mm/submm VLBI Science with ALMA

S. Doeleman, 26 Sept 2008

Very Long Baseline Interferometry (VLBI) is the highest angular resolution technique available to astronomers. Extending VLBI to high frequencies (230-345 GHz) and Earth-sized baselines can yield resolutions between 20-30 microarcsec. Over the past five years there has been a re-conceptualization of VLBI instrumentation, which has leveraged industry-driven standards in hardware and high-speed data protocols to create low-cost VLBI systems that are significantly more capable than those that were in use only 5 years ago. The new VLBI systems have increased the bandwidth of recorded data by more than an order of magnitude, increasing the sensitivity of continuum VLBI measurements and enabling use of the technique at the highest frequencies. With the maturation of VLBI at 230GHz and higher frequencies, ALMA is poised to become the pivotal element in future VLBI arrays that will target key science projects requiring the union of high angular resolution and high sensitivity.

SgrA*:

At a distance of ~8kpc, SgrA*, the compact radio, NIR and X-ray source at the Galactic Center, is thought to mark the position of a super-massive black hole of 4 million solar masses. Due to its proximity, SgrA* is the best opportunity we have to study a black hole of any mass with VLBI on Schwarzschild radius scales. The ionized ISM, however, scatter-broadens images of SgrA* with a wavelength squared dependence, and VLBI at the highest frequencies is the only available means to set important limits on intrinsic structures near the event horizon. New 1.3mm VLBI observations on a three station array (SMT, JCMT, CARMA) have now confirmed compact structure in SgrA* on 4 Rsch scales (Figure 1; Doeleman et al 2008, Nature, 455, 178).

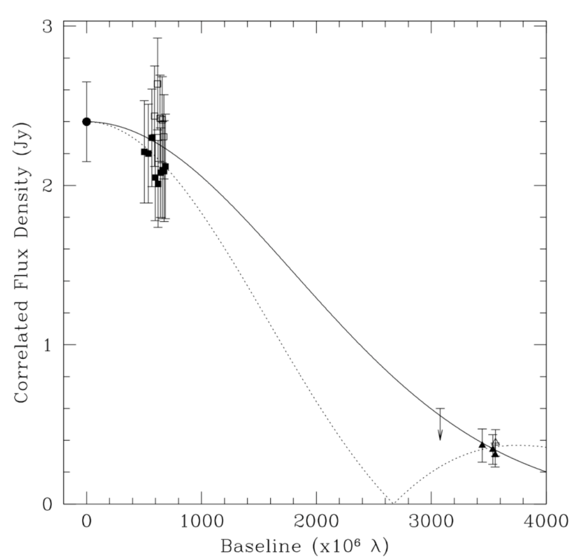

Fig 1: Correlated flux density of SgrA* as a function of baseline length for a three-station 1.3mm VLBI array. Squares show SMT (Mt. Graham, AZ) – CARMA baselines, triangles show SMT-JCMT baselines, and the upper limit is from JCMT-CARMA baselines. The solid curve is the fit to a Gaussian source of 43μas FWHM, and the dotted line shows the expected correlated flux for a uniform annulus of inner diameter 35μas and outer diameter 80μas (with scattering by the ISM included). The filled circle is the total flux density of SgrA* measured by the CARMA array.

Extending this VLBI array to include baselines to Chile will allow sensitive tests for asymmetric structures predicted by both jet/outflow and accretion models of SgrA*. These tests will not rely on imaging, but will utilize interferometric closure quantities formed by combining baseline phases and amplitudes around closed loops of baselines. Models that explain the variability of SgrA* with orbiting hot-spots of plasma predict time variable structures that produce periodic signatures in the VLBI closure phase and closure amplitudes – the innermost stable circular orbit (ISCO) period for a non-rotating 4 million solar mass black hole is ~27 minutes (Broderick & Loeb 2006, MNRAS, 367, 905). A single ALMA antenna added to the 1.3mm VLBI array adds enough baselines that, with easily achievable VLBI recording rates, the motion of orbiting hot spots can be detected for entire classes of models with high spin black holes and inclined (edge-on) accretion disks (Doeleman et al, astro-ph:0809.3424). When 10 ALMA dishes are phased together as one VLBI element, the signal to noise increases to the point that the closure quantities can be followed on 10 second intervals (Figures 2,3), and VLBI arrays at 345GHz with even higher resolution can detect orbiting hot-spots for almost any combination of black hole spin and accretion disk inclination. Thus, inclusion of ALMA, with a single dish or phased array, creates 1.3mm and 0.8mm VLBI arrays with the potential to *directly* detect material orbiting a black hole and extract the fundamental black hole spin parameter.

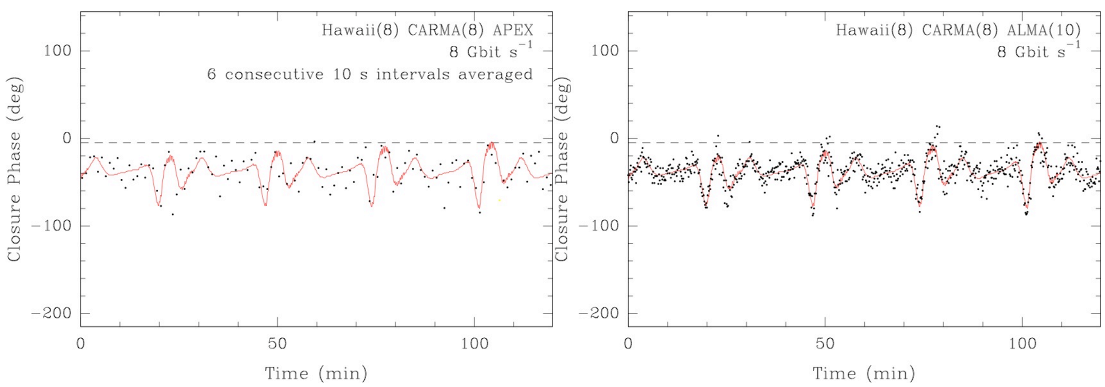

Fig 2: Closure phases on a VLBI array consisting of Hawaii, CARMA and either a single ALMA dish, or 10 ALMA dishes phased together. The model (red curve) is for a region of hot plasma orbiting a 4 million solar mass black hole with spin parameter a=0.9 and accretion disk inclination of 60 degrees. (left) Array with single ALMA dish (shown as the APEX dish) with closure phases computed on 10 sec intervals and averaged to 1 minute. (right) Array including 10 phased ALMA dishes on 10 sec intervals. Each panel shows 4 orbits of the hot-spot over a duration of only 2 hours.

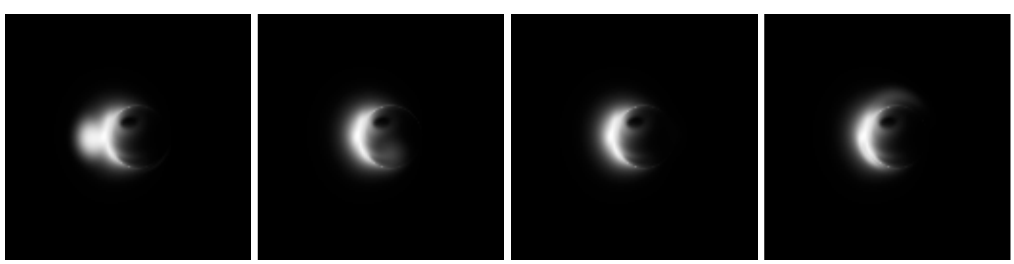

Fig 3: Model of a hot-spot orbiting SgrA* shown for 4 orbital phases (ϕ=0.19, 0.44, 0.69, 0.94: left to right). The black hole 4 million solar masses, spin a=0.9, orbital radius is 3xRsch. Closure phases corresponding to this model are shown in Figure 2.

In addition to looking for asymmetries in structure, 1.3mm and 0.8mm VLBI baselines to ALMA will provide important information on how the size of SgrA* changes during flare events. Synchrotron cooling times are long compared to observed variability, implying that SgrA* undergoes adiabatic expansion. If so, baselines to ALMA will easily detect SgrA* in early stages of the flare and source growth can be monitored with time to estimate physical parameters such as plasma density and magnetic field only a few Rsch from the black hole (e.g. Marrone et al 2008, ApJ, 682, 373). These baselines can also bring 2xRsch resolution VLBI polarimetry to bear on SgrA*, which will be sensitive to small scale polarization structures that can be modeled via the same closure techniques outlined above. The most recent polarimetric mm/submm observations of SgrA* use connected element arrays (Marrone et al 2007, ApJL, 654, 57), which may suffer from beam de-polarization effects that would not affect VLBI observations.

Jet Genesis (M87):

Though SgrA* presents the largest apparent black hole event horizon, the ~3 billion solar mass black hole candidate at the center of M87 will, at a distance of ~18Mpc, appear only 2 times smaller. This source exhibits a well-studied jet, and the latest high dynamic range synoptic VLBI observations (Walker et al, 2007, astro-ph: 0708.0428) show a wide jet opening-angle with edge brightening. M87 is the best prospect for studying jet genesis and collimation, and 1.3mm and 0.8mm VLBI on ALMA baselines will achieve angular resolutions corresponding to 5-8 Rsch of the black hole. Furthermore, observing at short wavelengths probes regions that are hidden and longer wavelengths by optical depth effects. A fundamental question is how the base of the jet is spatially related to the putative black hole. Firm size estimates for M87 at 230GHz combined with jet geometry determined from imaging at lower frequencies will trace the jet profile, setting limits on physical condition in the jet. But it would also constrain models of jet launching by limiting the jet base size to scales that would match the ISCO of the black hole. In addition to M87, there are ~4-5 other AGN with apparent black hole sizes that would allow these kinds of studies.

Astronomical Masers: (figure of VYCMA masers):

Astronomical masers are signposts and valuable tracers for star formation in the ISM and photosphere dynamics in both young stellar objects and evolved stars. Because the maser emission is typically high brightness temperature and compact, VLBI is well suited to map and study the phenomenon. Multiple transitions of various species can be present in a single source allowing information on chemical composition, abundances, and temperature and pressure gradients to be extracted. The mm/submm bands are host to a large number of observable maser lines from molecular species including HCN, water, Methanol, and SiO. There are also Hydrogen recombination masers that trace ionized disks around stellar sources (e.g. MWC349: Weintroub et al 2008, ApJ, 677, 1140). mm/submm VLBI arrays with only a few stations can produce maser spot maps with exceptional relative astrometry (e.g. Fig 4). A phased ALMA for VLBI will provide high sensitivity long baselines to study spectral line sources in a frequency range that has, hitherto, been largely unexplored with such high angular resolutions (much less than a stellar diameter).

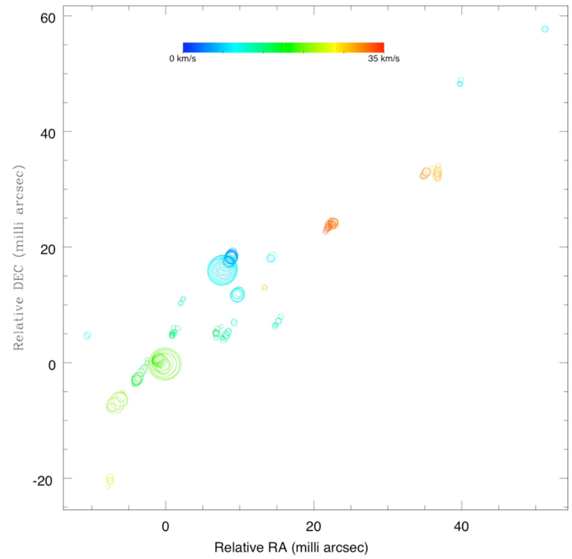

Fig 4: A maser spot map of the SiO v=1 J=3-2 transition in the evolved star VY CMa. This is the highest frequency spectral VLBI map made to date and uses data from the single SMT-Kittpeak12m baseline. The masers extend along a NW-SE direction and exhibit a non-keplerian velocity vs. position trend. The maser emission may arise in a disk that partially obscures the reflection nebula surrounding the star. (Doeleman et al, in preparation).