

### What's in a name?

The name of the Muon  $g - 2$  collaboration stems from the fact that the experiment measures the muon anomaly  $a_\mu = (g - 2)/2$ , where  $g$  is a dimensionless magnetic moment that relates a particle's spin  $\mathbf{S}$  to its magnetic moment  $\boldsymbol{\mu}$ , charge  $q$ , and mass  $m$ :  $\boldsymbol{\mu} = g(q/2m)\mathbf{S}$ .

The Dirac equation predicts that for a spin- $1/2$  particle,  $g = 2$  and  $a_\mu = 0$ . But because of interactions with the electromagnetic vacuum, the muon has a  $g$  slightly larger than 2. The most precise experimental value of the anomaly to date is  $a_\mu = 0.001\,165\,920\,61(41)$ ; the standard-model value is  $0.001\,165\,918\,10(43)$ .

muon anomaly was first discovered, researchers were hopeful that it would point to supersymmetry, the idea that each fundamental particle has a yet-unseen superpartner. Data collected by the ATLAS and CMS experiments during the Large Hadron Collider's first two runs have since ruled out the simplest supersymmetric models, though, so support for that explanation has weakened.

Ideally, another experiment will provide a second sign to narrow down the theoretical options. Fermilab's Mu2e experiment, which observes muon-to-electron conversions, and B factories, which study the decay of B mesons, are prime candidates for such a signal.

### Calculations and conjectures

Corrections to the theoretical value of  $a_\mu$  are also still being refined. They come from quantum electrodynamics calculations that account for muons interacting with the electromagnetic vacuum through the creation and annihilation of virtual parti-

cles. The first and largest correction, uncovered by Julian Schwinger in 1948, accounts for a muon emitting and reabsorbing a virtual photon.

Since then, the effects of more than 10 000 electromagnetic, electroweak, and strong-interaction corrections have been calculated and are included in the standard-model prediction for  $a_\mu$ . By far the largest source of uncertainty comes from the strong-interaction,

or hadronic, corrections, which are notoriously hard to calculate. Indeed, they can't be calculated directly, and the contributions from processes involving virtual quarks are estimated using a model informed by experimental data.

In 2017 dozens of researchers from around the world united to form the Muon  $g - 2$  Theory Initiative. Their goal was to improve the theoretical value of  $a_\mu$  so it could be compared with experiments—particularly the then-upcoming Fermilab results—and their focus was on lowering uncertainty in the hadronic contributions. The group's result,<sup>3</sup> published in 2020, was used for comparison with the Fermilab measurement. It represents a significant improvement and incorporates multiple independent calculations of the hadronic corrections, complete with quantified uncertainties.

Theoretical and experimental values of  $a_\mu$  currently have comparable uncertainty, but the experimental value's uncertainty is expected to drop by about a

factor of 4 with ongoing and planned experiments, and theory needs to keep up. One attractive approach is to use a first-principles calculation of the hadronic corrections to  $a_\mu$  based on lattice QCD, which approximates the physics of quarks and gluons on a grid of points. In fact, a lattice QCD calculation of  $a_\mu$  was published the same day as the Fermilab results and garnered significant attention for agreeing with experiments, thereby challenging the notion that new physics might lie behind the muon's magnetic moment.<sup>4</sup>

Although the lattice result is intriguing, Polly cautions against putting it on equal footing with the Theory Initiative's value. Multiple groups are still working to figure out the right way to use lattice QCD to calculate hadronic corrections for  $a_\mu$  and cross-check their results, whereas decades of work by hundreds of physicists underpins the data-reinforced approach. If mounting evidence continues to support a difference between the two techniques, understanding that difference will be essential to determining if the muon is actually exhibiting physics beyond the standard model.

Christine Middleton

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## Polarized light shows hot gas swirling around a galactic core

The images of galaxy Messier 87 provide evidence of magnetic field lines in its innermost region. Those lines likely trace the event horizon of a supermassive black hole.

The picture that the Event Horizon Telescope (EHT) collaboration released to the public in 2019 rocketed to fame under headlines lauding the first-ever photograph of a black hole. That image showed the bending of radio waves into a ring around the central region of an elliptical galaxy, Messier 87 (M87). The ring's dimensions matched general relativity's predictions of synchrotron emission from hot plasma swirling near the black hole's event horizon.<sup>1</sup>

The EHT collaboration has now reported an analysis of the polarization of the radiation emitted by that plasma. The results provide the first evidence of a dynamic magnetic field near a galaxy's core, seen in figure 1, and support the long-held conviction that a galactic core hosts a spinning, supermassive black hole.<sup>2</sup> With those observations in hand, astrophysicists can test theories about the forces that determine how fast a black hole accumulates material and

how plasma gets ejected from the galactic center out into space.

### A curious ray

In 1918 US astronomer Heber Curtis peered at M87 from the Lick Observatory in California and reported "a curious straight ray ... apparently connected with the nucleus by a thin line of matter." Curtis was looking at a jet of plasma launched at relativistic speed from the galaxy's center, although the theory to explain it came 30 years later. Radio observatories later linked the upstream end of the jet to a prominent

radio source at M87's center 55 million light-years from Earth in the Virgo galaxy cluster.

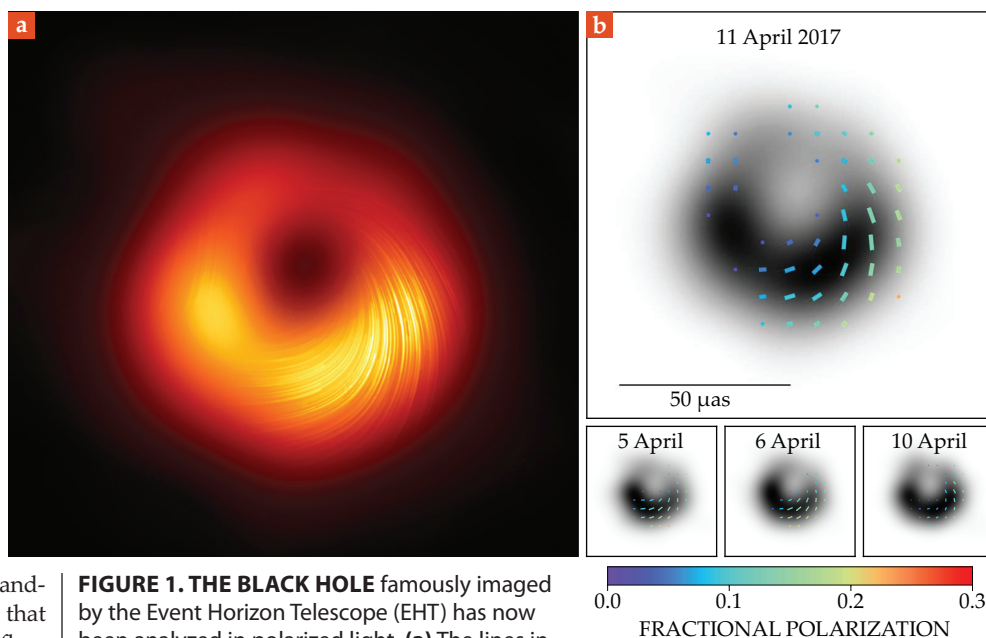
By the 1970s many theorists were convinced that such compact radio sources provided evidence that supermassive black holes occupy the centers of galaxies, including M87 and our own Milky Way, just as general relativity predicted. More specifically, Einstein's field equations describe the geometry of empty spacetime around a so-called Kerr black hole, one that spins about a central axis and is characterized entirely by its mass and angular momentum.

Inspired by Roger Penrose's theory of black hole formation, Roger Blandford and Roman Znajek suggested that jets emerge from galaxies as the outflow from an accretion disk—the region in which magnetized gas swirls around the event horizon.<sup>3</sup> (See *PHYSICS TODAY*, December 2020, page 14.) The spinning black hole acts like a magnetized conductor whose rotational energy is extracted and expelled in the form of jets.

Tracing the dynamics of those accretion and outflow processes, however, requires directly observing the immediate surroundings of a black hole. But the small-scale structure of a black hole's event horizon, tens of millions of light-years away, has the same angular size as would an apple on the Moon as seen from Earth. "To a radio astronomer in the 1960s and 1970s, the idea that you could resolve at this scale was complete fantasy. Only the most visionary would dream about it," says Blandford. But the development of very long baseline interferometry (VLBI), which combines observations from multiple radio antennas to create images of regions in space that are difficult to observe with a single antenna, led others to declare imaging a black hole as merely "a very hard thing to do," he says.

VLBI depends on a network of radio antennas. For the EHT, those antennas are spread across four continents to form a virtual telescope with an Earth-sized aperture. Each antenna records signals emitted by the target source, and the signals' arrival times are later cross-correlated for each pair of antennas. From those correlated signals, an image of the emission source can later be reconstructed.

The angular resolution of an array in-



**FIGURE 1. THE BLACK HOLE** famously imaged by the Event Horizon Telescope (EHT) has now been analyzed in polarized light. **(a)** The lines in this image mark the polarization's orientation in the accretion flow close to the edge of the black hole at the center of galaxy Messier 87. **(b)** Data collected over four days in April 2017 show maps of polarized radiation in the accretion flow. The swirling pattern reveals the gas flowing in the same direction as the black hole. The gray scale shows the emission intensity, and the colored ticks indicate the polarization direction and fraction. (Courtesy of the EHT collaboration; adapted from ref. 2.)

creases not only with the distance, or baseline, between antennas but also with the frequency of the observed radiation. At frequencies of 230 GHz, corresponding to a wavelength of 1.3 mm, Earth-sized baselines achieve the highest angular resolution in ground-based astronomy—sufficient to observe supermassive black holes in M87 and the Milky Way at the scale of the event horizon.

The EHT project, started in 2009, comprises a VLBI network of millimeter-wavelength radio telescopes, shown in figure 2. Those telescopes comprise arrays of individual radio dishes with baselines ranging from hundreds to thousands of kilometers.

## MAD spirals

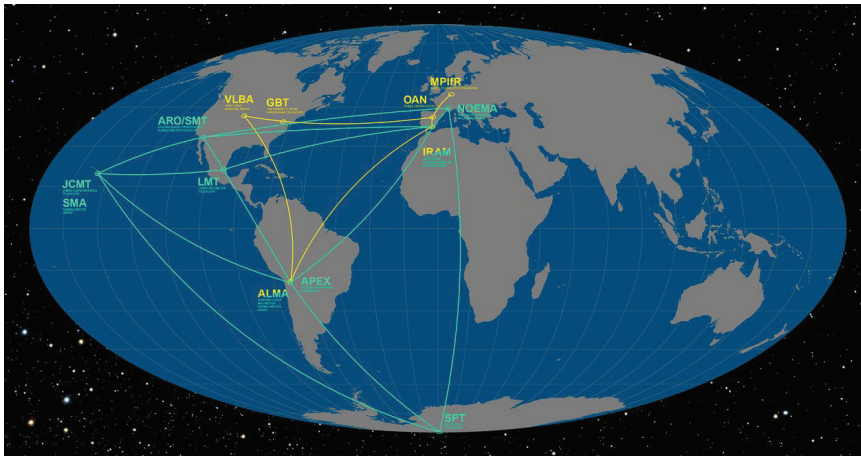
Over five nights in April 2017, the EHT monitored radio emission from the accretion disk around M87. There, spacetime curvature causes electromagnetic radiation to bend and twist. Electrons tightly orbit the magnetic field lines; as a result, the emitted radio waves are polarized by the orientation of the original fields.<sup>4</sup> Revisiting the 2017 data to establish measurements of the light's polarization, the collaboration has now published images that show the pattern of magnetic fields

near M87's core, plotted in figure 1b. "It's like looking at a medical x ray. All of a sudden you can see the underlying skeleton that supports everything," says Harvard University's Sheperd Doeleman, a collaborator on the EHT.

In one find, the total level of polarization measured was far below that expected given the fundamental processes involved. Although the radiation emitted by thermal electrons as they gyrate around magnetic field lines should be polarized, not all the light that travels to Earth is fully polarized. That's because as the radiation makes its way through the plasma along the observer's line of sight, another electromagnetic process—Faraday rotation—comes into play.

If all the magnetic field lines around M87 were neatly aligned, the radiation's polarization would be strong and rotated by the same amount. But if the field lines were instead tangled together, whatever polarization the radiation originally had would be reduced. The EHT's observation of up to 20% polarization in the brightest regions, then, is consistent with fields being tangled on small scales.

Another clue about the magnetic field's structure came from the polarization's orientation. Rather than a radial



**FIGURE 2. RADIO TELESCOPES** spanning half the globe make up the Event Horizon Telescope (turquoise) and the global Very Long Baseline Array (VLBA; yellow). The networks combine observations at 1.3 mm and 3 mm wavelengths, respectively, to provide high-angular-resolution images of radio sources. (Courtesy of ESO/O. Furtak.)

pattern, which would imply a field that followed the plasma and encircled the black hole, the polarization appeared with an azimuthal twist, seen in figure 1a. That distribution implies that electric fields are distributed in a spiral around the center and the magnetic field topology is poloidal—that is, along the direction of the jet.

With those observations, the EHT researchers could piece together the processes by which the black hole funnels material to its center. EHT team member Monika Moscibrodzka of Radboud University and her colleagues have simulated a library of templates

that represent 120 models of accretion flows and jets, especially their emissivity properties. From the emissivity, the researchers calculated millions of light trajectories that originate at points on the accretion disk and travel through curved spacetime until arriving at telescopes on Earth.

Comparing a gallery of 72 000 simulated images to the new observations showed that the data were compatible with the magnetically arrested disk (MAD) model.<sup>4</sup> In that model, magnetic flux accumulates and intensifies in the accreting gas. The field generates a pressure that's large enough to reduce the accre-

tion rate and create a bottleneck in the disk that pushes back against the inflow.<sup>5</sup>

## Future horizons

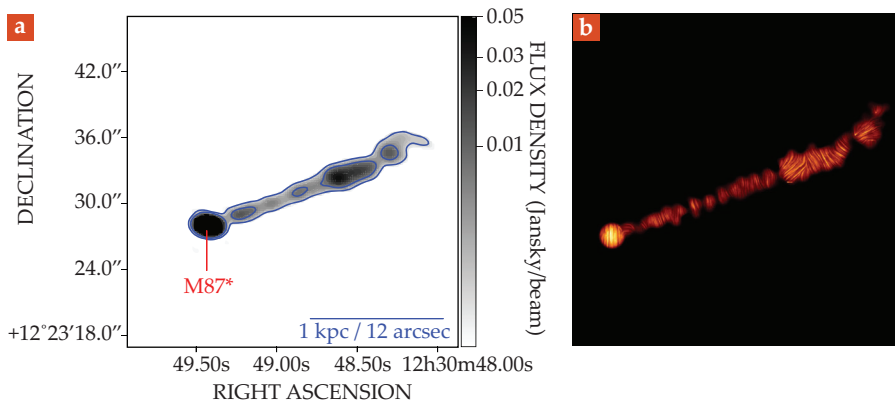
From the MAD models, the EHT researchers estimated that M87's 6-billion-solar-mass black hole swallows the surrounding gas at a rate of 1/1000th the mass of our sun per year. Still, that's powerful enough to launch relativistic jets of charged particles that stretch for thousands of light-years, according to energy conservation mechanisms first proposed in the 1970s.

Observations by the Atacama Large Millimeter/Submillimeter Array (ALMA) in Chile, whose 66 antennas dominate the overall signal collection of the EHT, captured images of the jet in polarized light, shown in figure 3. Those observations allowed the researchers to infer polarization and magnetic field properties along the jet on scales of up to 6000 light-years.<sup>6</sup> "Based on standard models, we expect the jet to be confined by very strong magnetic fields at its base, close to its launching point," says Ciriaco Goddi, who works at Radboud University and with the EHT collaboration. The combined information from ALMA and the EHT establishes that link.

The next-generation EHT will produce movies of the jet launch region and the magnetic field structures that propel matter outwards from M87. Showing dynamically how magnetic fields launch jets will answer the next big question: How exactly do magnetic fields extract energy from a spinning black hole?

More telescopes are already being added to the EHT. The collaboration will observe at more wavelengths and will target other galaxies and black holes. Says Blandford, "This is the start of the story, not the end."

Rachel Berkowitz



**FIGURE 3. PLASMA JETS** launch from the Messier 87 galaxy at nearly the speed of light. **(a)** The intensity of the light captured by the Atacama Large Millimeter/Submillimeter Array in Chile on 6 April 2017 shows the structure of the kiloparsec-scale jet composed of a bright core at the galactic nucleus (M87\*) and knots along the jet (blue contours). The image is shown in equatorial coordinates based on Earth's relative position on 1 January 2000. (Courtesy of ALMA/ESO/NAOJ/NRAO.) **(b)** Shown here in polarized light, the jet extends 6000 light-years from the center of M87. The lines mark the orientation of polarization and the structure of the magnetic field. (Adapted from ref. 6.)

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