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In 1921, an Army pilot dropped insecticide on crops, starting a dashing new profession that might or might not survive the age of drones.

PAGE 20

TOMORROW'S CROP DUSTERS

JUNE 2019 | A publication of the American Institute of Aeronautics and Astronautics | aerospaceamerica.aiaa.org

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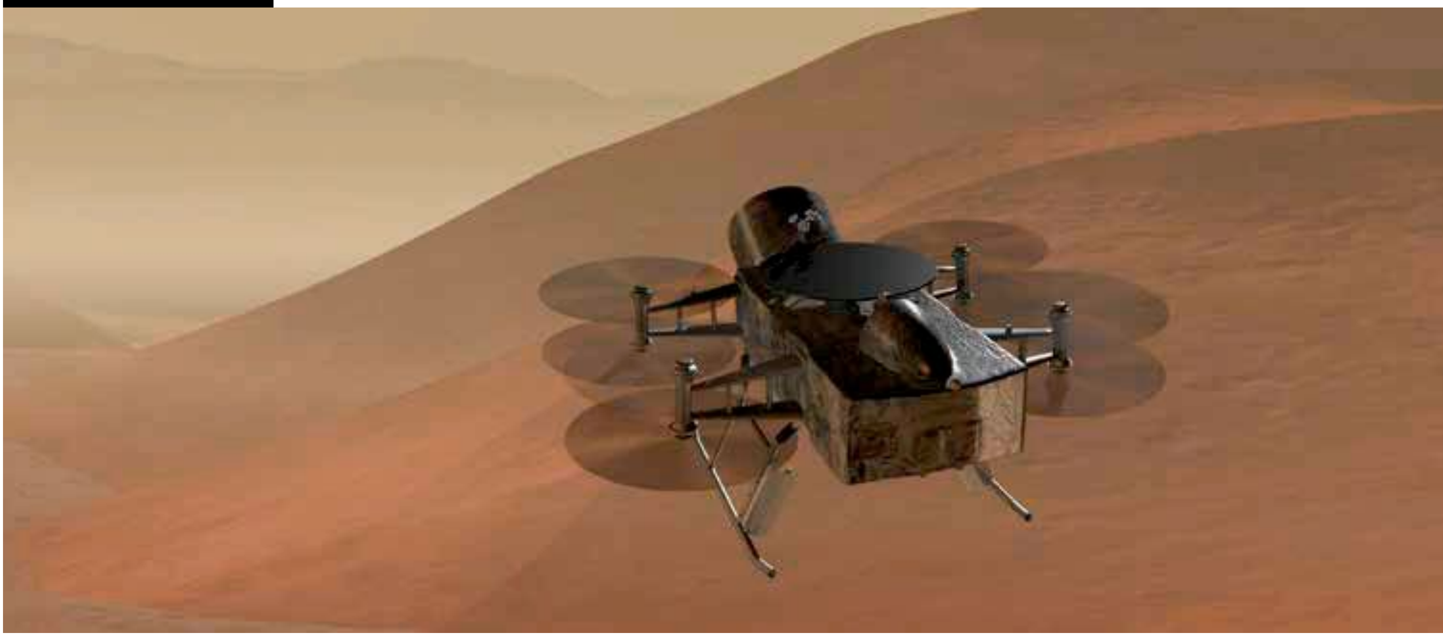


DECISION T·I·M·E

NASA'S NEW FRONTIERS

SUS ···········► CAESAR

NASA has limited dollars for exploring the solar system with robotic spacecraft, and it can take a decade to get such a probe to its destination. Careers are made or stalled when NASA selects a proposed mission, which is why the agency's latest New Frontiers competition is such a high-stakes affair. Adam Hadhazy spoke to the finalists vying for the prize.

BY ADAM HADHAZY | adamhadhazy@gmail.com

Where to: a comet or Saturn's icy moon Titan? That's the question NASA managers will need to answer in July 2019 when they select the next mission in the agency's New Frontiers series.

For planetary scientists, comets are tantalizing ancient messengers from the early solar system, while Titan is on the short list of places in our solar system that, though a long shot, could harbor life of some form. The decision is not an easy one.

"'Agonizing' falls far short of describing this" decision, says NASA's Curt Niebur, lead program scientist for New Frontiers. "The teams pour all of their talent and passion into this work, and they produce amazing missions. Picking only one is the worst part of my otherwise great job."

Whoever wins will have the challenge of continuing what has been a great run for New Frontiers since the initiative's founding in 2002. Its first three probes have achieved household name status among those who follow planetary science. New Horizons flew by Pluto in 2015 and is now flying by other mysterious Kuiper Belt objects. Juno began orbiting Jupiter in 2016, and OSIRIS-REx in 2020 will attempt a sample return from the asteroid Bennu.

For the fourth round, NASA in 2017 down-selected from an initial field of a dozen entrants, choosing CAESAR (Comet Astrobiology Exploration Sample Return) and Dragonfly, a rotorcraft inspired by consumer drones. CAESAR intends to bring back to Earth the first-ever sample of a comet's icy main body, critical for measuring the relative amounts of the primordial ingredients that went into making our solar system. Dragonfly, as the name implies, would flit about Titan, seeking clues about the emergence of life, both here on Earth and potentially elsewhere.

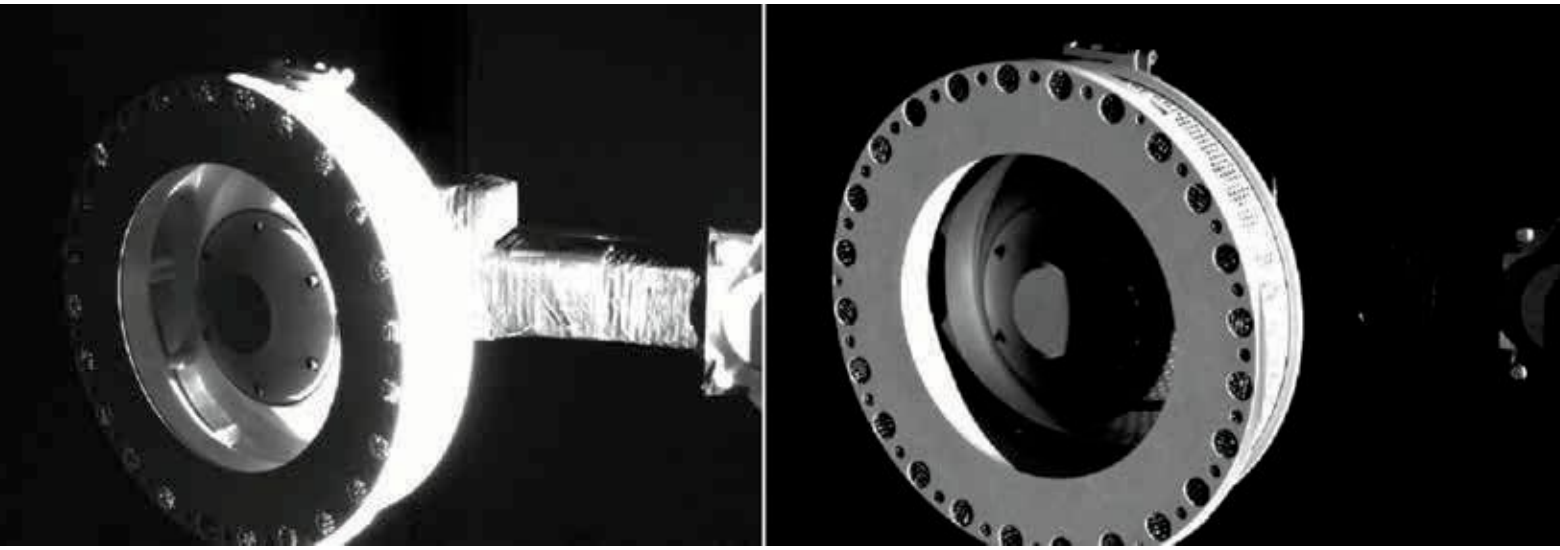
"The science content of both missions [is] extremely compelling," says Niebur.

The winner will proceed toward a flight no later than 2025 under a cost cap of $850 million. Once the launch vehicle and mission operations are factored in, NASA expects the tab to come to about $1 billion. The CAESAR and Dragonfly teams each received $4 million after the down selection to refine their concepts.

Like beverage cups, NASA's solar system exploration missions come in three sizes: small, medium and large. The smaller Discovery missions have budgets in the range of $600 million–$700 million, fly at a rate of up to a few per decade and focus on answering narrower sets of questions; arguably the most famous Discovery mission was the planet-hunting Kepler space telescope. On the large end, Flagship missions' budgets run upward of $2 billion and thus fly the least frequently. The next two Flagships are the Mars 2020 rover and the Europa Clipper.

Two review boards — one for science, the other covering technical, management and cost aspects — consisting of about 70 people are evaluating CAESAR and Dragonfly. The boards will soon submit their findings to NASA.

Here's a preview of the two proposals vying to be the next New Frontiers mission.



▼ **The OSIRIS-REx** Touch-and-Go Sample Acquisition Mechanism, or TAGSAM, sampling head is extended from the spacecraft in two views. The CAESAR team built a new sample collection device that was modeled on the TAGSAM.

NASA/Goddard/University of Arizona

▲ **A camera on the European Space Agency's** Rosetta probe took this close-up view of a flat region of Comet 67P/Churyumov-Gerasimenko, which would be the CAESAR probe's destination as well.

ESA/Rosetta

Hail CAESAR

In essence, comets are icy dirtballs left over from the solar system's formation 4.5 billion years ago, a fact that makes them scientific motherlodes.

"Comets represent the most primitive solar system material that's available to us for sample return," says Steven Squyres, a professor of astronomy at Cornell University and the principal investigator of CAESAR. "They're the best-preserved examples of the stuff from which the solar system was made. By sampling them, we can see into the past." Also, unlike asteroids, comets do not fall to Earth constantly as meteorites, and even if they did, their ices — made of water and other materials — would be burned off in the process. The only way to touch their constituents is to go to them.

Although multiple spacecraft have visited comets and observed them up close, these observations yield comparatively little information compared to bringing a portion of the cosmic body back home for analysis.

"When you do a sample return mission," says Squyres, "the instrumentation of your mission is essentially the combined scientific power of all the world's laboratories for decades to come." He points out that the best science ever done with the moon rocks retrieved half a century ago by Apollo astronauts is happening now, in modern labs. "Samples are a scientific gift that keeps on giving," says Squyres.

The only comet return mission to date is NASA's Stardust probe, which in 2006 returned about a milligram of cometary material, consisting of dust grains from Comet Wild-2's coma, or luminous atmosphere.

Building on Stardust's success, CAESAR's goal is to gather and return to Earth on the order of 80 to 800 grams of volatiles (frozen gases and ices) directly from a comet's nucleus. "Our motto is, 'it's all about the sample,'" says Squyres.

To avoid complications, the CAESAR team selected Comet 67P/Churyumov–Gerasimenko, one of the best-characterized space rocks in the entire solar system. The European Space Agency's Rosetta probe extensively mapped and studied 67P from 2014 to 2016. Its Philae lander module snapped high-resolution images mere meters from the surface before touching down. "One of the real keys to reducing risk," says Squyres, "is to know in advance what your target is like." Making the case, the team behind OSIRIS-REx is having to reconceive its sample return procedure because the target asteroid, Bennu, has surprised scientists by possessing a rough, rugged, boulder-strewn surface; remote radar surveying of Bennu from Earth had inaccurately suggested a smooth, easy-to-sample landscape.

Familiarity and risk reduction extend to the CAESAR spacecraft design as well, which leans on proven heritage components. The bus will be based on Northrop Grumman's GEOStar-3 communications satellites; the solar electric propulsion system, from NASA's Dawn spacecraft that journeyed through the asteroid belt; the sample return capsule, developed by JAXA, the Japan Aerospace Exploration

Agency, for its asteroid sample return missions; the sample retrieving arm, developed by NASA for the Mars 2020 rover. The CAESAR team did build a new sample acquisition device that goes at the end of the arm but drew heavily on OSIRIS-REx's, whose sampling head will emit a blast of nitrogen onto Bennu to stir up dust and pebbles. This material will be collected by a vacuum pump during the five-second touch-and-go maneuver.

Where CAESAR necessarily innovates is in sample preservation. Comet material cannot be simply hermetically sealed after capture, because putting volatiles and nonvolatiles in a confined space could trigger sample-damaging chemistry that wouldn't naturally occur on a comet. Prior asteroid sample return schemes have therefore let the samples vent to space en route back to Earth. CAESAR's designers had to hatch a plan so as to not lose the precious volatiles. That plan involves gently warming the sample to minus 30 degrees Celsius (minus 22 degrees Fahrenheit) — about the temperature Comet 67P's surface naturally reaches during its closest sun approaches. Doing so releases the comet's volatiles, but these are directly captured in a separate, chilled, 5-liter tank. This container is then sealed shut, while the mostly dried, solid sample innocuously vents to space. "This is the key innovation that distinguishes CAESAR from any prior attempts to do comet sample return," says Squyres.

The final obstacle will be to keep the comet material suitably cold through the capsule's entry, descent and landing, when friction with the atmosphere flame-broils a heat shield up to 3,000 degrees Celsius. Part of the solution will be to surround the sample container with aluminum housings filled with dodecane, a hydrocarbon that has a melting temperature of about minus 10 degrees Celsius (14 degrees Fahrenheit). During entry, heat will be pumped behind the heat shield, the frozen dodecane melts, plateauing the temperature at a sample-preserving level. Closer to the ground, the heat shield will drop from the capsule while it's coasting down via parachute. This prevents the capsule from coming to rest on the ground with a foundry-hot shield attached. Overall, these tactics buy a capsule retrieval team an ample four to five hours before any sample alteration would take place.

The capsule's landing zone will be the Utah Test and Training Range, some 130 kilometers east of Salt Lake City (and the same site employed for Stardust's sample return and OSIRIS-REx's, come 2023). Upon retrieval, the capsule will be airlifted into a cold storage vehicle — nicknamed the ice cream truck — for delivery to a planned dedicated CAESAR facility at NASA's Johnson Space Center in Texas.

Should the mission be greenlit, CAESAR would launch in 2024 and have to travel beyond the orbit of Jupiter to make its rendezvous with 67P come 2029. Out there, the comet will be far enough from the sun's warmth to be ideally stable and quiet for performing an astronomical biopsy. The CAESAR spacecraft wouldn't then return to Earth's vicinity until November 2038. It would be a long wait, but Squyres argues well worth it.

"We're talking groundbreaking science for decades to come," says Squyres.

Flight of the Dragonfly

In many respects, Saturn's moon Titan is a cold, bizarro version of our planet. Though the only other body in the solar system known to have liquid bodies on its surface, Titan's seas and rivers are not aqueous; instead, they're filled by tar-like hydrocarbons, replenished by seasonal, un-Earthly rains. Geologically, Titan has familiar features like mountains and dunes. Yet all have formed in an environment three times colder than Antarctica. The world further intrigues because it is thought to possess a global ocean of water, sloshing around under an icy surface shell. The proverbial cherry on top: Titan's rich chemical inventory, with organic (carbon-containing), "prebiotic" molecules, the building blocks of life, strewn about its surface.

Scientists know all this from the Cassini orbiter and Huygens lander. These spacecraft arrived in the Saturnian system in 2004.

Cassini mapped and remotely sensed Titan, while Huygens parachuted through Titan's thick, hazy atmosphere in January 2005, touching down and snapping pictures on the surface for 90 minutes; it still stands as the most distant landing humankind has accomplished.

Dragonfly would visit scores of sites on Titan, offering an unprecedented look at extraterrestrial conditions conducive to biology. Admittedly an extreme longshot, Titan might already host alien life, a tantalizing prospect Dragonfly could assess.

"Titan is just this incredibly unique opportunity to be able to really study in detail prebiotic chemistry and habitability," says Elizabeth Turtle, a planetary scientist at the Johns Hopkins Applied Physics Laboratory in Laurel, Maryland, and the principal investigator of Dragonfly. "It's an environment where we have all the ingredients we need for life as we know it."

Dragonfly would be an octocopter with a top-and-bottom pair of rotors at its four corners. It would make leapfrog-style jaunts between potentially scores of landing sites of interest, spread tens of kilometers apart. Space agencies have never before attempted to fly a probe in another world's atmosphere. Yet the technology is now at a place where this horizon-expanding search strategy and design looks feasible.

"The drone revolution has enabled all this autonomous flight and rotorcraft technology," says Turtle.

The first technology demonstration of an extraterrestrial science drone is slated to be a small, 2-kilogram helicopter accompanying NASA's Mars 2020 rover, scheduled to land on the red planet in February 2021. Compared to that Martian drone, Dragonfly would be a beast, standing about a meter tall and weighing a few hundred kilograms. If that sounds

▼ **The Dragonfly probe** is seen in various stages of its operations on Titan in an artist's concept. From left, the images represent entry, descent, surface activities and flight.

Johns Hopkins Applied Physics Laboratory

Flight control and navigation demonstrated at a Dragonfly field test.

Johns Hopkins Applied Physics Laboratory

"As a human being, if you put some wings on your arms, had an oxygen source, and a really good sweater, you'd be able to fly on Titan."

— **Elizabeth Turtle**, Johns Hopkins Applied Physics Laboratory

too heavy to fly on Earth, that's the point; Titan has only one-seventh of Earth's gravity and its atmosphere is denser, with about 60% greater pressure. "It is a lot easier to fly on Titan than on Earth," says Turtle. "As a human being, if you put some wings on your arms, had an oxygen source, and a really good sweater, you'd be able to fly on Titan."

Much of Dragonfly's curb weight is expected to be from the battery. As a rough, high-end estimate, designers assumed a 140-kilogram unit, about a quarter of the size of a Tesla electric car's battery pack. The battery would recharge by drawing power from a Multi-Mission Radioisotope Thermoelectric Generator, or MMRTG. NASA has access to enough plutonium fuel to construct two more MMRTGs after the generator already committed to the Mars 2020 rover.

If selected for New Frontiers Four, Dragonfly would launch in 2025, reaching Titan nine years later. The probe would bring science instruments including spectrometers for detailed chemical analysis, a meteorology package, a seismic sensor and — of course — cameras. The intended landing zone is Titan's equatorial dunes, at a similar latitude as Huygens' site. These sand seas offer a safe, mostly rock- and gully-free place to put Dragonfly through its paces before visiting more exotic Titanian environments. One such destination could be outflows from cryovolcanoes, possibly recently active, which spew a cold slurry of water and hydrocarbons, versus Earth's molten lava. Outflows could offer key insights into if and how the organics-laden surface of Titan interacts with the moon's internal water ocean.

Overall, Titan's astrobiological appeal is immense. "We want to understand how chemistry progresses to the point of biology," says Turtle. "With the drone revolution and all this information we have from Cassini, the timing is really perfect to go and study Titan's chemistry and implications for the development of life."★