INVESTIGATING THE GEOLOGICAL HISTORY OF ASTEROID 101955 BENNU THROUGH REMOTE SENSING AND RETURNED SAMPLE ANALYSES.

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Introduction: The NASA New Frontiers Mission **OSRIS-REx** will return surface regolith samples from near-Earth asteroid 101955 Bennu in September 2023. This target is classified as a B-type asteroid and is spectrally similar to CI and CM chondrite meteorites [1]. The returned samples are thus expected to contain primitive ancient Solar System materials that formed in planetary, nebular, interstellar, and circumstellar environments. Laboratory studies of primitive astromaterials have yielded detailed constraints on the origins, properties, and evolutionary histories of a wide range of Solar System bodies. Yet, the parent bodies of meteorites and cosmic dust are generally unknown, genetic and evolutionary relationships among asteroids and comets are unsettled, and links between laboratory and remote observations remain tenuous. The OSIRIS-REx mission will offer the opportunity to coordinate detailed laboratory analyses of asteroidal materials with known and well characterized geological context from which the samples originated.

A primary goal of the OSIRIS-REx mission will be to provide detailed constraints on the origin and geological and dynamical history of Bennu through coordinated analytical studies of the returned samples. These microanalytical studies will be placed in geological context through an extensive orbital remote sensing campaign that will characterize the global geological features and chemical diversity of Bennu. The first views of the asteroid surface and of the returned samples will undoubtedly bring remarkable surprises. However, a wealth of laboratory studies of meteorites and spacecraft encounters with primitive bodies provides a useful framework to formulate priority scientific questions and effective analytical approaches well before the samples are returned. Here we summarize our approach to unraveling the geological history of Bennu through returned sample analyses.

Mission overview: A level one requirement of the mission is to return a minimum of 60 g of pristine bulk asteroid regolith. These samples will be obtained by a touch-and-go sampling mechanism that will mobilize surface regolith with high pressure and high purity N_2 gas. Here pristine is defined to mean that no material is introduced that will hamper future scientific studies. In addition, the spacecraft will expose 26 cm^2 of contact pads to collect samples of the uppermost surface of the asteroid. This material will have special value for relating the atomic scale chemical and physical properties of the surface materials to their spectral properties and for investigations of space weathering processes. The science team will receive up to 25% of the bulk material and contact pad materials for analysis.

Formulating hypotheses: Asteroid Bennu is one of the best-characterized NEOs, with spectral, radar imaging and dynamical modeling placing good constraints in its density (~1.3 g/cm^3), surface grain size, dynamical history, and probable affinities to primitive carbonaceous chondrites [1-10]. While these inferences are not certain, they provide a useful starting point to understanding the origin of the asteroid and its place in Solar System history. Recent studies of particles returned from asteroid Itokawa by the Hayabusa spacecraft strongly support the hypothesis that many S-type asteroids are analogous to equilibrated ordinary chondrites, underscoring the merit of coordinating sample analysis with remote sensing data [11].

We have identified over 70 tests of 20 hypotheses relating to the origin and history of Bennu and its source materials that will be performed by analysis of the returned samples. Here we summarize these hypotheses and provide examples of related analytical tests. These hypotheses reflect our best understanding of the properties of Bennu derived from remote astronomical observations viewed in the context of observations of asteroids and laboratory studies of meteorites, cosmic dust, and Stardust cometary dust samples.

Organization. We classify these hypotheses into three levels: Level 1 hypotheses are fundamental to mission science and are (1) founded in investigations of chondrites and their (parent body) formation histories and/or (2) relate to ground and orbital observations of the surface of Bennu viewed in the context of meteoritic analogs; Level 2 hypotheses place additional constraints on level 1 hypotheses or delineate potential interpretations of data generated from tests of level 1 hypotheses; Level 3 hypotheses derive from level 2 hypotheses or the interpretations of the data generated from the testing of level 2 hypotheses.

Level 1 hypotheses. A broad working hypothesis is that (L1-1) the surface of Bennu is analogous to carbonaceous chondrites. Corresponding level 2 hypotheses are (L2-1) that Bennu is analogous to carbonaceous chondrite materials that are represented within our collections or conversely (L2-2) Bennu *is not* similar to carbonaceous chondrite materials that are represented within our collections but still carbonaceous chondrite-like in nature. Alternative level 1 hypotheses are that (L1-2) the surface of Bennu is not analogous to carbonaceous chondrites and (L1-3) the surface of Bennu is comet-like. These hypotheses arise in part from recent remarkable findings including the observation of outer belt asteroids exhibiting episodic outbursts of dust and volatiles [12] and the recovery of a meteorite (Almahata Sitta) that consists of at least 14 lithologies and two distinct meteorite classes [13].

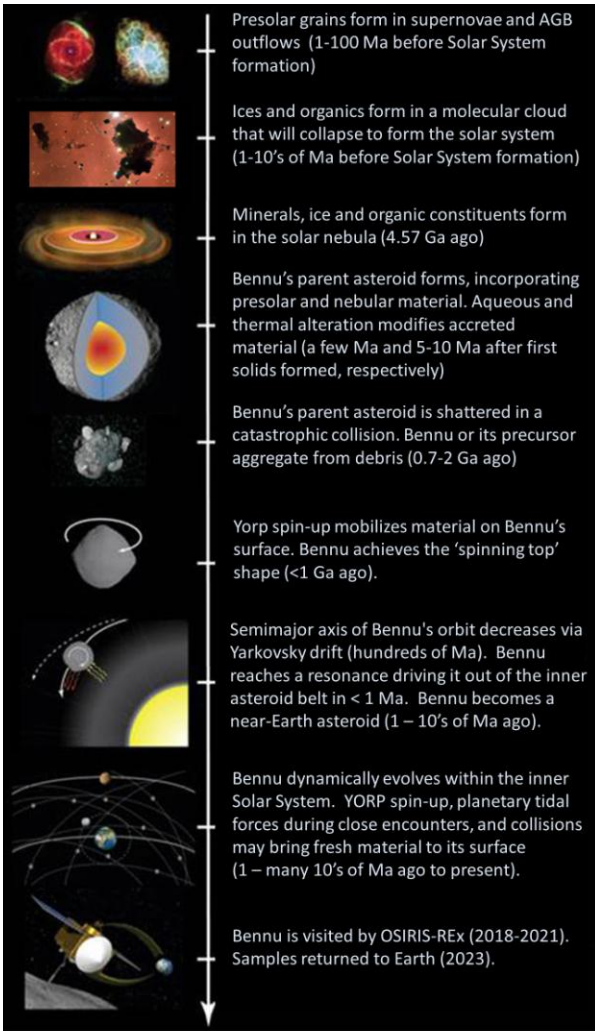
Hypothesis testing. The testing of hypothesis L1-1 is essentially achievable to a nominal level by visual inspections of the sample within the first few hours of opening the sample return capsule. If it is chondritic, we will determine the type of chondrite by petrographic study. After evaluating the potential meteorite classification, scientific investigations will be organized with reference to a timeline (Figure 1) following from the origins of the elements in evolved stars through the collapse of the protosolar nebula, formation of Bennu and its early geological history and subsequent dynamical and geological evolution.

Of course, most of the priority science investigations captured in the timeline are considerably more complex and will require a careful coordination of microscale chemical, petrographic, and isotopic study. As the full range of studies cannot be covered here, we present a few examples:

Hypothesis L3-1: Bennu contains abundant preserved interstellar and circumstellar materials. Test include (1) Isotopic measurements of micrometer-sized matrix grains, (2) Bulk noble gas measurements of fine grained regolith to identify nucleosynthetic signatures, and (3) Isotopic measurements of organic matter and organic grains to identify evidence of low temperature chemical mass fractionation.

Hypothesis L3-16: Bennu has been subjected to shock and heating by impacts over its geological history. Tests include (1) Examining consistency of Ar-Ar ages in regolith materials for evidence of impact resetting, as observed in ordinary chondrites and HED meteorites, (2) Searching for evidence of impact melts, and (3) Performing petrographic investigations for meteoritic material distinct from the host rock.

Hypothesis L3-6: Bennu formed beyond the 'snow line' in the outer portion of the asteroid belt. Tests include (1) Bulk elemental abundances constrain whether Bennu was highly heated and/or differentiated, (2) Measure abundances of volatile elements in bulk returned sample, (3) Precise measurement of the stable isotopic abundances of Cr, Ni, and Ti in bulk material differentiate among meteorite groups, (4) Determine the distribution and O and H isotopic composition of hydrous phases if present, and (5) Model the dynamical history of Bennu in context of spectroscopically similar asteroids and meteorites.



Presolar grains form in supernovae and AGB outflows (1-100 Ma before Solar System formation)

Ices and organics form in a molecular cloud that will collapse to form the solar system (1-10's of Ma before Solar System formation)

Minerals, ice and organic constituents form in the solar nebula (4.57 Ga ago)

Bennu's parent asteroid forms, incorporating presolar and nebular material. Aqueous and thermal alteration modifies accreted material (a few Ma and 5-10 Ma after first solids formed, respectively)

Bennu's parent asteroid is shattered in a catastrophic collision. Bennu or its precursor aggregate from debris (0.7-2 Ga ago)

Yorp spin-up mobilizes material on Bennu's surface. Bennu achieves the 'spinning top' shape (<1 Ga ago).

Semimajor axis of Bennu's orbit decreases via Yarkovsky drift (hundreds of Ma). Bennu reaches a resonance driving it out of the inner asteroid belt in < 1 Ma. Bennu becomes a near-Earth asteroid (1 – 10's of Ma ago).

Bennu dynamically evolves within the inner Solar System. YORP spin-up, planetary tidal forces during close encounters, and collisions may bring fresh material to its surface (1 – many 10's of Ma ago to present).

Bennu is visited by OSIRIS-REx (2018-2021). Samples returned to Earth (2023).

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