phase on a intra- to inter-day time scale. Modeling the closure amplitudes at 22 and 43 GHz verified its equivalence to self-calibration. At 86 GHz, the available data, although too sparse for a direct fitting, indicate a poor agreement with a single Gaussian model. This may be a signature of a more complex than point-like Gaussian structure and has to be addressed in future VLBI experiments. We present preliminary maps of the maser emission in VX Sgr addressing kinematics on a daily time scale and the pumping mechanisms.

References

[1] Lu, R.-S., Krichbaum, T. P., Eckart, A., et al. 2010, A&A, in press[arXiv:1010.1287]

[2] Lu, R.-S., Krichbaum, T. P., & Zensus, J. A. these proceedings

[3] Broderick, A. E., & Loeb, A. 2006, MNRAS, 367, 905

[4] Shen, Z.-Q., Liang, M. C., Lo, K. Y., et al. 2003, Astron. Nachr., 324(S1), 383

[4] Boboltz, D. A., Diamond, P. J., & Kemball, A. J. 1997, ApJL, 487, L147

[5] Diamond, P. J., & Kemball, A. J. 2003, ApJ, 599, 1372

[6] Boboltz, D. A., & Diamond, P. J. 2005, ApJ, 625, 978

[7] Monnier, J. D., et al. 2004, ApJ, 605, 436

[8] Bujarrabal, V. 1994, A&A, 285, 953

[9] Bujarrabal, V. 1994, A&A, 285, 971

[10] Lockett, P., & Elitzur, M. 1992, ApJ, 399, 704

[11] Humphreys, E. M. L., Gray, M. D., Yates, J. A., et al. 2002, A&A, 386, 256