OSIRIS-REX ARRIVES AT ASTEROID (101955) BENNU: EXPLORATION OF A HYDRATED PRIMITIVE NEAR-EARTH ASTEROID. D. S. Lauretta[1], M. M. Al Asad[2], R.-L. Ballouz[1], O. S. Barnouin[3], E. B. Bierhaus[4], W. V. Boynton[1], L. B. Breitenfeld[5], M. J. Calaway[6], M. Chojnacki[1], P. R. Christensen[7], B. E. Clark[8], H. C. Connolly Jr.[9,1], C. Drouet d'Aubigny[1], M. G. Daly[10], R. T. Daly[3], M. Delbó[11], D. N. DellaGiustina[1], J. P. Dworkin[12], J. P. Emery[13], H. L. Enos[1], D. Farnocchia[14], D. R. Golish[1], C. W. Haberle[7], V. E. Hamilton[15], C. W. Hergenrother[1], E. R. Jawin[16], H. H. Kaplan[15], L. Le Corre[17], T. J. McCoy[16], J. W. McMahon[18], P. Michel[11], J. L. Molaro[17], M. C. Nolan[1], M. Pajola[19], E. Palmer[17], M. E. Perry[3], D. C. Reuter[12], B. Rizk[1], J. H. Roberts[3], A. Ryan[11], D. J. Scheeres[18], S. R. Schwartz[1,11], A. A. Simon[12], H. C. M. Susorney[2], K. J. Walsh[15], X.-D. Zou[8], and the OSIRIS-REx Team. [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA (lauretta@lpl.arizona.edu), [2]Dept. of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada, [3]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, [4]Lockheed Martin Space Systems, USA, [5]Dept. of Geosciences, Stony Brook University, Stony Brook, NY, USA. [6]NASA Johnson Space Center, Houston, TX, USA, [7]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, [8]Dept. of Physics and Astronomy, Ithaca College, Ithaca, NY, USA, [9]Dept. of Geology, Rowan University, Glassboro, NJ, USA,[10]Dept. of Earth and Space Science and Engineering, York University, Toronto, ON, Canada, [11]UCA–CNRS–Observatoire de la Côte d'Azur, Nice, France, [12]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [13]Dept. of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN, USA, [14]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, USA, [15]Southwest Research Institute, Boulder, CO, USA, [16]Smithsonian National Museum of Natural History, Washington, DC, USA, [17]Planetary Science Institute, Tucson, AZ, USA, [18]Smead Dept. of Aerospace Engineering Sciences, University of Colorado, Boulder, CO, USA, [19]INAF–Astronomical Observatory of Padova, Padova, Italy.

Introduction: In May 2011, NASA selected the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) asteroid sample return mission as the third mission in the New Frontiers program [1]. The spacecraft departed Earth on September 8, 2016, on a seven-year journey to study and return a sample from near-Earth asteroid (101955) Bennu [2].

Mission Phases: The outbound-cruise trajectory resulted in optical acquisition of Bennu on August 18, 2018, when the asteroid was just bright enough for detection by the PolyCam imager. These first science observations marked the beginning of asteroid proximity operations and the Approach phase of the mission. This phase afforded adequate time to optically acquire the asteroid using the spacecraft's onboard cameras, and also to survey the vicinity of the asteroid for any hazards that may be present. The PolyCam and MapCam cameras and the OVIRS and OTES spectrometers characterized the asteroid's photometric and spectroscopic properties and enabled comparison to ground-based telescopic data.

The Approach phase was followed by Preliminary Survey, which consisted of five hyperbolic trajectories that crossed over the north and south poles and the equator at a range of ~7 km. The team obtained laser altimeter data from the OLA scanning lidar instrument for the first time, along with additional imagery. These passes permitted radio science measurements to determine Bennu's mass, a prerequisite to planning the maneuvers that placed our spacecraft into orbit. The imaging data from the Preliminary Survey passes provided the final data set to complete the 75-cm-resolution global shape model and corresponding rotation state data.

With the asteroid mass, shape, and rotation state constrained, the navigation team had all the information needed to finalize the design of the orbital insertion maneuver sequence. The spacecraft was placed into orbit on December 31, 2018, beginning the Orbital A phase. For stability, relative to solar radiation pressure, these orbits reside in the terminator plane. The orbital distance varies between 1.6 (periapse) and 2.1 (apoapse) km. The orbit has a 61.2-hour period and a ~5-cm/s orbital velocity.

Results: *Hazard Search.* A primary objective of the Approach phase was to survey the asteroid operational environment for potential spacecraft hazards. Discovery of either a dusty environment or a natural satellite would have triggered a safety assessment and review of the approach strategy. Spacecraft observations during these phases show no evidence for dust emission from Bennu, and we did not detect dust as an extended source along Bennu's orbital track. The spacecraft performed a series of natural satellite searches, and no satellites were detected.

Color and Spectral Properties. To provide ground-truth data for telescopic characterization, the team obtained "disk-integrated" photometric and spectral data of Bennu. These data supply an important link between the telescopic data and the spatially resolved data that will be obtained later in the mission. In addition, they provided important first-look information, constraining the rotation period and photometric properties, identifying important spectral features, and allowing for an assessment of the thermal inertia, a proxy for the average particle size.

Starting in mid-November 2018, PolyCam and MapCam obtained well-resolved images of Bennu. One of the most striking aspects of Bennu is the range of surface reflectance. The largest boulders (> 30 m) have geometric albedos near the average terrain. A population of bright decimeter-scale boulders also exist with albedos ranging from 7 to 10%. A small number of very bright features have been detected in PolyCam data, but are not yet fully resolved. These features have albedos of at least 17%.

The darkest material on Bennu has ~3.4% geometric albedo and includes a large exposed outcrop in the southern hemisphere. Dark boulders and diffuse units of dark material are well distributed across the asteroid. Some dark material also appears to show an absorption at 0.55 μm and is redder than the global average terrain, which may be related to the tentative magnetite from OTES.

OVIRS disk-integrated data from the Approach Phase reveal a visible to near-infrared spectrum that has a blue (negative) slope and no visible features above the level of the noise. At longer wavelengths, a 2.7-μm band is present, consistent with the presence of hydrated silicates, including those contained in CI and CM carbonaceous chondrites.

OTES spectra have low contrast (2%) and a spectral shape that is also consistent with CI and CM carbonaceous chondrites. A single spectral feature at 440 cm^{-1} is consistent with phyllosilicates in carbonaceous chondrites. The OTES spectra also show features at 555 and 346 cm^{-1} that we tentatively attribute to magnetite (Fe_3O_4).

Asteroid Shape and Surface Features. The asteroid shape model is a mission-critical data product that is required for successful proximity operations. It also provides the framework upon which all other map products are overlain. Images acquired during the final Approach allowed the creation of a shape model needed by both the navigation team and science planners using stereophotoclinometry (SPC).

Bennu exhibits a spinning top shape similar to asteroid (162173) Ryugu and (341843) 2008 EV5. Bennu's surface displays a wide variety of terrain. We find a substantial boulder population, impact craters, linear ridges, hemispherical dichotomy, retrograde rotation, and a small offset between the center of figure and center of mass. In contrast to the other spinning-top asteroids, Bennu lacks a distinct ridge.

Many of the boulders appear to be clastic rocks that are composed of large angular fragments, similar in appearance to impact breccias. There is substantial evidence for mechanical weathering, suggesting that thermal expansion and contraction plays an important role in regolith development. We have identified several areas, ranging from 10 to 20 meters in extent where apparent fine-grained material has collected.

In a first-of-its-kind investigation, Chesley et al. [3] applied a Yarkovsky model to develop a mass estimate for Bennu with a corresponding bulk density of 1260±70 kg/m^3. This result has been validated by our radio science mass determination from three flybys yielding an asteroid density of 1191±7 kg/m^3. The low density of Bennu is consistent with a rubble-pile structure with 25 to 50% macroporosity.

Given the mass, shape, and spin, we determine the surface and near-surface dynamical environment. We calculated the Roche Lobe of Bennu and found that it intersects the shape; material within the lobe is energetically bound to the surface. Observed changes in the global slope distribution are evident at this transition. The global acceleration profile across Bennu's surface ranges from 3 to 8 μG and shows Bennu to be a microgravity aggregate. The global geopotential across the surface defines the energetically favorable directions for migration of surface material. The global slope structure of Bennu shows a clear transitions at specific latitudes across the surface.

Conclusions: We infer that Bennu is an ancient object that has witnessed over 4.5 Gyr of Solar System history. Its chemistry and mineralogy were established within the first 10 Myr of the Solar System. The bulk material is likely to be similar to CI and CM chondrites. However, there are materials that do not appear to be related to these meteorites, i.e., the bright boulders. The clastic rocks likely formed by impact brecciation, mixing, and reaccretion on the surface of a large (~100-km) carbonaceous asteroid. Bennu likely originated as a discrete asteroid in the inner main belt as reaccumulated fragments from the catastrophic disruption of this larger parent body. The lack of a distinct equatorial ridge, the large number of well-defined impact craters, and the evidence for extensive thermal mechanical weathering suggest that Bennu's surface is old. The extensive mapping and site-specific characterization campaigns in 2019 will provide additional information in these areas.

References: [1] Lauretta, D. S. et al. *Space Science Reviews* 212 (2017): 925-984. [2] Lauretta, D. S., et al. *Meteoritics & Planetary Science* 50.4 (2015): 834-849. [3] Chesley, S R. et al. *Icarus* 235 (2014): 5-22.

Acknowledgments: This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program.