(Sub)Millimeter VLBI Science with ALMA

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Abstract

ALMA will be one of the most powerful millimeter and submillimeter ground-based observatories for many years to come. Its sensitivity and location make it an excellent candidate site for very long baseline interferometry with existing millimeter VLBI networks, including the VLBA, the Global Millimeter VLBI Array, and the Event Horizon Telescope. An international team is proposing to construct a phased-array processor to enable ALMA participation in these VLBI networks. This presentation will focus on the broad science impact of millimeter VLBI with phased ALMA on the high-resolution study of supermassive black holes, pulsars, AGN jets, and other astronomical objects.

1 Introduction

The Atacama Large Millimeter/submillimeter Array (ALMA), presently under construction in Chile, is an international project to produce a (sub)millimeter interferometer with unprecedented sensitivity, imaging dynamic range, and spectral coverage. The scientific case for ALMA as a stand-alone inteferometer is vast, covering all branches of astronomy from solar system science to cosmology [1,2].

ALMA will provide angular resolutions of approximately 100 mas at 43 GHz, 50 mas at 86 GHz, 20 mas at 230 GHz, and better than 15 mas at 345 GHz [3]. As impressive as this resolution may be, there nevertheless exists a wide range of science that can only be addressed by the increased resolution provided by (sub)millimeter very long baseline interferometry (VLBI). The development of a phased-array processor for ALMA would create a sensitive VLBI station with angular resolutions of tens to hundreds of microarcseconds when observing with existing networks, including the Very Long Baseline Array (VLBA) and the High Sensitivity Array at 7 mm, the Global Millimeter VLBI Array at 3 mm, and the Event Horizon Telescope (EHT) at 1.3 mm and 0.8 mm. Thanks to the highly capable ALMA correlator, the additional resources required to coherently add signals from the individual ALMA telescopes are modest. Phased ALMA would have a collecting area equivalent to a single 84 m dish (assuming 50 ALMA antennas) and be approximately ten times as sensitive as a VLBA antenna at 3 mm.

An international collaboration has proposed to produce a phased-array processor that integrates into existing ALMA systems. Details about the proposed implementation will be presented by Sheperd Doeleman at this conference. This presentation focuses on the broad scientific impact of including phased ALMA in millimeter and submillimeter VLBI networks.

2 Studying Black Holes on Event Horizon Scales

The galactic center radio source Sgr A* is believed to host a black hole with a mass of $\sim 4 \times 10^6$ M_{sun} [4]. At a distance of ~ 8 kpc, the Schwarzschild radius subtends ~ 10 μas, making the angular size of its event horizon the largest observable from the Earth. Observations with the EHT have been successful at detecting Sgr A* on a baseline between Mauna Kea and Mt. Graham, Arizona at 230 GHz, giving a fringe spacing of 60 μas [5,6]. For comparison, the resolution of a baseline between ALMA and Mauna Kea is about 30 μas at 230 GHz and 20 μas at 345 GHz.

The sensitivity provided by phased ALMA will be critical to detecting Sgr A* on such long baselines due to both partial resolution of Sgr A* and interstellar scatter broadening. In nominal weather conditions, 230 GHz observations on a baseline between phased ALMA and phased Mauna Kea (underway) will be able to achieve an rms noise of 2 mJy in an atmospheric coherence time of 10 s. This high sensitivity is important for (sub)millimeter VLBI of Sgr A* for three reasons. First, the (sub)millimeter emission is known to be rapidly variable on timescales of minutes to hours. Tracking structural changes in the accretion flow around the black hole requires high-sensitivity detections with a time

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resolution much finer than the period of the innermost stable circular orbit of material around the black hole, which is 4–30 min, depending on the black hole spin [7,8]. Second, phased ALMA will be sensitive enough to serve as an anchor for other telescopes in the array. Phased ALMA will allow Sgr A* (and other sources) to be detected on long baselines to telescopes of more modest aperture and improve the calibration of data from the entire array, enabling the accretion flow to be imaged at a resolution of ~ 2 Schwarzschild radii at 345 GHz. Third, high sensitivity will permit polarimetric VLBI, providing observational information on the morphology of the magnetic field in the inner accretion flow.

EHT observations of Sgr A* with phased ALMA will allow measurements of the spin of the black hole and the orientation and inclination of the accretion disk [9-11]. In both Sgr A* and the nearby low-luminosity AGN (LLAGN) M87, the EHT will be able to image the relativistic shadow of the black hole [12]. General relativity predicts that the shadow will be approximately circular and restricts its possible size to a very narrow range. Detecting the shadow would permit a novel test of the no-hair theorem of general relativity in a strong gravity environment [13].

The supermassive black hole at the center of the elliptical galaxy M87 has an event horizon whose angular size is nearly as large as that of Sgr A*. EHT observations of M87 will enable studies of jet genesis and collimation in LLAGN. (Sub)Millimeter observations can determine the size of the jet footprint, placing a lower limit on the black hole spin and elucidating the role of twisted magnetic fields in jet formation [14,15]. Understanding the advection-dominated accretion and outflow around M87 will also be important for models of the generation of very high energy TeV photons [16,17].

3 Other Science with Phased ALMA

Phasing ALMA opens up many science opportunities through beamforming or via joining other VLBI arrays. We present several scientific ideas below but note that, as for any general user facility, the best science will undoubtedly come in the form of new ideas from the overall astronomy community.

Pulsars have traditionally been observed at frequencies of a few GHz or lower, where emission is the strongest. Nevertheless, pulsars with relatively flat spectra have been observed at 43 GHz [18]. Observations of a pulsar in close orbit around the galactic center would allow strict testing of the Kerr metric around Sgr A*, but detecting pulsars near the galactic center at the usual frequencies is strongly inhibited by pulse broadening, which will not be an issue at ALMA frequencies. There are predicted to be numerous pulsars in orbit around Sgr A*, as well as some pulsar-black hole binaries in the vicinity of the galactic center [19,20]. Pulsar searches could be done in a commensal manner with other observations of Sgr A*, increasing the total scientific efficiency of ALMA observing time.

Magnetars were once thought to be a distinct class of neutron stars with a large magnetic field that quenches radio emission, but the detection of transient pulsed magnetar emission at frequencies as high as 144 GHz suggests that neutron stars may exhibit a continuum of properties at radio frequencies [21,22]. High time-resolution observations with phased ALMA may clarify the mechanisms that produce magnetic-field decay and coherent particle acceleration.

ALMA-anchored VLBI arrays at 3 mm and 7 mm can address questions related to AGN and jet physics. Unlike in LLAGN such as M87, the millimeter core in blazars is believed to mark the location of a standing shock in an ultrarelativistic jet [23]. Multifrequency millimeter observations can determine the core magnetic field and geometry, but very high resolution is required to track features within the outflow [24]. Polarimetric VLBI may elucidate the role that magnetic fields play in jet collimation as well as the importance of current-driven instabilities in explaining kink instabilities in AGN (and possibly pulsar) jets [25]. Phased ALMA adds a crucial very sensitive station doubling the north-south resolution of existing VLBI arrays.

Phased ALMA will have the necessary sensitivity to enable high-frequency spectral line VLBI. Masers have proven themselves to be useful tracers of dynamics, kinematics, and chemistry in the local universe. VLBI with phased ALMA will permit high-resolution maser studies of molecular species such as methanol and SiO as well as the hydrogen recombination line masers in MWC 349A [26]. Observations of the 3 mm SiO masers in the Large Magellanic Cloud

in conjunction with Australian telescopes may obtain a geometric distance, resolving distance uncertainties associated with Cepheid physics [27,28]. Phased ALMA observations of molecular line absorption systems at intermediate redshift toward gravitational lens systems will give subparsec resolution that is matched to the characteristic sizes of the absorbers [29], enabling high-precision studies of isotope ratios and fundamental constant variation [30].

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