Droplet Stream Momentum Exchange as the basis for an Extremely Efficient Solar System Transportation System. T. B. Joslyn[1]
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Introduction: Discoveries at three different universities between 1986 and 2012 indicate that it is feasible to transfer momentum in space over tens of kilometers using low-vapor pressure liquid droplets. Momentum transfer in space makes possible both low and high-impulse maneuvers that do not require the consumption of propellant. Instead, liquid transferred from one object to another can be collected and re-used later.

Prime candidates for suitable liquids include the Ionic Liquid [BMIM][BF4] which remains in a liquid state over a wide range of temperatures, is resistant to both radiation damage and plasma charging, and is currently used as a propellant for electrostatic thrusters. [BMIM][BF4] is roughly 50% Carbon by mass and could potentially be produced on Earth's moon, Phobos, Ceres, or other celestial bodies and then transferred directly to passing spacecraft.

The technology needed to project and collect droplets transferred in space has actually been in existence since the 1980s. Droplet stream generators and collectors were developed for the joint NASA/ USAF Liquid Droplet Radiator Program. This R&D effort resulted in working hardware that was successfully tested in vacuum free-fall conditions by NASA and Japanese engineers.[1],[2] Researchers at the University of Southern California studied how accurately droplets could be projected and concluded that 3-sigma dispersion angles of less than 1 micro radian are possible.[3]

In 2009, researchers at the University of Colorado at Colorado Springs studied the effects of space charging on droplets using predictive modeling and validated their results through experimentation. They concluded that the effects of Lorentz forces will have minimal impact on the trajectories of droplets in space. They also found that relatively small spacing between parallel droplet streams will allow for translation over tens of kilometers without significantly expanding the area of impact. Analysis also showed that relatively large amounts of liquid can be projected using relatively small amounts of energy. [4]

In 2012 experiments using an Electrostatic Thruster at the United States Air Force Academy showed that [BMIM][BF4] droplets survive impact with a metal plate in vacuum at speeds of over 1200m/s. None of the expected vaporized breakdown products of [BMIM][BF4] were seen by the Residual Gas Analyzer over the course of several hours of high-speed impacts. Further testing is needed to determine the speed at which droplet impacts produce breakdown products and the rate of liquid loss as a function of impact velocity and droplet size.

Momentum exchange in space enables a host of capabilities throughout the solar system, many of which are enhanced through the production of transfer medium liquid on airless celestial bodies where droplet streams can be projected directly from the surface to collectors on passing spacecraft.

In the short term, two applications are feasible that require relatively small amounts of liquid. First, droplet streams can be projected from a spacecraft into the path of large objects in Earth orbit that pose a breakup hazard to other orbiting objects. Impacted objects will be slowed without breaking apart, reducing their orbital life and removing them from orbits where they threaten operational spacecraft.[5]

In the second near-term application, a continuous transfer of droplets between side-by-side spacecraft provides sufficient thrust to maintain their relative position indefinitely, without consumption of propellant. This enabling technology is useful for certain sparse-aperture communications and interferometric remote sensing missions.[6] Both of these near term applications will likely advance droplet stream technology readiness in the coming years.

If Ionic liquids can be synthesized from resources extracted from the moon or asteroids, a host of exciting possibilities arise. Ionic liquid tankers with inflatable non-rigid tanks could bring liquid closer to earth where it could be used to reduce the amount of propellant needed to launch spacecraft into geosynchronous orbits. This capability is particularly useful to countries like China, Russia, and the U.S. who frequently launch to geosynchronous from non-equatorial launch sites.

Spacecraft could be launched from the surface of the moon or asteroids using a large stream of liquid that the spacecraft would collect and store in expandable, uninsulated bladders. If necessary, this stored liquid could be used as highly efficient electrospray propellant. Consumption of this propellant allows for minor orbit adjustments or large maneuvers when momentum exchange with other spacecraft is not possible.

Spacecraft in lunar orbit could transfer liquid to spacecraft arriving at the moon, slowing the arriving spacecraft in order to avoid the need to consume propellant to enter lunar orbit. Simultaneously, the spacecraft that was launched from the lunar surface could receive momentum from the arriving spacecraft, raising the orbital energy of the departing spacecraft in preparation for escape from lunar gravity. In this way, momentum could be transferred from spacecraft to spacecraft avoiding consumption of more than 90% of the propellant conventionally consumed in space during a lunar mission. For asteroid-bound spacecraft, even higher efficiencies are possible.

Spacecraft landing on the surface of the moon or on asteroids could receive a stream of liquid from the surface, avoiding the need for propellant consumption during landing. Transfers of momentum between spacecraft would involve significant g-loading, but could be kept below 10-g's with relaxed periods of g-loading to allow for efficient human transportation. Such deceleration would not be comfortable but could be tolerated safely by the vast majority of people.

Spacecraft returning to lower Earth orbits would be able to transfer some of their momentum to spacecraft that have depleted most of their liquid cargo in order to propel those empty spacecraft back to the moon or an asteroid. Simultaneously the slower Earth-orbiting spacecraft would transfer liquid to the faster Earth-returning vehicle to put it into an orbit where it can assist with the launch of geosynchronous spacecraft or increase the orbital velocity of spacecraft bound for exo-earth destinations

In this way, it is possible to transfer momentum between spacecraft hundreds of times in order to efficiently transfer large amounts of off-earth resources throughout the solar system. Missions to Mars are particularly interesting, because of the possibility of using the moon Phobos as a source of Ionic liquid that could both slow arriving spacecraft and accelerate departing spacecraft. Asteroids could be used to transfer momentum to spacecraft bound for the outer solar system with each of a series of asteroids providing the momentum needed to reach the next.

It may even be possible, and may prove feasible, to significantly alter the orbits of asteroids using droplet stream propulsion. An asteroid broken into two pieces with explosives or hydraulic actuators could be fitted with stabilizing thrusters and droplet stream transfer components. Then, by exchange of liquid, back and forth, one piece of the asteroid could be slowed while the other is accelerated, allowing for transfer of one piece to Earth's orbit. While enroute to Earth's orbit, the piece that was slowed could be broken again and the same momentum transfer process used to further slow part of the asteroid so that it stays in earth orbit, perhaps at a Lagrangian point.

In order for droplet stream propulsion technology to reach a level of maturity that can enable an intra-solar system transportation architecture, many steps are necessary. Research should be performed to determine the maximum collection speeds of known suitable liquids. Development of transfer mediums with higher heat tolerance or better Gamma radiation tolerance may be possible, and warrant further research. On-orbit experiments are probably needed to refine pointing and control algorithms that will allow accurate projection of large amounts of liquid. In-space refinement of charging models is also probably needed for long distance droplet projection. Lastly, it is necessary to demonstrate the synthesis of suitable liquids from lunar or asteroid materials.

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