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What it would mean and an idea for how to do it: The EmDrive explained PAGE 16

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NASA researchers rattled the propulsion community last year when they reported generating thrust inside a vacuum chamber with electromagnetism instead of propellants. Was the effect real or a product of an unknown source of error? Adam Hadhazy spoke to scientists who aim to find out.

Is it a breakthrough, or baloney? Not long after the turn of the millennium, the EmDrive — catchy shorthand for "electromagnetic drive" — was a mere glimmer at the fringes of space-propulsion research.

The idea was to generate thrust by harnessing a strange effect that seems to happen when electromagnetic energy is circulated in an enclosure. That's where things stood until November, when the concept began commanding mainstream attention after a team of NASA researchers reported in AIAA's Journal of Propulsion and Power that they may have generated an anomalous force with their version of an EmDrive, a force that would fly in the face of conventional physics.

Even the paper's lead author isn't sure whether the mysterious phenomenon is real. It's possible that an error source remains unaccounted for, and that the test article moved a distance imperceptible to the human eye — on the order of 4 to 10 micrometers — for completely mundane reasons. "The body of work we did in the paper helped us eliminate a number of those [error sources] fairly definitively," says aerospace engineer and physicist Harold "Sonny" White, who led the experiment. For other possible sources, "although maybe we put a little bit of a pencil mark through" them, they are "certainly not black-Sharpie-crossed-out."

Nevertheless, White and his colleagues at NASA's Eagleworks advanced propulsion physics laboratory in Houston are confident enough that they are busy planning more tests, despite sometimes skeptical reviews by other technologists who have gone over the paper.

Why has the paper generated so much intense scrutiny? If the effect turns out to be genuine and the technology can be expanded to a meaningful scale, it could portend a revolution in the space industry. Spacecraft would no longer need hundreds of kilograms or even tons of propellant to stay in orbit or explore deep space. The International Space Station, for instance, burns through approximately 4 tons of propellant each year, and more fuel must be delivered to it regularly at a cost of about $20,000 a kilogram.

The test

Specifically, the researchers found that per every kilowatt of microwave energy they pumped into their test article, which has the humble appearance of a tapered, copper bucket, 1.2 millinewtons of force was generated on the test article, roughly the equivalent of a honeybee landing on a flower.

Unlike EmDrive tests abroad that appeared to detect force, the NASA EmDrive experiments took place in a vacuum chamber, this one at the Johnson Space Center, home to Eagleworks. Conducting the test in a vacuum chamber slashed a major possible source of bogus thrust: air warmed up by the experiment's equipment could jar the test article.

How can it be?

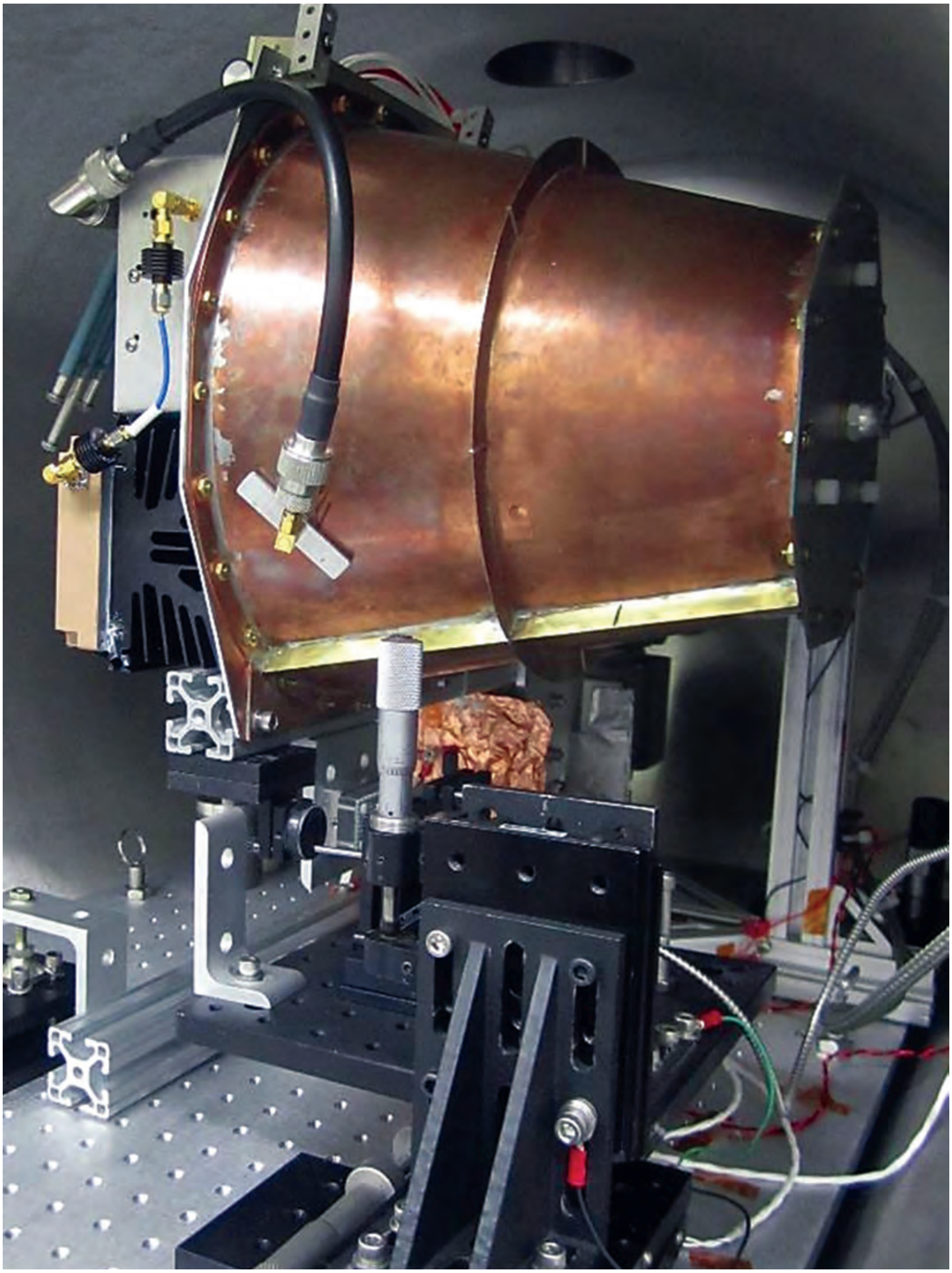
The paper, "Measurement of Impulsive Thrust from a Closed Radio-Frequency Cavity in Vacuum," went through about a year of peer review involving five expert "referees" instead of the more typical two referees. Even so, some physicists remain unconvinced about the EmDrive. "They have a huge hill to climb here, because regardless of how it works, the EmDrive would violate deeply fundamental and well-verified physical phenomena," says Brian Koberlein, a professor of physics at Rochester Institute of Technology in Rochester, New York.

Another skeptic put it even more bluntly. "My perspective is, there's no 'there' there," says Eric Davis, a senior research physicist at the Institute for Advanced Studies at Austin, Texas, as well as a former consultant on NASA's defunct Breakthrough Propulsion Physics Project and who visited White at the Eagleworks lab. "That conical cavity of theirs is a microwave oven," Davis continues, "and we know from physics that microwave ovens can't fly."

Part of the problem might be the breathless headlines touting NASA's verification of an "impossible" or "Star Trek" drive. Seeing this coverage, White is not at all ready to pop a champagne cork. "We're not there yet," he says. Although confident about the EmDrive on one hand, he calls for careful incrementalism on the other. "There are no shortcuts in scientific investigation and in doing empirical observation," White says. "You just have to have patience."

Trendy research

Patience seems to be in short supply, though. Researchers at the China Academy of Space Technology say they have been testing their own version of an electromagnetic drive in space, according to a December article in Science and Technology



NASA

◀ **NASA's EmDrive experimental setup:** Microwaves moving around inside this copper, bucket-shaped test article in Houston appear to have generated thrust toward the article's narrow end, hinting at a potentially propellant-free mode of propulsion.

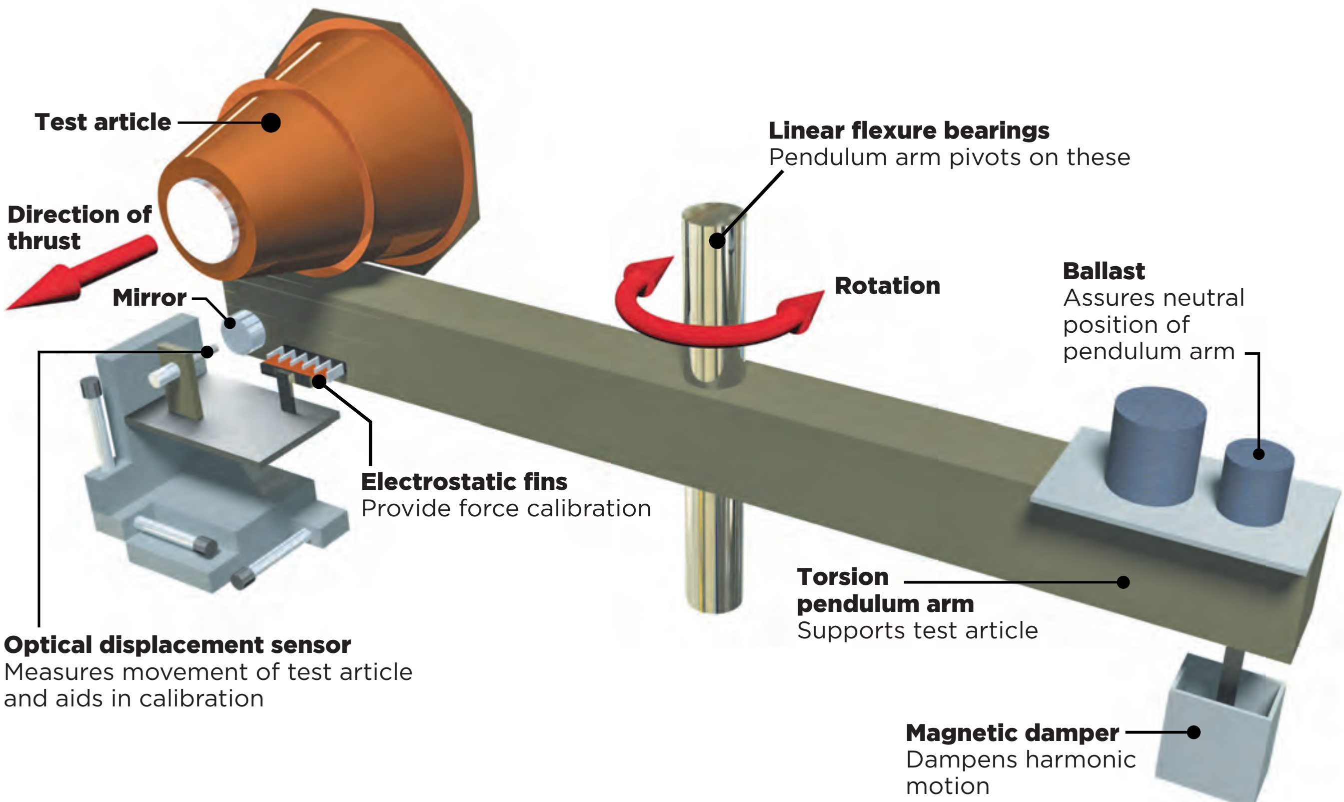
Daily, the newspaper of the Chinese Ministry of Science and Technology. Meanwhile, the Pennsylvania-based company Cannae Inc. has announced plans to launch an EmDrive-like, also-propellantless thruster into space on a cubesat as a technology demonstration.

All in all, it is a meteoric rise for an outré propulsion concept that is not even two decades old. Roger Shawyer, a British aerospace engineer, left Matra Marconi Space, forming his own company in 2001 to develop an electromagnetic drive, technically known as a radio frequency resonant cavity thruster. The concept had occurred to him while evaluating closed-system gyroscopes as a means of thrust for missile control. Despite critics who say his experiments are imprecise and his physical theories questionable, Shawyer has claimed success in experiments over the years. Along the way, his efforts have inspired the aforementioned researchers in China, Germany, and also White and his colleagues, to delve further into the potentially game-changing prospects of the EmDrive.

White and his colleagues recognized that the EmDrive was a long shot, but long shots are the Eagleworks

THE EXPERIMENT

NASA researchers think they may have moved the copper cone below just by circulating microwaves inside it. The results raise the possibility of generating spacecraft thrust without propellants. In a series of test runs, an optical displacement sensor detected subtle movements of a test article attached to a torsion pendulum arm.



Source: NASA Eagleworks

Illustration by John Bretschneider

lab's raison d'etre. Indeed, the EmDrive might be tame compared to other work at the lab, including theoretical and experimental forays into the possibilty of developing a faster-than-light "warp drive," courtesy of isolated bubbles of spacetime.

Not long after the founding of the Eagleworks lab in 2011, White's team decided it was time to take the EmDrive for a spin. What ensued were years of work to set up the experimental apparatus, report preliminary findings in 2014 and conduct a year of peer review for the paper published in November.

The tests at NASA

For his EmDrive, White hewed to Shawyer's design to construct the 23-centimeter-long, copper test article in the geometric shape of a frustum — a cone with its pointy end lopped off. A small antenna inside the test article floods its interior with resonating microwaves.

This test article was mounted to the aluminum arm of a torsion pendulum. This arm was free to rotate horizontally around a linear, vertically oriented flexure bearing, should it experience a force. An optical sensor transmitted a laser to measure the displacement of the movable arm portion of the torsion pendulum from its rest position. White and his team needed to describe this displacement in terms of force, which meant they had to know how far the pendulum would move with a given amount of force. They placed two electrostatic combs opposite each other, one on the pendulum arm and one on some gear near it, so that the fins of the combs interleaved. Before each test run, they charged the combs with particular voltages to induce specific levels of force, and then with the optical sensor measured the separation of the fins. The result was a touchstone they could consult to know how much force was generated on the test article on each run.

Direct current power and data signals traveled from the fixed portion of the torsion pendulum into the movable portion through brass screws into liquid metal contacts made of the trademarked alloy Galinstan, a mixture of gallium, indium and tin that stays liquid at room temperature. These connections eliminated cable interfaces and their confounding forces. To offset the weight of the test article on the torsion pendulum's one end, a ballast weight was placed on its other, while a magnetic dampener converted some oscillatory motion into heat. "That's a way to keep the system fairly well-damped so it's a nice, clean signal that we can look at," says White. The experiment was done on a "shoestring" budget in line with other low-technology-readiness-level, university or NASA center lab efforts. The cost was on the order of tens or hundreds of thousands of dollars, not millions. "You just try and be as frugal as you possibly can to make forward progress," White says.

The researchers ran the experiment at varying power levels of 40, 60 and 80 watts for periods of 30, 60 and 90 seconds. The optical sensor recorded any displacement of the copper frustrum in both forward and backward orientations on the torsion arm. When all was said and done, on average, a small, but persistent force unattributable to other aspects of the experiment emerged.

White's paper addressed nine possible sources of error for this force, ranging from air currents to vibration to electrostatic interactions of experimental components. Although White is confident that most were ruled out, perhaps the most difficult to counter was the thermal expansion and contraction of the various items mounted on the torsion pendulum arm. That expansion or contraction could tip the center of gravity and yield spurious thrust signals. "That was the thing we worked the hardest to understand and put in a box," White says. "As we move forward, we want to do some more due diligence."

Peer reviews

Rochester's Koberlein applauds White and his team for applying such rigorous peer review. "The whole point of peer review is it puts [research] out there publicly so people can rip it apart," said Koberlein. "That's how we do science and that's the only way we're going to get to the truth."

That said, Koberlein is quick to argue that pre-publication review is, of course, not any guarantee of a study's results, just that its general methodology passed muster with at least one, if not a few, independent scientists. "It's important not to overvalue peer review, because lots of things that have been subjected to peer review have been wrong," says Koberlein.

A recent swing-and-a-miss was BICEP2, short for Background Imaging of Cosmic Extragalactic Polarization, an experiment that gathered relic light from the Big Bang with a telescope near the South Pole. In March 2014, researchers announced collections reported finding evidence for a period of rapid expansion of the universe following the Big Bang. Less than a year later, the team withdrew the claim, and the data was chalked up to mundane, cosmic dust.

At this early stage of digestion of Eagleworks' EmDrive paper, the review from the wider community has ranged from lukewarm to skeptical.

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— Harold "Sonny" White, NASA Eagleworks

Marc Millis, the former head of NASA's defunct Breakthrough Propulsion Physics Project, and co-authors wrote about the paper on Cenaturi Dreams, the website for his interstellar travel advocacy group, the Tau Zero Foundation. The new study "is an improvement in fidelity on the prior tests and may be indicative of a new propulsive effect," according to the authors, but they went on to observe what they called some shortcomings. Philosophically speaking, the paper's authors lacked impartiality, given their assumptions that the EmDrive somehow or another worked. On the methodological front, Millis and colleagues write that White's team failed to fully characterize the performance of their torsion pendulum; quantitatively assess possible interactions with the vacuum chamber's wall; and exhaustively account for thermal effects. The analysis suffered, Millis and colleagues say, because it could not credibly discriminate which part of the data was due to actual impulse, versus thermal effects. "Questionable subjective techniques are used to infer the 'thrust' from the data," they write.

Davis, who was one of Millis' co-authors, says that before the experiment, White's team "cleaned up" a lot of the potential sources of error , but "they still engaged in a lot of wishful thinking."

Reaching for an explanation

As for the physics behind the EmDrive, White and his team speculate they may be seeing a manifestation of what's known among physicists as a quantum drive or Q thruster. Such a thruster works on

"THE WHOLE POINT OF PEER REVIEW IS IT PUTS [RESEARCH] OUT THERE PUBLICLY SO PEOPLE CAN RIP IT APART."

— **Brian Koberlein,** Rochester Institute of Technology

the well-accepted principle that empty space is not a vacuum but is frothing with fluctuations in quantum fields, with pairs of virtual particles perpetually forming and mutually annihilating.

Based on an interpretation of quantum mechanics known as pilot wave theory, these vacuum fluctuations can be thought of as a dynamic medium that guides, or pilots, individually observed, "real" particles. And as a medium, the quantum vacuum's constituents can interact and exchange momentum, not unlike a fluid, or a plasma.

As White sees it, the EmDrive can leverage electromagnetic fields to couple with the quantum vacuum and induce a slightly preferential flow in it. "A terrestrial analog to think of is a submarine that sits in the water," White explains. "It takes advantage of the fact it's embedded in its propellant." A submarine uses a propeller to couple with this liquid medium and generate a hydrodynamic pressure gradient. The water moves in one direction and, to conserve momentum, the submarine moves in the other, just like the EmDrive goes one way while a "wake" of virtual particles streams through the quantum vacuum.

According to this explanation, one of the biggest slams of the EmDrive — that it violates conservation

▼Cannae announced that it will launch its proprietary thruster — which it says requires no onboard propellant — into space on a cubesat.

Cannae

of momentum, a bedrock principle of physics — is averted. Yet other physicists are not buying that the Q-thruster argument conserves momentum, famously conveyed as Newton's third law: For every action, there is an equal and opposite reaction. Rochester's Koberlein says extending the third law to the quantum vacuum — in effect, the entire cosmos, anywhere and everywhere — cannot work, because then "what does the cosmos move against?" he asks.

Furthermore, some question that the quantum vacuum operates at all like a plasma, as White contends. The paper also does not present any equations or mathematical predictions for how to relate measured thrust back to a theoretical paradigm, even a wildly conjectured one. "They have nothing to go on theoretically," Koberlein says. "That means they have no convincing way to pull any signal they might have out of the noise [of the experiment]."

But backers posit entirely different theories for how they might work. Shawyer in the U.K. points to electromagnetic waves' momenta being linked to velocity, influenced by the geometry of the tapered EmDrive, thus creating asymmetric forces at its wide and narrow ends. Some speculate on theoretical Unruh radiation, a hypothesized inertia phenomenon caused by virtual particles and in this case felt by microwaves to differing degrees at opposite ends of the EmDrive. An even more outlandish conjecture is that an EmDrive's microwaves might interact with elusive dark matter particles, which although undetected to date, theoretically outnumber particles of regular matter by five to one.

Ames Research Center

▲ **Next, Harold "Sonny" White and NASA** Eagleworks want to test their EmDrive concept on a Cavendish balance. Additional findings might help to define the underlying physics.

What the future may hold

White seems unfazed by the hubbub surrounding his experiment and is planning his next move. To further tackle the possible bugaboo of EmDrive thermal expansion and contraction, he and his team want to run similar tests on a type of apparatus called a Cavendish balance. In such a setup, the EmDrive could rotate out to much larger angular displacements, such that the thrust force would dominate over any thermal effects. Additional findings also might help to define the underlying physics. "Those are two major brushstrokes that we'll be applying to the canvas," White says. Beyond these next steps, White says it is premature to consider, say, altering the shape of the test article or the frequency of the microwaves to try and squeeze out more oomph. "We really don't have a good sense yet of what particular dials there are for us to be able to grab onto and turn and be able to say you can do this, that or the other," he says. "We're very much in the early phases of trying to understand the engineering and physics and how they interact with one another."

Optimistically, a few years ago, White and a colleague ran some figures on what a "Q-ship" outfitted with a fully-fledged EmDrive, could do throughout the Solar System. The researchers assumed a conservative thrust of 0.4 newtons per kilowatt — about 300 times that hinted at in the recent, small-scale experiment, but a tenth of what they ballpark as achievable — supplied by a modest nuclear reactor in space, producing a megawatt or two of electrical power. In this scenario, a one-way trip to Mars could take 75 days — a far cry from the approximately eight months with current rocket technology. More eyebrow-raisingly, trips to the neighborhoods of Jupiter or Saturn would take around 200 and 260 days, respectively, opening up the outer solar system to human exploration.

White realizes this is pie in the sky for now, considering where the EmDrive's development is. "We've got some work to do," he says. "We're still potentially even in the mode of definitively eliminat[ing] all false positives."

Whether or not the EmDrive will ultimately prove itself in the years ahead, many will be rooting for the Eagleworks team to upend physics as we know it.

"I want them to succeed. I want warp drive, or EmDrive, or whatever. I want to go to the stars," said Koberlein. "But that doesn't make it so." ★