SHEPHERD: A Concept for Gentle Asteroid Retrieval with a Gas-Filled Enclosure

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ABSTRACT

Sealing a small asteroid within an enclosure enables innovative approaches to the Asteroid Redirect Mission concept that pave the way for future in situ *asteroid resource utilization. A sealed enclosure would make it possible to use an introduced atmosphere of xenon gas to detumble and despin the asteroid, and then to push the asteroid by using a steady xenon gas flow inside this enclosure to transfer the force of the spacecraft's exterior solar electric propulsion engine to the asteroid. The gas will affect the cohesion forces of the asteroid, but the differential pressures exerted on the asteroid and surface regolith will be much less than the expected combined cohesion forces of weakly consolidated rubble piles and fragile primitive asteroids, which are of prime scientific interest for planetary defense and origin-of-life studies. That makes it possible to bring such a weakly consolidated asteroid mostly intact to the Earth–Moon system. Once released into lunar orbit, a small intact asteroid can be a viable proving ground for manned missions to more distant and larger asteroids in solar orbit. The development of this technology will benefit future asteroid resource utilization operations, in which enclosures are essential for providing protection from loose regolith and dust, capturing volatiles from icy objects, and enabling the use of reactive gasses in processing the asteroid material.*

INTRODUCTION

All currently proposed systems for the asteroid capture module (ACM) of the asteroid recovery vehicle (ARV) in the Asteroid Redirect Mission (ARM) will disrupt the surface of the asteroid during despinning and are likely to turn a weakly consolidated near-Earth asteroid (NEA) into a bag of rocks.[1–2] The current concepts either settle for retrieval of a large boulder that is cohesive enough to not fall apart when handled, or wrap a bag around the asteroid in order to later collect the individual rocks after it partially or fully disintegrates inside the bag.

However, the most interesting materials for retrieval and study are primitive and fragile, especially those too frail to be represented in our meteorite collections. Loose agglomerations of rocks and regolith may be common materials in space. Understanding the internal strength of small asteroids may be the single most important parameter affecting planetary defense operations and future mining or volatiles resource utilization operations. Indeed, ARM mission candidate asteroid 2011 MD is thought to be a weakly consolidated rubble pile.[3–4]

Ideally, ARM would deliver the fragile asteroid in much the same condition as it was found in space, and so human space flight missions will visit an asteroid, not a bag of rocks. By interacting with a free-floating weakly consolidated asteroid, astronauts would face many of the same challenges as when interacting with a larger asteroid in heliocentric orbits in a longer mission. This would make the ARM mission a suitable stepping stone to the longer-duration mission of visiting asteroids in solar orbit, and ultimately Mars.[1]

Here, we propose a modification to current ARM system designs that makes them capable of capturing and despinning an asteroid that has uncertainty in its mass, shape, and spin rate, and that may be a rubble pile. The concept is based on creating a sealed enclosure around the asteroid, which is also key to enabling future asteroid mining operations.

AN ALTERNATIVE CONCEPT FOR ASTEROID RETRIEVAL

The concept modifies current designs for the ACM,[1–2] by using some of the 10 tonnes of Xe gas envisioned for use by the solar electric propulsion (SEP) module, and adding gas pumps and a control computer to the spacecraft module for navigation and communication (SM).

The concept is to create a sealed enclosure around the asteroid and fill it with up to 0.1 atm. Xe gas. The gas will gently detumble and despin the asteroid. A controlled flow of Xe gas inside the enclosure can also be used to gently push the asteroid and thus transfer the SEP supplied force to the asteroid. That same gas can be used to keep the enclosure positioned around the asteroid by ejecting gas into the enclosure. The concept thus is to guide an asteroid to its final destination rather than grabbing it, and is called "Secure Handling by Encapsulation of a Planetesimal Heading to Earth–moon Retrograde-orbit Delivery" (SHEPHERD).

The SHEPHERD concept is schematically illustrated in *Figure 1*. As in the current ARM design, the ACM's inflatable enclosure is initially stowed in a 5-m-diameter box. A 3D light detection and ranging (LIDAR) monitors the position of the asteroid. In our concept, the

DOI: 10.1089/space.2014.0024

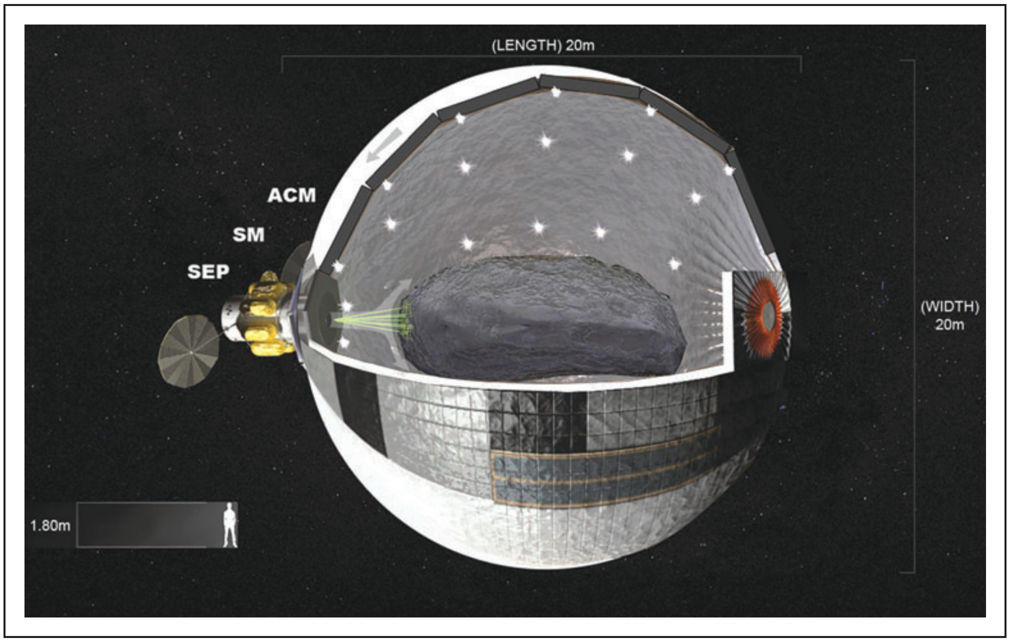

Fig. 1. The SHEPHERD concept.

enclosure consists of a sealed outer balloon facing space, an inner 19-m-diameter spherical tent with airbeam support, and a ribbon of sealing fabric (orange) that carries the bow cinch seal unit. The computer-controlled vents enable Xe gas to pass from the inner enclosure to the space between the tent and balloon (the "envelope"). High-pressure Xe gas is supplied from ARV to thrusters by a flexible pipes running along the airbeams. These control elements (lights, cameras, thrusters, gas vents, and temperature/pressure sensors) are all contained in blister-shaped units on the outer side of the inner tent at hemispherically distributed positions just offset from the airbeams. Power and data lines connect computer with camera units. To increase stability, less standoff of the SEP solar panels can be achieved if flexible solar blankets can be affixed to the balloon.

MISSION OPERATION CONCEPT

SHEPHERD will rendezvous with an NEA. Before capture, the ARV will first perform a 3D LIDAR scan of the surface and image the tumbling asteroid from all sides. This will provide the asteroid's shape, center of mass, and spin states. Various sensors can be deployed at the center of the stowage bays, but only the 3D LIDAR is essential. A redundant LIDAR would improve mission robustness, but the cameras can also provide backup capability for position control.

SHEPHERD will then fully inflate the (curved) airbeams supporting the inner tent to form a wide open C-shaped structure (*Fig. 2*). The envelope (between the airbeams) can also be inflated for added control. The tent and balloon material will be drawn from stowage bays around the perimeter of the ARV. The balloon material will float freely over the airbeams, avoiding stresses.

In this open C-shaped configuration, as in the current ARM design, SHEPHERD will then approach the asteroid to within 10 m along its principle spin axis (*Fig. 3*), choosing the pole that optimizes illumination of the asteroid and the solar panels of the ARV. Inflation will create a rigid structure, which can be controlled by the ARV stern and front thrusters. Additional (redundant) control during capture could come from the gas thrusters at hemispherically distributed positions on the enclosure, with adjacent cameras and lights, at the expense of losing Xe to space. Both 3D LIDAR and cameras could provide the positional awareness to keep the ARV and enclosure at a safe distance (≥ 3 m) from the spinning asteroid.

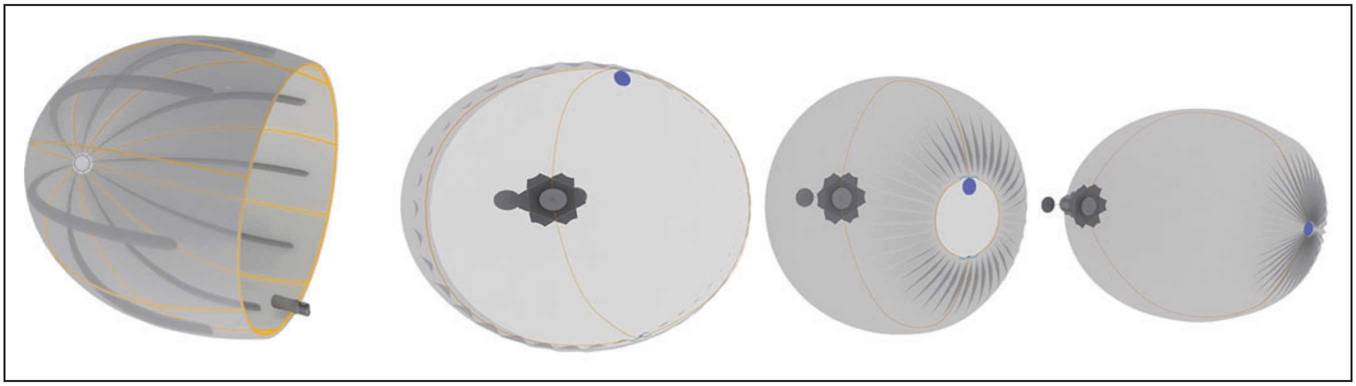

Fig. 2. Notional design for the airbeams, deployment, closing, and sealing mechanism. Blue is the bow cinch cylinder.

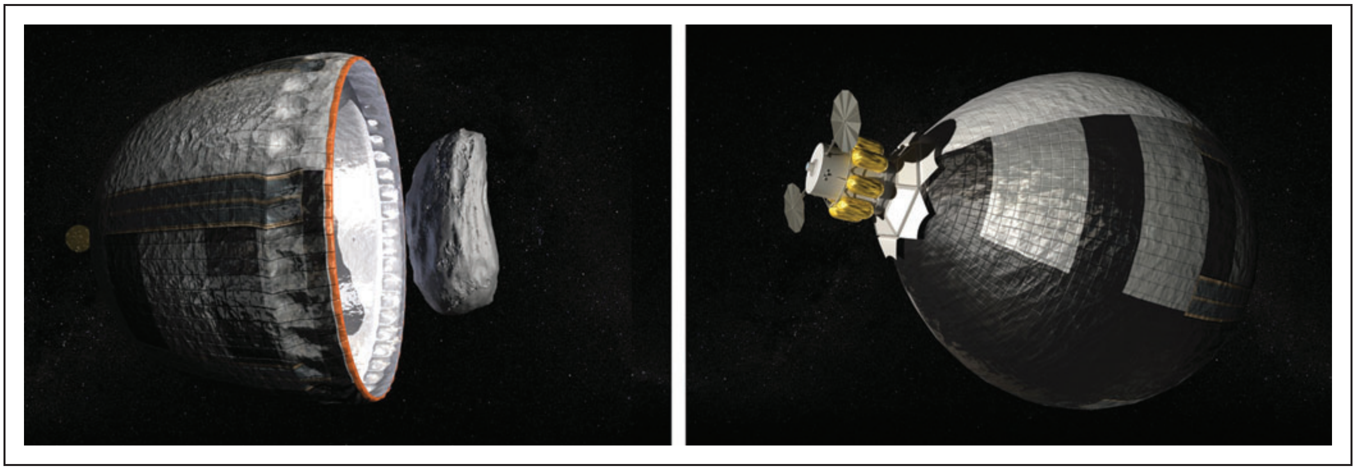

Fig. 3. Views of capture configuration (left) and the sealed state after the introduction of a Xe atmosphere (right). Dark and reflective panels for thermal management are depicted.

Once in position, the front of the enclosure will be pulled together, closed, and sealed. The sealing mechanism is key to creating a sealed enclosure. One way to achieve this (*Fig. 4*) is by making the front 2 m of fabric of the tent a specialized thin-layered material that has a soft component to it that can seal the space between fabric folds (the sealing fabric). Notionally, this fabric would have an existing space-rated NuSil CV-8151 or CV8251 silicone layer applied microns to millimeters thick on both sides. This material is tacky, and so one surface would adhere to the other and seal, but reversible like Post-it Notes®. It is elastic (able to stretch several hundred percent) and suitable for a wide temperature range, down to 170 K. A pair of Vectran ropes can run side by side in folds along the sealing fabric, tracing the full circumference of the opening (60 m). The inner tent fabric is tied to the end of the outer balloon fabric and the sealing fabric is a flap affixed to the balloon so that it can seal the entire structure.

To bring the front of the enclosure together, initially the front airbeams would be deflated, and if needed a further set of curved airbeams could be inflated. Once the enclosure is closed as far as the airbeams can accomplish, a pair of built-in cinch ropes are pulled by two motor-driven rollers attached to the sealing fabric at opposite ends of the enclosure. The prefolded fabric will gather up like a curtain, guided by rails shaped into C-clamps that will control the accumulated fabric similar to a curtain rod. When the rope brings the opening to final closure, the fabric and rails will be drawn around a cinch cylinder and be tightened down by the combined action of the rail clamps and rope (*Fig. 4*). In addition, the two cinching motors provide redundancy with only one functional motor needed to provide a tight seal. Each motor could be driven by a ratchet gear and pawl for fail-safe and reversible operations. The enclosure is sealed in vacuum, but tension on the sealing fabric and clamps will increase when the inner tent is pressurized.

The inner tent would be pulled in with the outer balloon. As seen from the inner tent enclosure, the sealing fabric is exposed for about 1 m around the cinch cylinder. The notional concept for managing the cinch rope is to draw the excess rope back around the balloon to a pair of 4-m-wide take-up spindles at the bottom of the stowage bay. Only 5 windings would be needed to collect the 60-m-long rope. These ropes can also be utilized to enable controlled deflation and

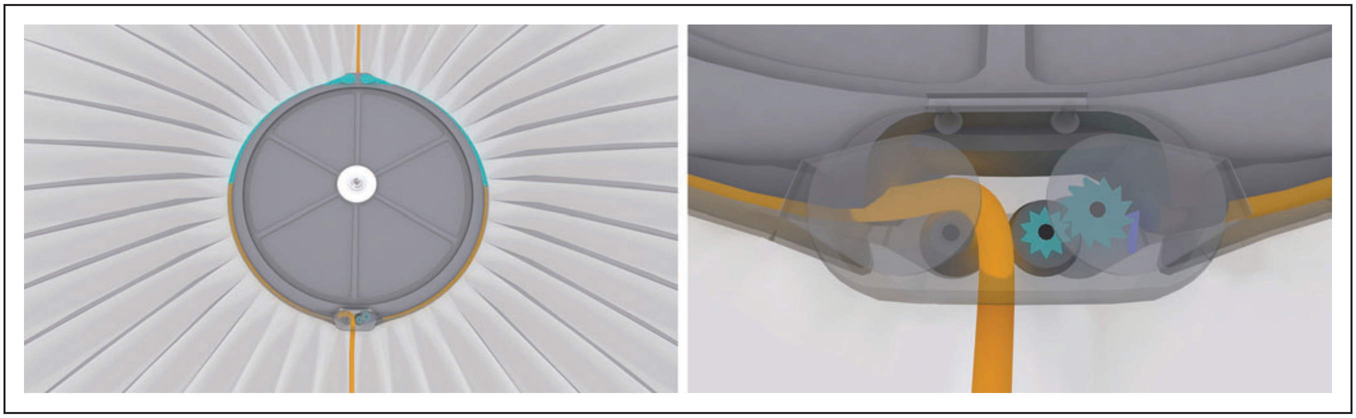

Fig. 4. Notional design for closing and sealing mechanism, outside view and detail.

enveloping of the entire enclosure around the asteroid for safety and fallback scenarios described below.

This system is reversible. The enclosure is opened again by releasing the rope and using the motors to gradually feed rope back into the sleeve in the sealing fabric. The C-clamps and airbeams will create the tension needed to force open the enclosure. Again, future work can investigate alternative sealing mechanisms to the approach proposed here.

Once the enclosure is sealed, SHEPHERD then detumbles and despins the asteroid using turbulent dissipation by gradually filling the inner tent enclosure from all hemispherically positioned vents with up to 0.1 atm. of Xenon gas. The spinning asteroid will spin the gas inside the inner tent enclosure into co-rotation (as when stirring coffee in a cup), gradually dissipating energy and angular momentum via gas heating and shear so as to minimize the transfer of angular momentum to the ARV. If slow enough, the ARV can compensate to despin the system completely over time utilizing its own directional thrusters.

After reaching peak pressure (up to 0.1 atm.), the gas at equilibrium would exert an evenly distributed pressure on the porous asteroid of 10 kPa. The ram pressure at the edges of the spinning asteroid would only be of order 0.05 Pa or less, much less than the roughly 25 Pa cohesive strength[5] of weakly consolidated asteroids such as 2008 TC_3.

The key to despinning the asteroid for improved control of flight, without disrupting it, is to manage the pressure forces on the asteroid by controlling the pressure of the gas in the inner enclosure. By gradually increasing the pressure, it is possible to monitor its effects on the tumbling/spinning asteroid. Full despinning is not necessary for completion of the mission.

SHEPHERD will control the relative position of the enclosure to the asteroid without using fuel, by thrusting Xe gas into the enclosed space (effectively pushing off against the asteroid). Gas thrust into the inner tent can be removed and recovered by opening vents to the envelope between inner tent and balloon, from where it can be pumped back to the ARV for reuse. A notional design for the control elements (thrust/vent units) is shown in *Figure 5*.

During the cruise phase back to Earth, the SEP module will push the SM and tent enclosure with a force of up to 1.5 N. That force to the enclosure can be transferred to the asteroid by pushing the asteroid with a gas flow from ARV to the tip of the enclosure as shown by the arrows in *Figure 1*. The flow is directed to the surface scanned by the 3D LIDAR, shown by the green lines in *Figure 1*. The gas is pumped back via the envelope through vents around the enclosure.

SHEPHERD achieves control of flight by actively keeping the center of mass of the asteroid fixed relative to the enclosure, and controlling the force vector and asteroid spin by changing the direction and magnitude of the gas flow by activating selected thrusters and opening selected vents, or by changing the relative position of the ARV.

Because of zero gravity, the warm gas near the sun-side of the enclosure will not buoyantly move to the cold side. However, temperature control can be achieved by circulating the gas using the thrusters and vents. The gas will be kept at constant overall temperature by controlling the sunlight reflected and absorbed by the balloon using exterior panels of reflective and absorptive fabrics (*Fig. 3*). For ~1 AU capture, the equilibrium temperature of the enclosed gas would be about 273 K (0°C), assuming an average albedo of the tent enclosure of 0.10. By rotating the tent relative to the line of sight to the Sun, the equilibrium temperature can be varied between 157 and 276 K by changing the albedo between 0.90 (reflective) and 0.05 (absorbing).

This proposed system works in an operational environment with residual surface velocities up to 1 cm/s, and is able to accommodate relative motion and irregular asteroid shapes until and after the capture process is completed. By first scanning the asteroid and measuring shape and spin states, the relative position of the ARV to the asteroid can be refined. Once the shape model and spin states are known, the 3D LIDAR can provide a relative position to the tumbling asteroid's center of mass. During unfolding, gas thrust at hemispherical positions along the struts will help adjust the relative speed and orientation of the structure, so that the enclosure stays centered on the spinning asteroid. Gas thrust can move the enclosure by 10 cm in about 5 s.

SAFETY AND FAILURE RECOVERY MODES

In case of catastrophic failure, such as loss of Xe, the SHEPHERD spacecraft can in effect collapse into the nominal ARM approach of bagging the asteroid and returning it using hard contact through the spacecraft with the thrust of the solar electric motor (*Fig. 6*). If the bagging occurs after despinning is complete, the overall collection is

Fig. 5. Detail of camera unit with (from left to right) lights, pressure/temperature sensors, vent to envelope, camera, and gas thruster. The thruster is mounted on a high-pressure supply gas line, while a data and power line connects computer with camera, lights, thruster, and vent.

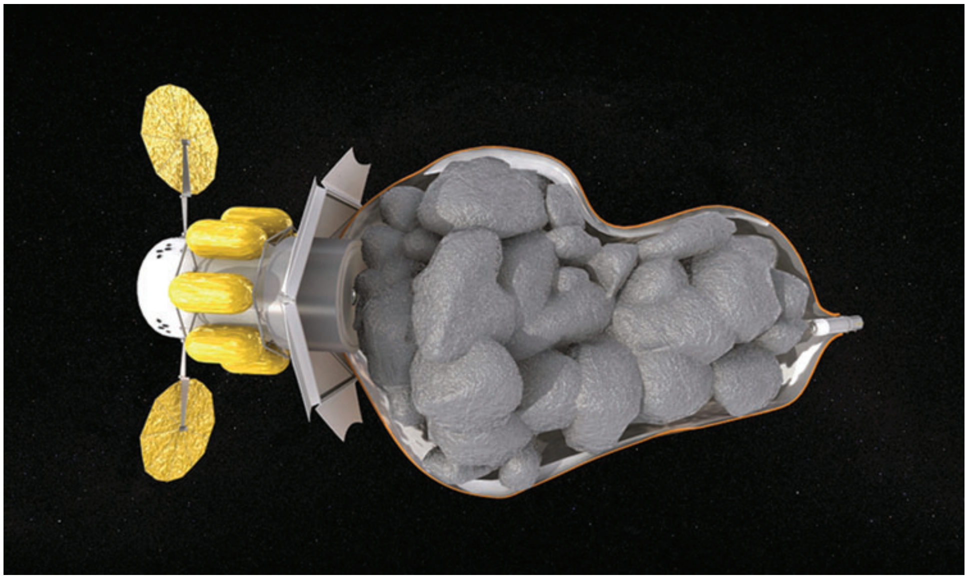

Fig. 6. Representation of fallback mission to nominal ARM hard-contact capture of asteroid.

relatively gentle. The collapse is achieved by deflating the airbreams and then retracting the collapsed enclosure to the stowaway bay by pulling back the remainder of the ropes to the spindle (keeping the seal intact).

If the asteroid disintegrates during despin, the breakup will be well documented and, together with the known pressure environment, will provide key information about internal strength and structure. The goal, however, is to determine such parameters later, in the Earth–Moon environment. Any induced change to the asteroid's surface during the cruise phase will be recorded, thus keeping a scientific record of all components. SHEPHERD's tent enclosure will protect the ARV engines and solar panels from debris, even if surface regolith is lifted or if the asteroid disintegrates.

The gas will lift up dust and smaller rocks from the asteroid. If unchecked, dust will scatter the internal illumination and may obscure the view to the asteroid. Dust is allowed to settle over time by circulating the gas and collecting dust in filters at the intake vents of the pumps. Dust is periodically removed from the window in front of the cameras by electric charging. All collected dust can later be studied. In an emergency, this material could also be vented to space in an orbit away from the ARV by opening the bow cylinder vent (at the expense of losing Xe).

Redundant units containing gas thruster, vent, camera, light, and sensors ensure that any one failing due to dust contamination or valve failure can be shut off. Any four of the remaining units, if suitably distributed, could provide directional flight control.

FEASIBILITY: ASTEROID CAPTURE AND DESPINNING

Preliminary studies show that SHEPHERD will be able to guide a 4–10-m-mean-diameter asteroid (maximum dimension of 13 m), weighting 100–1,000 metric tons, spinning and tumbling at any rate (not just <0.5 revolutions per minute), and having a composition, internal structure, and physical integrity that will likely be unknown until after the rendezvous and capture.

An operational pressure of 0.1 atm. was used in past high-altitude helium balloons of similar size as SHEPHERD (*Fig. 7*). To fill the tent up to 0.1 atm. (10^4 Pa) pressure for an Xe gas at this temperature, a total of about 2 metric tons of Xe is required. This is still only a fraction of the available 10 metric tons in the current ARM design, leaving the remainder for propulsion and operations.

The internal energy of the gas will be of order 6×10^7 J, compared with the expected spin kinetic energy of an asteroid about its minor axis of about 1×10^3 J. Assuming a rough equipartition of energy when a tumble occurs, the tumble energy will also be on the order of 10^3 J, or 10^{-4} times the gas thermal energy, so that the gas should absorb the energy from the asteroid without noticeable heating.

For Xe at 273 K and our gas densities, velocities, and dimensions, the Reynolds number is expected to be in the range $10{,}000<\mathrm{Re}<100{,}000$, well into the turbulent regime ($\mathrm{Re}>5{,}000$). This means that the asteroid's tumble and spinning energy should be lost to turbulent dissipation in wakes and eddies trailing the spinning arms. For turbulent gas the energy dissipation can be calculated statistically, the primary quantity of interest being at what rate energy is dumped into the turbulent cascade at long wavelengths. That energy is transferred into shorter wavelength modes due to nonlinear interactions that couple neighboring modes, stopping at the Kolmogorov scale, which is the scale at which the viscosity forces finally start to hinder the cascade. Initially, a steady state will quickly form, such that the energy is transferred to scales at which the viscous dissipation rate is equal to the rate at which energy is being taken up by the gas. If energy is fed into the largest scale eddies, the specific drag power would be about 2.7×10^{-2} J/s/kg. If that involves about 1% of the gas in the enclosure (20 kg), then the drag power is 0.5 J/s, capable of slowing the asteroid in about 7 h, if no bulk flow forms.

This naïve estimate does not take into account the process of slowing down or of corotating flow. It is expected that the gas will spin up into a bulk flow as the asteroid spins down, such that a second quasi-equilibrium is reached when the kinetic energy of the flow becomes comparable to that of the asteroid. Energy will then be lost in the boundary layer at the shell, and the process could be an order of magnitude slower than estimated above. The actual process of detumbling and despinning needs to be investigated further, with the

Fig. 7. Example of a 15-m-diameter high-altitude helium balloon, operated at 0.1 atmosphere pressure, during Nott's 1984 crossing of Australia.

aid of full 3D hydrodynamic flow modeling. The effect of turbulent gas flow on differential pressures at the surface of the asteroid needs study too. Possibly, the peak gas pressure can be lowered and still achieve a reasonable timescale for detumbling and despinning. The most suitable inner tent pressure is the lowest pressure at which sufficient energy dissipation can be achieved.

FEASIBILITY: GAS FLOW TO TRANSFER FORCE IN CRUISING PHASE

It may be necessary to have an internal pressure as high as 0.1 atm. to despin the asteroid initially. After that, however, the system could operate at a substantially lower pressure, dictated only by the rate at which the gas can be differentially pumped out of the enclosure for the Xe flux needed to push the asteroid. The balloon would keep its shape with an internal pressure of below 10^{-3} atm., reducing substantially the rate of leaking during the long cruise phase.

The SEP system is expected to deliver up to 1.5 N of force to the spacecraft for a period of ≥ 1 year to create the desired few 100 m/s delta *V*. To impart orbital changes to the asteroid when in a free-floating state is more complex than for the current ARM mission design, which calls for a rigid system involving stable physical coupling of the ARV with the asteroid.

Forcing an asteroid 10 times heavier than the ARV with a bulk flow of Xe from tail to tip of the enclosure, and at the same time keeping the ARV at constant distance from the asteroid, would require effectively pushing the ARV with 1.5 N with the SEP, and then supplying 1.36 N forward to the asteroid using gas thrust. In that case, both move forward as if they were a single object propelled at 1.5 N.

The required gas flux depends strongly on the effective area over which the gas needs to push the asteroid. Distributing the force equally over the full surface of the asteroid would require a flow velocity of about 0.15 m/s to impart 1.36 N over 100 m^2, which would require pumping about 50 m^3 of gas per second. On the other hand, a 0.1 atm. flow directed to an area of 1 m^2 of the asteroid surface would require an effective flow velocity of only 2 m/s (a 4-knot wind, less than a light breeze), pumping 2 m^3/s of Xe gas, for a peak ram pressure of 1.5 Pa, which is less than the 25 Pa cohesive strength of the asteroid. The gas would need to be pumped back to the ARV at the same molar rate, but lower pressure.

During cruise phase, the application of that flow is autonomously determined by measuring the center of mass of the now despun asteroid. Control is possible by knowing the 3D topography of the surface to which the gas is directed, as measured by the LIDAR. Spin-up can be avoided, and reversed, by controlling the direction of the gas flow. The asteroid will ultimately re-orient in a low-velocity flow with the side with smallest surface area facing the ARV. Once despun, the asteroid can be brought closer to the back plate, to within 3 m, increasing the efficiency of momentum transfer. A feature of this type of control is that it is stable in the sense that if the jets undersupply momentum in the direction of motion, the asteroid drifts closer to them such that their delivery becomes more efficient.

Other environmental concerns related to the use of an enclosure do not affect the net propulsion. The pressure from solar radiation on the enclosure (assuming a fully reflecting surface) is 9×10^{-6} Pa. The pressure from solar wind is only 2.5×10^{-10} Pa. For a 20-m-diameter enclosure, the force is 1×10^{-3} N from solar wind and 1×10^{-7} N from radiation pressure. This is significantly less than the 1.5 N from the SEP. Leaking of Xe from the enclosure (including from punctures by meteoroids not stopped by the balloon fabric layers) will impart a weak force on the structure, which is automatically compensated by deliberate gas thrusts into the enclosure to re-position the enclosure around the asteroid. Those thrusts too will put weak forces on the asteroid, but will tend to be nondirectional, under penalty of moving the enclosure off-center. The net force on the system will be significantly less than that from the equivalent mass of Xe being propelled by the ion engines.

The effect of micro-meteoroid impacts can be minimized by the use of multiple thin layers (Whipple shield) for the outer balloon fabric, and by maintaining a lower pressure between inner tent and balloon. During a 5-year mission, the largest meteoroid to likely hit a 20-m-diameter sphere at 1 AU is about 0.003 g with diameter $d \sim 0.2$ cm, according to the Grün dust model.[6] Punctures from larger meteoroids will result in loss of Xe over time. If the internal pressure drops to zero, the airbeams will prevent the inner tent from collapsing. As long as sufficient Xe is available to push the asteroid, the mission can continue. If the loss becomes too large, the enclosure can be collapsed gently on the now despun asteroid.

APPLICATIONS: CREWED SAMPLING RENDEZVOUS MISSION

The goal of SHEPHERD is to bring a frail asteroid in as pristine a condition as possible to the Earth–Moon system, where the enclosure can be opened into the C-shape by loosening the cinch ropes to reveal and release the intact asteroid into a lunar orbit. Closer to Earth, human crew missions could deploy advanced techniques to study the asteroid's internal strength and sample its material variety in context.

A human crew that would rendezvous with a free-floating asteroid would face some of the same challenging conditions as encountered in larger asteroid missions. Even 10-m-sized asteroids are complicated worlds. Bringing an intact asteroid to the Earth–Moon system will create a proving ground for future manned missions to more distant targets in solar orbit, making ARM a viable stepping stone for future longer duration missions to Mars.

To keep the asteroid untouched and uncontaminated, docking with the ARV is not recommended. It is, however, possible to keep the asteroid in the tent enclosure as long as the autonomous active monitoring of the tent position relative to the asteroid can be maintained by having sufficient Xe available. Continued enclosure will protect the asteroid from contamination during the crewed vehicle approach and proximity operations. After the sampling mission, the asteroid can be recaptured by the ARV and guided to lunar surface impact or continue in its orbit around the Moon as a destination for future missions. If the ARV is resupplied with Xe by the crewed mission, it could be reused to retrieve another candidate object.

In the contingency that the asteroid disintegrated en route and was secured as a bag of rocks by collapsing the enclosure (*Fig. 6*), then access is provided by unwinding the cinch rope at the tip of the collapsed tent. Handles on the bow cinch seal cylinder will help astronauts release the ropes and access the bag. For further science value, the enclosure could also be re-sealed and re-inflated to 10^{-4} atm. and spun along the long axis of the ARV to create a laboratory to study asteroid re-accumulation under weak centrifugal forces.

APPLICATIONS: ASTEROID RESOURCE UTILIZATION

SHEPHERD's enclosure concept is a technology demonstrator that could be applied in a number of later applications, including asteroid resource utilization. All mining operations at asteroids need a sealed enclosure to prevent dislodged rocks and dust from interfering with the spacecraft. Once it is demonstrated that a sealed enclosure can be created surrounding an asteroid, it becomes possible to replace the Xe gas with other gasses to facilitate the extraction of minerals.

Further into the future, the encapsulation of icy planetesimals would enable the collection of outgassing volatiles. These volatiles could be used for thrust to move the assembly to key points in the solar system, or be used as refueling stations for robotic and crewed missions, thereby supporting a sustainable spaceflight architecture. Even more, a gas atmosphere can keep water in a liquid phase, in which case the asteroid may provide a substrate for introduced biological agents for the generation of foodstuffs and other consumables. In one such scenario, human exploration of Mars could be preceded by the positioning of one or more SHEPHERD resource extraction craft with their source objects in Mars orbit such that upon arrival crews would have a full supply of return propellant and consumables for surface operations resupplied from orbit.

COST DIFFERENTIAL

An effort to evaluate the differential cost between this approach and that of the previously proposed concepts of ARM is outside the scope of this article. The key cost variables used in the NASA and Air Force Cost Model are mass, power, and complexity (related to some baseline or analogy). Compared to the current "bag" concept, from which the SHEPHERD concept evolved, SHEPHERD will require about 2 metric tons of additional Xe gas. Power is required to operate the gas pumps, attitude control computer, LIDAR (and/or cameras), and vents for the duration of the cruise phase. Technical risk, particularly for systems with no heritage, can also be an important contributing factor. For example, it still has to be demonstrated that an enclosure can be sealed around the asteroid. On the other hand, technical advantages may include being able to handle asteroids with less well-determined physical properties, less concern about tearing fabric, a better protection of the spacecraft from debris kicked off from the surface, and no need to negotiate physical contact with a boulder of unknown properties.

Heritage comes from inflatable spaceborne structures that have been deployed since NASA's echo communication and geodesy satellites in 1960 and 1964. In recent years, the Genesis orbital missions by Bigelow Aerospace and the upcoming deployment of that company's gas-inflated BEAM module to the International Space Station demonstrate heritage and a high Technology Readiness Level (TRL) for certain components needed to deploy SHEPHERD. The use of gasses for propulsion, living systems, and other applications is ubiquitous in spaceflight, but the use of gasses in enclosures for guiding objects in microgravity has no heritage. Systems to fix the position of a spacecraft around an object are complicated, but have been investigated in various concepts for drag-free relativity and gravity wave missions.

For such concepts, SHEPHERD may serve to advance the technology needed for future robotic applications.

CONCLUSIONS

By adapting the current "bag" design of ARM by sealing the enclosure and by filling it with Xe gas, it becomes possible to despin intact even a weakly consolidated rubble-pile asteroid of unknown spin state and size (but less than a maximum size determined by the size of the enclosure), and to use gas pressure to guide it gently and safely to the Earth–Moon system in as close to a pristine state as possible. Hard contact with the asteroid can be avoided.

In case of catastrophic failure, such as loss of xenon, the SHEPHERD concept can in effect collapse into the nominal ARM approach of bagging the asteroid for return. Even in this fallback case, the captured material would be handled more gently than in the current ARM designs, since hard closure occurs after despinning is complete. The enclosure protects the ARV from material shed by the asteroid.

The SHEPHERD mission concept keeps intact the most interesting science of asteroid internal structure and surface features for a more in-depth study during the later crewed sampling mission. Understanding the physical processes that determine the internal structure of 10-m-scale asteroids is key to understanding and preventing future Chelyabinsk airburst events. Small 10-m-sized asteroids may present physical processes that are not seen in larger >100 m asteroids, nor in the smaller <1 m meteorites that survived impact with the Earth's atmosphere. In addition, SHEPHERD makes possible the collection of fragile materials in primitive asteroids that are perhaps not yet represented in our meteorite collections. Recovered primitive materials can be used in research on the origins of life. The retrieved intact asteroid becomes a proving ground for future manned missions to asteroids in heliocentric orbit and a testing ground for several planetary defense technologies. Finally, the development of a sealed enclosure is an important technology demonstration to enable future *in situ* resource utilization.

The key technological challenges to making SHEPHERD a reality are the deployment and sealing of the enclosure, the robotic attitude control of the enclosure relative to a spinning asteroid, and learning how to use Xe gas to safely control the enclosure and handle various sizes and types of encapsulated asteroids. The notional solutions we have described here have yet to be tested through prototyping and computational modeling.

ACKNOWLEDGMENTS

P.J. learned to appreciate the potential complexity of small asteroids from the fall and recovery of 4-m-sized asteroid 2008 TC$_3$. For that, he thanks Muawia Shaddad and students of the University of Khartoum, Sudan.[7] P.J. is supported by NASA's Near Earth Object Observation program. B.D. is supported by DigitalSpace Research.

AUTHOR DISCLOSURE STATEMENT

No competing financial interests exist.

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