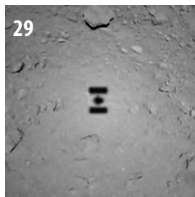


Space News

IAN O'NEILL

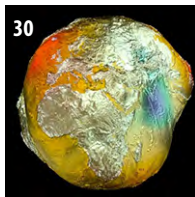
A rundown of some of the most exciting developments in space and time.



Cosmic Views

JASON MAJOR

An Earthly shadow on an alien world.



The Gravity of Climate Change

MATTHEW R. FRANCIS

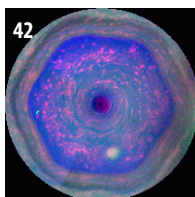
The GRACE Follow-On mission measures the effects of climate change through fluctuations in Earth's gravitation.



Learning to Fly

STEVE MURRAY

NASA's asteroid sample return mission OSIRIS-REx will require operators to learn new navigation skills on the job.



Saturn's Six-Sided Storm

TRACY STAEDTER

New analysis from Cassini stirs up even more intrigue around the hexagonal jet stream in the Ringed Planet's enigmatic atmosphere.

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on the cover

Front: This dramatic photograph was captured by one of two rovers exploring the surface of asteroid Ryugu after landing on Sept. 21, 2018. The hopping MINERVA-II1 probes were released by the Japanese Hayabusa-2 spacecraft and are the first mobile rovers to ever land on an asteroid. *Credit: JAXA.*

Back: This illustration depicts NASA's exoplanet hunter, the Kepler space telescope, and an array of stars with their orbiting exoplanets. On Oct. 30, 2018, NASA announced that Kepler had run out of fuel and is being retired within its current and safe orbit, away from Earth. Kepler leaves a legacy of more than 2,600 exoplanet discoveries and a slew of astronomical data that will undoubtedly uncover more alien worlds orbiting distant stars. *Credit: NASA/Wendy Stenzel.*

Learning To Fly

NASA's asteroid sample return mission OSIRIS-REx will require operators to learn new navigation skills on the job.

By Steve Murray



This artist's impression shows NASA's OSIRIS-REx carrying out its deep space maneuver in 2016 to put it on course for asteroid Bennu. *[University of Arizona]*



The main objective of the NASA OSIRIS-REx mission will be realized in 2020, when the spacecraft gathers up a sample of asteroid Bennu. Operating so close to a body with virtually no gravity will be risky, so mission science and engineering teams will be cautiously exploring the asteroid before moving in for the final maneuver. There will be a lot to learn over the next few months as the spacecraft travels in company with asteroid.

After two years of cruising in space, OSIRIS-REx began its approach phase in August, and will arrive at Bennu on Dec. 3. Things are already getting busy and the lessons are already starting.

Why Bennu?

NASA's expansive goals for the OSIRIS-REx mission are wrapped in its name: A sample of pristine asteroid material could yield insights into how the solar system began (Origins); close-in scans of surface constituents could help scientists calibrate data on asteroid composition gathered with ground-based instruments (Spectral Interpretation); isolating chemical and mineral components could help determine the feasibility of commercial extraction (Resource Identification); measurements of the solar forces acting on asteroids could generate better predictions about their orbits and their potential danger to the Earth (Security); characterizing the nature and distribution of surface material could yield new knowledge of how these bodies came to be (Regolith Explorer). Achieving these goals, however, requires selection of just the right asteroid.

Bennu has been comprehensively scanned at multiple wavelengths, and imaged by radar from Arecibo Observatory in Puerto Rico, since its discovery in 1999. It's the most studied asteroid that hasn't yet been visited by a spacecraft. Bennu was selected as the OSIRIS-REx mission target because it was at the right distance, it was the right size, and it had the right composition.



This artist's concept shows OSIRIS-REx collecting samples at the surface of asteroid Bennu. [NASA Goddard Space Flight Center]

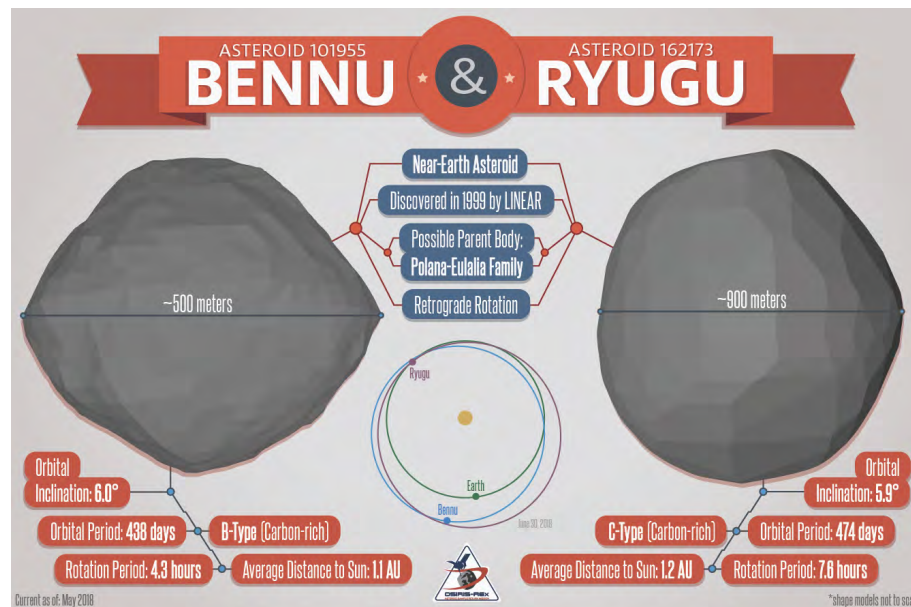
Bennu is one of fewer than 200 asteroids with fairly circular orbits aligned with the Earth's orbital plane. This simplifies the design of spacecraft rendezvous paths. Because these orbits can bring asteroids close to the Earth, scientists are also interested in studying them because they're potentially dangerous to the planet.

Objects with diameters less than about 650 feet (200 meters) are considered too small to approach with a spacecraft because they spin too rapidly. Bennu has a mean diameter of about 1,614 feet (492 meters) and a rotational period of about 4.3 hours, which mission planners considered slow enough for safe approach and contact. (Ryugu – the asteroid being explored by the JAXA Hayabusa 2 spacecraft – has a diameter almost twice as big and a rotational period almost twice as long.)

Lastly, Benu is a dark, carbonaceous B-type asteroid with a density similar to coal. Such asteroids are the most primitive bodies in the solar system and likely hold clues to its formation. Some may have brought water and organic material life – the building blocks of life – to the early Earth. Carbon materials in meteorites tend to burn up in the atmosphere, however, so finding samples on the ground is rare. The asteroid offers an opportunity to bring back an uncontaminated specimen directly from space.

The Mission Toolset

The OSIRIS-REx spacecraft was built by Lockheed-Martin and is operated from their Mission Support Area (SMA) in Denver, CO. Spacecraft systems aboard OSIRIS-REx can trace their lineage to previous Lockheed-Martin projects like MAVEN, Juno and the Mars



Humanity will soon have a chance to compare and contrast the asteroids Benu and Ryugu as the two missions explore them and return samples to Earth. [University of Arizona]

Reconnaissance Orbiter (MRO). Even the OSIRIS-REx Sample Return Capsule (SRC) came directly from the Stardust mission.

The Touch-And-Go Sample Acquisition Mechanism (TAGSAM) is the tool that will “deliver the goods” from Benu. TAGSAM carries a round sampling device at the end of an 11 foot (3.35 meter) articulated arm. When OSIRIS-REx eventually drops down toward the asteroid, the arm will push the device briefly against the surface and nitrogen jets will fire to stir regolith material up through its collection chamber. The device is then pulled away after less than five seconds. Although the design has been well-tested, TAGSAM carries enough nitrogen for three sampling attempts.

The rest of the spacecraft equipment suite consists of sensors needed to explore and characterize the asteroid before the final sampling event is carried out.

Three instruments designed at the University of Arizona make up the OSIRIS-REx Camera Suite (OCAMS) that affords a range of imaging capabilities. MapCam will first be used to look for outgassing dust plumes and small moonlets near Benu that could be hazardous to the spacecraft during its approach. It will later build maps of the asteroid and image the sample site. PolyCam is a telescopic camera for high-resolution work, while SamCam is optimized to continuously document the sample collection process.

The Touch-And-Go Camera System (TAGCAMS) includes two redundant Navigation Cameras (NavCams) to track surrounding star fields and landmarks on the asteroid and provide the precision navigation needed for accurate positioning. A third TAGCAMS instrument, StowCam, will be used to confirm storage of the regolith sample, once collection is complete.

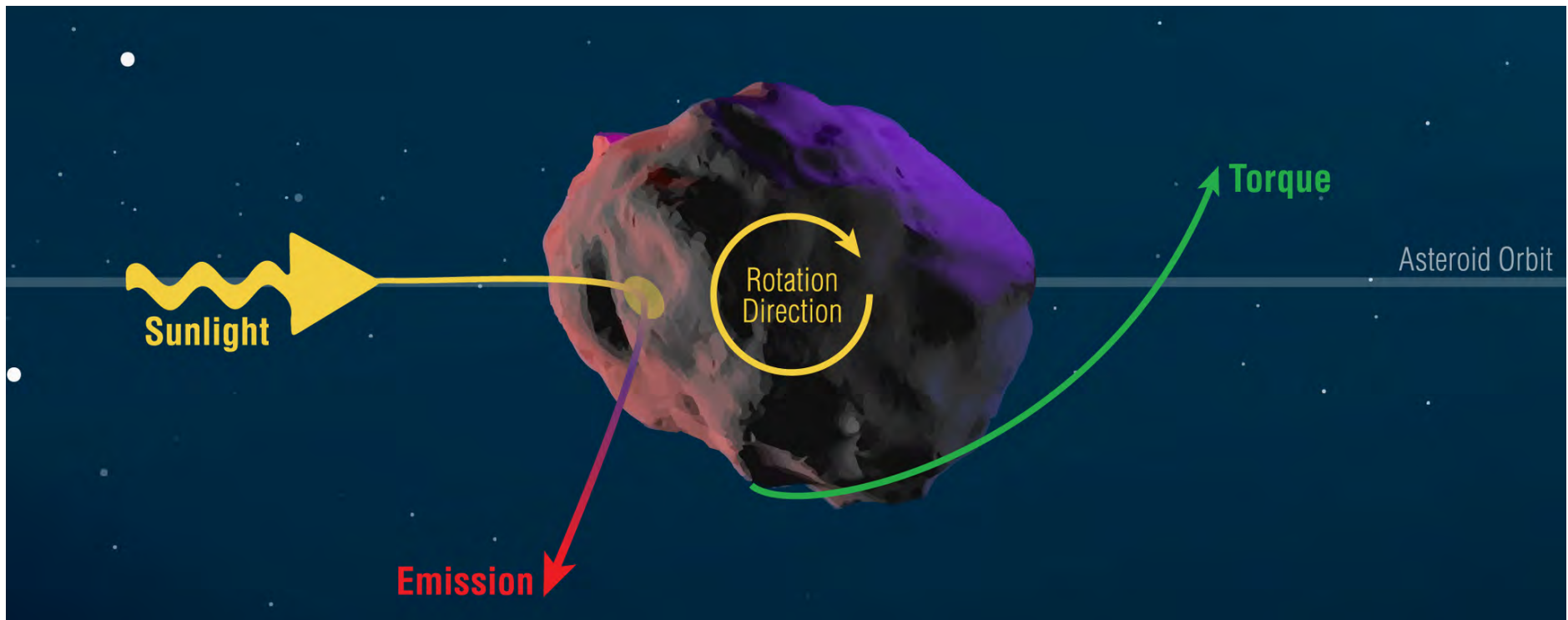
Spectrometers are an important addition to the mission sensor suite. “That’s the ‘Regolith Explorer’ part,” says Bashar Rizk, Senior Staff Scientist at the UA Lunar and Planetary Laboratory (LPL),

OSIRIS-REx Co-Investigator, and instrument scientist for OCAMS. “We’ve augmented the spacecraft with high-performance spectrometers that will hopefully allow us to validate or disprove theories about the asteroid’s origin. We can find out more about regolith genesis than we could using only imaging cameras.” The OSIRIS-REx Thermal Emission Spectrometer (OTES) will be used to characterize the mineral composition of the surface and to generate thermal emission maps to help evaluate candidate sample sites. The OSIRIS-REx Visible and IR Spectrometer (OVIRS) will work with OTES to characterize candidate sample sites. OTES data will also be used to model the Yarkovsky Effect, the slight push created when an asteroid absorbs sunlight and re-emits the energy as infrared radiation. A

small force but, acting over a long time, can perturb orbits of small bodies like meteors and asteroids, moving them into the inner solar system or closer to the Earth.

A collaboration involving over 50 students at the Massachusetts Institute of Technology (MIT) and Harvard University is responsible for developing the Regolith X-ray Imaging Spectrometer (REXIS). The instrument will come into play later in the mission timeline generate an X-ray spectroscopy map of Bennu.

Finally, the Canadian Space Agency (CSA) has sponsored the OSIRIS-REx Laser Altimeter (OLA), a LIDAR that will continuously scan the asteroid surface and help the mission team develop gravitational models and navigation strategies.



How the Yarkovsky Effect acts on an asteroid: Sunlight heats up the surface and infrared radiation is emitted by the asteroid, forcing it to spin. [University of Arizona]

Some Early Events

OSIRIS-REx has been traveling for two years, a journey that included an Earth gravity assist about a year after launch. In that time, it's already been working for science. "We operated our cameras during cruise to look at stars," says Rizk. "They're not optimized for star-field imaging but that's your target when you're traveling through interplanetary space." MapCam took about 135 color images each day during an eleven day period in February 2017, looking for Earth-Trojan asteroids as it passed through the Earth L4 Lagrange point, and PolyCam imaged Jupiter and three of its moons during that same month.

"The focal planes on these cameras can degrade in space due to radiation damage from high energy particles from the sun and other sources," says Rizk. "We track that in case we have to tweak certain calibrations such as the flat field we gathered on the ground. Although we've noticed changes in the camera in space, everything is still going very well."

The OSIRIS-REx approach phase began in August when the spacecraft captured its first image of Bennu from more than 1.3 million miles (2 million kilometers) away. The tempo on the ground picked up as the science and engineering teams began a preliminary survey to learn everything they could about the asteroid and its environment. On October 1, Lockheed-Martin controllers executed the first of four planned burn maneuvers to fine-tune the spacecraft approach trajectory toward Bennu. Two people at the center of these maneuvers are Mark Fisher, OSIRIS-REx Spacecraft Engineer, and Olivia Billett, OSIRIS-REx Spacecraft Lead for the Science Phase. "We're screaming up on this asteroid and trying to approach it as safely as we can," says Fisher. "Our first maneuver burn was specifically to take out a lot of the speed difference between us and the asteroid." The first burn was designed to reduce the closure rate



Olivia Billett, OSIRIS-REx Science Phase Spacecraft Lead, monitors mission progress from the main Mission Support Area. [Lockheed-Martin]

toward the asteroid from about 1,100 mph (491 m/sec) to 313 mph (140 m/sec).

Controllers have to start preparing well in advance for such trajectory corrections. "Even though these maneuvers have been planned since the initial mission design," says Billett, "operational preparation for a maneuver of this size begins four to five weeks out. We then build and test it about three weeks ahead of execution." Validation testing of spacecraft maneuvers is performed on platforms that include both engineering hardware and simulations.

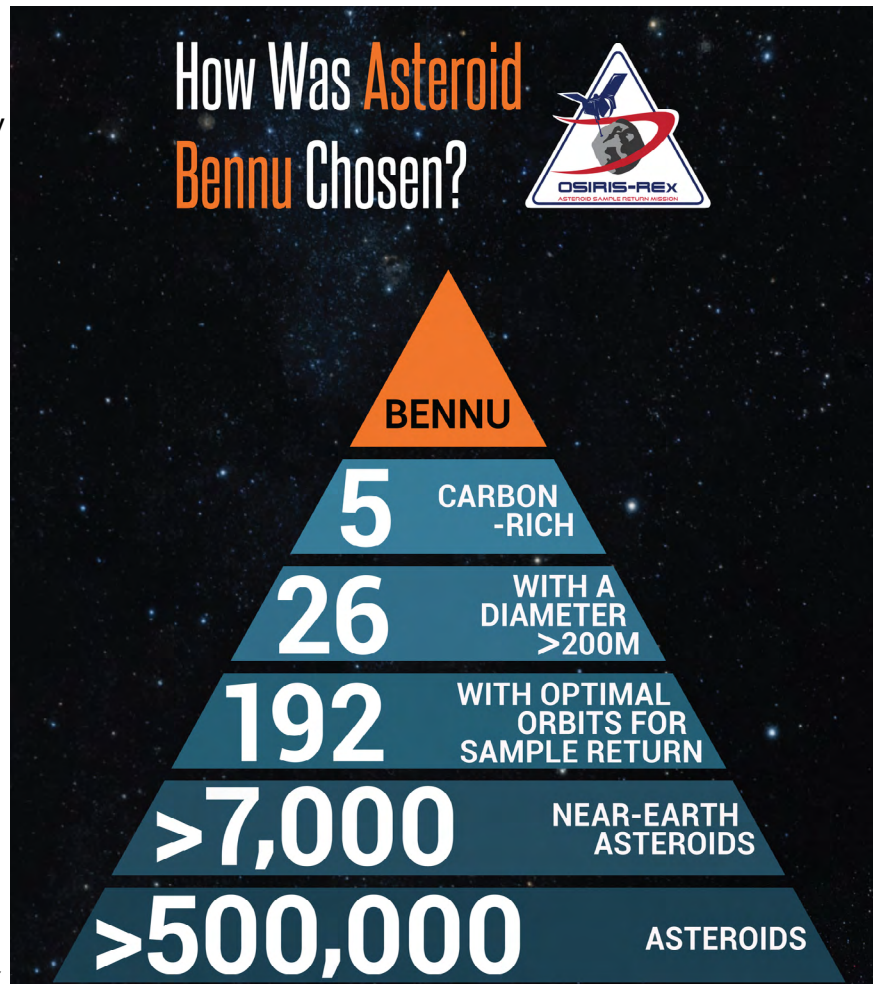
"There's another burn in two weeks to finalize our corridor up to Bennu before we begin asteroid operations," adds Billett, "so it's a fairly intensive navigation period for the next two months." The complete sequence of planned control burns will reduce the final spacecraft approach speed to less than .09 mph (4 cm/sec).

The LPL science team in Tucson and the Lockheed-Martin opera-

tions team in Denver are integrated more tightly than most other planetary missions; there are simply too many unknowns about flying around the asteroid to support a sequential or hierarchical task flow. "One of the unique aspects of this mission is that it's run out of a university and the science team has an operational role," says Rizk. "We've tried to streamline the work between the scientists and engineers, and it's been a happy marriage so far." Coordination requires fast information loops and efficient information routing. The Deep Space Network, for example, feeds OSIRIS-REx data directly to the LPL, even before routing it to the rest of NASA.

Moving Up Close

Once it arrives at Bennu, OSIRIS-REx will begin what is known as proximity operations, or "prox ops." The ultimate goal of this phase is to find sampling sites that are safe and that offer a high probability of collecting a meaningful sample. Accomplishing this, however, will require station-keeping in close quarters to a body about the size of the Empire State Building (and with about the same amount of gravity), so much of the mission timeline will be spent learning how to control the spacecraft in those conditions. "The first thing we do is



The asteroid characteristics that led scientists to the selection of Bennu. [University of Arizona]

determine the asteroid's shape and derive a gravity field from that, says Rizk. "Then we confirm our ability to take an orbit around this thing. When we do take an actual orbit, we can start short-listing sample sites."

About half of the forces acting on the spacecraft will come from charged particles of the solar wind and the pressure of sunlight itself reflecting off of the asteroid. Those pressures push the spacecraft away, but controllers won't be able to assess their effects until the spacecraft actually gets there.

"We'll have to do much smaller and more variable maneuvers as we get closer to the asteroid," says Billett. "That's when we're going to need up-to-the minute data from our navigation team to feed onto the spacecraft. Because that's risky, we'll be modifying the size and direction of each burn within twenty-four

hours of executing it. And we could keep that pace going throughout the entire two years of proximity operations."

Orbital insertion will occur on Jan. 1, placing OSIRIS-REx between 5,000 and 6,500 feet (1.5 and 2 kilometers) from the surface of Bennu. It will be the closest that humanity has ever orbited a body with a spacecraft. Orbits will be confined to the terminator plane (i.e., moving perpendicular to the axis between Bennu and the sun)

to ensure good data connectivity and to balance the effects of solar radiation pressures. During its first month at the asteroid, OSIRIS-REx will make a total of five passes over the north pole, the equator, and the south pole to help mission scientists establish its mass, refine its spin state model, and generate a high-resolution model of its shape.

OSIRIS-REx will drop down to 3,000 feet (1 kilometer) in April 2019 for another orbital period. The spacecraft will be flying at an altitude lower than most general aviation aircraft fly on Earth. Over the next two years, operations will be conducted as low as 800 feet (240 meters) from Bennu to map the surface in more detail. These later surveys will allow controllers to shift from star-based to landmark-based navigation, to prioritize candidate sample sites, and to rehearse approach maneuvers in advance of the real thing.

The Big Finish

Several checks are included in the mission design to ensure that enough material has been gathered. Two cameras will provide visual confirmation of sample recovery and storage, and scientists will measure the angular acceleration of the spacecraft before and after collection to evaluate how much mass has been picked up.

Although 2 ounces (60 grams) of material would count as basic mission success, development tests of the TAGSAM design showed that it could gather much more. The OSIRIS-REx team is hoping to recover an impressive 4.4 pounds (2 kilograms) of Bennu regolith – the largest sample of extraterrestrial material returned since 1976, when Luna 24 brought back 170 grams of moon soil. The sample will arrive back on Earth in September 2023, when OSIRIS-REx will eject the SRC into the atmosphere and then continue into a solar orbit.

Collaborations are strong within the small asteroid exploration community. The NASA OSIRIS-REx and JAXA (Japan Aerospace



Mark Fisher (left), OSIRIS-REx Spacecraft Engineer, reviews mission data in the main Mission Support Area. [Lockheed-Martin]

Exploratory Agency) Hayabusa 2 programs have been sharing science and engineering expertise for years, and both agencies will share their respective samples after they're recovered. NASA is also providing some of their sample to the Canadian Space Agency, but the majority (75%) of Bennu regolith will be set aside for study by future scientists armed with improved methods and tools, and asking questions that no one has yet thought to pose.

All of these achievements, however, will depend on the navigation and control skills developed by the spacecraft teams over the next few months as they gingerly test the effects of maneuvering around a small asteroid. Things are getting busy for OSIRIS-REx. ✪



STEVE MURRAY is a freelance science [writer](#) and NASA Solar System Ambassador. A former research engineer, he follows developments in astronomy, space science, and aviation.