METEOROID IMPACTS AS THE SOURCE OF BENNU'S PARTICLE EJECTION EVENTS.

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Introduction. (101995) Bennu is the target of the NASA's OSIRIS-REx sample return mission [1]. It is a 490 m NEO with a spectral signature consistent with primitive carbonaceous chondrites. An unexpected attribute of Bennu, however, is that it is currently ejecting small particles to space in distinct events [2].

Multiple particle ejection events were observed starting in January 2019, the time when OSIRIS-REx entered into Bennu orbit, and throughout the rest of the encounter. Bennu reached perihelion in early January, so there may be an association between the initially observed events and Bennu's orbital location at that time. The three largest events occurred at 6 January, 19 January, and 11 February 2019. This corresponds to a roughly bi-weekly cadence during this timeframe.

Here we investigate the possibility that these largest events can be caused by meteoroid impacts. Meteoroids, mostly derived from comet particles, collide with Earth, the Moon, and presumably Bennu at very high speeds. We hypothesize that some of these events are substantial enough to eject material off of Bennu and into trajectories where they can be observed by OSIRIS-REx. To test this scenario, we have simulated the primary meteoroid flux onto Bennu using NASA's Meteoroid Engineering Model (MEM) [3].

More Particle Ejection Constraints. All three large events took place in the late afternoon, between 15:22 and 18:05 local Bennu time (i.e., about 3.5-6 hours after local noon) [2]. They also took place within days to weeks of Bennu reaching perihelion. Together these event produced hundreds of observed particles, though all observed fragment were < 10 cm in diameter and had ejection velocities < 3.3 m/s. The kinetic energies of the observed particles were collectively < 200 mJ. The locations of all events, big and small, are fairly ubiquitous, ranging from 75˚S to 20˚N, though the small events have a preference for low latitudes.

Model Runs. MEM describes the mass-limited flux, directionality, velocity, and density distribution of meteoroids impacting a chosen target body orbiting between Mercury and the main belt (e.g., [3]). A common application of MEM is to evaluate impact risk and potential damage to Earth-orbiting satellites (e.g., International Space Station) and spacecraft traveling in the inner solar system. MEM builds on several studies of the interplanetary dust population and the nature of the near-Earth environment [4].

An ephemeris for Bennu was obtained from JPL HORIZONS; we downloaded state vectors at one-day intervals between 10 Jan 2019 and 22 March 2020. We consider one orbital period, starting with its 2019 perihelion passage. MEM generates a mass-limited flux for a given target; the code also divides the total flux into bins by the angle and speed with which they encounter the target. We scaled the flux on our bins to kinetic energy and summed the results to find the overall kinetic-energy-limited flux of meteoroids onto Bennu. We convert this flux to a cratering rate assuming that Bennu's surface area is 0.782 km^2 [1].

We find that impacts with kinetic energies of 7000 J take place every two weeks near perihelion, the same cadence as the three largest observed events. We use this value as our metric in the figures below.

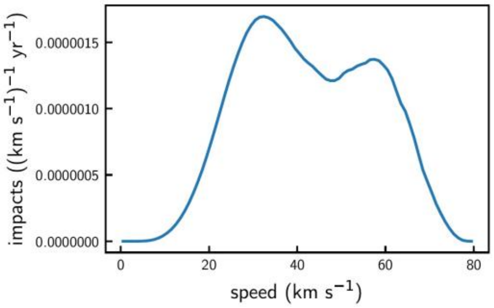

Fig. 1. Impact velocity distribution of sporadic meteoroids on Bennu with limiting kinetic energies of 7 kJ. The average speed is 42.8 km/s.

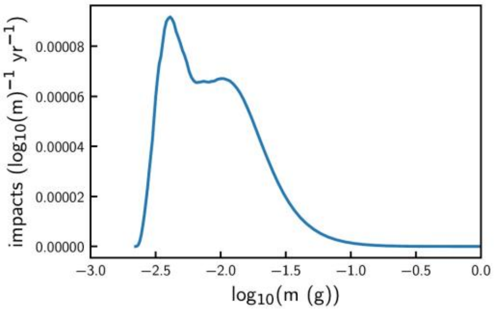

Fig. 2. Impactor mass distribution for meteoroids striking Bennu at the limiting kinetic energy of 7 kJ. The mean velocity of 42.75 km/s corresponds to a mass of 0.00766 g, whose log10 value is -2.12.

The impact velocity and mass distributions are shown in **Figs. 1 and 2**. The highest speeds and lowest masses mainly come from meteoroids derived from long period comet particles on retrograde orbits. The lowest speeds and most massive particles are mainly coming from Jupiter-family comets. Bennu's impact rates are also higher that by more than a factor of 5 near perihelion than near aphelion.

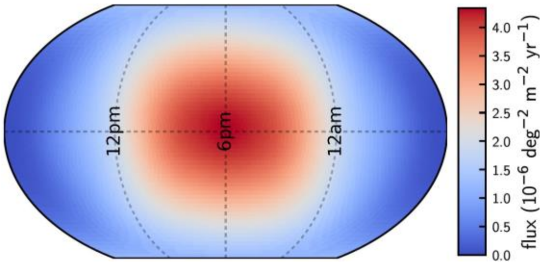

Fig. 3. The directionality of the meteoroid impact flux across the surface of Bennu at perihelion for a limiting kinetic energy of 7 kJ. Most impacts should occur in the late afternoon near the terminator.

In **Fig. 3**, we show the impact flux on Bennu's surface at perihelion for a limiting kinetic energy of 7 kJ is shown in Fig. 3. Bennu is a retrograde rotator with an obliquity of nearly 180 deg, and so the vertical dashed line in the middle of the plot corresponds to the evening terminator and is labeled "6pm".

We find that the majority of impacts should occur in the late afternoon near the terminator over a range of latitudes. This prediction is consistent with the three most largest observed events that occurred between 15:22 and 18:05 local Bennu time (i.e., about 3:30-6 PM). While more events and better statistics will be needed to confirm this relationship, it is reasonable to assert that impacts are a strong candidate to be Bennu's primary particle ejection event mechanism

For additional context, consider that LADEE observed a secondary dust ejecta cloud orbiting the Moon that was created by meteoroid impacts that launch material off the surface of the Moon at high velocities [5, 6]. It was found to be most dense at 5:00-8:00 lunar local time, 4-7 hours prior to lunar noon. This time range is the reverse image of what was observed on Bennu because the Moon spins in a prograde sense.

Impact Ejecta Tests. To test whether 7kJ collisions are capable of reproducing observations, we employed the Impact and Explosion Effects web tool [7]. This application determines the crater size and ejecta mass from impacts, and it is based on Pi-crater scaling methods that have been validated by experiments, field data, and numerical simulations.

We input Bennu's diameter and bulk density as 490 m and 1190 kg m^{-3}, respectively [7], yielding a mass of 7.33 $\times 10^{10}$ kg. The projectile's impact energy and velocity was 7 kJ and 43 km/s, respectively **(Fig. 1**). MEM's meteoroid bulk densities of 860 and 3800 kg m^{-3} yielded impactor diameters of 2.6 and 1.6 mm, respectively. We tested impact angles that were vertical (0 deg) and 45 deg to the surface.

If we assume Bennu's surface material acts like generic soil, which the code assigns as having cohesion of 10,000 dynes cm^{-2}, a 33 deg friction angle, and a porosity of 30%, our impactors create craters 14 to 16.1 cm diameter, with the ejected mass 230-350 g. Such craters have been observed in Bennu boulders.

Placing the ejecta into a single object yielded a 8.0-9.2 cm diameter body, a match to the sizes of the largest particles observed around Bennu. This size would also be a good match to all of the ejected material if (i) the ejecta size distribution followed a power law with a shallow slope, a reasonable approximation for the observed particles [2], and (ii) and very little material escaped Bennu prior to OSIRIS-REx observations.

Our results are also consistent with Hayabusa2's SCI impact experiment, where a 2.5 kg copper plate shot into Ryugu at 2 km/s made a 13 to 17 m diameter crater [8]. If we convert the plate mass into a comparable comet projectile (i.e., 0.17 m for 800 g cm^{-3}), it yields a crater to projectile ratio of f ~76-100, nearly the same as our impact calculation above (f ~53-100).

If instead we assume that the impactor hit generic rock, which the code assigns a cohesion of 1×10^9 dynes cm^{-2}, a 40 deg friction angle, and a porosity of 0%, it would make a crater 2-2.4 cm in diameter. The ejected mass would be 0.6-1.1 g, the equivalent of a 0.7-1.3 cm diameter particle, too small to explain observations.

Conclusions. Meteoroid impacts onto Bennu can reproduce the timing and magnitude of the largest observed events observed to date, provided that the majority of target materials are highly porous and structurally weak. This outcome is consistent with observations of boulders on Ryugu, which have porosities as large as 55% [9]. The frequency of particle ejection events should decrease as Bennu moves toward aphelion. This can be checked by future observations.

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