Widely Distributed Exogenic Materials of Varying Compositions on Asteroid (101955) Bennu

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CONTEXT

The rubble-pile asteroids formed as a result of the catastrophic disruption of a parent body and re-accumulation of the resulting fragments. This process could incorporate materials from both the parent body and its catastrophic impactor. Evidence of this was shown for rubble-pile asteroid 2008 TC3 and the corresponding Almahata Sitta meteorite [1].

Using data provided by the Hayabusa 2 mission, Tatsumi et al. [2] reported bright, anhydrous-silicate–rich materials on the surface of rubble-pile asteroid (162173) Ryugu. These exogenic objects are more consistent with ordinary chondrite meteorites, based on their albedo and weak or even absent absorption band at 2 μm.

Also, DellaGiustina et al. [3] reported six unusually bright, basaltic, meter-scale boulders identified on the dark surface of another rubble-pile asteroid, (101955) Bennu, in images acquired by the OSIRIS-REx mission. The closest spectral matches to these boulders are with the Howardite-Eucrite-Diogenite (HED) meteorites and with V-type asteroids.

In this work, **we report additional possibly exogenic boulders on Bennu's surface within the latitude range –70˚ to 70˚**. These were found by using the multi-band images obtained by the OSIRIS-REx mission in order to find surface materials with possible 1-μm absorptions representative for mafic minerals. We classified them by visible spectrophotometry and morphology.

DETECTION OF EXOGENIC MATERIAL

Methods

- Find the 1-µm absorption feature which is indicative of olivines and pyroxenes.
- The images used were obtained by MapCam on 26 September 2019, with a resolution of ~0.25 m/pixel [4].
- The four chromatic filters, *b'*: 473 nm, *v*: 550 nm, *w*: 698 nm, and *x*: 847 nm allow to identify the reflectance drop in x-band associated with 1-µm band.

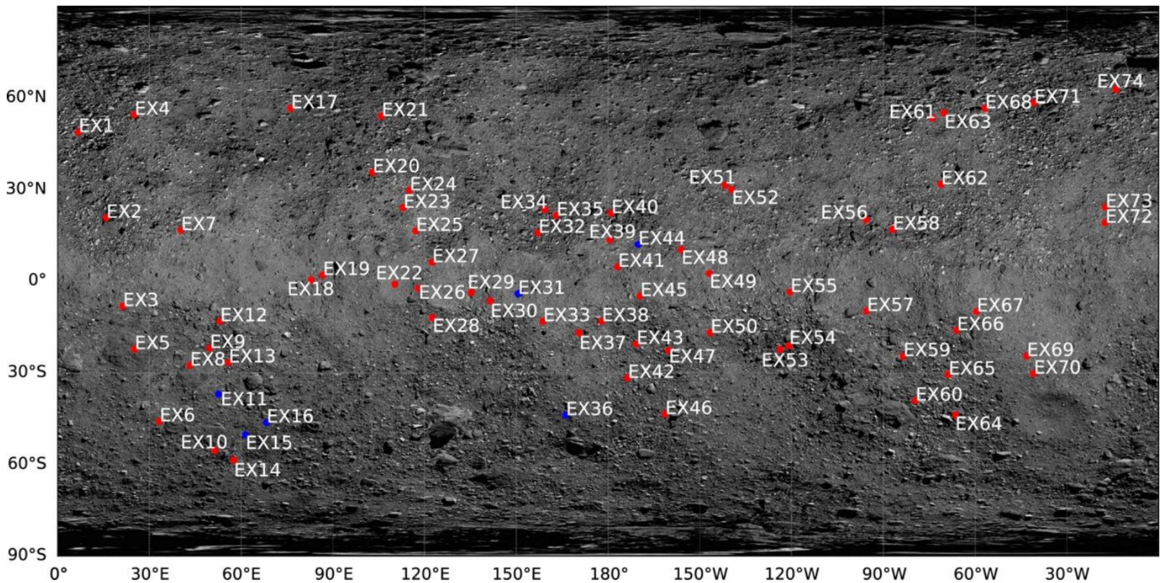


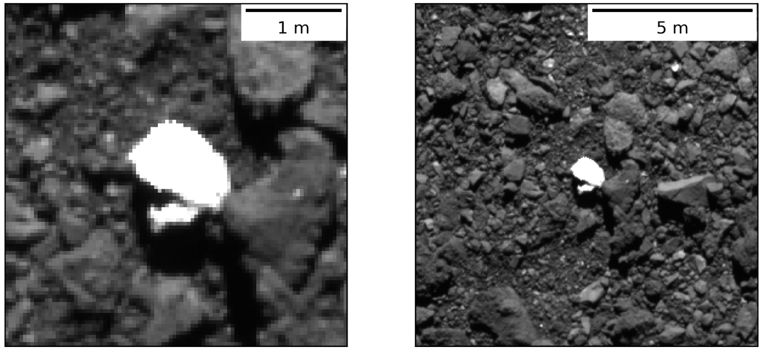
Fig. 1. Locations of candidate exogenic materials [5], overlaid on a global mosaic basemap of asteroid Bennu (Bennett et al. 2020). The red points highlight the newly identified exogenic boulders, while the light blue points are boulders reported by [3].

Morphology

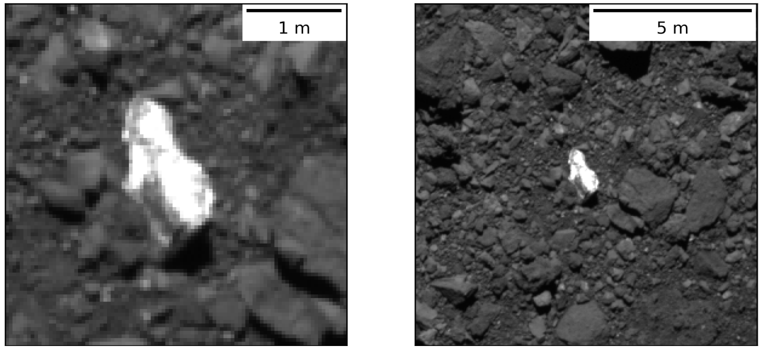
- The PolyCam (the narrow-angle panchromatic imager [4]) images are obtained with a high resolution (0.05 m/pixel).

They allow to discriminate the texture.

- Wide morphological variation. Four groups are defined in order to quantify it: 1) homogeneous rocks; 2) breccia-like rocks; 3) inclusion-like features; and 4) partially bright rocks .
- The most common are the inclusion-like features, which are observed in boulders all over the surface. They usually occur in dark and cauliflower-like host rocks.
- The brightest candidates are preferentially pristine or breccia-like rocks.



<--- ***Homogeneous rock***



<--- ***Breccia-like rock***

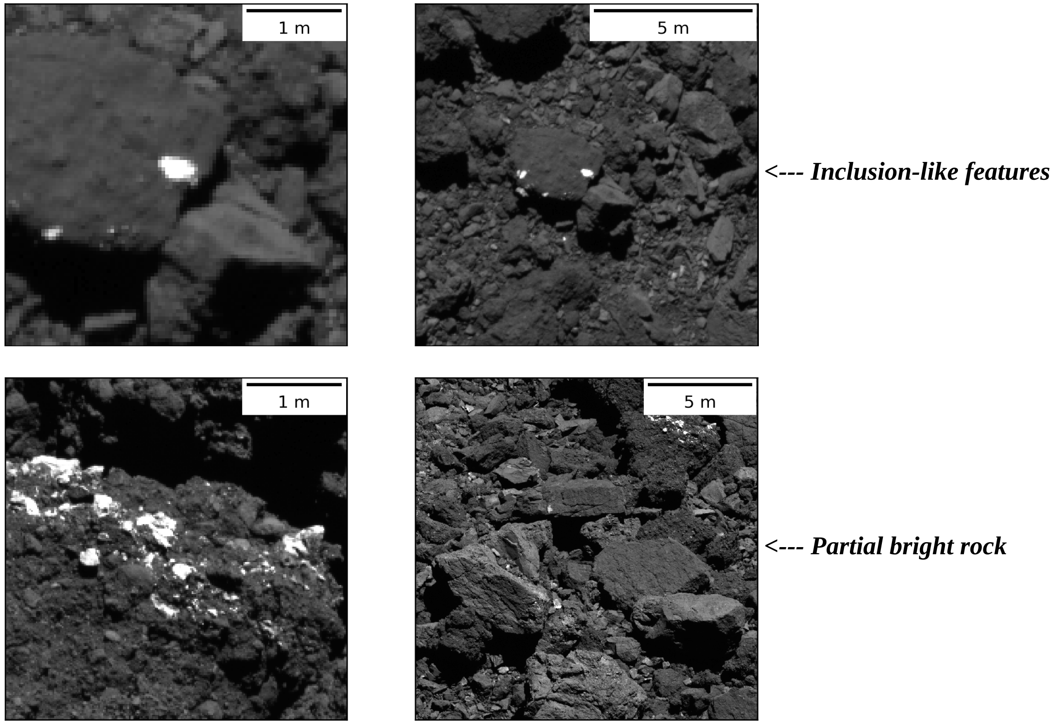


Fig. 2 Examples of PolyCam images which outlines the morphological classification of various candidate exogenous material.

DATA ANALYSIS

- We report ***77 boulders containing possible exogenic material widely distributed across Bennu's surface***.
- There is correspondence between spectrophotometric curves and the morphologies.

Principal Component Analysis (PCA)

- PCA of MapCam spectrophotometric data reveals two gradients, Trend I and Trend II (Fig. 3).

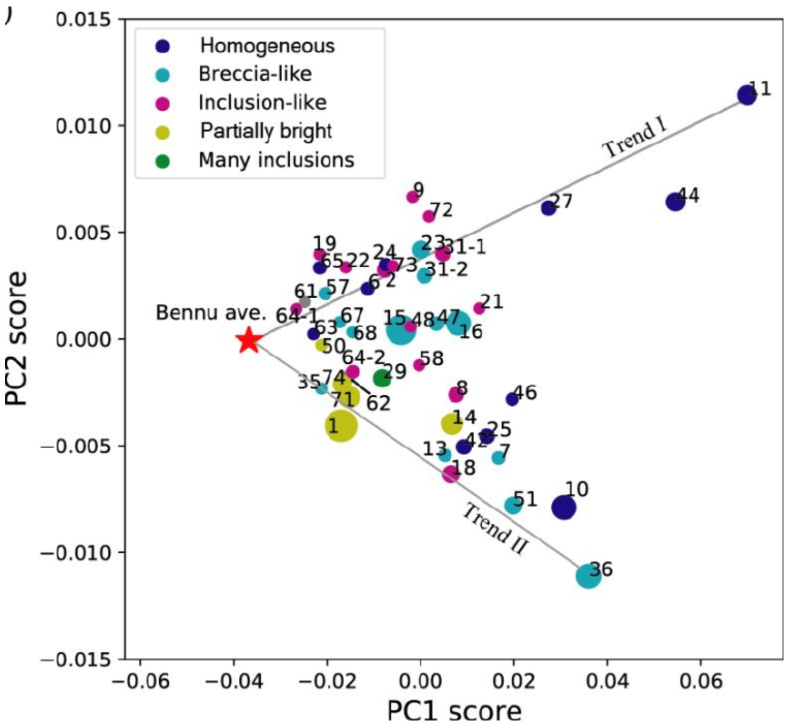


Figure 3. Morphology, location, and spectral characteristics of exogenic materials. The size of the marjer is set according to the relative size of the objects. Source: [5].

1. ***Trend I*** has a deep 1-µm band absorption indicating pyroxene-rich material. These boulders only match the HED meteorite spectral data (Fig. 4).
2. ***Trend II*** has a shallow 1-µm absorption. They can have spectral matches with HED meteorite, ordinary chondrite, and carbonaceous chondrite spectra (Fig. 4).

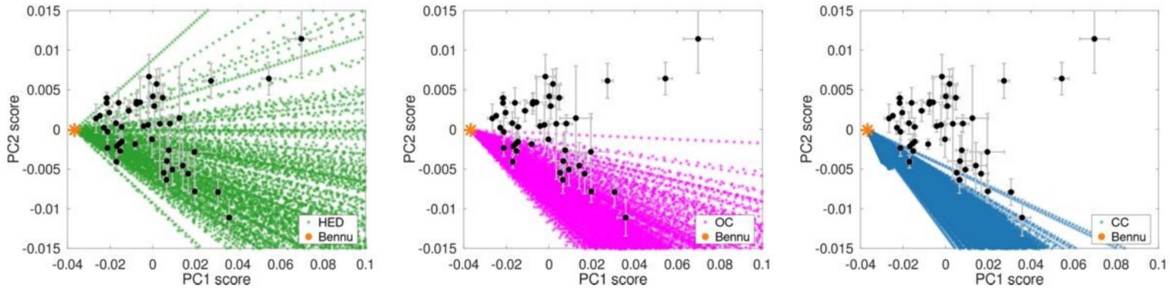


Figure 4. Comparison between exogenic boulders and the spectro-photometric data generated as linear mixtures between average Bennu and the laboratory spectral curves of meteorites, Left: HEDs, Middle: ordinary chondrites, and Right: carbonaceous chondrites. The principal components space was used to highlight the variations[5].

Comparison with meteorites spectra

- The exogenic candidates are likely mixtures of pyroxens and olivines with the low albedo Bennu's material
- We considered linear mixtures for explaining the composition
- The linear mixtures between two meteorites spectra can explain most of the spectrophotometric curves of exogenic material
- The likelly compostions include a mixture of 85 - 95 % of CM carbonaceous chondrite meteorites and 15 - 5 % of various HEDs or pyroxen.
- The candidate exogenic boulders with a spectral peak in the v-filter are spectrophotometrically matched by the Macibini Cl.3 melt sample (Fig. 5). This is consistent with impact melt resulting from Vesta-family material colliding with Bennu's parent body.
- Laboratory spectra of some carbonaceous chondrites match some of our exogenic candidates in visible wavelength. Thus, we cannot exclude an endogenic origin for the relatively dark candidates.

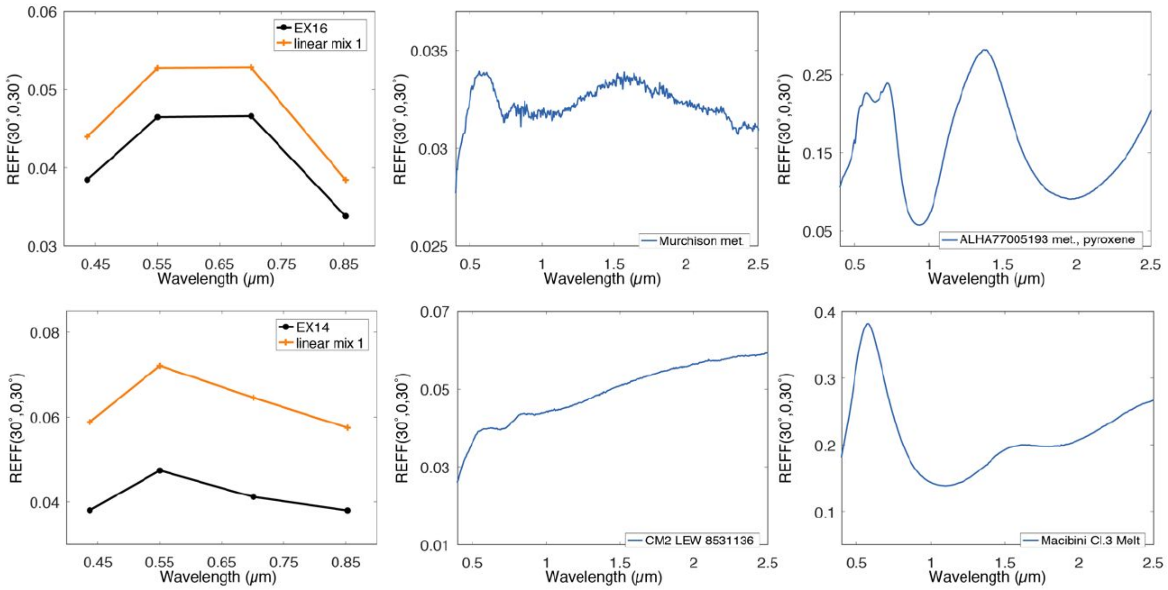


Fig.5 Top -> Left: MapCam spectrum of bright boulder EX16 (black) versus mixtures of 90% CM2 Murchison (SampleID: MS-CMP-002-E, FileID: CFMS02) and 10% pyroxene from ALHA77005193 meteorite (SampleID: DD-MDD-034, FileID: C1DD34) in orange curve. Center: visible-to-near-infrared spectrum of Murchison (MS-CMP-002-E). Right: visible-to-near-infrared spectrum of ALHA77005193 meteorite (DD-MDD-034). Bottom -> Left: MapCam spectrum of bright boulder EX14 (black). A mixture between CM2 LEW8531136 (SampleID: MP-TXH-024, FileID: C1MP24) and eucrite Macibini Cl.3 melted clast (SampleID: TB-RPB-030, FileID: C1TB30), shown in orange explains the peak of EX14 at 0.55 µm. Visible-to-near-infrared spectra of the two meteorite samples are shown in the central and right panels.

Spectroscopy

- There are four spectra obtained with OVIRIS (OSIRIS-REx Visible and InfraRed Spectrometer) that cover areas which include four of identified exogenic candidates
- For two of the candidates, the spectra show deep absorption bands at 1 and 2 µm (Fig. 6). These bands are consistent with calcium poor pyroxenes
- The other two candidates spectrally characterized show a weaker 1-µm feature and a possible shallow absorption band around 1 µm.

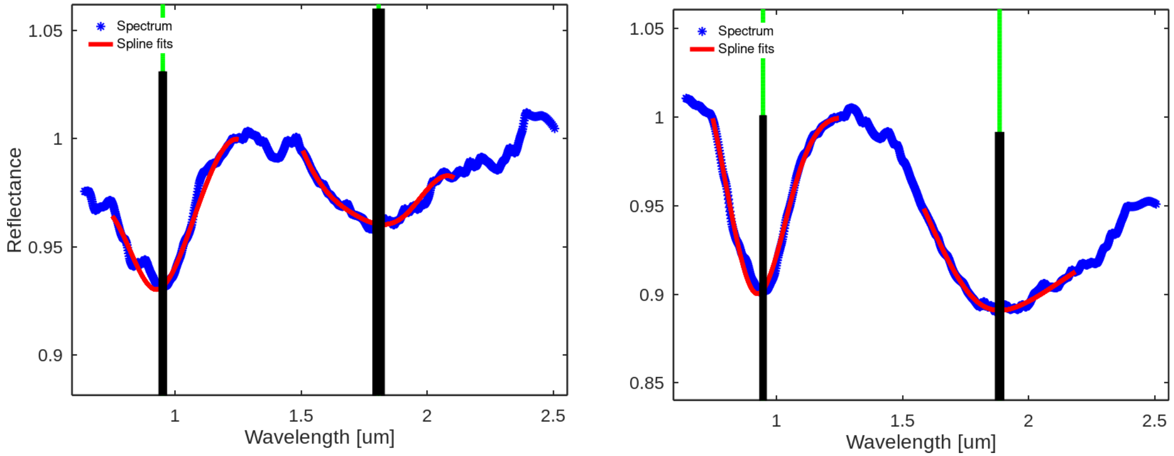


Fig.6 The available OVIRS spectra for EX44 and EX72 (top curves). The band minima are highlighted by the two vertical markers. The spectra are generated by averaging together any overlapping OVIRS spots (areal resolution of ~40 m^2 per spot).

DISCUSSIONS

Orbital environment for the source region of (101955) Bennu

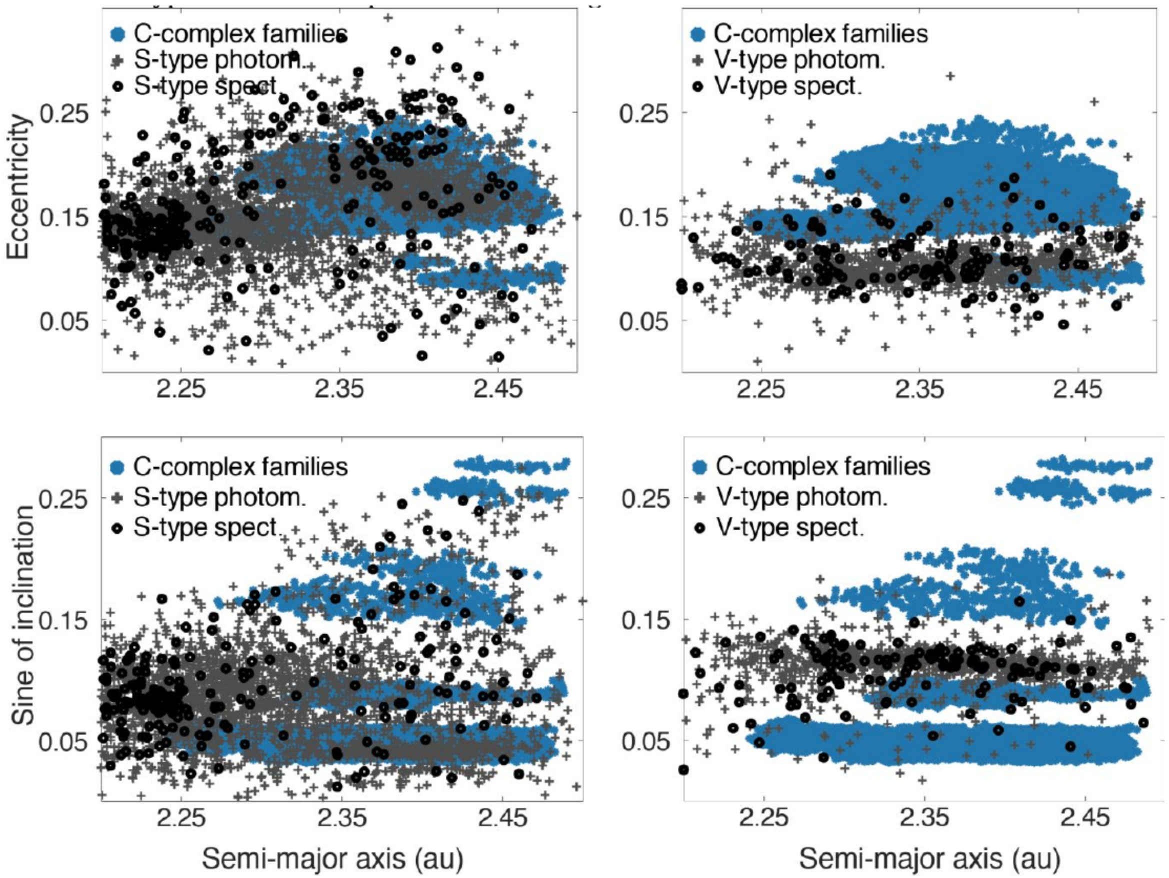


Figure 7. Proper semi-major axis versus eccentricity (top panel) and sine of proper inclination (bottom panel) for C-complex collisional families (blue dots) in the inner belt. We include photometry (grey crosses) and spectra (black dots) of asteroids with olivine-pyroxene compositions (S-types) and basaltic asteroids (V-types) for comparison. These data are retrived from the literature.

Comparison of exogenic boulders found on (101955) Bennu and (162173) Ryugu

- Both asteroids show a compositional diversity among exogenic boulders. This may reflect that the mixture process with other asteroids could be general.
- In both cases the exogenic boulders include breccia-like morphologies.
- The exogenic material is much more abundant on Bennu than on Ryugu.
- The comparison of candidate exogenic boulders on Bennu with those on Ryugu suggests different compositions and abundances between the two asteroids, indicating **different impact histories for these two bodies.**

Find out more: Tatsumi, Popescu et al. MNRAS 2021 (submitted)

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ABSTRACT

We report additional exogenic boulders on Bennu's surface. These are found within the latitude range –70˚ to 70˚. First, we searched the multi-band images obtained by the OSIRIS-REx mission in order to find surface materials with possible 1-µm absorptions representative for mafic minerals. Then, we classified the identified exogenic boulders by visible spectrophotometry and morphology. Finally, we discuss the origin of this materials on Bennu. A comparison between the exogenic compositions found on (101955) Bennu and those found on (162173) Ryugu is included.

REFERENCES

[1] Jenniskens et al. (2009) Nature 458, 485-488. [2] Tatsumi et al. (2020) Nature Astronomy, DOI: 10.1038/s41550-020-1179-z. [3] DellaGiustina et al. (2020) Nature Astronomy, DOI: 10.1038/s41550-020-1195-z. [4] Rizk et al. (2018) Space Sci. Rev. 214, 26. [5] Tatsumi et al. 2021, "Widely distributed exogenic materials of varying compositions and morphologies on asteroid (101955) Bennu" (submitted to MNRAS). [6] Le Corre et al. 2021 "Characterization of exogenic boulders on near-Earth asteroid (101955) Bennu from OSIRIS-REx color images" (submitted to Planetary Science Journal)