

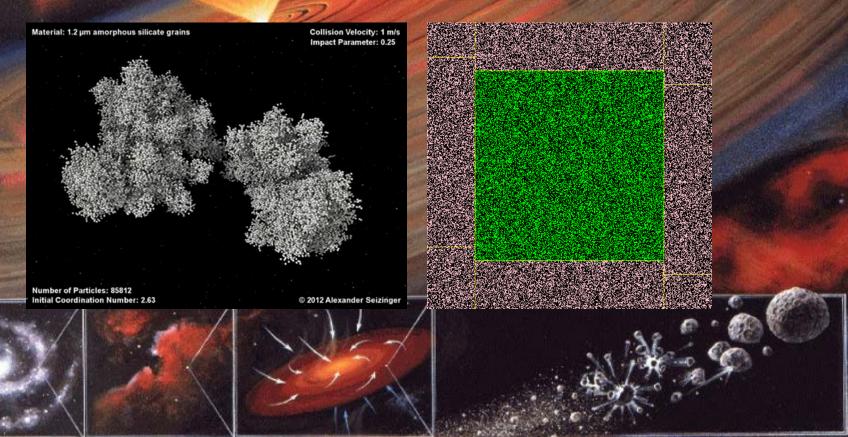
Planetary Protection for Small Bodies

- Are there identifiable populations of solar system small bodies that are sufficiently numerous, of sufficiently similar accessibility, and/or of sufficiently low relevance to the study of chemical evolution related to the search for extraterrestrial life that the contamination of one object in the population would reasonably be expected to have no tangible effect on the potential for scientific investigation using other objects in the population? If so, provide a list of these identifiable populations and their defining parameters;
- For the populations identified in #1, is it appropriate to categorize all missions to objects in these as planetary protection Category I?
- If, after the publication of the study, new information indicates that a previously defined identifiable population is sufficiently inhomogeneous with regard to planetary protection to warrant reassessment, what protocols should be followed in order to revise the defining parameter ranges and corresponding planetary protection categorizations?



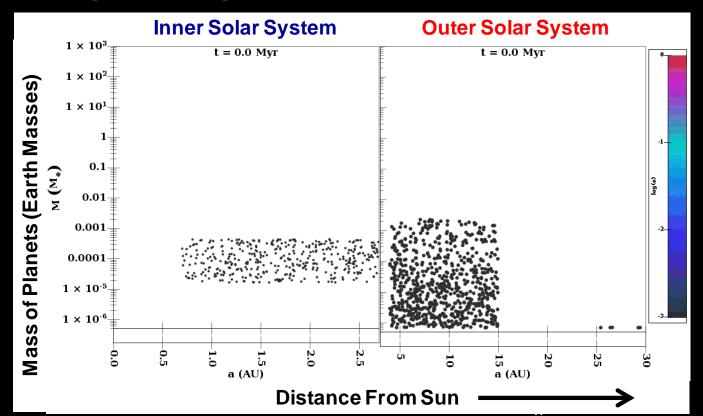


Formation of Asteroids and Comets



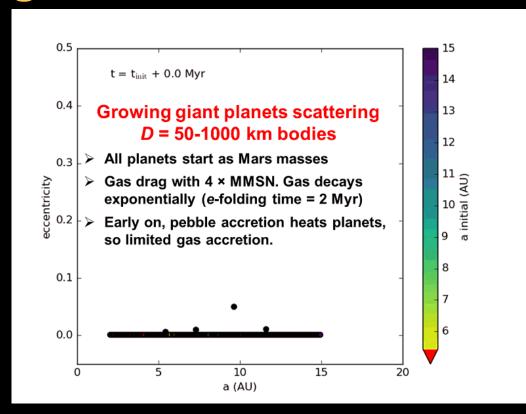
Sample reference: Johansen et al. (2015)

The Beginning



Over 10 to 100 Myr, hundreds of mini-planets collided to yield our planets

Capturing Giant Planet Zone Planetesimals

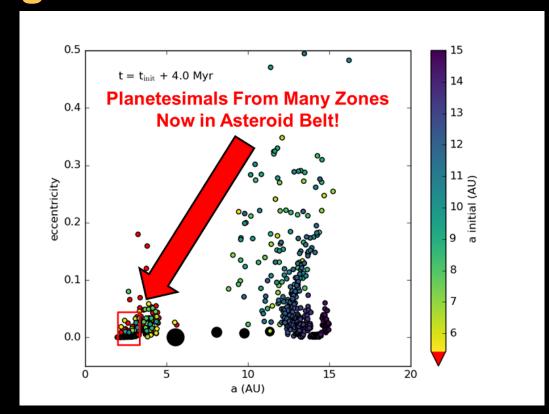


Kretke, Levison, Bottke, and Kring (2018)

See also Raymond and Izidoro (2017)

Growth of giant planets scatter planetesimals. Many are captured into main asteroid belt by gas drag.

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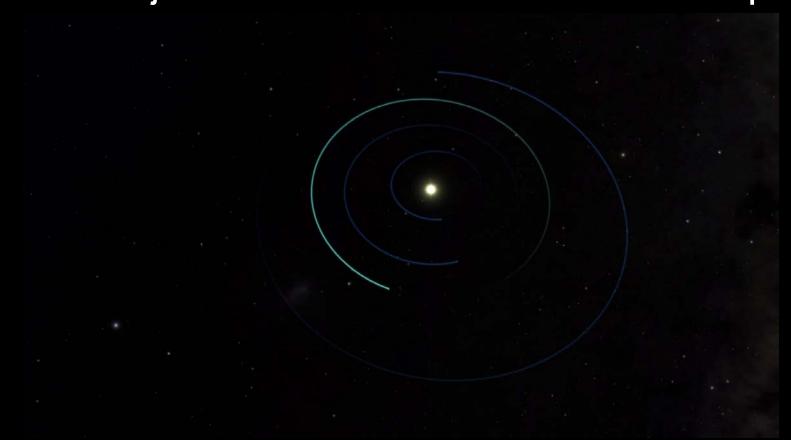
Bottom Line

■ The primordial asteroid belt was filled with a diversity of D > 100 km bodies from across the solar system.

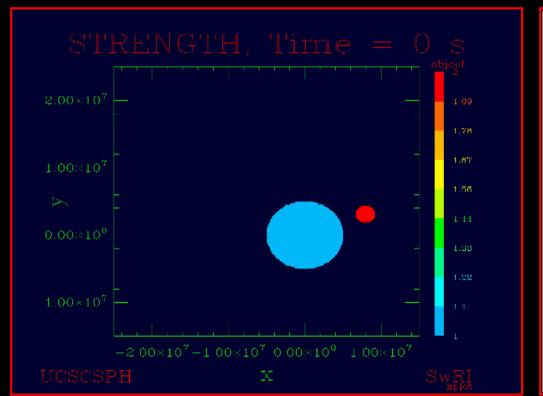


Asteroids: Fossils of Formation

~1 million objects at least 1 km across between Mars and Jupiter



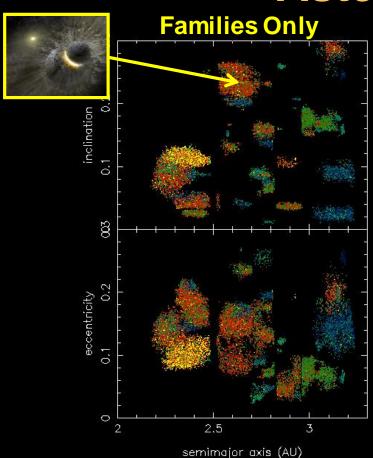
Asteroid Collisions

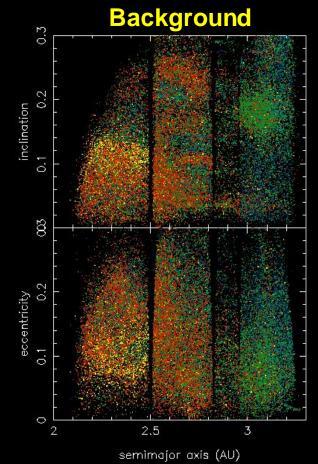




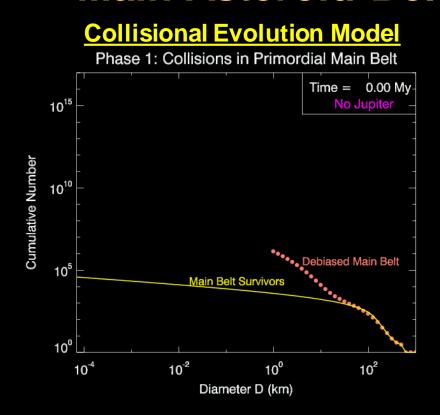
■ Large collisions take place, fragments stay fairly close to impact site.

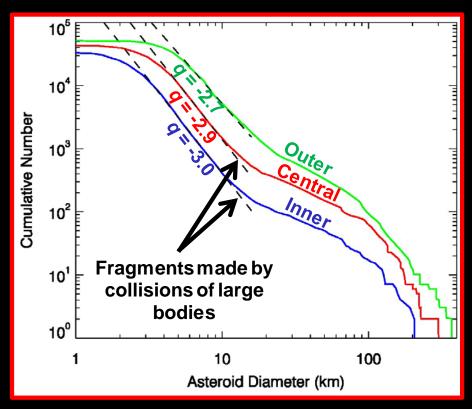
Asteroid Families





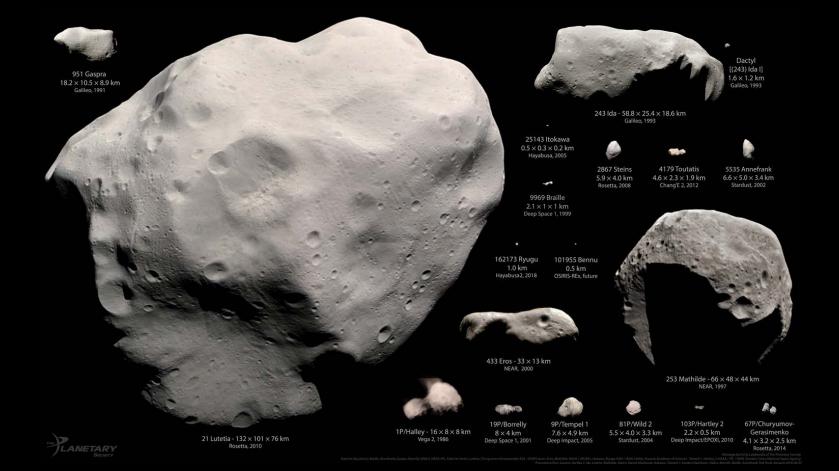
Main Asteroid Belt Size Distribution



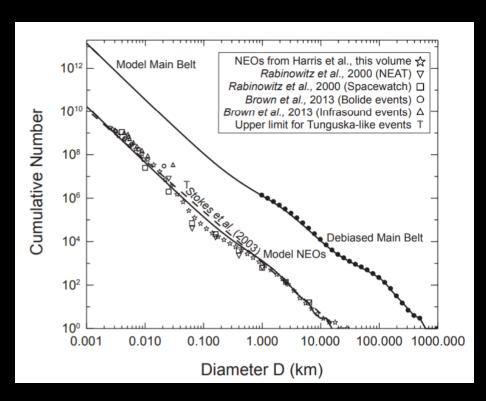


Most D < 20 km bodies are fragments of much larger bodies

Small Bodies in the Solar System



Main Belt & Near-Earth Asteroid Populations



- The asteroid belt is 5×10⁻⁴ the mass of the Earth, but collectively it is 0.13 times Earth's surface area!
- There are ~1000 D > 1 km bodies in the NEO population and ~10⁸ D > 10 m bodies.

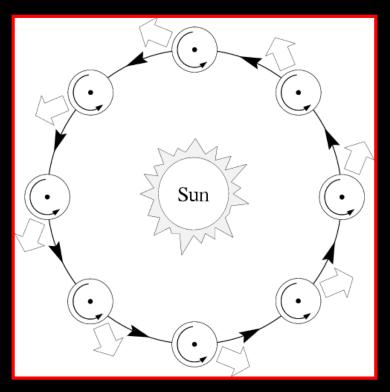
Bottom Line

- The primordial asteroid belt was filled with a diversity of D > 100 km bodies from across the solar system.
- **There are enormous numbers of asteroids!**
- Most *D* < 20 km bodies are fragments from asteroid collisions, so few are geochemically unique.



The Yarkovsky Effect

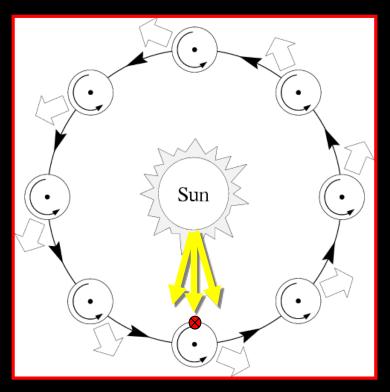
The "Diurnal" Effect



- Asteroids absorb sunlight and heat up.
- The energy is reradiated away after a short delay, causing asteroid to recoil.
- This "kick" causes the asteroid to spiral inward or outward.

The Yarkovsky Effect

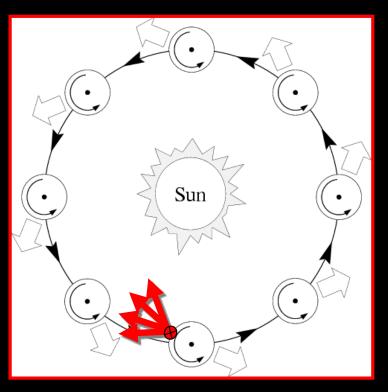
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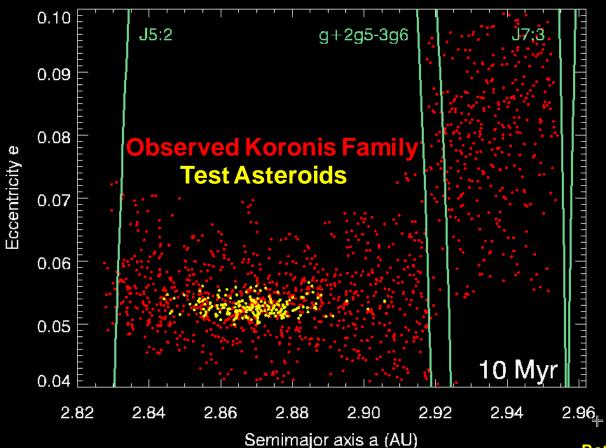
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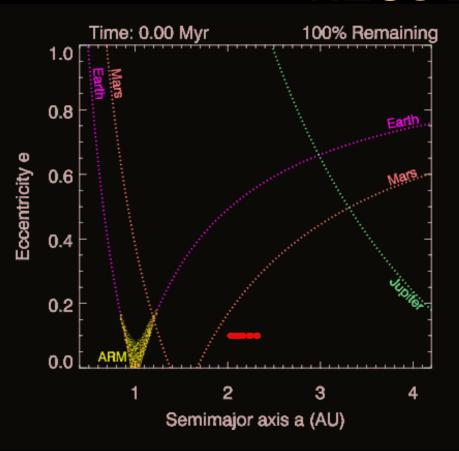


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Fragments Reach "Escape Hatches"



NEOs Evolution



- Objects reach resonances and travel throughout planet-crossing space.
- NEOs sample the diversity of the main belt fragments.

Meteorite Source Bodies

| TABLE 2. Meteorite groups and their postulated parent or source bodi | TABLE 2. | Meteorite groups | and their i | postulated | parent or | source bodie |
|--|----------|------------------|-------------|------------|-----------|--------------|
|--|----------|------------------|-------------|------------|-----------|--------------|

| | Fall Percentage | | |
|----------------------------|-----------------|---|--|
| Group | (%)* | Postulated Parent or Source Bodies† | |
| L | 38.0 | S(IV) asteroids (Gaffey et al., 1993) | |
| H | 34.1 | 6 Hebe [S(IV)] (Gaffey and Gilbert, 1998) | |
| LL | 7.9 | S(IV) asteroids (Gaffey et al., 1993) | |
| Irons | 4.2 | M asteroids (Cloutis et al., 1990; Magri et al., 1999) | |
| Eucrites | 2.7 | 4 Vesta (V) (Consolmagno and Drake, 1977; Drake, 2001) | |
| Howardites | 2.1 | 4 Vesta (V) (Consolmagno and Drake, 1977; Drake, 2001) | |
| CM | 1.7 | 19 Fortuna (G, Ch) (Burbine, 1998) | |
| Diogenites | 1.2 | 4 Vesta (V) (Consolmagno and Drake, 1977; Drake, 2001) | |
| Aubrites | 1.0 | 3103 Eger (E) (Gaffey et al., 1992) | |
| EH | 0.8 | M asteroids (Gaffey and McCord, 1978) | |
| EL | 0.7 | M asteroids (Gaffey and McCord, 1978) | |
| Mesosiderites | 0.7 | M asteroids (Gaffey et al., 1993) | |
| CV | 0.6 | K asteroids (Bell, 1988) | |
| CI | 0.5 | C asteroids (Gaffey and McCord, 1978) | |
| CO | 0.5 | 221 Eos (K) (Bell, 1988) | |
| Pallasites | 0.5 | A asteroids (Cruikshank and Hartmann, 1984; Lucey et al., 1998) | |
| Ureilites | 0.5 | S asteroids (Gaffey et al., 1993) | |
| "Martian" | 0.4 | Mars (McSween, 1994) | |
| CR | 0.3 | C asteroids (Hiroi et al., 1996) | |
| CK | 0.3 | C asteroids (Gaffey and McCord, 1978) | |
| Acapulcoites | 0.1 | S asteroids (McCoy et al., 2000) | |
| Angrites | 0.1 | S asteroids (Burbine et al., 2001a) | |
| Lodranites | 0.1 | S asteroids (Gaffey et al., 1993; McCoy et al., 2000) | |
| R | 0.1 | A or S asteroids | |
| Winonaites | 0.1 | S asteroids (Gaffey et al., 1993) | |
| (Tagish Lake) [‡] | 0.1 | D asteroids (Hiroi et al., 2001) | |
| Brachinites | Only finds | A asteroids (Cruikshank and Hartmann, 1984; Sunshine et al., 1998 | |
| CH | Only finds | C or M asteroids | |
| "Lunar" | Only finds | Moon (Warren, 1994) | |

^{*}Fall percentages are calculated from the 942 classified falls that are listed in *Grady* (2000), *Grossman* (2000), and *Grossman and Zipfel* (2001).

- Stony meteorites only represent a few tens of parent bodies
- This makes sense if meteorites are debris from asteroid families
 - The number of prominent families from large parent bodies are a few tens
 - With collisional cascades, they dominate meteorite (and small body) delivery

[†]Asteroid classes are a combination of those of Tholen (1984), Gaffey et al. (1993), and Bus (1999).

^{*}Tagish Lake is a newly discovered type of carbonaceous chondrite (*Brown et al.*, 2000) and is listed in the table because of its spectral similarity to D asteroids.

Burbine et al. (2002)

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- There are enormous numbers of asteroids!
- Most *D* < 20 km bodies are fragments from asteroid collisions, so few are geochemically unique.
- NEOs are an unstable extension of the main belt, with nearly all objects fragments from large collisions.

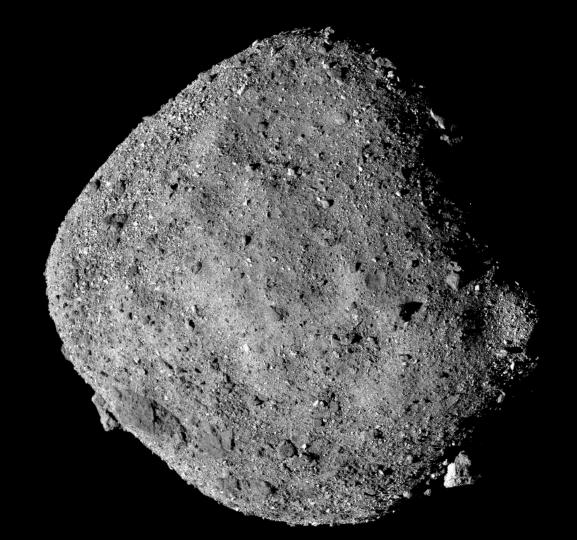


Bennu

About 0.5 km across

4.3 hr rotation period

Note the top shape and the presence of craters!

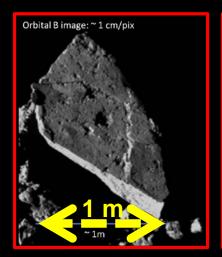


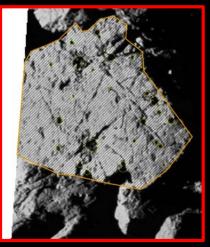
NEO Evolution by YORP

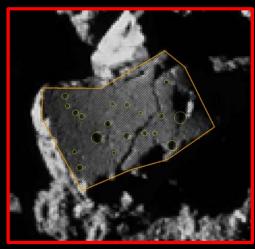


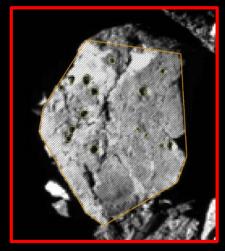
:Or

"Bullet Holes" on Bennu's Boulders









- Impact features have been found on Bennu's boulders.
 Most are probably from meteoroid impacts.
- Regular impacts occur with the energy of shotgun blasts!

Effects of Extreme Heating





The Biggest Surprise – Bennu is an Active Asteroid!

January 19th Ejection event

Events like this occur every two weeks near Bennu's perihelion

What caused it?





Large amount of mobilized material during TAG

- Time of Contact (C) triggered by accelerometer
 - The surface provided a contact force of ~10N
 - Compliant, low-cohesion material
- C+1 sec: TAGSAM gas bottle fired
 - Substantial cm-scale particles mobilized by gas for >5 sec
- C+6: Backaway burn initiated
 - Residual forward velocity of 4 cm/s
- C+9: Spacecraft velocity changed directions
 - Max penetration depth: 48.8 cm
- C+16.6: Altitude rose above original surface





Nightingale Site – Pre-TAG – March 2019 – BBD-FB1





Nightingale Site – After TAG – April 7, 2021 – BFT



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- Most *D* < 20 km bodies are fragments from large asteroid collisions, so few are geochemically unique.
- NEOs are an unstable extension of the main belt, with nearly all objects fragments from large collisions.
- Asteroids affected by many processes. They can change individual rocks and surface properties
 - Most work on timescales that are long compared to human lives

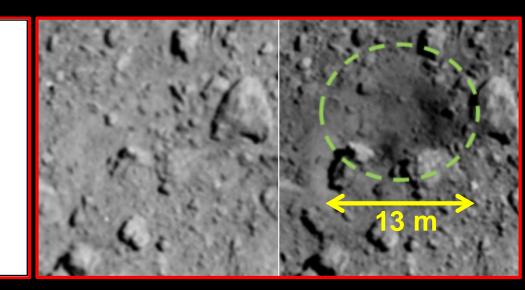
Conclusions

- Asteroids are numerous and widespread!
 - They have a large collective surface area
 - They do not influence one another very much
 - Most NEOs and small main belt bodies are derived from families, so their chemical nature is preserved in enumerable bodies.
- **■** Processes affect asteroids on wide range of timescales
 - Meteoroid and thermal cracking affect asteroids today
 - Major collisions and YORP occur over longer timescales
 - They do not strongly modify the chemical nature of rocks/boulders
- Our ability to meaningfully affect asteroids is limited

Moving asteroids to Category 1 seems reasonable.



Collisions



- **SCI** impact experiment on Ryugu:
- 30 cm copper plate (2 kg) fired at ~2 km/s
- **Impact created a 13 m crater.**
- Small and medium impacts occurs on NEOs from time to time

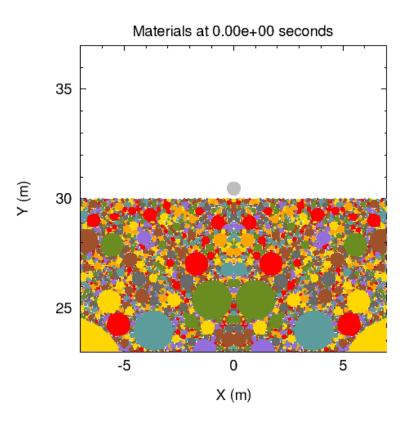


Favorable sampling conditions resulting from surface interaction

- Post-contact, disturbance on all sides around the TAG head, indicating flush contact with the surface
- 4.5 cm of penetration pre-gas release
- Sampleable material visibly lofted and moved
- Dust cloud precedes particle ejecta debris in post-gas release imaging
 - Substantial degradation of SamCam and NavCam optics
 - Indicates reservoir, or production, of dust accessible for sampling



Understanding DART's Impact





DART – Double Asteroid Redirection Test 24 January 2022