IAC-14-D2.8-A5.4.1

TECHNOLOGY DEVELOPMENT FOR NASA's ASTEROID REDIRECT MISSION

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Abstract

NASA is developing concepts for the Asteroid Redirect Mission (ARM), which would use a robotic spacecraft to capture a small near-Earth asteroid, or remove a boulder from the surface of a larger asteroid, and redirect it into a stable orbit around the moon. Astronauts launched aboard the Orion crew capsule and the Space Launch System rocket would rendezvous with the captured asteroid mass in lunar orbit, and collect samples for return to Earth. This mission will advance critical technologies needed for human exploration in cis-lunar space and beyond. The ARM could also demonstrate the initial capabilities for defending our planet against the threat of catastrophic asteroid impacts. NASA projects are maturing the technologies for enabling the ARM, which include high-power solar electric propulsion, asteroid capture systems, optical sensors for asteroid rendezvous and characterization, advanced space suits and EVA tools, and the utilization of asteroid resources. Many of the technologies being developed for the ARM may also have commercial applications such as satellite servicing and asteroid mining.

INTRODUCTION

NASA is developing concepts for the Asteroid Redirect Mission (ARM), which would use a robotic spacecraft with a solar electric propulsion system to capture a small near-Earth asteroid, or to remove a boulder from the surface of a larger asteroid. In both mission concepts, the robotic spacecraft would redirect the asteroid mass into a distant retrograde orbit around the moon. Astronauts launched aboard the Orion capsule and the Space Launch System (SLS) rocket would rendezvous with the captured asteroid mass in lunar orbit and perform an extravehicular activity (EVA) to collect samples for return to Earth (Fig. 1). The robotic mission would be launched around 2019, and the crewed mission would be launched around 2025 (Ref. 1).

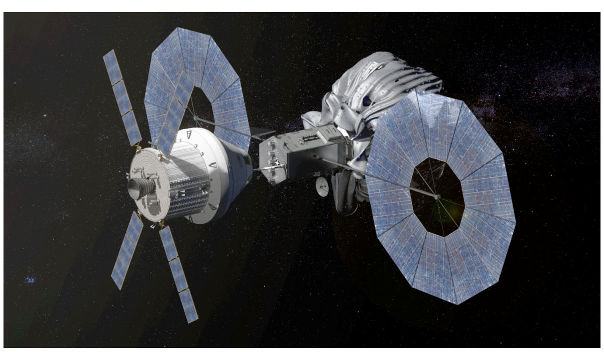

Fig. 1 : Orion docking with the Asteroid Redirect Vehicle (ARV).

The ARM leverages and integrates multiple activities in human exploration, space technology, and space science in order to make progress toward a range of objectives, including:

- Conduct a human exploration mission to an asteroid in the mid-2020's, providing systems and operational experience required for human exploration of Mars.
- Demonstrate an advanced solar electric propulsion system, enabling future deep-space human and robotic exploration with applicability to private and public sector space needs.
- Enhance detection, tracking, and characterization of near-Earth asteroids (NEA), enabling an overall strategy to defend our home planet.
- Demonstrate basic planetary defense techniques that will inform impact threat mitigation strategies required to defend our home planet.
- Pursue a target of opportunity that benefits scientific and partnership interests, expanding our knowledge of small celestial bodies and enabling the mining of asteroid resources for commercial and exploration needs.

To begin the process of identifying key technologies for enabling the ARM, NASA issued a request for information in June 2013 to gather a wide range of ideas from the broad community. Over 400 ideas were submitted by industry, universities, government agencies, non-profit organizations, and individuals from around the world. The 96 most promising ideas were synthesized in public workshop held in November 2013 (Ref. 2). Building upon these ideas, a Broad Agency Announcement (BAA) was issued in March 2014 to solicit proposals in five high-priority areas : asteroid capture systems, rendezvous sensors, adapting commercial spacecraft for the ARV, partnerships for secondary payloads, and partnerships for enhancing the crewed mission (Ref. 3). Eighteen proposals were selected for six-month studies to define and mature system concepts and to assess the feasibility of potential commercial partnerships to inform the ARM Mission Concept Review, which is planned for February 2015. The BAA contracts and other NASA activities that are maturing the technologies needed for the ARM, such as high-power solar electric propulsion, asteroid capture systems, optical sensors for asteroid rendezvous and characterization, advanced space suits and EVA tools, and utilization of asteroid resources, are described in the following sections.

SOLAR ELECTRIC PROPULSION

The ARM robotic spacecraft would use a 50-kilowatt Solar Electric Propulsion (SEP) system to spiral out of low Earth orbit, rendezvous with a near-Earth asteroid, and redirect the captured asteroid into a stable lunar orbit. NASA is developing the main components for a high-power SEP system, which are the solar arrays, a high-voltage power management and distribution subsystem, Hall thrusters, and Power Processing Units (PPUs).

In October 2012, NASA awarded contracts to ATK Space Systems and Deployable Space Systems (DSS) to develop high-power prototype solar arrays for future SEP systems (Ref. 4). The ATK MegaFlex array is a circular fanfold flexible blanket array with radial ribs. It is 9.6 meters in diameter and is capable of generating 25 kilowatts per wing. Deployment of the array was validated in thermal vacuum chamber tests at NASA Glenn Research Center’s (GRC) Plum Brook Station (Fig. 2). The DSS ROSA (Roll-Out Solar Array) is a modular flexible blanket array that is 4.5 meters wide and 14 meters long. It is capable of generating 25 kilowatts per wing. Solar cell coupons that operate at 300 volts are being fabricated and tested for both arrays.

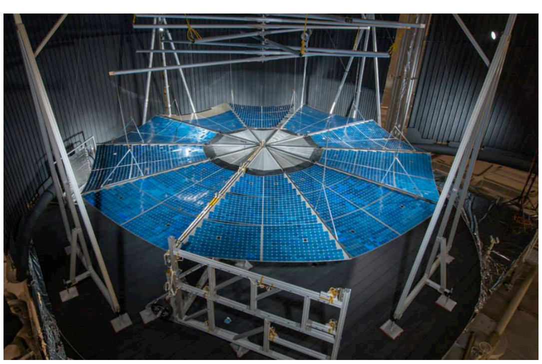

Fig. 2: ATK MegaFlex solar array

The solar arrays will supply power to four 12.5-kilowatt Hall thrusters on the ARV. A Hall thruster generates thrust by ionizing xenon gas and accelerating it to high velocity using magnetic and electric fields. The Jet Propulsion Laboratory (JPL) and NASA GRC are developing magnetically shielded Hall thrusters to reduce channel erosion rates and extend the thruster life by more than an order of magnitude (Ref. 5). The JPL H6 Hall thruster has been operated at 3,000 seconds specific impulse, and the GRC 300M thruster has been tested at 20 kilowatts (Fig. 3). GRC is designing and building a prototype magnetically shielded 12.5-kilowatt thruster for the ARM.

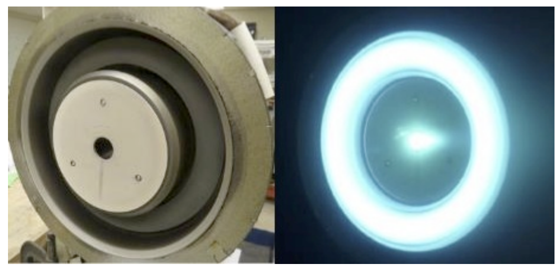

Fig. 3: GRC 300M Hall thruster

PPUs are needed to convert the input power from the solar arrays to the output power needed to run the thrusters. Two prototype PPUs are being developed: a PPU with 120 volts input and 800 volts output, and a PPU with 300 volts input and 400 volts output. Both PPUs are throttleable. A high-voltage direct drive unit is also being developed to potentially eliminate the need for a PPU. An integrated test of the prototype Hall thruster and PPU is planned.

NASA awarded BAA contracts to Boeing, Lockheed Martin, Space Systems/Loral, and ExoTerra Resource to study how existing commercial spacecraft buses could be adapted for the ARV to reduce development costs. The major challenges with using existing spacecraft are integrating the SEP system and the asteroid capture system. Extensive structural modifications may be required to accommodate the tanks that hold 10,000 kilograms of xenon propellant. These companies will also investigate commercial applications of a separate SEP module and its extensibility to 300 kilowatts for future human missions to Mars.

RENDEZVOUS SENSORS

Optical rendezvous sensors are needed for a wide range of mission applications including automated rendezvous and docking, asteroid characterization and proximity operations, and satellite servicing. To minimize costs, NASA would like to develop a common suite of rendezvous sensors that could be used for the ARV, Orion, and other missions. The common sensor suite would include a visible camera, a long-wavelength infrared camera, and a 3D lidar. The visible and infrared cameras would be used for long-range navigation during the rendezvous phase. The 3D lidar would be used to characterize the asteroid's size, shape, and spin rate during proximity operations and provide range information during the approach and capture phase.

The Sensor Test for Orion Relative Navigation Risk Mitigation (STORRM) experiment flown on the Space Shuttle in 2011 demonstrated prototype rendezvous and docking sensors for Orion (Ref. 6). To continue the maturation of existing rendezvous sensors for the ARM and to integrate them into prototype common sensing systems, NASA awarded BAA contracts to Ball Aerospace and Boeing. Further flight tests are planned in the Raven experiment on the ISS in 2016.

ASTEROID CAPTURE SYSTEMS

Since an asteroid capture system has never been developed before, it is the least mature and highest risk technology required for the ARM. NASA is considering two options for the asteroid capture system.

In Option A, a whole small asteroid that is four to ten meters in size would be captured in a cylindrical fabric bag that is deployed from the ARV by inflatable or mechanical booms (Fig. 4A). Key technical challenges are capturing an asteroid that may be rotating at up to 0.5 revolutions per minute, and that may consist of a loose agglomeration of rocks and regolith (rubble pile) that is held together by the asteroid's weak gravity. The mass of the asteroid could be up to 1,000 metric tons.

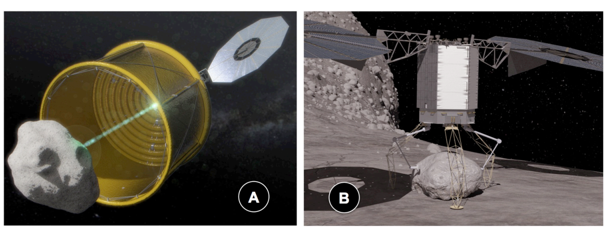

Fig. 4: (A) Deployable bag captures a whole small asteroid; (B) Robotic manipulators pick up a boulder from the surface of a larger asteroid.

The ARV would approach the asteroid along its primary spin axis, and try to match the asteroid's rotation rate as closely as possible. After the asteroid has been positioned inside the open-ended bag, winches would cinch cables attached to the capture system's structure to collapse the bag around the asteroid and restrain it firmly against the spacecraft. The bag would contain any loose material, and friction between the bag and the asteroid would help to slow its spin. Thrusters on the ARV would then fire to null the asteroid's residual spin.

JPL has developed a 1/5-scale proof-of-concept capture system using six mechanically deployable petals and inflatable tubes, and demonstrated the capture of a simulated rotating asteroid (Fig. 3, Ref. 7). BAA contracts were awarded to Airborne Systems and Jacobs Engineering to develop and test alternate capture system designs using inflatable and mechanical booms, respectively.

Fig. 5: Proof-of-concept inflatable asteroid capture system (JPL)

An innovative approach for de-spinning the asteroid before it is captured is to use a tether for angular momentum exchange. A nanosatellite deployed from the ARV anchors one end of the tether to the asteroid. The nanosatellite then unreels a long tether as it increases its distance from the asteroid and the asteroid's spin is slowed. Tethers Unlimited, Inc. is investigating this approach (Ref. 8).

In Option B, a boulder that is one to five meters in size would be picked up from the surface of a larger asteroid using robotic manipulators (Fig. 4B). The mass of the boulder could be up to 50 metric tons. In this mission scenario, the ARV would rendezvous with a near-Earth asteroid that has already been well characterized by a previous robotic mission such as Hayabusa or OSIRIS-REx. The main technical challenge with this capture system concept is overcoming the unknown cohesive forces between the boulder and the surrounding regolith. Boulder jacking or pneumatic excavation devices may be needed to augment the force from the robotic manipulators.

NASA is developing a concept for Option B that uses three articulated spaceframe trusses and two robot arms (Ref. 9). The four-segment spaceframe trusses would act as landing legs. They would contact the surface of the asteroid and slow the ARV to a stop by flexing their joints to absorb energy. The robot arms would grasp the boulder using microspine grippers on the end of each arm. The microspine grippers, which were developed by JPL, use hundreds of tiny hooks to grip rough surfaces (Fig. 6, Ref. 10). To break the captured boulder free from the asteroid's surface, the spaceframe trusses would straighten their joints to push the ARV away from the asteroid. The spaceframe trusses would then be retracted around the boulder to cradle it against the spacecraft for the trip to lunar orbit.

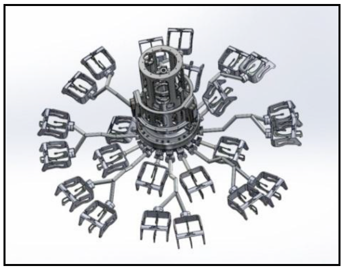

Fig. 6: Microspine gripper (JPL)

NASA Goddard Space Flight Center is demonstrating boulder capture with microspine grippers on seven degree-of-freedom robot arms, and testing relative navigation sensors and algorithms. NASA Langley Research Center is testing full-scale articulated spaceframe trusses in two dimensions on a flat floor.

To investigate alternate concepts for picking up a boulder, NASA awarded BAA contracts to Space Systems/Loral and Altius Space Machines. A down select decision between Option A and Option B will be made in December 2014.

PLANETARY DEFENSE DEMONSTRATIONS

Various techniques for deflecting a potentially hazardous asteroid could be tested on the ARM to enable planetary defense capabilities (Ref. 11). These techniques include Ion Beam Deflection, Enhanced Gravity Tractor, and kinetic impactors.

In Ion Beam Deflection, the plumes from the Hall thrusters would be directed towards the asteroid to gently push on its surface over a wide area. A thruster firing in the opposite direction would be needed to keep the spacecraft at a constant distance from the asteroid. The Ion Beam Deflection approach is independent of the size of the asteroid, and it could be demonstrated on either mission Option A or B.

In the Enhanced Gravity Tractor approach, the ARV would first pick up a boulder from the asteroid's surface as in mission Option B. The ARV with the collected boulder would then orbit in a circular halo around the asteroid's velocity vector. The mass of the boulder augments the mass of the spacecraft to increase the gravitational attraction between the spacecraft and the asteroid. The ARV would have to fly in close formation with the asteroid for several months in order for the very small gravitational forces to produce a measurable change in the asteroid's trajectory.

A kinetic impactor could be launched as a secondary payload with the ARV or on a separate launch vehicle, and it would collide with the target asteroid at high velocity while the ARV observed the impact. The Deep Impact mission to comet Temple 1 demonstrated this technique in 2005 (Ref. 12). Honeybee Robotics was awarded a BAA contract to study a concept called Shotgun to deploy multiple small impactors from the ARV at low velocity to characterize the properties of asteroid regolith over a wide area.

NANOSATS AND SECONDARY PAYLOADS

Nanosats could be deployed from the ARV or launched as secondary payloads to address Strategic Knowledge Gaps (SKGs), support commercial interests such as resource prospecting, and scout candidate asteroids for future human missions. The SKGs represent unknown environments, hazards, and the availability of resources at potential destinations that could affect the design of human space flight systems (Ref. 13). NASA uses the SKGs to guide the planning of robotic precursor missions.

The ARV is being designed to accommodate deployers for up to six CubeSats. A CubeSat could provide images of the ARV during the asteroid capture sequence from a standoff vantage point. A swarm of CubeSats could deploy various scientific instruments at multiple points on the asteroid to determine its surface properties and internal structure. CubeSats could also prospect for water and metals and return small samples from multiple locations to the ARV. Deep Space Industries and Planetary Resources Inc. were awarded BAA contracts to study how their microspacecraft could be leveraged to increase the commercial utility of the ARM.

NASA Marshall Space Flight Center is developing a low-cost robotic precursor mission called the NEA Scout (Ref. 14). This secondary payload would be deployed from SLS during its first mission in 2018. NEA Scout is a 6U CubeSat that uses an 80 square meter solar sail for propulsion. After several lunar flybys, it would fly by a NEA and take high-resolution images to reduce the risk of unknown hazards to future human missions.

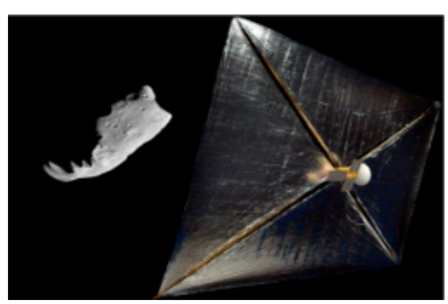

Fig. 7: NEA Scout asteroid precursor mission

In addition to CubeSats, there are other types of secondary payloads that could be carried by the ARV. The Johns Hopkins University Applied Physics Laboratory was awarded a BAA contract to develop a prototype hopper that would be dropped on the asteroid surface to measure elemental composition of the asteroid regolith at multiple locations. The Planetary Society would provide a small canister containing extremophile bacteria, which would be attached to the ARV during its journey through deep space. The canister would be retrieved by astronauts and returned to Earth to test the panspermia theory of astrobiology.

ADVANCED EVA AND HABITATION

In the reference scenario for the crewed mission, two astronauts will be launched aboard Orion to explore the captured asteroid mass in lunar orbit. After rendezvousing with the robotic spacecraft, Orion will dock to the ARV. The cabin will then be depressurized and the astronauts will exit through the hatch to conduct an EVA. A translation boom will be extended from Orion to allow the astronauts to reach the ARV. They will use handrails on the ARV to move along its body until they reach the captured asteroid mass, which may be contained in a fabric bag. They will cut away a section of the bag material and collect samples for return to Earth.

Due to mission mass limitations, it is not possible to launch both a pressure suit and a space suit for each astronaut. Consequently, NASA is adapting an existing pressure suit called the Modified Advanced Crew Escape Suit (MACES) so that it can also function as a space suit (Ref. 15). The astronauts wear the basic pressure suit during launch and landing. For EVA, a Portable Life Support System (PLSS) is attached to the astronaut's back, and a lightweight thermal management garment is donned over the pressure suit. Astronauts wearing the MACES will be capable of performing short-duration EVAs that last about four hours.

The PLSS is the first new space suit system developed by NASA since the Shuttle Extravehicular Mobility Unit was introduced in 1981 (Ref. 16, Fig. 8). The PLSS uses new several technology components such as a regenerative rapid cycle amine unit for carbon dioxide removal, a suit water membrane evaporator for thermal control, a variable oxygen pressure regulator, and lithium ion batteries for energy storage. The PLSS has been tested with a human metabolic simulator and a mockup space suit, and vacuum chamber tests with a human will begin in 2015.

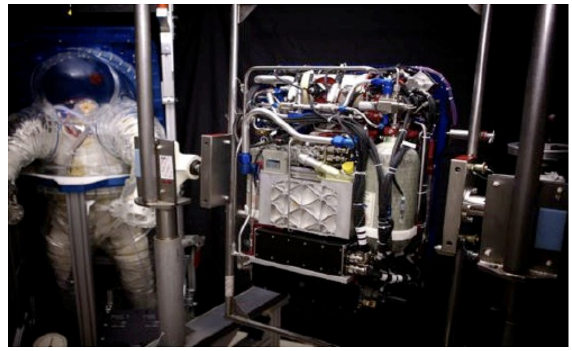

Fig. 8: Portable Life Support System for EVA

The crew has conducted several underwater tests of the MACES in a neutral buoyancy facility to simulate the tasks they would perform during the ARM (Fig. 9). Mockups of the Orion capsule and the ARV were used in the pool for these tests. The astronauts were able to egress from the Orion hatch, move across the translation boom to the docked ARV, and collect samples from the surface of a simulated asteroid using handheld tools. Honeybee Robotics was awarded a BAA contract to begin development of the drilling tools and sample caching systems that will be needed for EVA.

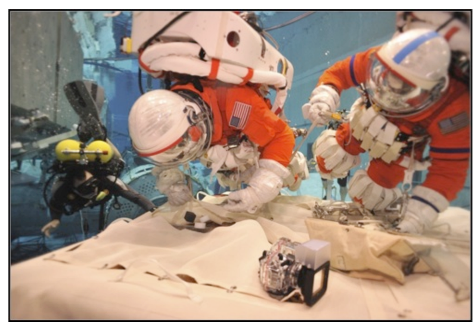

Fig. 9: Astronauts testing the MACES in a neutral buoyancy facility.

The maximum duration of the crewed mission using only Orion is limited to about 25 days. The duration could be extended up to 60 days by deploying a small habitat module in lunar orbit prior to launch of the crewed mission. The habitat module would first dock with the ARV, and then Orion would dock with the habitat module. NASA is developing concepts for an Exploration Augmentation Module (EAM) that would provide more consumables for life support, a larger habitation volume, docking ports, and an EVA airlock. The EAM may allow the ARM crew size to be increased to four astronauts. The EAM could also be used to test capabilities needed for a long-duration Mars transit habitat.

IN-SITU RESOURCE UTILIZATION

One of the goals of asteroid exploration is to identify sources of ice, metals, and rare earth elements that could be mined and used for in-space production of water, oxygen, propellants, lightweight structures, solar arrays, and spare parts. In-situ utilization of asteroid materials could enable more affordable and capable human exploration missions because consumables such as propellants and oxygen do not have to be launched from Earth. Refined asteroid materials could also be used as the feedstock for 3D printers to enable in-space manufacturing. Technology needs for asteroid mining include instruments for surface and subsurface prospecting, systems to collect subsurface samples and excavate asteroid materials, and systems for in-situ materials processing. A major technical challenge for asteroid mining is the asteroid's ultra-low gravity, which requires systems that can be anchored to the surface.

Many of the technologies needed for asteroid mining and in-space manufacturing will first be tested on the moon and the International Space Station (ISS). NASA and JAXA are planning a joint mission called Resource Prospector that will search for water and other volatiles in the polar regions of the moon in 2019 (Ref. 17). This project is developing prospecting instruments, a subsurface sampling drill, and a miniature oven that will process lunar regolith to produce water. In 2014, NASA and Made In Space, Inc. are also planning to demonstrate a 3D printer on the ISS to fabricate plastic spare parts (Ref. 18).

Several small companies have recently been formed to pursue commercial exploitation of asteroid resources. BAA contracts were awarded to Deep Space Industries and Planetary Resources Inc. to study how the ARM can support commercial objectives. For example, the ARM could target a carbonaceous (C-type) asteroid that is rich in hydrated minerals, and the astronauts could deploy a small in-situ resource utilization experiment to extract water from the collected asteroid material.

EXTENSIBILITY TO HUMAN EXPLORATION OF MARS AND OTHER MISSION APPLICATIONS

NASA's long-range goal is to land humans on Mars in the mid-2030s. In the next decade, the advanced capabilities needed for human missions to Mars will be demonstrated in the proving ground of cis-lunar space. Many of the technologies being developed for the ARM are extensible to human exploration of Mars.

The ARM SEP system could be scaled up in power to 300 kilowatts and used to efficiently transport heavy cargo to Mars. The automated rendezvous and docking sensors being developed for ARM will be needed to assemble large vehicles and systems in orbit for the trip to Mars and the return to Earth. The autonomous robotic systems being developed for asteroid capture could enable robots that set up and checkout equipment on Mars before the crew arrives. The next generation space suit and EVA tools that will be tested on ARM will allow astronauts to explore the surfaces of Mars and its moons. The Exploration Augmentation Module could be used to demonstrate capabilities needed for a deep space Mars transit habitat. The in-situ utilization of asteroid materials may enable in-space propellant depots to refuel Mars exploration vehicles.

NASA is studying an Evolvable Mars Campaign to define the overall architecture of missions for reaching Mars (Ref. 19). One possible scenario is to send humans to Phobos before landing on Mars. It is not too big of a step from the ARM to Phobos because the moons of Mars are likely to be captured asteroids. We will know what environments and hazards to expect, and how to conduct operations on low-gravity bodies.

The technologies being developed for ARM may also have commercial applications such as satellite servicing, orbital debris removal, and asteroid mining. The synergies with the technology needs for satellite servicing are particularly strong (Ref. 20). A satellite servicing system would probably use a SEP tug to reposition satellites, automated rendezvous and docking sensors, and autonomous robotic manipulators. The asteroid capture system could be used to capture defunct spacecraft and orbital debris for disposal.

CONCLUSION

The ARM will be a milestone in human history. For the first time, we will be able to rearrange a small piece of the solar system that has been circling the sun for billions of years and use it to increase our prosperity and security. Just as we have learned to modify our terrestrial environment and harness the Earth's resources, we are now beginning to transform our neighborhood in space for our purposes. Who knows where this may lead us in the far future? It has been hypothesized that an advanced technological civilization could rearrange their solar system to construct a Dyson Sphere that completely encompasses their star to capture all of its energy output (Ref. 21).

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