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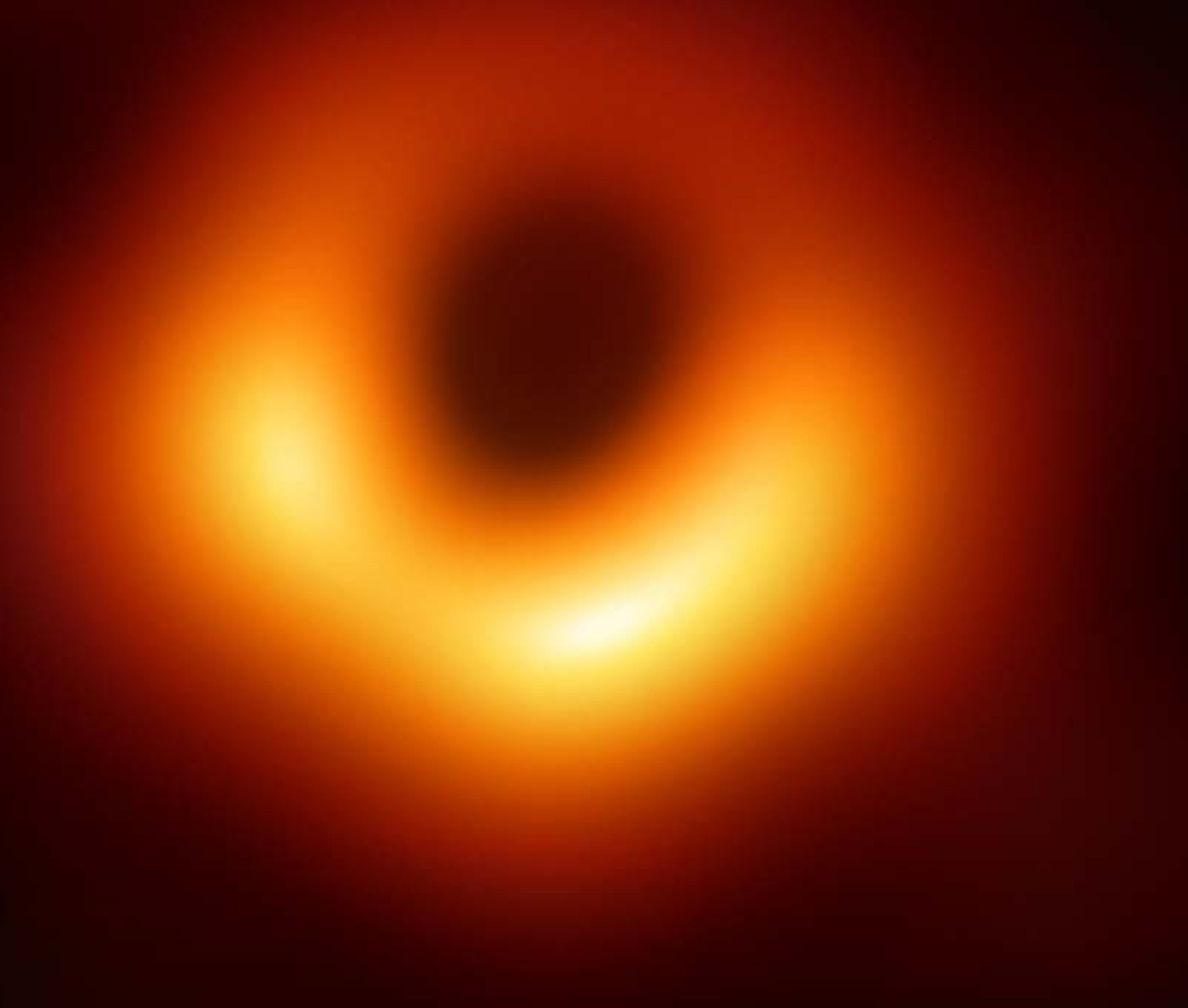

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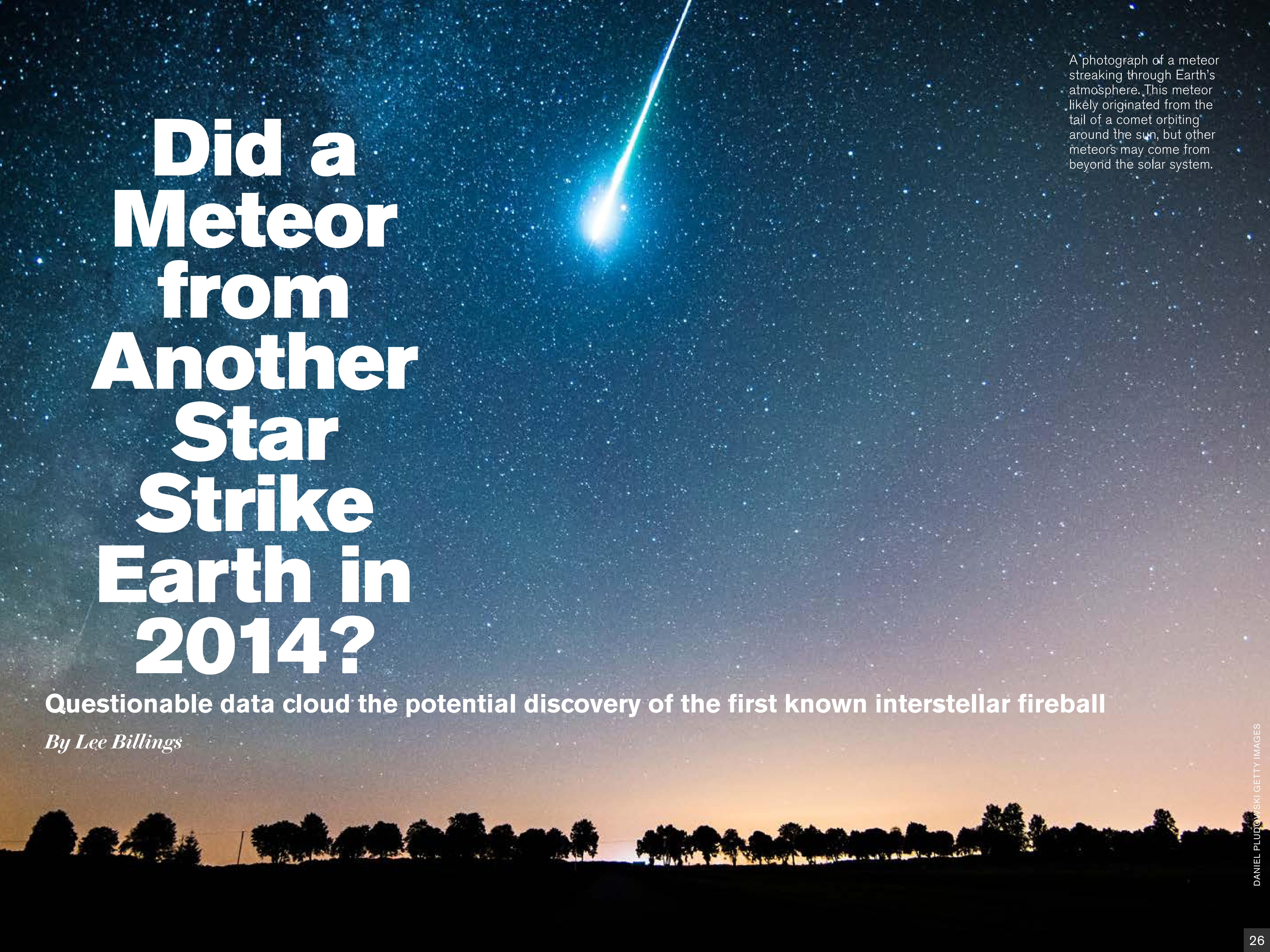

Did a Meteor from Another Star Strike Earth in 2014?

Questionable data cloud the potential discovery of the first known interstellar fireball

By Lee Billings

A photograph of a meteor streaking through Earth's atmosphere. This meteor likely originated from the tail of a comet orbiting around the sun, but other meteors may come from beyond the solar system.

DANIEL PLUDOWSKI/GETTY IMAGES

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By most standards, space is exceedingly empty, containing on average just one proton per four cubic meters of volume. In this cosmic ocean, so incomprehensibly desolate and vast, entire galaxies are akin to scattered spots of sea foam—not to mention the stars, planets and other lesser objects that fade to insignificance against the void. For random clumps of matter adrift in the deep to somehow find each other seems to border on the miraculous.

Yet find each other they do, and in surprising numbers. Stars and planets routinely hurl smaller objects into interstellar space as an inescapable consequence of orbital mechanics. And the recent discovery of ‘Oumuamua—a mysterious and first-of-its-kind interstellar object spied by chance when it passed close by our sun last year—confirms as much. Statistical extrapolations suggest that a quadrillion trillion similar objects may lurk as yet unseen in the dark spaces between the stars of the Milky Way, so many that there should always be one such far-flung passerby flying through the notional sphere bounded by Earth’s orbit around our star. With an estimated size of roughly half a kilometer, ‘Oumuamua in some respects represents the tip of the interstellar iceberg; just as grains of sand greatly outnumber large rocks on a beach, for every ‘Oumuamua-sized body wandering the galaxy there should be many, many more objects even smaller. Scientists already know of many microscopic interstellar immigrants—cosmic rays and micron-sized flecks of stardust that occasionally strike spacecraft—but other than ‘Oumuamua, nothing larger has ever definitively been found.

Now two researchers—Avi Loeb, chair of astronomy at Harvard University, and Harvard undergraduate Amir Siraj—say that has changed, arguing that a modest meteor observed in January 2014 was actually an outcast from another star. They detail their result in a preprint submitted for peer-reviewed publication in the *Astrophysical Journal Letters*. If confirmed, the finding could help open a new frontier in the detection and study of interstellar meteors.

A HYPERBOLIC CLAIM

“Previous approaches to this problem were like looking for your keys under a lamppost, where our sun is the lamp illuminating its surroundings and passing interstellar objects are the keys,” Loeb explains. “That’s a good technique—that’s how ‘Oumuamua was found—but it really limits you, particularly in trying to figure out an object’s composition.”

For their study, Loeb and Siraj used a different method, looking for evidence of interstellar objects in more than three decades of data from the Center for Near Earth Object Studies (CNEOS), a NASA-run global catalog of meteors detected by networks of U.S. government sensors.

Because there should be many more interstellar objects at smaller sizes, Loeb says, “there is a good chance those will appear to us as meteors, since the chances of their intersecting Earth are higher.” Monitoring a meteor’s bright trail as it burns up in our planet’s atmosphere can reveal not only the object’s size and composition but also its trajectory and velocity with respect to Earth and the sun. If a meteor’s inferred incoming speed exceeds about 42 kilometers per second—the solar system’s escape velocity in Earth’s vicinity—its trajectory could be considered “hyperbolic,” meaning it could have been an “unbound” interstellar passerby moving too fast to be captured by the sun’s gravity.

Only one event in the CNEOS database met Loeb and Siraj’s conservative criteria: a fireball off the coast of Papua New Guinea on January 8, 2014. According to the pair’s analysis of the CNEOS data, the meteor was half a meter in size and massed nearly 500 kilograms, entering the Earth’s atmosphere at nearly 44 kilometers per second before exploding high above the Pacific Ocean. Tellingly, the meteor’s trail showed it had not impacted Earth head-on, as one might expect of a fast-moving but native object in a retrograde orbit around our star. Instead it appeared to have swooped in from behind, overtaking our planet as the Earth moved around the sun—suggesting its actual velocity with respect to our solar system had been in blistering excess of 60 kilometers per second. Reconstructing the object's most probable path to Earth, Loeb and Siraj found no previous close encounters with Jupiter or other large bodies that could have boosted its speed.

The case for the meteor being a rock from another star seemed almost too good to be true, particularly since CNEOS data is best interpreted with caution. The catalog's primary sources are classified Earth-observing satellites operated by the U.S. military, which can record the brightness, orientation and duration of fireballs entering our planet's atmosphere. For reasons of national security, the government refuses to release information about potential sources of uncertainty in the satellites' secretive measurements.

"At first I didn't believe it," Siraj says. For a week, he and Loeb repeatedly checked their analysis of the CNEOS data, always arriving at the same conclusion: the meteor must have had an interstellar origin. Ultimately they chose to test their methods on a different, much more well-studied event—the 20-meter meteor that exploded over and wreaked havoc on the Russian city of Chelyabinsk in 2013. Using video recordings of the Chelyabinsk fireball, "we derived its orbit using our methods, and it was a very close match [to the CNEOS data]," Siraj says. "When I saw that, I thought, 'Oh, my God, this is real.'"

AN INTERSTELLAR ORIGIN OF LIFE?

The meteor's estimated extreme speed was not only much higher than that of objects orbiting the sun, but also well above what would be typical of other nearby systems swirling through the Milky Way's thin, star-studded disk. That, Loeb says, means its putative interstellar origins are decidedly exotic. "Either it came from a star in the galaxy's thick disk [a small and diffuse subset of speedy stars that surround the thin disk like a halo]," he says, "or it came from the galaxy's thin disk, from inner regions of a planetary system where objects orbit at higher speeds."

> **"Some of these objects could potentially transfer life between planetary systems."**
> **—Avi Loeb**

The pair's analysis also suggests interstellar objects of this scale strike Earth at least once per decade—meaning perhaps almost half a billion have rained down upon our planet throughout its 4.5-billion-year history. Stars near our own should eject anywhere between 0.2 and 20 Earth masses of such objects over the course of their lives, Loeb and Siraj estimate—and at any time, on the order of a million should be somewhere within Earth's orbit around the sun.

Such possibilities carry profound implications. "Some of these objects could potentially transfer life between planetary systems," Loeb says, referring to a broad theory known as panspermia (ancient Greek for "all seeds") that posits life first began in outer space and can readily migrate between planets. In principle, alien microbes sheltered within rocks blasted into space by a giant impact on some life-bearing world might survive an interstellar voyage and a fiery entry into a planet's atmosphere. Some researchers have posited this may even explain life's early emergence on Earth, which the fossil record suggests occurred with shocking rapidity more than four billion years ago, practically as soon as our planet became cool enough to harbor liquid water. "If this meteor is indeed interstellar, it shows a proof of concept," Loeb says. "Sure, it burned up, but bigger, rarer ones won't. And we don't need an impact every decade to seed the early Earth."

Even if Loeb and Siraj's meteor had managed to reach Earth's surface, however, other experts in the arcane topic of panspermia suggest it would not have brought anything living with it. "More likely, this object is not from a habitable (much less inhabited) body, but rather is a piece of a frozen, comet-like body," says Benjamin Weiss, a planetary scientist and meteorite expert at the Massachusetts Institute of Technology. More fundamentally, Weiss says, the claim that this particular space rock was interstellar is problematic. "The meteor catalog that [Loeb and Siraj] used does not report uncertainties on the incoming velocity," he notes. "These uncertainties need to be quantified before this meteor can be accepted as interstellar."

UNKNOWN UNCERTAINTIES

That is also the view of Paul Chodas, the CNEOS catalog's manager at NASA's Jet Propulsion Laboratory. "We at CNEOS simply post the fireball data that is reported to us; we have no information on the uncertainties," he says.

In March of this year, Chodas says, he and other CNEOS staffers flagged 2014's Papua New Guinea meteor as potentially interstellar based on their own calculations of its orbit—but did not publish that result due to concerns about the data's quality. Loeb and Siraj's "quite extraordinary" and "highly speculative" claim, he says, "is based on just a few numbers that are likely highly uncertain." (In their paper, Loeb and Siraj cite previous work reporting that the CNEOS catalog's typical uncertainty for the velocity of a meter-sized meteor is less than a kilometer per second—an insignificant offset in the enormous measured speed of their candidate interstellar fireball.)

Asked about uncertainties in the CNEOS fireball catalog, Lindley Johnson, NASA's "planetary defense officer," notes that its entries represent the use of data "in a way it was never, ever originally intended." Although initially conceived as a simple list of fireball times, locations and energy levels, more than a decade ago the catalog also began incorporating estimates of speed and directionality for particularly data-rich events, in hopes that researchers could use those projections to track down meteorite debris fields from large fireballs that occurred over land. Soon, particularly bold analysts were using those projections to look back in time, piecing together the potential orbital histories of meteors to link them and any meteorites they produced to certain families of asteroids. That was "already stretching the credence in the data beyond anything really scientifically valid," Johnson says. "Now [Loeb and Siraj] want to speculate based on such tenuous data that some could be interstellar objects? That really stretches the credibility past the breaking point for me."

Peter Brown, a planetary astronomer and leading meteor expert at Canada's Western University, says that even though the CNEOS catalog is on average of very high quality, the validity of any single data point—particularly for smaller meteors—remains questionable. "Statistically, I think the catalog's derived orbits and velocities and trajectories are fine," he says. "But we simply don't know which ones are good and which ones are bad." Furthermore, Brown says, of the thousands of small fireballs previously detected by other, independent surveys using ground-based cameras and radar stations, not one has clearly exhibited a hyperbolic trajectory. "If a tenth or a twentieth of a percent of the population was hyperbolic as Loeb and Siraj claim, you'd expect to have a fair number of hyperbolics in the data from ground-based networks—but we don't see that."

Even so, Brown adds, "it is a fantastic thing that others are coming from different disciplines and applying their own approaches to this rich data set.... Interstellar meteorites must be hitting Earth's atmosphere, and fireballs are the natural way to look for them. We just have to find them convincingly, in ways that can't be dismissed as measurement uncertainties."

This, naturally, is part of Loeb and Siraj's grand plan. The next step in the quest for interstellar meteors, they say, is to ensure that potentially hyperbolic fireballs can be not only detected but also characterized. Observed with the right equipment, a fireball's light can be broken up into a multicolored spectrum which acts as a "barcode" to reveal the object's chemical composition—a critical clue as to whether or not it formed around our sun.

"Every few years we should have one of these hyperbolic meteors," Loeb says. "If we just ensure observers are flagging fireballs with excess velocities, we should be able to set up spectroscopic surveys to get each one's spectrum as it burns up in the atmosphere and indeed demonstrate an origin beyond our solar system. Surely this is something worth investing in!"