Chondrulic Rockets

Abstract

"Chondrulic Rockets" describes a class of propulsion systems that use mass from asteroids as rocket propellant, considers their necessary principles, benefits, and potential hazards, and urges NASA to encourage new research projects in this area.

Primary Response Area: 3

3. Asteroid Deflection Demonstration: propulsion effective against objects large enough to do significant damage at the Earth's surface.
3b: Use of a "gravity tractor" technique on an asteroid.
3c: Planetary defense.
4: Asteroid Capture Systems: systems to capture and de-spin an asteroid.

This response to the **ASTEROID INITIATIVE REQUEST FOR INFORMATION** is submitted pursuant to, and by, the following:

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System Concept

A **Chondrulic Rocket** means any propulsion system that uses mass obtained from an asteroid as propellant mass to develop rocket thrust.

Most asteroids are composed of chondrules, which are typically small grains of silicate minerals. Chondrulic rockets refer broadly to any kind of mass obtained from the asteroid, including chondrules, the matrix that surround the chondrules, the surface dust, and any other metals or minerals that may be present.

Figure 1. Chondrules, roughly the same size as coarse sand. [1]

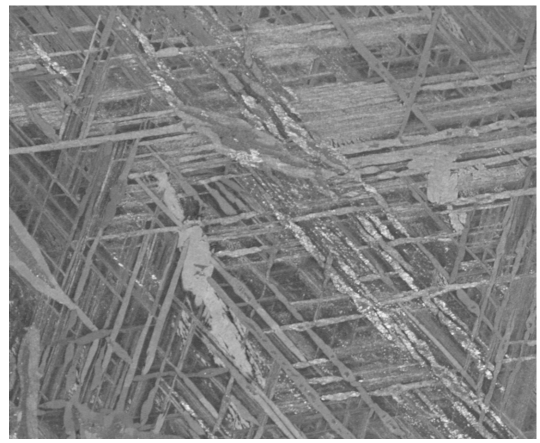

Figure 2. Asteroid Metal, showing Widmanstätten pattern [2]

Introduction

Asteroids have a lot of mass. The Asteroid Redirect Mission mass is $1000\ t$, maximum. Asteroid Itokawa has a mass[3] of about $3.5 \times 10^7\ t$, while the largest, Ceres, has a mass[3] of about $9.5 \times 10^{17}\ t$. Asking the Asteroid Retrieval Vehicle to move Ceres would be like asking a laden swallow to carry quadrillions of coconuts.

Mass is required to accelerate mass. Since momentum is conserved, if one part of a system is to change momentum, the rest of the system must also change momentum in an equal and opposite manner. The purpose of any rocket is to eject propellant mass at a high velocity, so that the craft will accelerate in the opposite direction.

A spacecraft on a mission to move an asteroid might carry all of its propellant mass from launch. Since mass is very expensive to lift from Earth, the spacecraft would not be able to carry very much propellant mass, and therefore must rely on engines that eject propellant with very high velocity, that is, with a very high specific impulse.

However, a spacecraft that obtains propellant mass from the asteroid instead of from Earth would have a massive advantage. A chondrulic rocket with a low specific impulse could produce a useful velocity change with very low power. Chondrulic rockets with high specific impulse, times the large mass, could provide a very large total impulse.

A chondrulic rocket that uses half of an asteroid to push the other half uses less energy than any other method for accelerating an asteroid.

Suppose an asteroid was split into two pieces, A and B. To accelerate A by $\Delta\vec{v}_A$, a chondrulic rocket accelerates propellant mass B by $\Delta\vec{v}_B$. Since momentum is conserved in a closed inertial system, $m_A\Delta\vec{v}_A + m_B\Delta\vec{v}_B = 0$, and so the velocity of B must be $\Delta\vec{v}_B = -(m_A/m_B)\Delta\vec{v}_A$. If A has more mass than B, then the change in speed of B must be greater than that of A, so that $(m_A > m_B) \Rightarrow (\Delta\vec{v}_B^{\,2} > \Delta\vec{v}_A^{\,2})$. When the masses of A and B are equal, the speeds of the propellant masses become equal, and also minimal.

A rocket does work on the propellant mass equal to its change in kinetic energy, $E_k = \frac{1}{2}m\Delta\vec{v}_B^{\,2}$. Since the energy varies by the square of the velocity, higher propellant velocities require more energy. The least-energy solution is the one with the slowest propellant velocity, and that is when half of the asteroid pushes the other half.

Using half of an asteroid as propellant is often impractical. However, this result hints at the benefits of consuming at least some of the asteroid as propellant to move the rest.

Space Elevator Chondrulic Rocket

A Space Elevator Chondrulic Rocket illustrates this low-energy approach. It converts the angular momentum of a tumbling asteroid into two pieces, accelerated in opposite directions. This is how it works.

1. Put the entire asteroid in a bag, A, to contain loose dust and regolith.
2. Attach a long, strong tether to the asteroid, leading to a second bag, B.
3. Gather asteroid mass from bag A and transport it along the tether to bag B.
4. The rotation period of A will de-spin, to match the orbital period of B.
5. At a very precise instant in time, cut the tether.
6. Bags A and B will fly off in opposite directions.

A space elevator chondrulic rocket is an excellent way to *partially* de-spin an asteroid. The longer the tether, and the more equal the masses of A and B, the slower the spin. Some additional energy would be required to *completely* de-spin it.

This case is oversimplified, because asteroids are not in an entirely closed inertial system. Asteroids follow the peculiar mechanical laws of orbiting bodies. Although the asteroid and ballast would initially take separate paths, it may be possible that the two pieces may take a rendezvous or collision course because all of the thrust is applied instantaneously.

Common Characteristics

Spacecrafts that use chondrulic rockets will share some common characteristics, including ballast tanks, propellant mass processing, and propellant energy. They also produce micrometeorites, which may be hazardous enough to require mitigation.

The most fundamental difference between chondrulic rockets and other rockets is the ability to gather propellant *energy* separately from propellant *mass*.

Ballast Tanks

The spacecraft must accept mass and mechanically stow it onboard. The spacecraft might land on an asteroid, or it might dock with a refueling craft. A daughter craft might even be dispatched to harvest surface regolith and bring it back to the mother craft.

In any case, the spacecraft's total mass will increase and its mass distribution will change. In a gravity tug, the ballast might be stowed low in the craft. For human spaceflight, the ballast might be stowed in the walls of the craft as radiation shielding.

Propellant Mass Processing

Material obtained from the asteroid must be sorted or processed into a useful form depending on the chondrulic rocket thruster design.

Grain size will be one factor to consider. Some thrusters might be able to accept boulders or gravel, while other thrusters might require sand or very fine dust.

Grain composition will be another factor to consider. Silicate minerals might be valuable as dielectrics that can hold a static charge. Water might be too valuable for propellant. Metals may need to be harvested, melted, and shaped into projectiles or cathode screens.

Potential Energy

The spacecraft must carry and store some form of potential energy onboard, which will be converted to kinetic energy. The energy source might be chemical, solar, or nuclear. Even wireless power transfer is possible, from either microwave or coherent sources.

The energy might be available in either a continuous or explosive form. Chemical explosives can create high velocity and well-collimated exhaust. Ultra capacitors can deliver an explosive-like burst of electricity after charging from a continuous supply. Nuclear explosions are hard to collimate, which greatly reduces their effective velocity.

Chondrulic rockets have an affinity for electric energy sources. Electric thrusters can be as simple as a spring catapult, solenoid catapult, motor-driven impeller, or as futuristic as a coilgun, railgun, ion thruster, plasma pinch, or cyclotron. Since both power and mass can be replenished in space from solar power and asteroids, electric chondrulic rockets can power very long duration flights.

Micrometeorite Hazard

The exhaust from chondrulic rockets will usually consist of solid particles. These small particles pose no hazard to people living on Earth, because our atmosphere protects us, but they may be hazardous to spacecraft. Micrometeorites can carry a lot of kinetic energy, and can damage satellites on impact, even if they are as small as a pebble.

NASA should study this hazard and produce mission safety rules governing the use of chondrulic rockets, especially near Earth. Grain size limits may be very important.

Conceptual Design Brainstorm

In addition to the above Space Elevator Chondrulic Rocket, here are several more chondrulic rocket design concepts to inspire further research.

Chemical Explosive Chondrulic Rocket

Place an explosive charge under the propellant mass, so that the explosion will eject the propellant. A mortar can increase the effective velocity and direct the blast.

Nuclear Explosive Chondrulic Rocket

To use a nuclear explosion as a chondrulic rocket, put the bomb near the middle of the asteroid, so that the pieces push away from each other. However, a large uncontrolled nuclear explosion would probably shatter the asteroid, producing an extremely large and extremely hazardous field of micrometeorites and asteroids. ***This is a catastrophically extreme hazard!***

Instead of an explosion, consider using that same nuclear power to generate electricity to power a high-impulse electric chondrulic rocket. ***High impulse means safer exhaust because the individual particles tend to be much smaller.***

Electromechanical Catapult Chondrulic Rocket

Use electricity to cock a spring catapult arm. Put the propellant mass in a bucket on the end of the catapult arm. Release the catapult to eject the propellant mass. A catapult may be useful for attitude control and to completely de-spin an asteroid because it tends to produce torque.

Electric Multiple-Impeller Chondrulic Rocket

Use electricity to spin an impeller, into which dust or sand is gradually introduced and directed through an exhaust nozzle, like a garden leaf blower. Multiple impellers would be required to cancel torque, but they could also produce controlled torque to de-spin an asteroid. Impellers may be useful as the primary thrusters for a gravity tug because they tend to produce multiple streams of gentle continuous thrust. Propellant mass flow rate adjustments would control the amount of thrust and torque. A quantitative scenario is worked below, based on this kind of chondrulic rocket.

Electric Solenoid Chondrulic Rocket

Use electricity to charge a bank of ultra-capacitors. Put the propellant mass in a bucket mounted on top of a solenoid armature. Momentarily close the switch between the ultra-capacitors and the solenoid windings to eject the propellant mass. Retain the solenoid armature and bucket, and reset it for the next load. There is no restriction on the composition of the propellant mass, just as long as it is small enough to fit in the bucket.

Several small solenoids may be useful for maneuvering thrusters because they can produce small instantaneous bursts of rectilinear thrust.

A larger bidirectional solenoid could be used as the primary thruster on a gravity tug by driving it with alternating current to produce two streams of chondrulic exhaust, but the spacecraft vibration would probably be excessive, and it would be ***messy***.

Electric Coilgun Chondrulic Rocket

A coilgun is like a solenoid, except that the armature is not retained. Instead, it is ejected as a projectile. It is also like a railgun, except that a coilgun requires an iron projectile, to react to the electromagnetic field. The projectile is typically cylindrical, which can be fashioned from the iron found on some asteroids. Like a railgun, the iron bullet exhaust would be ***very hazardous***.

Electric Railgun Chondrulic Rocket

A railgun consists of two long, parallel metal rods with a metallic projectile between them. It uses the Lorentz force to accelerate the metallic projectile to high velocity when a strong electric current is applied to the rods. To use it, charge up a bank of ultra-capacitors, place the projectile in the breach, and throw the switch. A railgun requires a conducting projectile, which can be fashioned from metal found on asteroids.

An electric railgun chondrulic rocket is an interesting choice as the primary thruster for a very large gravity tug to move a very large metallic asteroid. However, so much effort would go into creating all those projectiles that it might not be a feasible solution.

The U.S. Navy has already conducted some large-scale experiments with hypersonic rail guns. They "have proved capable of sending projectiles a distance of 100+ nautical miles at speeds of up to 5,600 mph"[4]. The 2,500 mps metal bullets would be ***very hazardous***, which is the whole point of a weapon, but not of a spacecraft thruster.

Electric Ionic Chondrulic Rocket

An ion rocket uses high voltage electricity to ionize and accelerate propellant. The SEP thruster proposed for the ARV uses terrestrial Xenon gas as propellant because it has a high atomic weight, can be ionized, and does not erode the cathode screen as much as other materials. It is a very useful thruster design for many purposes.

An ionic chondrulic rocket would use a different material as the propellant mass, something that can be found on asteroids, such as fine surface dust. This abrasive propellant would surely erode the cathode screen very quickly. If the asteroid contains metal, the spacecraft can manufacture new cathode screens.

The fine surface dust might be collected by a daughter craft using a static electric generator to electrify the entire asteroid. This may levitate the dust and cause it to travel along electric field lines to a central collection site.

Electric Plasma Pinch Chondrulic Rocket

A plasma pinch chondrulic rocket would use electricity to convert chondrulic material into plasma within a magnetic containment field. The plasma would then be ejected at very high velocity by pinching it through a small hole in the magnetic field.

Cyclotron Chondrulic Rocket

Physicists have devised many ways to accelerate small particles to extremely high velocities. Perhaps some of these methods can be adapted to accelerate fine grain dust from asteroids to a significant fraction of the speed of light, such as the cyclotron.

Such technologies could enable interstellar travel. Nuclear power, an electric chondrulic rocket with a very high specific impulse, and plenty of chondrulic propulsion mass could sustained long duration thrust.

However, the energy consumption would be tremendous. Maybe we could send our weapons-grade nuclear material and radioactive waste on an unmanned barge, as far away as possible.

Quantitative Scenario: Planetary Defense against Itokawa

Q: Suppose Itokawa were on a collision course with Earth and we consider using a solar-electric multiple-impeller chondrulic rocket craft weighing 2t to save the planet. If it is laden with 1000t of ballast, consisting of chondrules the size of gravel, can it hover in front of asteroid Itokawa in a gravity tug configuration? What would be the average mass flow rate of propellant required to maintain the hover? How much time would it take to consume 1000t of propellant mass? How fast would the ballast need to be replenished?

For mass containment, primary thrust, de-spin torque, and directional maneuvering, presume the spacecraft were designed as a regular cuboctahedron with 12 chondrulic impellers, with one impeller mounted on a gimbal at each vertex.

Propellant mass is metered through 12 mass-rate-regulating valves, moves through vibrating tubes, and empties into each impeller, which accelerates the mass through an exhaust nozzle. Each impeller resembles the size, shape, and performance of an ordinary garden leaf blower, driven at a constant speed by an AC electric motor, producing an effective exhaust velocity of 100 mps relative to the craft.

A flight computer controls the mass flow rate through each of the 12 valves, and can adjust the direction of the 12 exhaust nozzles. The nominal hover maneuver would deliver a flow of propellant mass to 6 thrusters at once. The remaining 6 thrusters would idle on standby, ready to effect course and attitude corrections. To thrust more, the computer would deliver propellant mass at a higher rate.

ANSWER: The average thrust of a gravity tug equals the weight of the craft over the asteroid. To hover, the spacecraft cannot thrust more or less. Optimally, it would be as close to the asteroid as possible without touching.

Our gravity tug's diameter is 10m and mass including ballast is 1,002,000. Itokawa's longest axis is 535 meters[3], and mass[3] is $3.5 \times 10^{10}\ kg$. The minimum safe distance between the centers of mass of the gravity tug and Itokawa is 275m. The tug's gravitational force over Itokawa, its weight according to Newton, is:

Givens

$$\vec{f}_{AC} = \frac{(6.67384 \times 10^{-11}) \times (3.5 \times 10^{10}) \times (1{,}002{,}000)}{(275)^2} \approx 31\ N$$

Thrust from Ballast!

With 6 thrusters operating, each leaf-blower thruster would be required to develop $31/6 = 5.2\ N$ of continuous force, ignoring angled thrust, or about 19 ounces at 1g.

Weight equals thrust, so $\vec{f}_{AC} = m\frac{dv}{dt} - u\frac{dm}{dt}$, with exhaust velocity $u = 100ms^{-1}$.

Since the gravity tug is hovering, we take the limit as $\frac{dv}{dt} \to 0$ to find the mass flow rate:

$$\frac{dm}{dt} = -\frac{\vec{f}_{AC}}{u} = -\frac{5.2}{100} = -0.052\ kg\,s^{-1}$$

A chondrulic mass flow rate of 52 grams of chondrules per second, on each of 6 thrusters, for a total mass flow rate of 310 grams per second, would *let this craft successfully hover over Itokawa*. At that rate, the 1000t of propellant will be exhausted in 37 days, or $10^9/310 = 3.2 \times 10^6$ seconds. A daughter craft would need to gather 27t of ballast daily.

The specific impulse and change in velocity are:

$$I_{SP} = v_e/g_0 = (100ms^{-1})/(9.8ms^{-1}) = 10.2s$$

$$\Delta\vec{v}_A = v_e \ln\frac{m_0}{m_1} = (100ms^{-1})\ln\left(\frac{(3.5 \times 10^{10} - 1{,}000{,}000)}{(3.5 \times 10^{10})}\right) \approx -2.9 \times 10^{-3}\,ms^{-1}$$

Yes, a dozen leaf blowers could change Itokawa's velocity by about 3mm per second.

BUT WHAT AN AWFUL MESS!! One qualification of a mad scientist is to devise an experiment that would have dire consequences if attempted, and this is one!

If this were a planetary defense mission, the asteroid core might not hit Earth, but a million kilograms of gravel would create a meteor shower the same size and duration as a 40-day global flood. It would destroy almost every satellite in orbit and leave an orbital debris cloud to ***permanently end all space travel!*** That's a hazard!
(See also: Nuclear Explosive, which was devised by mad scientists other than me.)

Conclusion: *Chondrulic Rockets*

We explored the use of asteroid mass as propulsion mass.

1. ***It is easier to move half of an asteroid than a whole one!***
   The lowest-energy solution to move an asteroid is a chondrulic rocket.

2. ***Chondrulic Rockets with a low specific impulse can be hazardous!***
   The smaller the specific impulse, the more mass must be ejected, which increases the chances of micrometeorite impacts on spacecraft.

3. ***Rockets with a high specific impulse are less messy and use more energy.***
   Since their propellant mass flow rate is lower, they can thrust for more time, and produce more change in velocity, but require tremendous energy.

4. ***Ballast mass is the key design parameter to determine gravity tug thrust!***
   For a gravity tug, weight equals thrust, *regardless of specific impulse*.
   If the hovering gravity tug continuously replenishes its ballast, then

$$\vec{f}_{AC} = \frac{G(m_A - m_B)(m_B + m_C)}{r^2} = (m_A + m_C)\frac{d\vec{v}}{dt} - u\frac{dm}{dt}$$

$$\frac{dm}{dt} = -\frac{G(m_A - m_B)(m_B + m_C)}{ur^2}$$

$$\Delta\vec{v}(t) = v_e \ln\left(\frac{m_A - \frac{dm}{dt}t + m_C}{m_A + m_C}\right)$$

Maturity (Technology Readiness Level)

No chondrulic rocket designs are flight-ready today. The Space Elevator Chondrulic Rocket is the most likely design for use on the Asteroid Redirect Mission, as a contingency design to de-spin a rapidly spinning target.

Many basic enabling technologies already exist which could be easily combined to create a simple chondrulic rocket design. However, some very simple chondrulic rockets can create hazards. In the future, it may be possible for researchers to create new kinds of chondrulic rocket designs with a high specific impulse to accelerate very small chondrulic particles without creating such a hazardous debris field.

Development approach:

NASA should encourage research and development of chondrulic rockets.

Several futuristic technologies and ideas are outlined above with the intent to inspire new research and development. Research projects should not be limited to chondrulic thrusters alone. There are many unsolved problems.

Doctoral candidates should research chondrulic rockets. There are plenty of questions to ask, ideas to explore, and new discoveries to make in this expanding field.

- How should we construct a daughter craft to gather regolith from the asteroid and transport it to the mother craft?
- How can a spacecraft crush, process, and sort chondrulic mass to prepare it for propulsion?
- How can the propellant mass be measured, metered, and fed into the thruster at a carefully controlled flow rate?
- How can conductive grains be separated from dielectrics?
- How can metals be cut, isolated, melted, and formed into projectiles and other useful parts?
- How can the most valuable precious metals, minerals, and water be mined and isolated from the rest of the asteroid?

A particularly interesting challenge would be to develop a working ion thruster that accelerates chondrulic dust, while using metal from the asteroid to build replacement anode and cathode screens.

The discovery of a chondrulic rocket design that can eject mass at a significant fraction of the speed of light might be an enabling technology for starships. The ability to replenish both propellant energy and propellant mass might even allow for a round trip.

NASA should also encourage research into how to mitigate the hazards from solid particular chondrulic exhaust. NASA should produce new mission safety rules governing the use of chondrulic rockets, especially near Earth.

References and Credits

(1) Chondrules from Bjurböle, Stone, chondrite (ordinary, L), fell 1899, Nyland, Finland, USNM 695, Smithsonian Museum of Natural History, Moon, Meteorites, and Solar System Gallery, "The Solar System Through Time". Photo by Rick DeWitt, June 16, 2013.
(2) Brenham, Stony-iron, pallasite, found 1882, Kiowa County, Kansas, W.A. Roebling, USNM 890, Smithsonian Museum of Natural History, Moon, Meteorites, and Solar System Gallery, "The Solar System Through Time". Photo by Rick DeWitt, June 16, 2013.
(3) http://home.earthlink.net/~jimbaer1/astmass.txt
(4) http://www.smartplanet.com/blog/bulletin/navy-gets-another-hypersonic-railgun-fires-test-shots/3317

Thank you NASA, for asking for my input.