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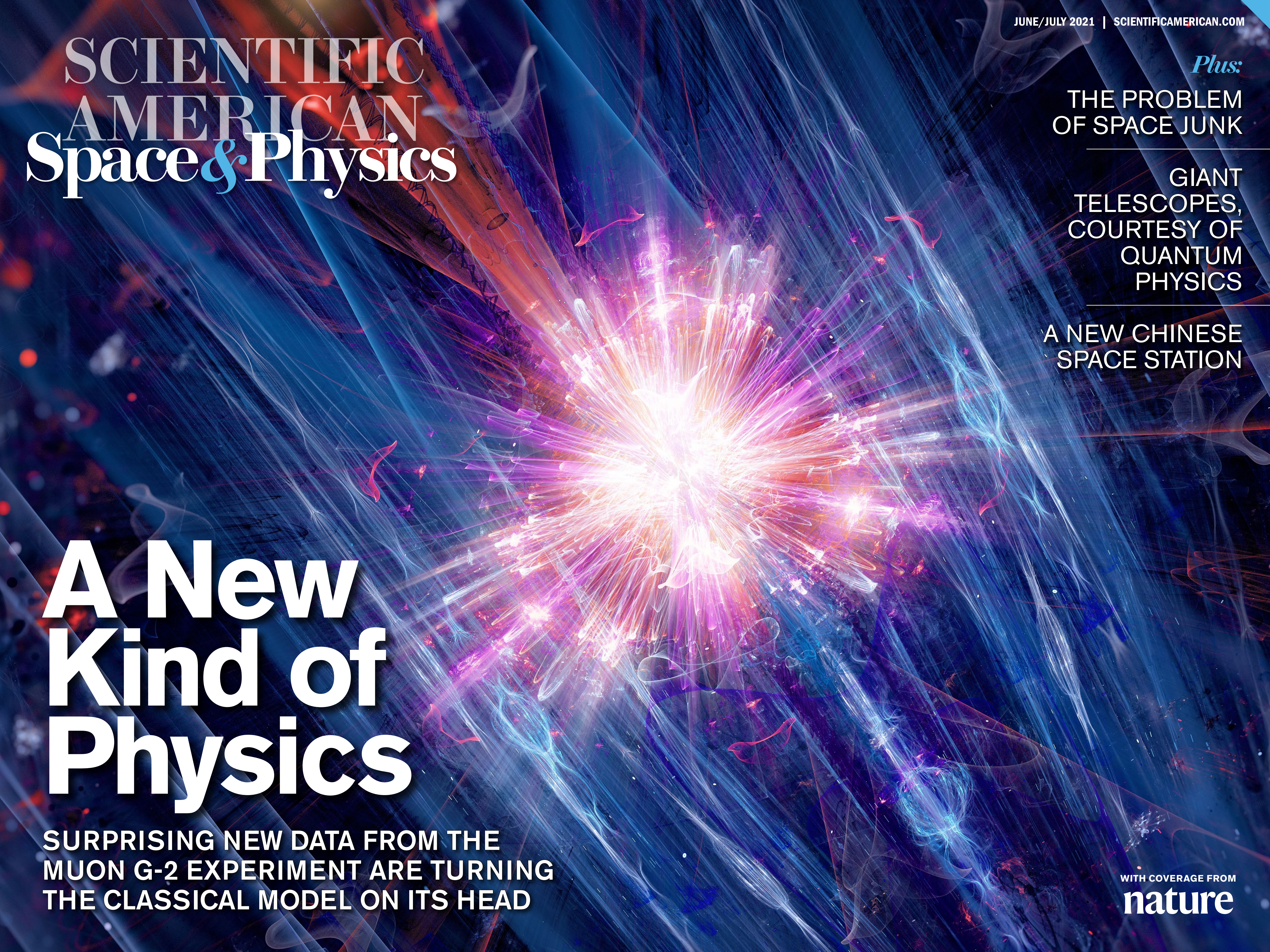

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Quantum Astronomy Could Create Telescopes Hundreds of Kilometers Wide

Astronomers hope to use innovations from the subatomic world to construct breathtakingly large arrays of optical observatories

By Anil Ananthaswamy

Composed of four 8.2-meter telescopes that can act as one, the European Southern Observatory's Very Large Telescope in northern Chile is the world's premier astronomical facility for optical interferometry. New approaches from the quantum world, however, could allow astronomers to make far larger and more capable optical interferometers.

JUAN CARLOS MUÑOZ-MATEOS/ESO

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A FEW YEARS AGO RESEARCHERS USING THE RADIO-BASED EVENT HORIZON TELESCOPE (EHT) PERFORMED AN EXTRAORDINARY observation, the likes of which remains a dream for most other astronomers. The EHT team announced in April 2019 that it had successfully imaged the shadow of a supermassive black hole in a nearby galaxy by combining observations from eight different radio telescopes spread across our planet. This technique, called interferometry, effectively gave the EHT the resolution, or the ability to distinguish sources in the sky, of an Earth-sized telescope. At the optical wavelengths underpinning the gorgeous pictures from the Hubble Space Telescope and many other famed facilities, today's interferometers can only combine light from instruments that are a few hundred meters apart at most. That may be set to change as astronomers turn to quantum physicists for help to start connecting optical telescopes that are tens, even hundreds, of kilometers away from one another.

Such optical interferometers would rely on advances being made in the field of quantum communications—particularly the development of devices that store the delicate quantum states of photons collected at each telescope. Called quantum hard drives (QHDs), these devices would be physically transported to a centralized location where the data from each telescope would be retrieved and combined with the others to collectively reveal details about some distant celestial object.

This technique is reminiscent of the iconic double-slit experiment, first performed by physicist Thomas Young in 1801, in which light falls on an opaque barrier that has two slits through which it can pass. The light recombines on the other side of the barrier, creating an interference pattern of bright and dark stripes, also known as an interferogram. This works even if individual photons trickle through the slits one by one: over time, the interference pattern will still emerge.

"If we have two telescopes that can be made to behave like Young's slits, and we are able to get an interferogram on a source of light, like a star on the sky, the interferogram tells you a lot of things about the source," says astronomer Jonathan Bland-Hawthorn of the University of Sydney, whose team is proposing the use of quantum hard drives to build optical interferometers. Such instruments could one day help astronomers measure the sizes and intrinsic motions of stars and galaxies with greater precision, a crucial ingredient in our understanding of the evolution of the cosmos.

Although radio astronomers have already built impressive interferometers such as the EHT, that is mainly because interferometry is easier to achieve in radio than at optical frequencies in three important ways: First, radio antennas are cheaper to build than optical telescopes, so one can construct large numbers of them (to increase the signal collecting area and hence sensitivity) and spread them apart (to increase resolution). Second, astronomical objects emit powerful radio waves, making it simpler to record these signals at individual antennas for subsequent correlation. Optical sources, however, are usually much, much fainter—so faint, in fact, that telescopes often must accumulate a celestial target's light literally one photon at a time, turning interference into a quantum-mechanical phenomenon. Third, Earth's atmosphere distorts optical light, leaving telescopes little time in which to collect the photons before the overlying layers of turbulent air disrupt their phase or coherence.

Such constraints have limited the baselines of optical interferometers—that is, the longest separations between any linked telescopes. For example, the Center for High Angular Resolution Astronomy (CHARA) is an array of six one-meter optical telescopes operating at Mount Wilson Observatory in California, and it boasts a maximum baseline of 330 meters. And the European Southern Observatory's GRAVITY interferometer, which connects four 8.2-meter telescopes at Paranal Observatory in Chile, has a maximum baseline of 130 meters. "The most impressive interferometer of any kind in the world is the ESO Gravity instrument," Bland-Hawthorn says. "Now imagine ESO Gravity [with a baseline of] over a kilometer, three kilometers or 10 kilometers."

With conventional optics technology, such concepts would remain elusive. The photons collected by each telescope have to be sent via optical fibers to some location where they can be combined. Also, photons from some telescopes may have to be kept in abeyance in "delay lines," often involving optical fibers, to ensure that the light from all telescopes has traveled the same distance. If the transmission or delay lines get too long—which occurs well short of kilometer scales—the photons are eventually absorbed or scattered, making interference impossible.

It is impossible, at least, without a helping hand from quantum physics. In 2011 Daniel Gottesman of the Perimeter Institute for Theoretical Physics in Ontario and his colleagues suggested putting a source of entangled photons midway between two distant telescopes. The source sends one of a pair of entangled photons to each telescope, where the particles are made to interfere with another photon received from a celestial target. The interference measurements in each telescope can be recorded and later used to reconstruct an interferogram. Although this may sound simple in principle, longer baselines for optical interferometry would require quantum repeaters—expensive and complex custom-built devices for distributing entanglement over great distances that are the antithesis of off-the-shelf tech.

Now Bland-Hawthorn has teamed up with quantum technologist John Bartholomew of the University of Sydney and Matthew Sellars of the Australian National University in Canberra to design optical interferometers that avoid the use of entangled photons and quantum repeaters. The basic idea is simple: Consider two eight-meter telescopes separated by tens of kilometers. The quantum states of the photons collected by each telescope—meaning the amplitude and phase of light as a function of time—are stored in quantum hard drives. Astronomers would physically transport these QHDs—by road, rail or air—to one location, where the quantum states would be read out and made to interfere, generating an interferogram.

Bartholomew and his colleagues have been working together on QHDs that could one day be used to build such an interferometer. In 2015 the group argued that photonic states could be stored in the nuclear spin states of certain ions in a crystal of europium-doped yttrium orthosilicate (or, more simply, Eu:YSO). In theory, in a crystal kept at a frosty temperature of two kelvins, the spin states should remain coherent for up to a month and a half, Bartholomew says. In a lab-based demonstration, his team managed a more modest but still impressive result, showing it could keep the spin states coherent for six hours. "We used to joke about putting the memory system in the back of a Toyota Corolla and driving down the highway," he says. "You'd be able to go quite a distance."

But the 2015 experiment did not store photonic states in the spin states and retrieve them later. It merely demonstrated that the spin states remained coherent for hours. In a December 2020 preprint study, Chuan-Feng Li of the University of Science and Technology of China and his colleagues reported using Eu:YSO crystals to store the coherent states of photons and retrieve them after an hour, verifying their fidelity via interference experiments. "It is a great idea to connect distant optical telescopes via QHDs," Li says. "It should be feasible to do so using the quantum memories based on Eu:YSO that we are working on. The QHD can be transported by trucks and helicopters."

Nora Tischler, a quantum physicist at Free University Berlin, who was not involved with any of this work, is also impressed by the idea of using QHDs to build optical interferometers. "Even though the proposal is technically very demanding, it is worth noting that this can take advantage of already (and independently) existing developments and efforts," she says. "The quantum community is working hard to optimize quantum memories as part of the effort to build future quantum networks." These memories could form the basis of quantum hard drives.

Bartholomew says that the next step is to ensure that QHDs are resilient against the vibrations and accelerations they would experience during transport. "The impact of those forces on the quantum storage needs to be characterized," he says. "But the reason for optimism is that these nuclear spin states are very insensitive to those types of perturbations."

Even so, there is no guarantee the technique will be a practical success. And it has a competitor. In 2019 Johannes Borregaard, now at Delft University of Technology in the Netherlands, and his colleagues augmented Gottesman's 2011 solution by designing a method to compress the information being received by telescopes, keeping only the relevant photons and discarding the rest. This would then require interactions with far fewer entangled photon pairs, which are difficult to produce at rates necessary for interferometry if the incoming information at the telescopes is not first compressed. And even with compression, longer baselines would still warrant quantum repeaters. Borregaard says it is still unclear whether QHDs or a combination of entangled photons and quantum repeaters will be the first to solve the problem of optical interferometry. "Both of them are challenging," he says.

Even if the quantum side of the equation can be solved, astronomer John Monnier, an expert in optical and infrared interferometry at the University of Michigan, is circumspect. Optical interferometers with longer and longer baselines will be observing smaller and fainter objects, meaning fewer photons per unit of time. To counter the atmosphere's deleterious effects, astronomers always have the very expensive option of making telescopes bigger—or the extraordinarily expensive one of putting them in space, where there is no atmosphere at all. Alternatively, they can use adaptive optics, which involves using the light of a bright reference object that is close in the sky to the star or galaxy being observed to correct for the atmosphere's blurring effects. But unlike in radio astronomy, where luminous sources are relatively abundant, in optical wavelengths, "it's super rare to find a bright object [close to] whatever you want to study," Monnier says.

It is possible that in the future, optical interferometers with large baselines will also employ the kind of adaptive optics used by individual telescopes today, which involves firing powerful lasers to create artificial reference stars, or guide stars, in the sky. But today's laser guide stars are not suitable for interferometers with baselines of tens of kilometers. Given such constraints, building optical interferometers is going to require more than QHDs, Monnier says. "[QHDs] could be a very interesting piece of a future that also involves some kind of new laser guide star for interferometers or large telescopes."

If that future comes to pass, Bland-Hawthorn says that a whole new era of optical astronomy will open up, particularly with interferometers using 30- and 39-meter telescopes that are being built in Hawaii and Chile, respectively.

Bland-Hawthorn also envisages being able to resolve white dwarfs such as Sirius B and binary systems into their component stars, measure stars' size and their intrinsic speed across the sky (also called proper motion) with greater precision and resolve, in finer detail, the stars moving around the black hole at our galactic center. "Tracking the stars around the black hole will allow us to probe the general theory of relativity in new ways," Bland-Hawthorn says.

Outside the Milky Way, he thinks 40-meter-class telescopes connected by QHDs will resolve stars in galaxies out to the Virgo cluster and also measure the proper motions of these galaxies. "This last experiment has key implications for the study of how large-scale structure evolves with cosmic time because of the underlying dark matter and the emergence of dark energy," Bland-Hawthorn says. SA