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New results from the Event Horizon Telescope

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The Event Horizon Telescope is a project to observe and eventually image the Schwarzschild radius–scale structure around nearby supermassive black holes using 1.3 mm VLBI. Observations in recent years have made use of telescopes in Hawaii, Arizona, and California, with telescopes in Chile and Europe likely to participate in future observing sessions as well. Sensitivity upgrades—including an ongoing project to phase up the ALMA array—and increased baseline coverage will soon make imaging a reality. In the meantime, non-imaging observations have been successful in producing scientific results. This contribution reports on three recent results: the detection of Schwarzschild radius–structure in the 1.3 mm emission from the black hole in the center of M87, which strongly supports the existence of an accretion disk rotating in a prograde sense around a rotating black hole; the detection of nonzero closure phases in AGN sources such as 1924$-$292, which allow their submilliarcsecond structure to be modelled; and the detection of cross-polarized fringes, which hints at complicated linear polarization structure in at least one source.

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1. Introduction

The Event Horizon Telescope (EHT) is a collaborative project to observe supermassive black holes at a wavelength of 1.3 mm with a global VLBI array [1]. The resolution of the EHT is well-matched to the angular sizes of the black holes in the center of the Milky Way (Sagittarius A*) and M87. The primary goal of the array is to image the innermost accretion and outflow region, where general relativistic effects dominate, around Sgr A* and M87. Upgrades to improve the array sensitivity and resolution in order to achieve this goal are currently being implemented. In the meantime, substantial scientific progress is being made on these and other sources via non-imaging methods [2, 3, 4, 5].

2. Status of the EHT

Science observations with the EHT have been taken in 2007, 2009, 2011, and 2012, with several other test observations along the way. Results from observations with the US telescopes in the array are reported here: the three submillimeter observatories on Mauna Kea—the Submillimeter Array (SMA), the James Clerk Maxwell Telescope (JCMT), and the Caltech Submillimeter Observatory (CSO)—, the Arizona Radio Observatory Submillimeter Telescope (SMT), and the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in California. Phased array processors were used at the SMA and CARMA [6]. First fringes to the Atacama Pathfinder Experiment (APEX) telescope in Chile are reported elsewhere in these conference proceedings [7]. The Institut de Radioastronomie Millimétrique telescopes—the 30 m in Spain and the Plateau de Bure Interferometer in France—have also successfully obtained fringes [8, 9].

Several upgrades to improve the sensitivity of the array are underway. Most importantly, a multinational team is developing a phased array processor for the Atacama Large Millimeter/sub-Millimeter Array (ALMA) that will turn it into an extremely sensitive aperture for inclusion in VLBI arrays [10, 11, 12]. US EHT sites are upgrading their signal chains to match ALMA's bandwidth. Next-generation digital backends and Mark 6 recording systems are being developed to capture and record these data.

New telescopes will also come on line in the upcoming years, improving the angular resolution and (u,v) coverage of the array (Fig. 1). Funding has been secured to equip the South Pole Telescope with VLBI receivers and instrumentation. Construction of the Large Millimeter Telescope in Mexico continues. There are also prospects of relocating a telescope to Summit Station in Greenland [13].

3. M87

The giant elliptical galaxy M87 is believed to host a central black hole with a mass of $\sim 6.6 \times 10^9\ M_\odot$ [14]. A prominent jet is launched from this black hole, with a core shift with frequency that suggests that the 1.3 mm emission is located within a few Schwarzschild radii ($r_{\rm Sch}$) of the black hole [15]. The base of a very weak counterjet at 7 mm is seen in the opposite direction very near the black hole position [16], providing further evidence associating the black hole with this position.

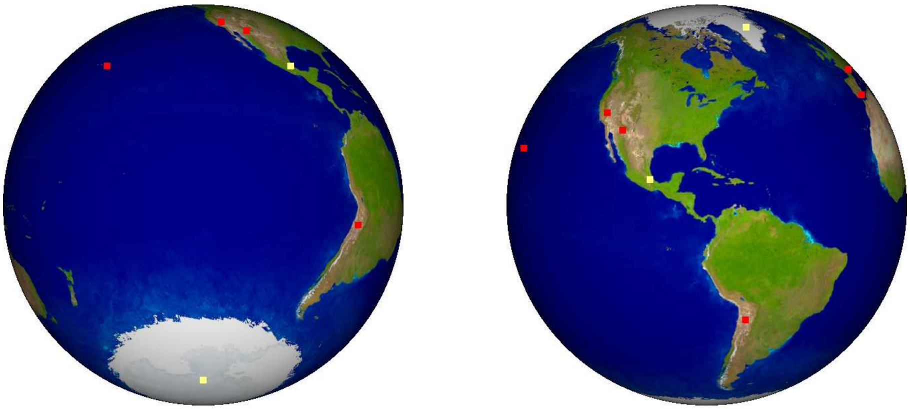

Figure 1: The EHT as viewed from Sgr A* (*left*) and M87 (*right*). Red squares show telescopes that have successfully obtained fringes in the 1.3 mm band; yellow squares show the locations of future telescopes.

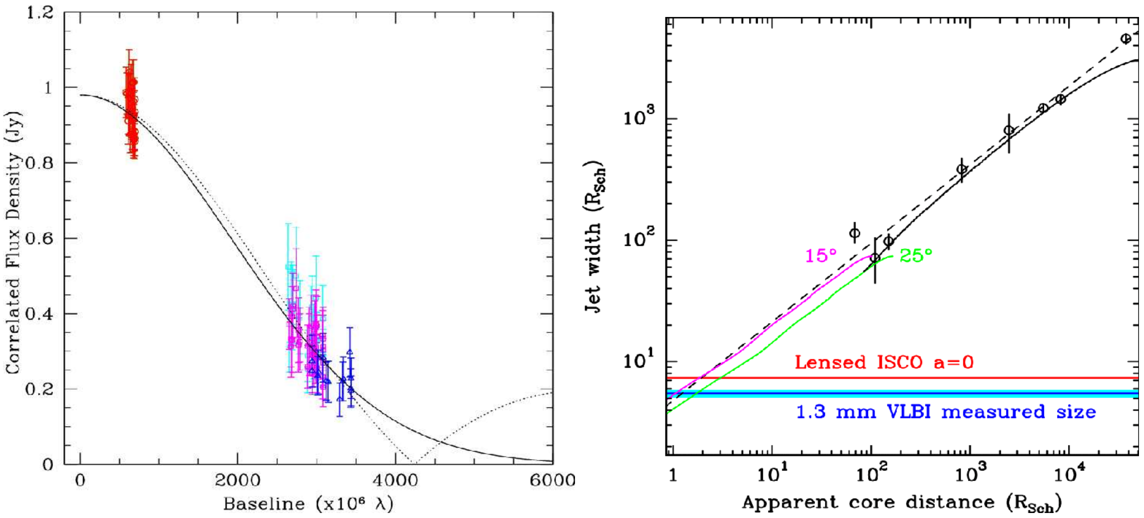

Figure 2: *Left*: EHT detections of M87 in 2009 [4]. SMT-CARMA detections are shown in red, JCMT-CARMA in cyan and magenta, and SMT-JCMT in blue. The solid line shows the best-fit Gaussian with a size of 40 μas. *Right*: The apparent jet size is consistent with data at longer wavelengths (circles [17]) and general relativistic magnetohydrodynamic models of the larger jet (black line [18]) and inner jet (magenta and green lines, labelled by inclination to the line of sight [19]) that produce a parabolic profile for the jet width. The measured 1.3 mm size (dark blue line with 3σ range in cyan [4]) is significantly smaller than the lensed size of the ISCO for a non-spinning black hole (red line).

EHT observations of M87 at 1.3 mm using the JCMT, the SMT, and two CARMA telescopes produced numerous detections on all baselines (Fig. 2) [4]. The size of the emission, 40 μas (5.5 r_{Sch}), is consistent with the expected size of an $r^{2/3}$ jet-width profile at an apparent core distance of about 1–2 r_{Sch}, or a deprojected distance of 2.5–4 r_{Sch}.

A plausible interpretation of these results is that the jet is being launched and collimated via the Blandford-Payne mechanism [20] from a disk wind tied to the accretion flow. Particles are most efficiently accelerated from the high-density inner edge of the accretion flow, known as the

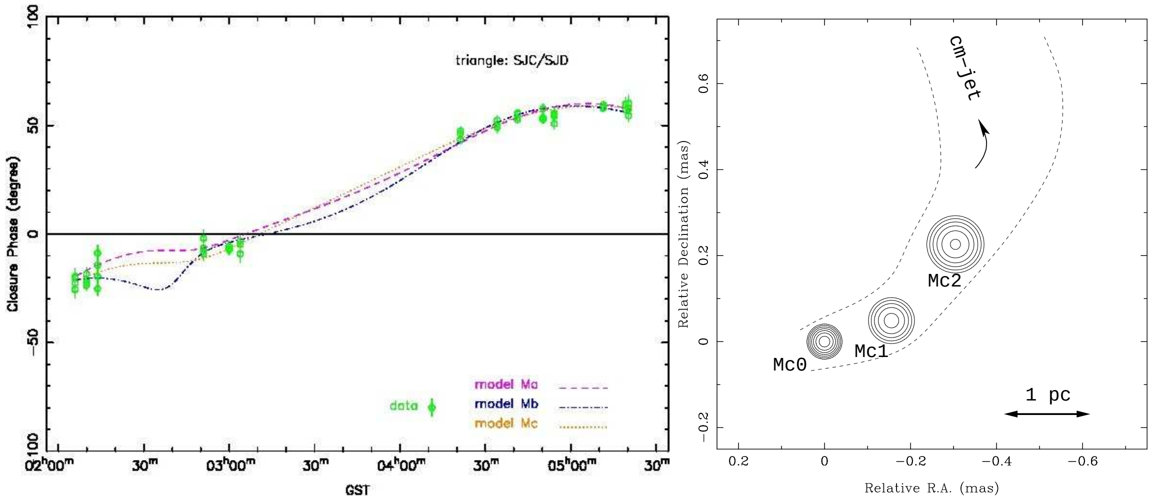

Figure 3: *Left*: Closure phases of 1924−292 measured with the EHT on the SMT-JCMT-CARMA triangle in 2009 (green points) [5]. Colored lines show three different models. *Right*: Model image of 1924−292, showing three different components that curve toward the direction of the larger-scale jet seen at centimeter wavelengths.

innermost stable circular orbit (ISCO) [21]. The ISCO radius is a strong function of the black hole spin. The measured size is significantly smaller than the lensed ISCO diameter for a Schwarzschild black hole. Models of the inner jet of M87 find that the apparent jet size is strongly correlated with the black hole spin [22], consistent with the conclusion that M87 hosts an accretion disk that is likely rotating in a prograde sense around a high-spin black hole.

4. Quasars

Observations of the quasar 1924−292 are typically interspersed with the target source Sgr A* to provide calibration information at the same elevation as Sgr A*. EHT observations in 2009 detected 1924−292 on all baselines at sufficiently high signal-to-noise ratio (S/N) to obtain closure phase measurements [5]. These data have been used to construct a model image of the 1.3 mm emission on submilliarcsecond scales (Fig. 3). The low brightness temperatures of the components—approximately 10^{11} K in the core and $10^{10.5}$ K in the downstream components—supports decelerating or particle-cascade jet models [23]. Similar analyses are being conducted on other sources, including 3C 279 [24].

Although closure phase information has previously been reported on Sgr A* [3] and used to constrain its structure [25], these observations represent the first time that *nonzero* closure phases have been measured on a source at 1.3 mm. Most of the source structural information is contained in the phases [26], and nonzero closure phases are unambiguous markers of asymmetric source structure. As the sensitivity and angular resolution of the EHT improve over the next few years, high-S/N detection of nonzero closure phases should become routine in Sgr A* too.

5. Polarization

Both circular polarizations were observed simultaneously at all three US sites in 2012, using the SMA and JCMT to provide opposite circular polarizations at Mauna Kea. Cross-polarized fringes were obtained on several sources. The polarization characteristics are qualitatively different between sources. At least one source shows a relatively constant cross-polarized amplitude ratio on interstate baselines as well as on the baseline between a single CARMA antenna and the CARMA phased array, possibly indicative of linearly polarized source structure similar to the total-intensity structure at the resolution of the EHT. Another source shows much larger cross-polarized amplitude ratios on interstate baselines than on the intrasite CARMA baseline, suggesting that the linearly polarized structure may be quite different from the total-intensity structure. Further analysis will be required to fully interpret the polarimetric VLBI data, but these initial results demonstrate that the era of polarized 1.3 mm VLBI has begun.

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