Asteroid Mining: The State of Play in 2016

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For an hour, I would like you to think outside the Sphere.

Everyone you have ever known was born here. Our lives, our economies, our future have been based on what is available on this sphere. That is going to change.
Why are we here today?
One reason.

LETTER

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A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors


The small asteroid (∼20 meters in diameter) that exploded over Chelyabinsk could easily have severely damaged the city, if it had come in a few km lower. The Tunguska event could have destroyed a large city, should it have hit one.

The existing surveys of such small bodies are grossly incomplete: We have probably found fewer than one in a thousand of the 20-meter diameter Near Earth Asteroids (or NEA). Improving the rest of these bodies is the major goal of the Asteroid Day effort. (To be fair, we have identified almost all of the larger “civilization killer bodies that NASA was directed to find by Congress.)
Another.

Luxembourg to Invest $227 Million in Asteroid Mining

by David Z. Morris  @davidzmorris  JUNE 5, 2016, 10:53 AM EDT

The Trillion-Dollar Industry in Search of Ambitious Entrepreneurs

Google co-founder Larry Page and the tiny country of Luxembourg are angling for first-mover advantage in the asteroid mining industry.

John D. Lewis of Deep Space Industries: I don’t want to make a million Dollars. I want to make a quadrillion Dollars.
In the Solar System, Mining and Defense have Similar Interests

- For both *Planetary Defense* and *In Situ Resource Utilization* (ISRU), most of the interest lies in the Near Earth Asteroids:
  - For Planetary Defense, they aren’t a threat if they don’t come near the Earth.
  - For asteroid mining / ISRU: The closest NEA, in orbits very similar to the Earth’s, are going to be by far the most *most cost effective* objects to extract resources from for some time to come.
- To mine an asteroid with current technology requires that it have a very Earthlike orbit (the relative $\Delta V$ needs to be very low).
  - There are asteroids that are easier to get to (energetically) than the Moon.
- What Do We Really Know About Small Near Earth Asteroids (and the Asteroids in general)? Are they good targets for resource extraction?
- What Upcoming Missions Will Help Provide the Technological and Scientific Base for Mining and Planetary Protection?
Asteroid Mining: It won’t be like this.
Or like this.

(But this is a bit closer, as the initial interest will be in small Near Earth Asteroids, not the large bodies in the belt.)
What Could Be Mined?

- There are two possible types of “ore.”
  - Valuable minerals, such as the platinum group metals, which would have to be brought back to Earth, or
  - Simple things, like water, petrochemicals, and even just sand, for use in space travel. That is known as *In Situ* Resource Utilization (ISRU) or “living off the land”

- The most obvious initial market is astronauts exploring deep space, and in general the exploration and development of the solar system.
  - Space resource will be developed for use in space first; terrestrial uses will come later.

- The first thing to be “mined” is likely thus water.
  - Water can help with life support, radiation shielding and rocket fuel, and it’s very expensive to bring it from Earth.

- Next (or simultaneously) will come the use of chemicals such as CO$_2$ and Methanol, which can be used for propulsion (solar thermal or solar electric), biomass, and 3-D printing.

- All of these chemicals are volatile, and can be produced simply by heating carbonaceous asteroid material.
The Realm of the Small Bodies.
We have good orbits for 469,275 asteroids (the numbered asteroids, as of last week). Where are these bodies found? This shows the number of bodies as a function of their average distance from the Sun (called the semi major axis). Most asteroids are in the Main Belt. The obvious Kirkwood gaps in the Main Belt are cleared by Jupiters strong gravity. Asteroids that wander into these gaps will be rapidly pushed out of the belt; the Near Earth Asteroids are made of these exiles.
Where are the Asteroids?

This image, courtesy of Planetary Resources, shows the distribution of asteroids in the Main Belt. (Note - this image increases their visibility - you wouldn’t see them at all (with the naked eye) if you were sitting up above the solar system.)
The gaps first noticed by Kirkwood (and now named after him) are created by the gravity of Jupiter. An asteroid that moves into an orbit with a strong resonance with Jupiter (for example, the 3:1 resonance, with three asteroid orbits for every one orbit of Jupiter) is likely to be rapidly perturbed out of Main Belt. This causes the Kirkwood gaps, and also supplies (most) of the NEA, as the bodies strongly perturbed by Jupiter are likely to be to have their perihelions (the point in an orbit closest to the Sun) lowered until they come near to the Earth or Mars.
As you can see, there are not nearly as many NEA as Main Belt Asteroids. The NEA are perturbed by passing near the Earth, Mars or other bodies, and by radiation pressure, and are thought to have typical lifetimes of $\sim 10$ million years. They are thus our temporary neighbors, in between being thrown out of the Main Belt by Jupiter and their ultimate fate (hitting something, falling into the Sun, or even being ejected from the Solar System).
One thing you can estimate from a survey is how complete it is, by looking at how the numbers of objects change with size. Surveys have brightness limits, and should be nearly complete for sufficiently large objects, but will miss most objects below their limit. Asteroids are observed to follow a power law - a relation where the cumulative number of objects is a power of their size (in this case, the cumulative number is roughly $\propto R^{-2.3}$). With this assumption, the Main Belt surveys appear to be complete down to asteroids as small as $\sim 2$ km, while the NEA appear to be complete down to $\sim 1$ km. This modeling indicates that there should be a million or more 50 - 100 meter diameter NEAs remaining to be found.
What Are the Near-Earth Asteroids Like?
As of May 21, 2016, there are 714,845 known asteroids. For the vast majority of these objects nothing is known except for their optical brightness (and, thus, crudely their size). Only 469,275 asteroids even have good enough orbits to reliably find them again. However, there are rotation period estimates for about 7% of these bodies; even this simple data can be surprisingly revealing.
The change in the character of asteroid rotation rates at $R \sim 200$ m is obvious to the eye, with most asteroids with $R < 200$ m having rotation periods $< 1$ hour while almost all asteroids with $R > 200$ m have periods $\gtrsim 2.2$ hours. The horizontal solid line is the Rubble Pile Limit for a uniform density of 2300 kg m$^{-3}$ - the fastest an asteroid with that density could rotate and still be bound by gravity.
Asteroid Rotation Rates: What do the data mean?

- Large bodies ($\gtrsim 200$ meters) do not appear to rotate faster than about 2.2 hours.
  - These bodies are assumed to be rubble piles (collections of smaller rocks and dust) with not enough internal cohesion to survive rotational disruption.
  - The 2.2 hour limit implies an effective bulk density of $\sim 2.3$ grams / cm$^3$, or 2.3 times the density of water.

- Most of the smaller bodies rotate much faster (some with rotation periods of a few tens of seconds).
  - Something is giving these bodies internal strength. Are they blocks of rock? Is there a chemical binding?
  - Asteroid mining will have to either avoid, or learn to deal with, these rapid rotators.
What About Particular Objects?
A Closer Look with Spacecraft and Radar
This is (243) Ida, a 60 km long Main Belt asteroid

The most prominent features are craters. Lots and lots of craters. Just like the Moon. Everyone figured the smaller NEA would be just like this.
This is (25143) Itokawa, a 500 meter long Near Earth asteroid

See any Craters? No one really knows why the small asteroids we’ve looked at so far don’t have many craters, but a reasonable guess is an impact makes the whole body shake like a bowl of pudding. This shaking might go on for hours after a (relatively) large impact, erasing all surface features.

Credit & Copyright: ISAS, JAXA (from the Hayabusa I Spacecraft).
Another view of (25143) Itokawa

Again, no craters, but this view shows a smooth region the Japanese scientists called the “Muses-Sea,” - it appears to be made of something similar to pebbles - small, centimeter sized objects. What holds these in place in the $\sim 10 \, \mu g$ gravity of Itokawa? van der Waals forces? How then does it survive hours of shaking? If we want to mine something here, can we scoop it up?

Credit & Copyright: ISAS, JAXA (from the Hayabusa I Spacecraft).
For NEA that happen to come close to the Earth, there is also radar. As of April 9, 2015, 687 asteroids and comets have been detected by radar. Of the bodies greater than 200 meters in diameter, many (∼ 20 %) have been found to be binary asteroids. Of the smaller bodies, there are basically no binaries.
A radar image of (66391) 1999 KW4

(I have a hard time interpreting these raw radar images too, but this is clearly a binary.)
That’s better. How does something like this happen? The theory is that the larger body is spun up by radiative torques (the “YORP” effect), first forming an equatorial ridge, and then spinning off material from the equator, which then coalesces to form the cigar-shaped secondary [Ostro et al., 2006, Scheeres et al., 2006]. This appears to be pretty common for kilometer-sized asteroids.
Asteroid Missions: Past, Present and Future
Several Upcoming Asteroid Missions that will Provide Fundamental Knowledge and Technology Needed for Planetary Defense and Asteroid Mining

- Hayabusa II
  - Return a sample from the 1-km NEA (162173) 1999 JU3.

- OSIRIS-REx
  - Return a sample from the 250-meter NEA (101955) Bennu back to Earth.
  - The next to launch, currently scheduled for September 8th.

- The Asteroid Redirect Mission (ARM)
  - Return a 10 ton boulder from a NEA to Lunar Orbit, and samples back to Earth.

- The Asteroid Impact and Deflection Assessment (AIDA) Mission, a Joint NASA - ESA Mission for Planetary Defense:
  - AIM - the Asteroid Impact Monitoring Mission (ESA)
  - DART - the Double Asteroid Redirection Test (DART)
ARM: The Asteroid Redirect Mission

- A precursor mission for human exploration.

- Mission goals
  - Rendezvous with a relatively large NEA
  - Identify a boulder in the 2 - 10 ton size class.
  - Pick it up to bring back to near-Earth space - a Distant Retrograde Lunar Orbit.
  - Before returning, use the mass of the spacecraft + boulder as a ”gravity tractor” to demonstration that means of deflecting a future hazardous body.

- The boulder manipulation and return in ARM will test technologies essential for future mining operations.
A big question is how robust are the boulders seen on small bodies.
And Away We Go...
Enhanced Gravity Tractor Test

The goal is to perturb the asteroid by about $1\text{ mm / sec.}$
Eventually, the asteroid boulder is brought back to a Distant Retrograde Lunar Orbit (or DRO), maybe 70,000 km from the Moon...

DROs are very stable “parking orbits” that will be essential for future solar system exploration and for asteroid mining operations.
AIDA: The Asteroid Impact and Deflection Assessment Mission

- A complicated (and very cool) joint ESA + NASA Mission.

- The target is the binary asteroid (65803) Didymos.
  - It seems very similar to 1999 KW4 at 2/3 scale.
  - The primary is about 800 meters in diameter.
  - The secondary about 170 meters long.

- Mission goals
  - An ESA spacecraft, AIM, will rendezvous with Didymos
  - On about October 1, 2022, the US DART spacecraft will hit the Didymos moon at 6.25 km / second.
  - AIM will observe the impact, and see what happens. The change in the orbit of the moon should be easy to observe.
  - This is thus a full-up test of the kinetic-impactor asteroid deflection technique.
AIDA is relevant for many disciplines

**Planetary Defense**
- Deflection demonstration and characterization
- Orbital state
- Rotation state
- Size, shape, gravity
- Geology, surface properties
- Density, internal structure
- Sub-surface properties
- Composition (mineral, chemical)

**Science**
- Orbital state
- Rotation state
- Size, shape, gravity
- Geology, surface properties
- Density, internal structure
- Sub-surface properties
- Composition (including isotopic)

**Human Exploration**
- Orbital state
- Rotation state
- Size, shape, gravity
- Geology, surface properties
- Density, internal structure
- Composition (mineral, chemical)
- Radiation environment
- Dust environment

**Resource Utilization**
- Geology, surface properties
- Density, internal structure
- Sub-surface properties
- Composition (mineral, chemical)
The AIM Spacecraft Arrives at Didymos.

The Primary is on the left, the secondary on the right, in this artist’s impression.
AIM Deploys its CubeSat sub-payload at Didymos.
Here Comes DART.
Bang!

This is an artist’s impression, of course. There is in reality a profound uncertainty as to what will actually happen when the DART impact occurs.39
The impact from different points of view

We feel it is vital to adequately instrument the surface of the Didymos moon. The body may be disrupted entirely, it may shake for hours, there may be huge surface mass movements, we just don’t know. Multiple cameras, accelerometers, etc., will help to nail this down.
What About Commercial Resource Extraction?

- There are three companies working on this (I expect more will arise later).
  - Planetary Resources.
  - Deep Space Industries.
  - And my own start-up, Asteroid Initiatives. I am going to talk a little about the Pixie swarm spacecraft we are developing for near Earth observations and asteroid prospecting.
Capturing a Resource Rich Asteroid.

Courtesy of Planetary Resources.
Asteroid Prospectors

• What is the best way to Determine the Availability of Resources in the NEA?
  ○ The best way to confirm the existence of resources would be simply to visit candidate asteroids.
  ○ A candidate could be explored with tiny femtospacecraft in a low speed rendezvous,

• From the current set of asteroids in the Light Curve Database, we have identified 12 asteroid candidates with $\Delta V \lesssim 6 \text{ km / sec}$ relative to the Earth.

• Preliminary design work indicates an adequate prospector spacecraft could have
  ○ Mass $< 50$ kg, with a payload mass $< 3$ kg
  ○ Payload would be cameras, and 50-gm Pixie femtospacecrafts to drop onto the surface.
  ○ Sponsored Pixies would be available to partners, such as Universities.
  ○ Propulsion could be a Solar Sail or an Electric Sail, which require no fuel (so that many asteroids could be prospected by one spacecraft).
What are Pixies?

- Pixies are a new type of femtospacecraft being developed for deep space missions
- A Pixie is 80 x 40 x 10 mm with a mass < 50 grams.
- A Pixie can have a robust set of instruments:
  - A 2-axis Sun Sensor.
  - A MIMS 3-axis Gyroscope.
  - A MIMS 3-axis Accelerometer.
  - A MIMS axis Magnetometer.
  - A retroreflector
  - A flashing diode (for the imaging from the main spacecraft)
  - A camera.
  - Other instruments to explore the electrical and chemical properties of the surface.
Swarm Science

- To act as a Swarm, the Pixies must *collectively*
  - Communicate: Determine which swarm members are within reach, and by what means.
  - Collect: Collect and share data from the collected swarm
  - Evaluate: Compare data from each Pixie reachable by the swarm.
  - Distill: Convert the analyzed data into a higher-level summary.
  - Assess: Assess the quality of each data set and the coherence of the whole. Determine whether data represents the passage of an alert threshold.
  - Report: Report the high level reduced data to the Bradbury (and eventually to Earth) upon passage of an alert threshold or based on other reporting criteria.
The Three Plane Pixie FemtoSpacecraft: Dimensions

Viewport - 10 x 40 mm exposed to sky

Solar Cell Plane: 70 mm long

Full Length: 80 mm

Width: 40 mm

Height: 9 mm
The Three Plane Pixie FemtoSpacecraft:
(with hot box MLI)
The Three Plane Pixie FemtoSpacecraft: Visible Components

- Top Solar Cell Plane
- Middle Data Plane
- Bottom Solar Cell Plane
- Solar Cells (top)
- Sun Sensors
- 802.15.4-2011 Patch Antenna
- Retroreflector
- Flashing Diode
- Battery
- Cross Connects

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Pixies: the Swarm Communications Protocol

- The baseline design uses a 400 MHz UHF communications system for communications between Pixies and the Bradbury deployer.

- At 6 GHz, there is the potential of using 802.15.4-2011. There is COTS industrial equipment available that supports:
  - Better than 10 cm real time range accuracy.
  - Support for up to 11,000 communications nodes.
  - Coherent receivers that support real time ranging up to 300 meters distance.
  - Native Support for Pixie-Pixie store and forward communication.
  - Intermittent communication modes that fit within the Pixie power budget by devices that fit within the mass budget.
A very slight spin imparted to the Bradbury will result in the cm/sec relative velocities needed for hemispheric deployment.
Pixie InterSwarm Ranging after Deployment Near the L2 Lagrange Point.

With round-robin three way ranging the swarm can sync clocks and determine the swarm geodetic network to < 10 cm during deployment, and bounces and after landing.
Pixie Swarm Resulting from a L2 deployment (i.e., above the anti-primary point).

A single passive Pixie deployment near the \{\hat{r}^2_1,L2\} point will be roughly symmetric about the \{sub-primary,anti-primary point\}. If the Bradbury does not have autonomous navigation, only a single swarm covering one hemisphere can be deployed before the Bradbury hits the Didymoon. (All impacts are at a few cm / sec.)
Conclusions

• We are beginning to explore the Near Earth asteroids, for both resources and hazards.
  ◦ There is lots of work yet to be done.
  ◦ We don’t even know where they all are, by a long shot.

• Asteroid mining is coming.

• The first thing likely to be “mined” is going to be water. This will be essential to “living off the land” in space.

• There is a strong commonality of interests between asteroid science, asteroid mining, and planetary defense, and that is likely is likely to continue for some time to come.
  ◦ Asteroid mining will benefit from the technology being developed by NASA, ESA, JAXA and other governmental space agencies.

• Although the proposition is risky, the long-term payoff from asteroid mining will be immense. This is truly a game-changing possibility for space exploration and for humanity.
References
