The Brane Craft Phase II Program: Redefining Spacecraft Design and Applications

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ABSTRACT

The NASA Innovative Advanced Concepts (NIAC) group funded a concept study for an active membrane spacecraft to cost-effectively remove kilogram-class orbital debris in the spring of 2016. This Phase I effort showed that an 81-gram mass, 1-square meter Brane Craft (short for membrane spacecraft) with a thickness of only 50 microns could deorbit up to 0.9-kg of orbital debris from anywhere in low Earth Orbit (LEO; altitudes less than 2000-km). Removing 5,000 1-kg class debris objects from LEO would cost at least 2 billion USD using CubeSats, while fabrication, testing, launch, and operations costs would be at least an order-of-magnitude lower using Brane Craft. That would leave close to 1.8 billion USD for non-recurring costs to develop this new type of spacecraft.

The Phase II effort started in 2017 to initiate technology development on key components, subsystems, and systems. To date, this effort has demonstrated radiation-hard, thin film, flexible ZnO transistors on Kapton, and is now focusing on logic gates and sensors that can survive in the harshest radiation regions of LEO for a month without any physical shielding. Additional tasks include demonstrating thin film actuators for membrane curvature control, developing robust thin-film computing networks that can handle 50 or more micrometeoroid impacts per square meter of membrane per month, performing higher-fidelity mission analyses for the LEO orbital debris removal mission, and analyzing cis-lunar and interplanetary applications for Brane Craft that take advantage of its unprecedented 16 km/s delta-V (ΔV) capability.

1. THE BRANE CRAFT CONCEPT

Spacecraft generally require a certain minimum aperture size to generate power, enable a required gain for communication antennas, and/or provide a minimum optical resolution. The Brane Craft concept evolved from the realization that the third spacecraft dimension, and hence total mass, is determined by technology and design, not basic physics. Minimum spacecraft mass occurs when the third dimension is reduced as much as possible, resulting in an essentially sheet-like two-dimensional vehicle. A two-dimensional mem**Brane** space**Craft**, or Brane Craft, can provide unprecedented power-to-weight and gain-to-weight ratios for highly-agile spacecraft.

Figure 1 shows a rendering of a 1-meter square Brane Craft with a thickness of 50 microns and an estimated mass of 81 grams about to wrap itself around a piece of space debris. Figure 2 shows a cross-section of this basic design that uses two 10-micron thick Kapton® sheets as the main structural elements. A 21.6-micron gap between these sheets is filled with an ionic liquid, the propellant for a distributed nano-electrospray thruster system that provides a total ΔV of 16 km/s.

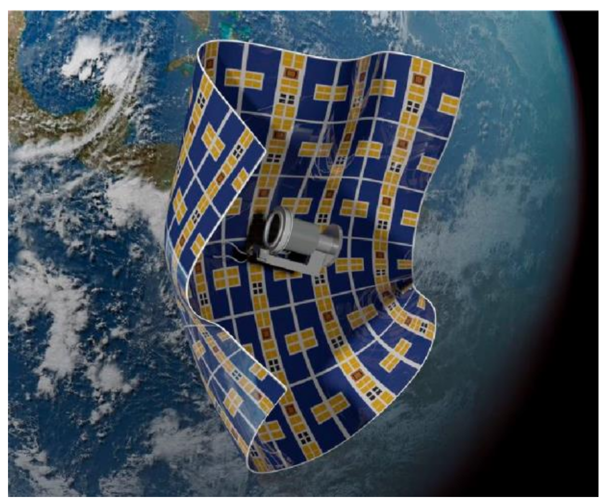

Figure 1: Rendering of a 1 square meter Brane Craft for active orbital debris removal.

Figure 2 shows electronics sheets, with thin film solar cells deposited on the outer surfaces, bonded to the main structural sheets. The electronics sheets contain most of the spacecraft systems (command and control, spacecraft solar power and power conditioning, communications, attitude determination and control, navigation, etc.). These sheets are smaller than the 1-meter square main structural sheets to provide inexpensive fabrication of micron-scale thin-film transistors (TFTs) and microelectromechanical systems (MEMS) on one surface, and thin film solar cells, diodes, and switching transistors on the other surface. We don't need transistors and other elements with minimum feature sizes approaching 10 nanometers, like current nanoelectronics, because Brane Craft have thousands of square centimeters of substrate area. Note that typical integrated circuits have substrate areas of a few square centimeters or less. Transistors with one-micron minimum feature size were typical for mid-1980's digital electronics, providing processing speeds between 1 and 3 million instructions per second. While slow by today's standards, this speed is more than adequate for Brane Craft command and control and attitude control using ten or more distributed processors.

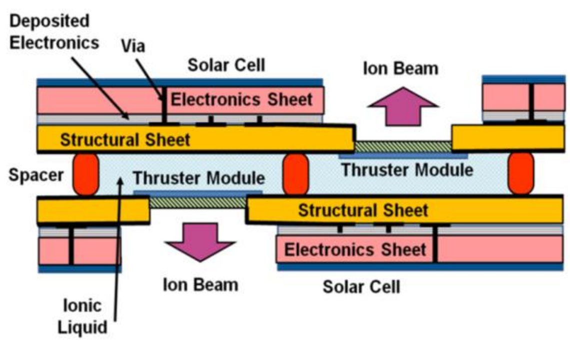

Figure 2: Schematic cross-section of a Brane Craft.

The structural sheets in Fig. 2 act as primary structure, propellant tank, shape control system, and circuit board. These sheets are patterned with a 10-micron minimum feature size to enable inexpensive screen or roll-to-roll printing, like a newspaper, over one or more square meters of area. Shape-changing surface actuators are printed onto the outer surfaces, and provide local curvature control over the entire surface.

Figure 3 shows a schematic cross section of a flat panel display using liquid crystal optical shutters. White light in each display pixel (right side in Fig. 3), enters a bottom polarizer, transits through a structural glass panel and transparent electronics, passes through the liquid crystal material held between the glass plates, passes through the top glass plate, a color filter (blue in this case), and another polarizer before exiting. Transparent, electrically-conducting indium tin oxide (ITO) electrodes, controlled by transparent TFTs deposited on the bottom glass panel, apply a twisting electric field between the top and bottom panels of each pixel. This field twists the liquid crystal molecules between the top and bottom glass plates, resulting in a rotation of the light, about a vertical axis for this figure, passing from the bottom polarizer to the top polarizer. For polarizers with a 90º difference in the direction of polarization (crossed-polarization), the pixel will be black when the controlling transistor is "off", and blue when the transistor is "on". Typical TFTs used in large flat panel displays use amorphous silicon as the semiconductor, with ~30-micron minimum feature size. Unfortunately, amorphous silicon is too slow and does not possess sufficient radiation tolerance for our Brane Craft application.

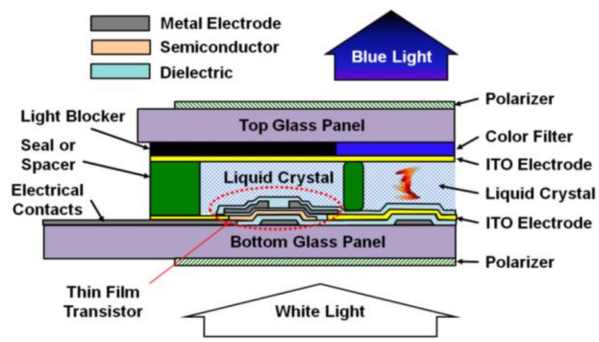

Figure 3: Schematic cross-section of flat panel display.

Note the similarity between the basic structures in Figs. 2 and 3. Both systems have main structural sheets that contain a liquid between them using capillary action, and both require millions of thin film transistors for proper operation. Modern 4K displays require at least 25 million transistors. An Intel 80286 microprocessor, the "brain" of the IBM AT personal computer introduced in 1984, used only 134,000 transistors. The Brane Craft design is much thinner and flexible (the flat panel display glass sheets are 1 to 4 mm thick).

2. ACTIVE ORBITAL DEBRIS REMOVAL

NIAC requires a mission application, and our mission was to actively remove thousands of kilogram-class objects in low Earth orbit (LEO; between 200 to 2,000 km in altitude). LEO has the highest density of debris and active spacecraft, and collision rates are expected to increase from about one every few years to once a year as object densities double within the next decade.[1,2]

A Brane craft will start in a low LEO orbit like the ISS orbit, fire on-board electric thrusters to reach the target debris orbit, fine-tune the orbit for rendezvous, maneuver within a few cm of the orbital debris, wrap itself around the debris object in a cylinder, fire thrusters to decrease altitude, and burn up as the altitude drops below 200 km due to atmospheric drag. While significant orbit inclination changes are typically required on the way "up" to rendezvous, no inclination change is required on the way "down". The nominal ΔV required to go "up" from a 400-km altitude, 51.6º inclination ISS orbit to a 2000-km altitude, 90º inclination circular orbit is 4.8 km/s. The nominal DV required to go "down" from a 2000-km altitude circular orbit in LEO to a 200-km altitude circular disposal orbit is only 884 m/s. This allows a Brane Craft with a residual 11 km/s ΔV capacity at rendezvous (16 km/s at start, minus 4.8 km/s to go "up", and minus an additional 0.2 km/s for rendezvous and docking) to deorbit a debris mass that is 11.43 times heavier; about 0.9 kg.

To make economic sense, Brane Craft should be able to remove debris objects that are more than an order-of-magnitude larger in mass, with recurring fabrication and testing costs equal to traditional spacecraft, on a per mass basis. 3U CubeSats that could perform this mission would currently cost about ~$150,000 each in quantity, with a launch cost of approximately $250,000 per spacecraft. Since a Brane Craft would have a mass of only ~80 grams, launch cost to LEO should be less than $25,000 each. Fabrication and testing costs are expected to be less than $15,000 each due to mass-production and automated testing. Removing 5,000 1-kg class debris objects from LEO would cost approximately 2 billion USD using CubeSats, while fabrication, testing, launch, and operations costs would be at least an order-of-magnitude lower using Brane Craft. That would leave close to 1.8 billion USD for non-recurring costs to develop this radically new type of spacecraft.

3. PHASE I RESULTS

The Phase I results are chronicled in the Final Report and a conference paper.[3,4] Mission analyses showed that an 81-gram mass Brane Craft with a maximum 180-W of available solar power for thrusting and 4,000-s specific impulse nano-electrospray thrusters could perform an active deorbit mission with the maximum possible debris mass within 1 month. Environmental analyses of Brane Craft with a one-month operational lifetime in LEO showed that electronics degradation due to trapped particle radiation, and impacts by the local micrometeoroid population, were the largest technological issues. A Brane Craft has essentially no radiation shielding, and requires a radiation tolerance of about 5 megarads total integrated dose (TID) over a one-month long mission for the worst-case environment. Note that consumer electronics have a TID limit of only 1 to 10 kilorads; they would survive for 1 to 2 hours, unshielded, in the highest radiation environment in LEO. We identified thin film zinc oxide and carbon nanotube electronics as having the required physical flexibility and radiation tolerance. Both technologies would be used in creating complementary metal-oxide semiconductor (CMOS) electronics, the workhorse of our current micro/nanoelectronics industry.

The micrometeoroid environment was a concern because the main structural elements of a Brane Craft are only 10 microns thick. A 4-micron diameter particle, impacting with a potential relative velocity of 10 km/s, could penetrate these sheets. Based on the Master micrometeoroid model, which includes man-made debris in LEO, a 1-meter square Brane Craft could be penetrated ~40 times during a one-month long mission. Solar cells can be protected by adding bypass diodes, but the electronics, sensors, and propulsion system need to be designed with redundancy and the ability to isolate shorted subsystems and swap in functional elements. Brane Craft require a resilient internal power bus and intranet.

Thermal control was the next issue. Brane Craft are two-dimensional spacecraft with almost no thermal mass. They cool down rapidly after entering eclipse, to settle at a temperature primarily determined by the absorptivity/emissivity properties of the solar cells. A simulation of overall Brane Craft temperature was run using a 1350 W solar flux, a 200 W thermal flux from the Earth, a Kapton® specific heat of 1.09 J-gram/K, an EMIM-BF4 (1-Ethyl-3-methylimidazolium tetrafluoroborate) propellant, a specific heat of 1.9 J-gram/K, an absorptivity of 0.8, and an emissivity of 0.8. This simulation used the current Brane Craft structural mass of 82 grams, plus a full load of 27 grams of propellant. The simulations showed that the maximum equilibrium temperature was 342 K (+69º C) in sunlight, and 205 K (-67º C) while in eclipse. The cool-off time constant was less than 60 seconds. The high temperature could be acceptable, but the eclipse temperature will freeze EMI-BF4 ionic liquid propellant. Its freezing point is 298 K; 15º C. A Brane Craft with no internal batteries or heat sources would become a frozen hibernating spacecraft during most of eclipse. No thrusting, attitude control, or shape-changing would occur during eclipse, with the rest of the spacecraft in deep sleep mode running off energy stored in thin film capacitors. Fortunately, warmup to operating temperature would occur within 60 seconds. Hibernation mode was an integral part of the orbit-raising and lowering simulations.

Brane Craft use distributed nano-electrospray thrusters for attitude control and primary propulsion. Electrospray thrusters use applied electric fields on the order of 1 V/nm to electrodynamically pull a conducting liquid into a "Taylor Cone" with a ~3-nm radius sharp tip at the apex. This sharp tip further amplifies the applied electric field by about an order-of-magnitude, thus generating ~10 V/nm fields that directly field evaporate the liquid ions. This ionization process is extremely efficient and can yield ion currents of 500 nA or more per tip. Thrust is between 6 and 20 nanonewtons per tip for specific impulse (I_{sp}) between 2000 and 5000 s, and overall thrust scales as the number of active tips.

Ion current per tip, which is proportional to thrust, is independent of overall Taylor cone size. It should therefore be possible to create nano-electrospray thrusters with smaller Taylor cones and significantly reduced overall dimensions. Molecular dynamics simulations of electrospray thrusters performed at Penn State showed Taylor cone formation with 500 nA ion currents using base diameters as small as 12 nm with tip base-to-extractor distances of less than 0.07 microns.[5] These simulations used the ionic liquid EMIM-BF_4 flowing out of platinum capillaries. Nano-electrospray thruster arrays can be thin film structures a few microns thick, and a centimeter or less in lateral dimension. With a thrust of about 13 nanonewtons per tip at 4000-s I_{sp}, an 8 mm x 8 mm array with 10-micron lateral spacing between tips could generate 8.2 millinewtons of thrust using 630 thousand emitters. Input power is 180 W; 200 W maximum input with 20 W diverted to other spacecraft functions. In practice this single array would be split into 5 or more smaller arrays distributed about the 1-meter square surface area to enable attitude control and primary propulsion.

Development of nano-electrospray thrusters should start in the next few years as conventional micro-electrospray thruster systems reach a TRL of 6 or higher.

4. PHASE II EFFORTS

The 2-year long Phase II effort started in the spring of 2017. The major tasks have been:

- Development and testing of radiation-tolerant thin film electronics,
- Development and testing of fault-tolerant distributed computers and buses,
- Evaluation of shape-changing surface actuators,
- Identification of potential Brane Craft applications in cis-Lunar and interplanetary space,
- Evaluation of increased delta-V possibilities using nano-electrospray propulsion, and
- Evaluation of ultra-thin active membrane spacecraft based on solar sail propulsion.

4.1. Radiation-tolerant Thin Film Electronics

We've fabricated ZnO test structures, TFTs, and logic gates on polyimide thin films. Polyimide is our analog of Kapton®. The films were spin-coated on silicon wafers, and the various electronics layers were patterned on top. The polyimide could then be peeled off to leave flexible thin film electronics on a thin plastic layer. Radiation-hard ZnO process recipes based on published literature were used. Processing occurred at The Aerospace Laboratories, with some steps performed at the University of California, Santa Barbara Nanofabrication Facility. Figure 4 shows a mask set with different colors representing the masks for the various metal, oxide, and semiconductor layers.

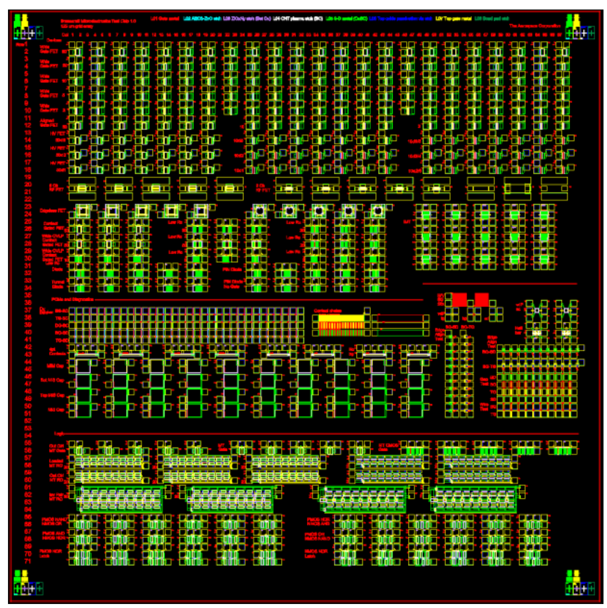

Figure 4: Mask set for development and testing of radiation-tolerant thin film transistors and circuits.

To date, we've completed five different fabrication runs with process and design improvements after each run. Overall, yield is improving, but more improvements are still needed. The threshold voltage of 2-micron devices, the preferred size for Brane Craft, is now at the ideal level of 0.5 V. Figure 5 shows measured I-V characteristics for one 2-micron transistor, with a 0.5 V threshold voltage. Larger transistors in the 5 to 50-micron range still have a large negative threshold value of -8 V, most likely due to trapped charges in atomic layer deposition (ALD) oxide layers. Trans-conductance was measured at 0.1 μS/μm; typical of ZnO transistors reported in the literature.

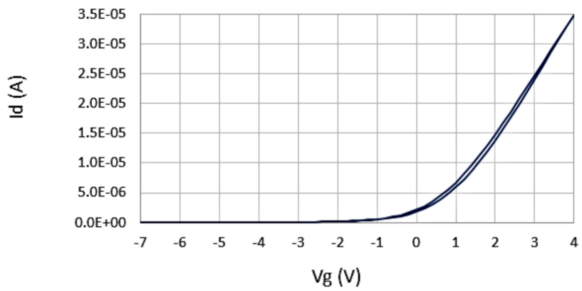

Figure 5: Measured current-voltage characteristic of one particular 2-micron thin-film ZnO transistor fabricated on a thin-film polyimide substrate on silicon.

On-going efforts include measurement of capacitance in various MOS structures, modification of masks to support larger gate oxide overlaps, a switch to negative photoresist processing, and integration of 2-micron devices into logic gates. This should result in improved metal layer edge quality and elimination of unintentional shorts and open circuits that have impacted overall yield.

Radiation testing of fifth-batch transistors in our Cobalt-60 source has started with a maximum dose of 10 Megarads (Si). A new mask for Lot 006 has been designed and fabricated to support negative photoresist processing with larger gate oxide overlaps to ease alignment requirements.

4.2 Fault-tolerant distributed electronics

We assembled a breadboard to simultaneously operate eight single-board Arduino microcontrollers to test fault-tolerant interconnections for data buses in Brane Craft. There is a reasonable probability that a microprocessor will be pierced by a micrometeoroid during a nominal 30-day active debris removal mission in LEO, and we are evaluating capacitively-coupled data lines that can tolerate a shorted or open data pin. This breadboard enables rapid testing of different values of capacitive coupling and modulation schemes to enhance the robustness of data transfer.

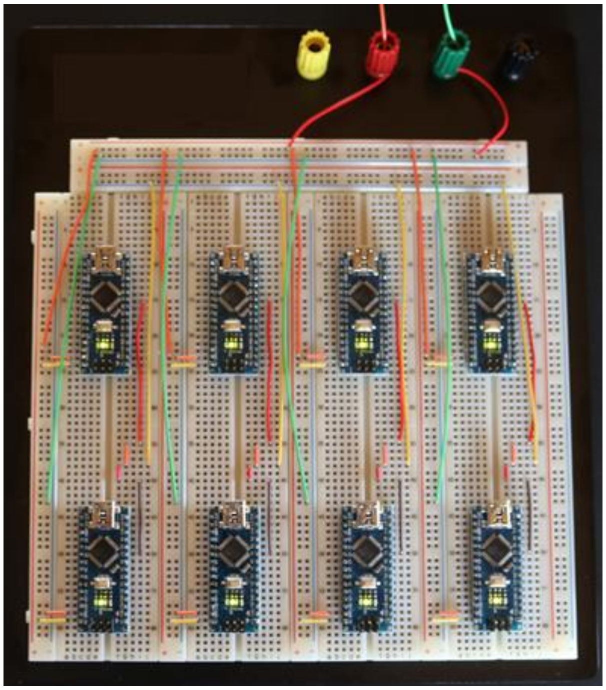

Figure 6: Photograph of an eight processor breadboard network using Arduino Nano microcontrollers.

4.3 Shape-changing Surface Actuators

Shape control is a key requirement for Brane Craft, and a number of potential actuator concepts are available. The simplest actuator is a capacitor with a flexible dielectric. Application of a potential difference, typically hundreds to thousands of volts, causes the capacitor plates to attract and compress the dielectric. The dielectric expands in the plane parallel to the electrodes, generating an expansion force that can put an attached structure into tension. The advantage of this approach is that no liquids are involved, the structure does not have to be sealed, and it won't freeze if the Brane Craft gets too cold. The disadvantages are that high voltages are required, and the deformations are small.

"Muscle" wires, or titanium-nickel shape memory alloys, contract up to 5% in length when heated to 90° C. We tested these as potential surface curvature actuators by stapling 150-micron diameter Flexinol® LT (low temperature) wires every 4-to-10 cm onto thin card board sheets up to 76-cm long, and applying up to 0.7 amperes of current across the wire. Figure 7 shows one example where a 50-cm wide orange cardboard substrate was curled into a 120° arc using a double-folded wire across its midsection. Individual wires of this diameter can generate a tension of 570 grams, so the total tension force in this case was about 1.1 kg.

The cardboard in this case was 250-microns thick and generated orders-of-magnitude more bending resistance than a Brane Craft composed of two structural layers of 10-micron thick Kapton®.

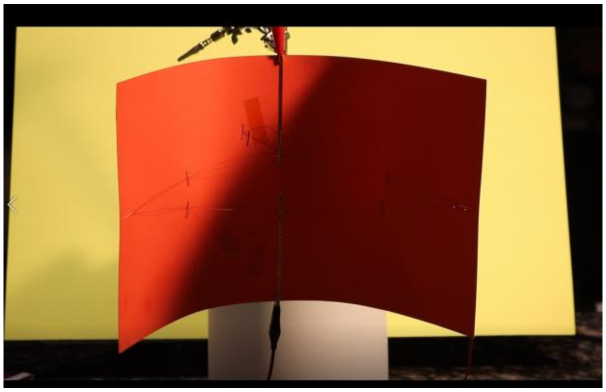

Figure 7: Photograph of an active Flexinol® shape memory alloy wire bending a cardboard substrate.

Although thermally-driven actuators are problematic for a Brane Craft in low Earth orbit that can experience temperature swings of greater than 100 ^{o}C between full sunlight and eclipse, they may still provide critical functions if the "on" temperature can be increased beyond the normal high operating temperature, or if they are used for passive control beyond LEO where orbit eclipse fractions decrease, and eventually vanish.

We attempted to demonstrate a thermal actuator based on sub-micron droplets of alcohol distributed in silicone that vaporize above 78 ^{o}C, resulting in an up to 100x volume increase. These materials have been demonstrated using ethanol dispersed in silicone in a number of soft actuator designs.[6] We deposited a 100-micron thick layer of isopropyl-silicone on a 50-micron thick Kapton layer to test if the transition temperature could be raised by a few degrees (isopropyl has a boiling point of 82 ^{o}C vs. 78 ^{o}C for ethanol). This test failed; apparently isopropyl does not form the required sub-micron droplets when mixed with silicone. We are now testing an ethanol-based thin-film version.

Ionic polymer-metal composites are another approach that we are evaluating in the laboratory.[7] In this actuator, a sheet of ion exchange polymer such as Nafion is coated with flexible metallic electrodes, and the interior filled with an electrolyte. When a potential is applied between the electrodes, anions head toward one electrode and cations head towards the other. If the cations, e.g., Na (H2O)4+, are bigger, the region near the negative electrode swells, and the entire sheet bends with the negative electrode convex outward. These devices actuate at a few Volts, but they require liquid containment and can't tolerate high-velocity particle-induced leaks. We are evaluating use of ionic liquids instead of an aqueous salt solution since ionic liquids have essentially no vapor pressure and can therefore tolerate small physical leaks in the electrodes. A filled actuator can still freeze when a Brane Craft enters eclipse, but this is not a problem.

4.4 Cis-Lunar and Interplanetary Applications

The Phase I proposal identified orbiting Mercury, Venus, Mars, Jupiter, Saturn, Uranus, and Neptune as other potential missions within the nominal 16 km/s delta-V capability for a Brane Craft. Brane Craft could also orbit, or land on, tens-of-thousands of asteroids and moons in our solar system, starting from a nominal International Space Station (ISS) orbit. Can a Brane Craft escape from Earth without exceeding a 5 megarad TID while transiting the high-radiation Van Allen belts?

Figure 8 shows an altitude vs. time profile for a Brane Craft on an Earth escape trajectory starting from a 400-km altitude circular orbit at 0^{o} inclination. There is no inclination change, just orbit-raising, and the equatorial starting orbit was chosen to maximize the trapped radiation dose on the outbound trajectory. This chart shows the first 32 hours of the escape trajectory, and the Brane Craft hit Earth escape velocity a little later at 38.7 hours after start. Earth eclipses are included, during which no thrusting occurs. The Brane Craft spends 21 hours in the main radiation belts where the radiation dose levels for Brane Craft electronics approach 3 x 10^{8} rads per year. A trajectory calculation yields an integrated dose of ~700 kilorads during the outbound trajectory; significantly less than the baseline 5 megarad total integrated lifetime dose.

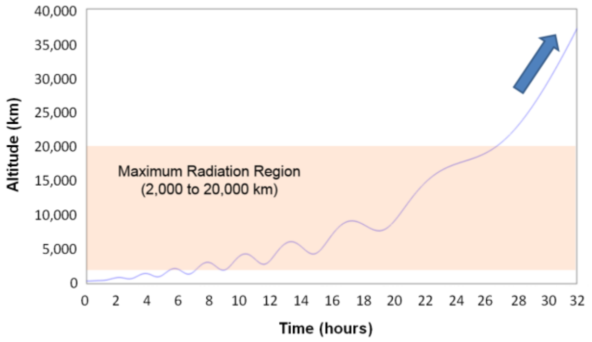

Figure 8: Escape trajectory simulation of a Brane Craft starting in a 400-km circular orbit with no inclination changes.

Figure 9 shows calculated minimum delta-Vs to complete various legs of outbound journeys to reach various solar system targets using the "Subway Map" approach. In this case, going from one end of a colored line to the other requires a certain delta-V in m/s rather than monetary cost typically used in terrestrial subway maps. To go from the ISS to a low orbit about Mars' moon Deimos, for example, requires 3180 m/s to reach Earth escape velocity ("Earth Intercept" in Fig. 2), an additional 1080 m/s to reach Mars Intercept, an additional 990 m/s to reach Deimos Intercept, another 2 m/s to go into a low orbit about Deimos, and a final 4 m/s to land on Deimos. The outbound journey requires a total delta-V of 5256 m/s. The return leg, under ideal conditions, requires the same delta-V for a total round trip value of 10.5 km/s. A Brane Craft could therefore start in LEO, land on Deimos, and return to LEO, potentially carrying a gram or more of surface material, and/or many gigabytes of data. It could also start in LEO, travel to a 100-km altitude Lunar orbit, and return to LEO (total delta-V of 7.78 km/s), twice. Brane Craft could also be used to shuttle small masses, up to 270 grams, from the ISS to a Lunar Gateway station, or reverse.

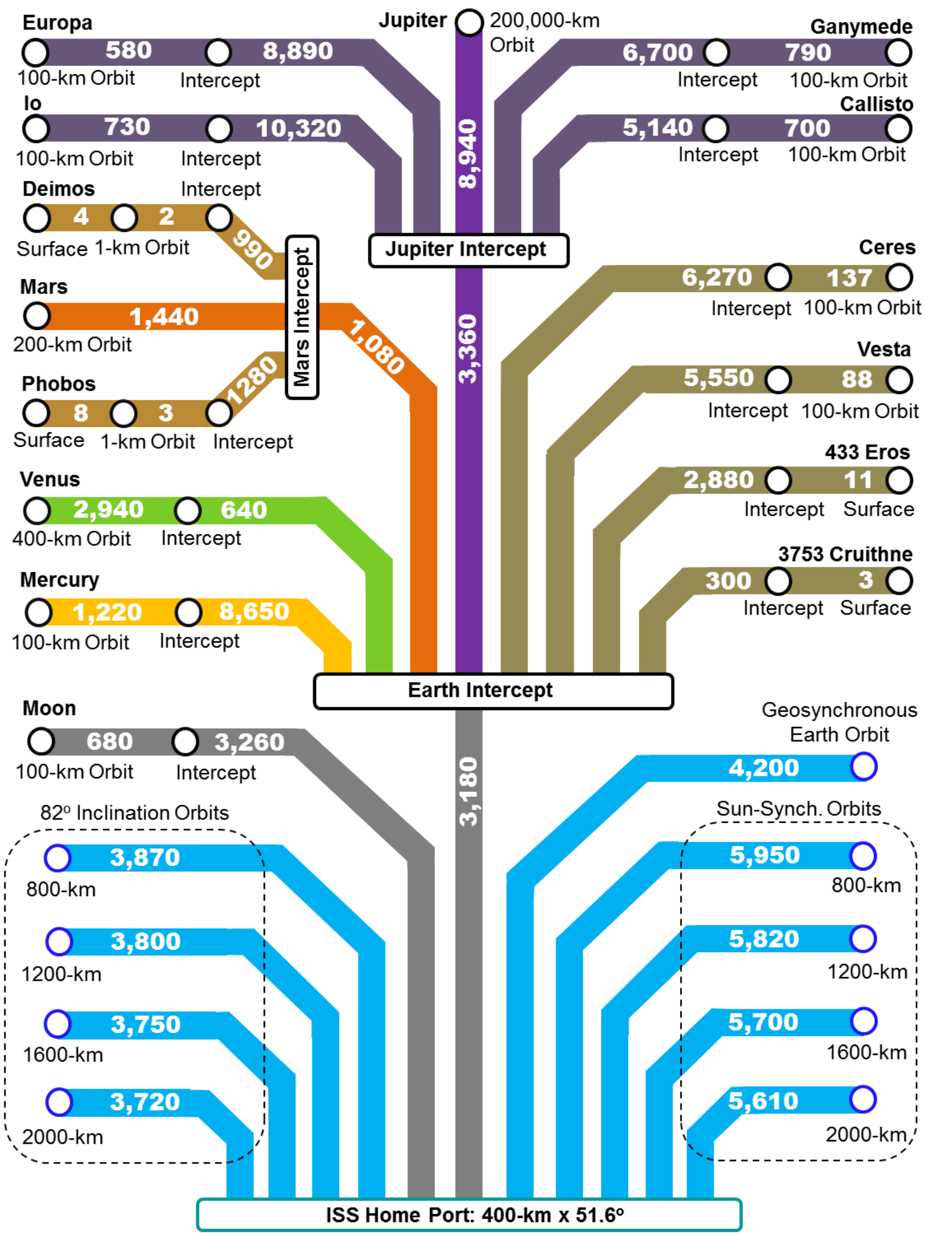

Figure 9: Solar system delta-V map for reaching various solar system targets.

Figure 9 gives delta-V values for landing on the surface of various moons and asteroids when maximum Brane Craft acceleration (0.1 m/s^2) is higher than the surface gravity. The maximum diameter for a spherical asteroid or moon with a 3.5 gram/cc density is ~220 km. Ceres is much larger and has a surface acceleration of ~0.27 m/s2, so a low orbit is listed as the final destination. In this case, a minimum total delta-V of 3,180 + 6,270 + 137 = 9.59 km/s is required to orbit Ceres starting from an ISS orbit. To enable a return to the ISS, the Brane Craft delta-V must be increased to 19.2 km/s. This could be accomplished by increasing propellant mass, and hence thickness of the propellant storage region, by a modest 25%.

4.5. Extended Delta-V Design and Applications

While traditional ion engines are typically operated for thousands of hours, an 81-gram mass Brane Craft with a 4000-s I_{sp} nano-electrospray thruster system and 180 W of available solar power can "burn" its entire 27.2-grams of propellant, generating a delta-V of 16 km/s, within 36 hours. This propellant load requires that the main structural sheets be 21.6 microns apart. Unlike standard propulsion systems where increasing the propellant load leads to an increase in tank volume and mass, the "tankage fraction" (mass of tank divided by the mass of stored propellant) of a Brane Craft is essentially zero since the main structural sheets serve a double duty as the propellant tank. Figure 10 shows calculated wet mass, propellant layer thickness, and total continuous thrusting time at full power for a standard Brane Craft design with a dry mass of 54.0 grams, as a function of ΔV due to increased propellant volume. A total DV of 40 km/s is achievable using a propellant layer thickness equal to the diameter of a typical human hair (76 microns). Total thrusting time at full power is only 126 hours.

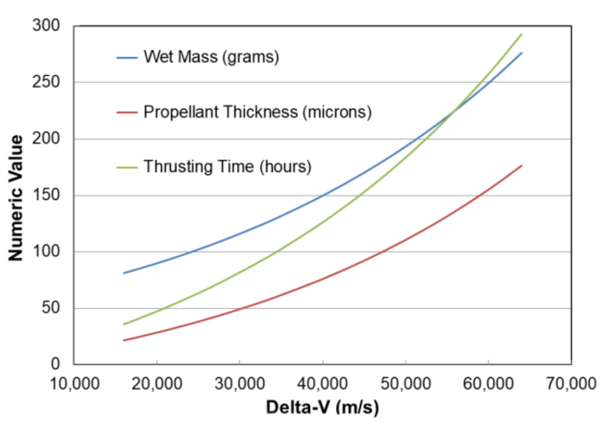

Figure 10: Wet mass, propellant layer thickness, and maximum thrusting time at full power for a Brane Craft with a dry mass of 54.0 grams, vs. ΔV.

An enhanced Brane Craft with a delta-V of 32 km/s would enable visiting all prograde asteroids sunward of Jupiter, with a return to LEO. It would also enable flybys of fast extra-solar asteroids like Oumuamua (interstellar asteroid 1I/2017 U1). Oumuamua was unique object with an estimated length-to-diameter ratio of 10, based on its reflected light curve. Images in the popular press were merely artist's impressions; no Earth-based images with resolved detail were obtained. Rapid-response enhanced Brane Craft could obtain images and up-close spectral data from future interstellar interlopers.

4.6 Solar-Sail Possibilities

While the distributed electrospray thruster system provides an unprecedented delta-V capability that is readily-scalable to even higher values by increasing the thickness of the propellant-filled gap between the main structural sheets, simpler active membrane spacecraft based on solar sails are also possible. These spacecraft can be a few microns thick using a single ultra-thin Kapton® structural sheet, with micron and sub-micron thicknesses possible in the future. Solar cells, power conditioning, command and control, communications, attitude determination and control, and shape-changing actuators could be integrated onto portions of the solar sail. This could eliminate struts and other physical structures typically required in solar sails.

5. SUMMARY

At the time of writing, the Brane Craft Phase II effort still had almost three months to go before completion. This work has focused on the main technology issues identified in the Phase I study: the need for radiation-hard thin-film electronics with at least 5 megarads of TID, resiliency to over 40 micrometeoroid impacts per month, development of surface-mounted thin-film shape-changing actuators, and evaluation of spin-off applications within, and beyond, LEO. Technology readiness is still at TRL 3 levels, but this should increase to higher levels as the potential monetary and mission benefits of this radical spacecraft design become known by the greater aerospace community.

Acknowledgements

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