Have Starship, Will Travel

The Newsletter of the Interstellar Research Group

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Laser Thermal Propulsion for Rapid Transit to Mars

by Andrew Higgins

Before we launch complex interstellar missions, we'll test out propulsion concepts much closer to home. Andrew Higgins and team at McGill University (Montreal) have been actively developing laser-thermal rocketry designs in the context of fast missions to Mars, work Higgins explains in the article that follows. Dr. Higgins is a professor of Mechanical Engineering at the university, where he teaches courses in the discipline of thermofluids (and where the Interstellar Research Group's next symposium will be held in 2023). Dr. Higgins has 30 years of experience in shock wave experimentation and modeling, with applications to advanced aerospace propulsion and fusion energy. His background includes a PhD ('96) and MS ('93) in Aeronautics and Astronautics from the University of Washington, Seattle, and a BS ('91) in Aeronautical and Astronautical Engineering from the University of Illinois in Urbana/Champaign.

Directed energy propulsion continues to be the most plausible, near-term method by which we might send a probe to the closest stars, with the laser-driven lightsail being the Plan A for most interstellar enthusiasts. Before we use an enormous laser to send a probe to the stars, exploring the applications of directed energy propulsion within the solar system is of interest as an intermediate step.

Ironically, the pandemic that descended on the world in the spring of 2020 provided my research group at McGill University the stimulus to do just this. As we were locked out of our lab for the summer due to covid restrictions, our group decided to turn our attention to the mission design applications of the phased-array laser technology being developed by Philip Lubin's group at UC Santa Barbara and elsewhere that has formed the basis of the Breakthrough Starshot initiative. If a 10-km-diameter laser array could push a 1-m lightsail to 30% the speed of light, what could we do in our solar system with a smaller, 10-m-diameter laser array based on earth?

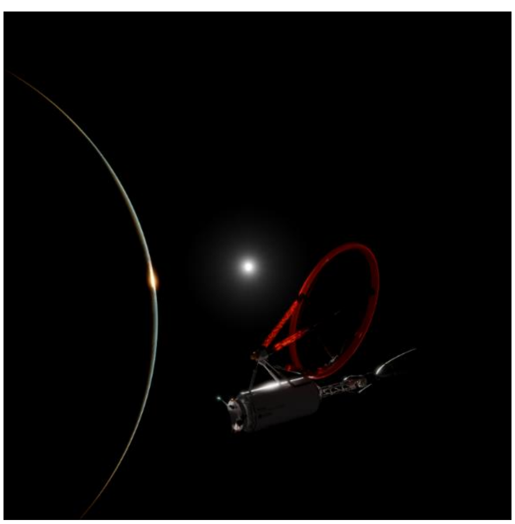

Image: Laser-thermal propulsion vehicle capable of delivering payload to the surface of Mars in 45 days.

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For lower velocity missions within the solar system, coupling the laser to the spacecraft via a reaction mass (i.e., propellant) is a more efficient way to use the delivered power than reflecting it off a lightsail. Reflecting light only transfers a tiny bit of the photon's energy to the spacecraft, but absorbing the photon's energy and putting it into a reaction mass results in greater energy transfer. This approach works well, at least until the spacecraft velocity greatly exceeds the exhaust velocity of the propellant; whenever using propellant, we are still under the tyranny of the rocket equation. Using laser-power to accelerate reaction mass carried onboard the spacecraft cannot get us to the stars, but for getting around the solar system, it will work just fine.

One approach to using an Earth-based laser is to employ a photovoltaic array onboard the spacecraft to convert the delivered laser power into electricity and then use it to power electric propulsion. Essentially, the idea here is to use a solar panel to power electric propulsion such as an ion engine (similar to the Deep Space 1 and Dawn spacecraft), but with the solar panel tuned to the laser wavelength for greater efficiency. This approach has been explored under a NIAC study by John Brophy at JPL [1] and by a collaboration between Lubin's group at UCSB and Todd Sheerin and Elaine Petro at MIT [2]. The results of their studies look promising: Electric propulsion for spaceflight has always been power-constrained, so using directed energy could enable electric propulsion to achieve its full potential and realize high delta-V missions.

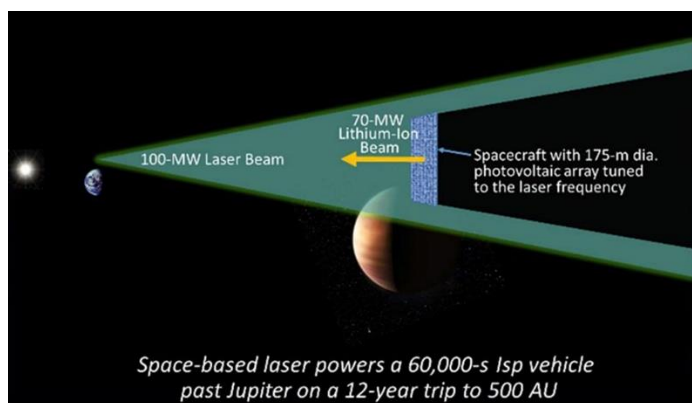

Image: Laser-electric propulsion, explored as part of a NIAC study by JPL in 2017.

Image source:
https://www.nasa.gov/directorates/spacetech/niac/2017_Phase_I_Phase_II/Propulsion_Architecture_for_Interstellar_Precursor_Missions/

There are some limits to laser-electric propulsion, however. Photovoltaics are temperature sensitive and are thus limited by how much laser flux you can put onto them. The Sheerin et al. study of laser-electric propulsion used a conservative limit for the flux on the photovoltaics to the equivalent of 10 "suns". This flux, combined with the better efficiency of photovoltaics that could be optimized to the wavelength of the laser, would increase the power generated by more than an order of magnitude in comparison to solar-electric propulsion, but a phased-array laser has the potential to deliver much greater power. Also, since electric propulsion has to run for weeks in order to build up a significant velocity change, the laser array would need to be large—in order to maintain focus on the ever-receding spacecraft—and likely several sites would need to be built around the world or perhaps even situated in space to provide continuous power.

I had spent my sabbatical with Philip Lubin's group in Santa Barbara in 2018 and was fortunate to be an enthusiastic fly-on-the-wall as the laser-electric propulsion concept was being developed but—being an old-time gasdynamicist—there was not much I could contribute. There is another approach to laser-powered propulsion, however, that I thought was worth a look and suited to my group's skill set: laser-thermal propulsion. Essentially, the laser is used to heat propellant that is expanded out of a traditional nozzle, i.e., a giant steam kettle in space. The laser flux only interacts with a mirror on board the spacecraft to focus the laser through a window and into the propellant heating chamber, and these components can withstand much greater fluxes, in principle, up to the equivalent of tens of thousands of suns. The greater power that can be delivered results in greater thrust, so a more intense propulsive maneuver can be performed nearer to earth. The closer to earth the propulsive burn is, the smaller the laser array needs to be in order to keep the beam focused on the spacecraft, making it more feasible as a near-term demonstration of directed energy propulsion. The challenge is that the laser fluxes are intense and do not lend themselves to benchtop testing; could we come up with a design that could feasibly handle the extreme flux?

Our effort was led by Emmanuel Duplay, our "Chief Designer," who happens to be a gifted graphic artist and whose work graces the final design. We also had Zhuo Fan Bao on our team, who had just finished his undergraduate honors thesis at McGill on modelling the laser-induced ionization and absorption by the hydrogen propellant—the physics that was at the heart of the laser-thermal propulsion concept [3]. Heading into the lab to measure the predictions of Zhuo Fan's thesis research was our plan for the summer of 2020, but when the pandemic dropped, we pivoted to the mission design aspects of the concept instead. Together with the rest of our team of undergraduate students—all working remotely via Zoom, Slack, Notion, and all the other tools that we learned to adopt through the summer of 2020—we dove into the detailed design.

Image: McGill Interstellar Flight Experimental Research Group meeting-up in person for the first time on Mont Royal in Montreal, during the early days of the pandemic, summer 2020.

Our design team benefitted greatly from prior work on both laser-thermal propulsion and gas-core nuclear thermal rockets done in the 1970s. Laser-thermal propulsion is well-trodden ground, going back to the seminal study by Arthur Kantrowitz [4], who is my academic great grandfather of sorts. In the 1970s, the plan was to use gas dynamic lasers—imagine using an F-1 rocket engine to pump a gas laser—operating at the 10-micron wavelength of carbon dioxide. With the biggest optical elements people could conceive of at the time—a lens about a meter in diameter—combined with this longer wavelength, laser propulsion would be limited to earth-to-space launch or low Earth orbit. To the first order, the range a laser can reach is given by the diameter of the lens times the diameter of the receiver, all divided by the wavelength of laser light. So, targeting a 10-m diameter receiver, you can only beam a CO_2 laser about a thousand kilometers. The megawatt class lasers that were conceived at the time were not really up to the job of powering earth-to-orbit launchers, which typically require gigawatts of power. For many years, Jordan Kare kept the laser-thermal space-launch concept alive by exploring how small a laser-driven launch vehicle could be made. By the 1980s, most studies focused on using laser-thermal rockets for orbit transfer from LEO, an application that requires lower power [5].

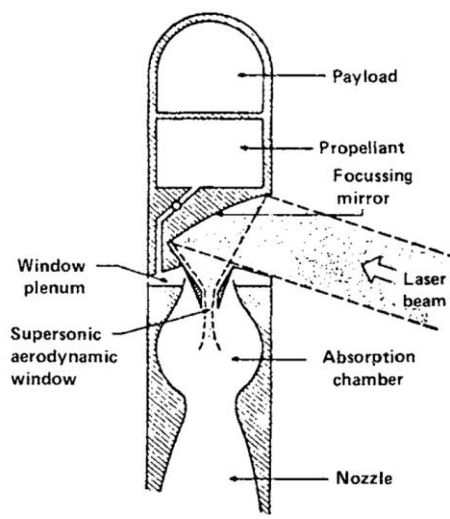

Image: Concept for a laser-thermal rocket from the early 1980s, using a 10-micron-wavelength CO_2 laser.

Image Source: Kemp, Physical Sciences Incorporated (1982)

As a personal footnote, I was fixated with laser-thermal propulsion in the 1980s as an undergraduate aerospace engineering student studying Kantrowitz and Kare's work and, in 1991, visited all of the universities that had worked on laser propulsion, hoping I could do research in this field as a graduate student. I was told by the experts—politely but firmly—that the concept was dying or at least on pause; with the end of the Cold War, who was going to fund the development of the multi-megawatt lasers needed?

The recent emergence of inexpensive, fiber-optic lasers that could be combined in a phased array changed this picture and—thirty years later—I could finally come back to the concept that had been kicking around the back of my mind. The fact that fiber optic lasers operate at 1 micron (rather than 10 microns) and could be assembled as an array 10-m in effective optical diameter means they could reach a hundred times further into space than previously considered. Greater power, shorter wavelength, and bigger optical diameter might multiply together as a win–win–win combination and open up the possibility to rapid transit in the solar system.

The other prior literature we greatly benefitted from is gas-core nuclear thermal rockets. Unlike classic, solid-core NERVA rockets that are limited by the materials that make up the heating chamber, gas core nuclear thermal rockets contain the fissile material as plasma in the center of the heating chamber that does not come into contact with the walls. Work on this concept progressed in the 1960s and early 1970s, and studies concluded that containing temperatures of 50,000 K should be feasible. The literature on this topic is extensive, but Winchell Chung's Atomic Rockets website provides a good introduction [6]. Work from the early 1970s concluded specific impulses exceeding 3000 s were achievable, but leakage of fissile material and its products from the gas core were both a performance limiting issue and an environmental nonstarter for use near earth. But what if we could create the same conditions in the gas core using a laser, without loss of uranium or radioactive waste to worry about? The heat transfer and wall cooling issues between gas core NTR and the laser-thermal rocket neatly overlap, so we could adopt many of the strategies previously developed to contain these temperatures while keeping the walls of our heating chamber cool.

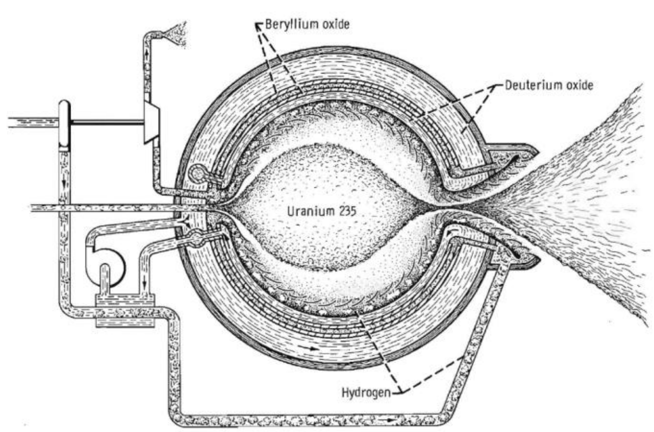

Image: Gas-core nuclear thermal rocket.

Image source: Rom, *Nuclear-Rocket Propulsion*, (NASA, 1968)

Laser-thermal propulsion is sometimes called the *poor person's nuclear thermal rocket*. Given its lack of radioactive materials and associated issues, I would argue that laser-thermal propulsion is rather the enlightened person's nuclear rocket.

With this stage set, in the next installment, we will take a closer look at the final results of our Mars-in-45-day mission design study.

We now turn to the detailed design our team at McGill University came up with for a laser-thermal mission capable of reaching Mars in 45 days. Our team took the transit time and payload requirement (1 ton) from a NASA announcement of opportunity that appeared in 2018 that was seeking "Revolutionary Propulsion for Rapid Deep Space Transit". Although being in Canada made us ineligible to apply to this program, we adopted this mission targeted by the NASA announcement for our design study; being in Canada also means we are used to working without funding.

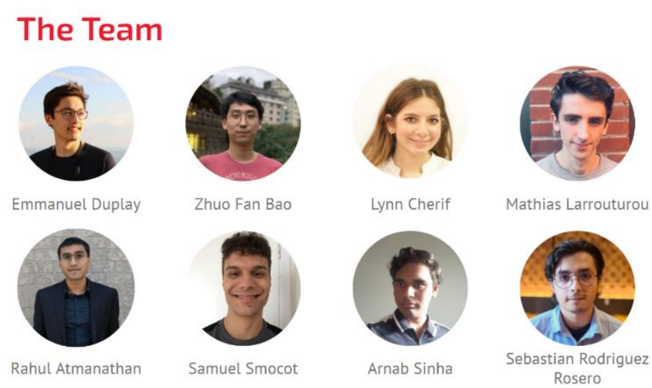

Image: McGill University students responsible for the design of the laser-thermal mission to Mars.

The NASA-defined payload of 1 ton would be a technology demonstration mission (what we call Mission Mars 1 in our study). Placing a premium on minimizing the transit time presumably reflects NASA's eventual interest in lessening astronaut exposure to galactic cosmic rays, which increases sharply once a spacecraft leaves the Earth's protective magnetosphere. Once on the surface of Mars, data from the Curiosity rover have shown that the radiation environment there appears to be more benign, comparable to or even less than the radiation exposure encountered on the ISS. Throwing regolith to cover the habitat on Mars would lower the radiation risk further, so astronauts leading a hobbit-like existence on Mars should stay healthy, provided they get there quickly.

Our Mars 1 mission starts with our spacecraft already in medium Earth orbit (MEO), so that it remains in view of the ground-based laser during the entire laser-powered burn, which takes about an hour. Given the ongoing revolution in space access, we did not bother to explore using laser propulsion to get to orbit. Chemical propulsion is well-suited for reaching orbit, so we selected a Falcon 9 to bring our vehicle to MEO and focused on using the laser for the transit to Mars.

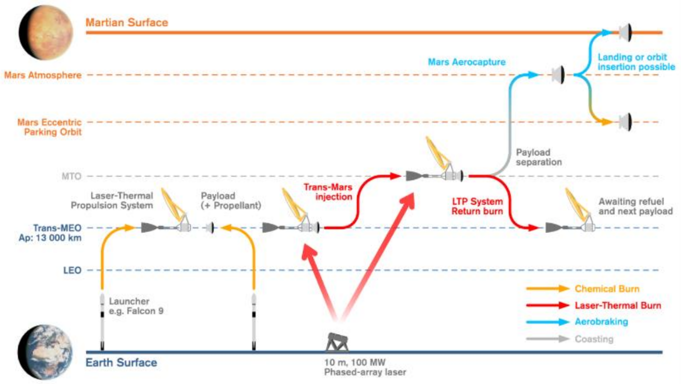

Image: The concept of operations for a rapid transit to Mars mission using laser-thermal propulsion. Note the use of a burn-back maneuver to bring the laser-thermal stage back to medium Earth orbit after sending the payload to Mars.

The laser array on Earth is about 10 m by 10 m, comparable to a volleyball court, and for the 1-ton payload mission, the laser would operate at 100 MW output for an hour, using power taken from the grid or generated via solar and then stored in a battery farm. (It is worth noting that a battery farm capable of providing 100 MW for an hour was built in South Australia in 2017 from scratch in just 60 days, in response to a taunt posted in a tweet [7].) So, powering the laser is not a problem.

When the laser beam arrives at the spacecraft, it is focused into the propellant heating chamber by a large, inflatable reflector—a balloon that is transparent on one half and reflective on the other. Inflatable space structures like this are fairly mature, including a demonstration of an inflatable antenna that flew on the Space Shuttle in 1996; a comprehensive overview of this technology was given by Jamey Jacob at the 6th TVIW/IRG in Wichita [8]. Inflatable collectors such as these have shown sufficient optical quality for our purposes. While the laser flux on the inflatable is intense, we found fluorinated polyimide films have sufficiently low absorptivity to avoid overheating.

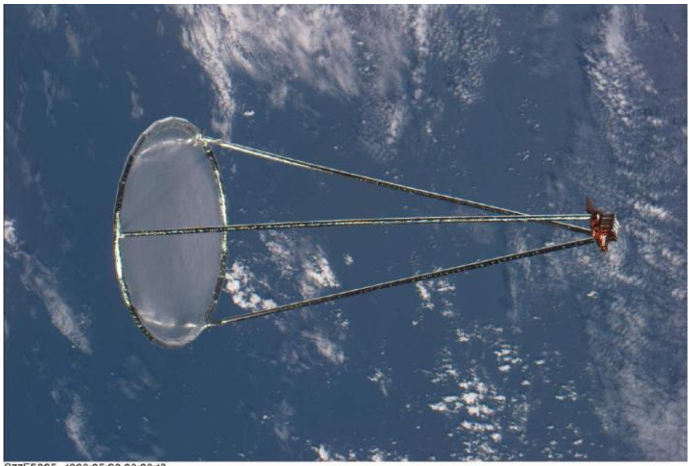

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Image: Inflatable Antenna Experiment deployed from the Space Shuttle Endeavor (STS-77).

Image Source: https://apod.nasa.gov/apod/ap960525.html

The inflatable reflector focuses the laser into the heating chamber, raising the temperature of the hydrogen flowing through the chamber to greater than 10,000 K. Keeping the walls of the chamber cool is the central challenge of the design, but our team found a combination of regenerative cooling (cool hydrogen flowing through the walls), transpiration cooling (injecting hydrogen through porous walls), and seeding the hydrogen (to trap thermal radiation in the propellant, similar to the greenhouse effect) should be sufficient to keep the walls cool. The heat absorbed via regeneration is used to power the turbopumps needed to pump the hydrogen via an expander cycle. The fully ionized hydrogen propellant is then exhausted through a conventional bell nozzle to generate thrust. Based on our own calculations and prior work on laser thermal propulsion and gas-core NTRs from the 1970s, a specific impulse of 3000 s appears feasible.

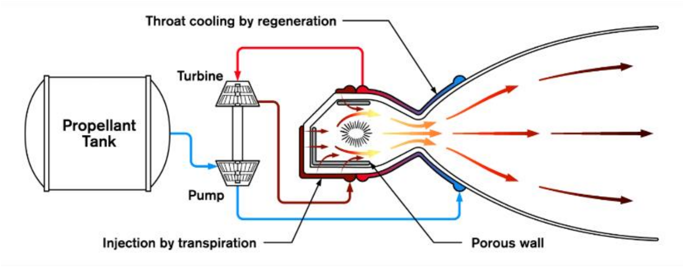

Image: Details of the propellant heating chamber and associated propellant feed and cooling systems.

The laser propulsion hardware is just dead mass once the spacecraft exceeds the focal length of the laser (which is about 50,000 km), so our team proposed bringing the laser thermal propulsion stage back to Earth via a flip-and-burn-back maneuver while still within range of the laser in cis-Lunar space. Once the propulsion stage is brough back to low or medium Earth orbit, it can be refilled and readied for use again. This would allow a single laser-thermal stage to throw multiple payloads to Mars over the duration of a given launch window.

The 14 km/s Delta-V laser thermal burn sends the spacecraft to Mars on a nearly straight-line trajectory: no need for looping ellipses and Venus flybys. Our astrodynamicist optimized the trajectory for a 2020 departure. Even though our design had the launch two months after Perseverance, the vehicle would arrive at Mars three months before the newest Mars rover, overtaking it on the way.

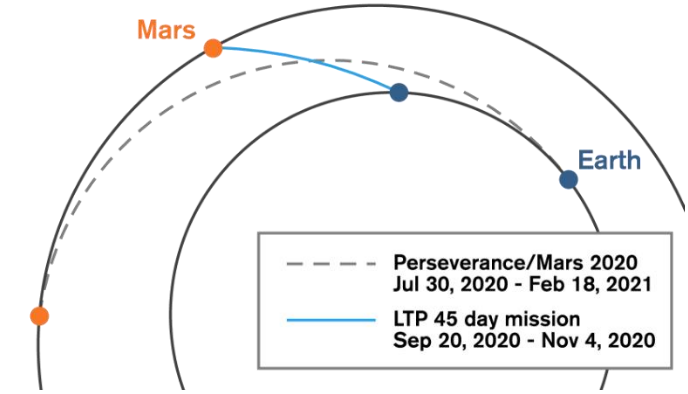

Image: 45-day transfer orbit to Mars via laser thermal propulsion, in comparison to the 7-month journey of the Perseverance rover.

When the spacecraft arrives at Mars, there is no laser to perform a laser-assisted deceleration burn (at least, not yet) and at the high approach velocity, aerocapture appears the best option. At an approach speed of 16 km/s, aerocapture is going to be harsh and is another critical link in the mission design. The heat flux will be intense, but the new Heatshield for Extreme Entry Environment Technology (HEEET) developed by NASA in recent years appears to be rated to withstand even greater heat flux. The vehicle entering the Martian atmosphere would need to use lift pointed down (toward the surface of Mars) to keep the vehicle in a trajectory that skims the atmosphere. This maneuver is a delicate balance between heat load, the g-load, and the lift and ballistic coefficients of the spacecraft, which we first modelled analytically and then backed-up with full three-degree-of-freedom simulations. The g-load limit was set at 8-gees for our study; for the scaled-up design with astronauts, the g-load will be severe and sustained for several minutes, but within the limits of what humans can tolerate. (Relevant to note that, at the recent Interstellar Symposium in Tucson, Esther Dyson reported from her centrifuge training at Star City that, "8-gees going through you was actually a lot of fun." [9]) The aerocapture would be a wild ride, for sure.

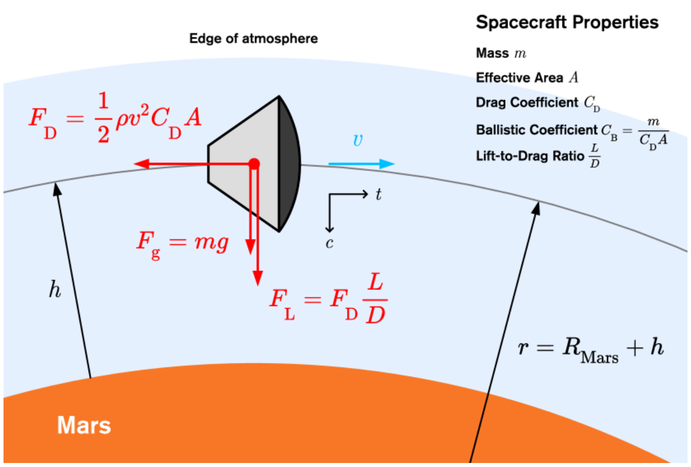

Image: Details of model used for aerocapture upon arrival at Mars.

The scaled-up version of our design (Mission Mars 2a) intended for crewed missions used a 40-ton spacecraft derived from the Orion capsule and European Service Module. The greater payload requires a more powerful (4 GW) laser to effectuate the same 45-day transit to Mars, but the laser array occupies the same 10-m footprint on earth.

The other mission we considered was a cargo mission (Mission Mars 2b). Robert Zubrin often makes the point that—even if advanced propulsion capable of high thrust and high specific impulse was available—he would *still* opt for a 6-month free-return trajectory and use the enhanced propulsion capability to bring more payload. So, the Mars 2b mission uses the performance of laser thermal propulsion to maximize the amount of cargo that could be brought to Mars with a Hohmann-like transfer, and shows that the payload could be increased by a factor of more than 10 over what a Centaur upper stage—with the same mass of propellant—could throw to Mars.

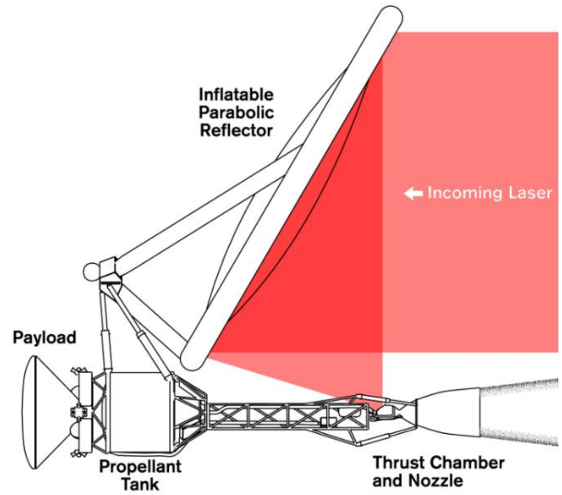

Image: Final design of laser-thermal propulsion spacecraft capable of reaching Mars in 45 days.

While a more thorough vetting of our design is called for and much work remains to be done, one encouraging finding is that the specific power of the laser thermal propulsion design is so good—an "alpha" on the order of 0.001 kg/kW—that even if the mass of the entire propulsion system were to increase by a factor of ten, the increased mass would not significantly affect the overall performance or payload capacity of the design. There is sufficient margin in the concept to accommodate the inevitable upward creep in mass that occurs as the design is refined.

Laser thermal propulsion may be well suited to other high Delta-V missions, such as flybys of interstellar comets, the mission to the solar gravitational focus, and a probe to the hypothetical Planet 9—if it is found. There is no reason the laser-thermal approach cannot be combined with laser electric propulsion or other techniques such as an Oberth maneuver. Perhaps it is best to think of laser thermal propulsion as a dragster that burns a lot of propellant quickly to get you up to speed, but from there, you can invoke laser electric propulsion that is well suited to the diminishing laser flux as the spacecraft exceeds the focal length of the laser. Appendix A in our paper details where we calculate the tradeoff between laser thermal and laser electric propulsion occurs. Hopefully, the laser-thermal concept can contribute to a further appreciation of directed energy as a disruptive technology for high-velocity missions in the solar system and beyond.

The complete details of our study can be found in our published paper:

Duplay et al, "Design of a rapid transit to Mars mission using laser-thermal propulsion," *Acta Astronautica* Volume 192 (March 2022), pp. 143-156 (abstract / preprint).

A browser-friendly version of the paper is available here: https://ar5iv.org/html/2201.00244

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Interstellar Research Group IRG

HOW WILL ALIENS LAND THEIR SPACECRAFT? PROBABLY USING MAGNETOHYDRODYNAMICS

BY COLIN WARN

A voyaging alien civilization has recently become intrigued by radio signals emanating from the Orion-Cygnus arm of the Milky Way Galaxy. Curiosity gets the better of them, and they decide to maneuver their spacecraft in for a closer look.

A solar system near Polaris seems to be generating these signals, and upon flying deeper in it becomes clear that these signals are coming from a small blue dot inside it. It quickly becomes apparent to them however, that this blue isn't a blue of a gas cloud, but of a planet with lively liquid ocean rife for exploring. A marshmallow-like atmosphere comes into their view, and they begin to make out what seems like faint embers of light emanating from the land masses scattered between the cloud cover.

They go in for a closer look, but to their chagrin they quickly realize that the same atmosphere that seemed so beautiful from afar is quickly putting their spacecraft through the most challenging forces it has experienced yet. Moving at thousands of kilometers per second, without proper thermal protection their spacecraft will quickly turn into a meteoroid, giving UFO-deniers prominent on this planet the satisfaction of reminding all believers that yes, that unknown object is called such because it didn't survive atmospheric entry.

The technique that has the potential to enable our alien civilization to survive the incredible thermal loads is known as magnetohydrodynamic braking. This is commonly referred to by the acronym 'MHD Braking,' a method of decelerating a spacecraft by means of the plasma surrounding it as it enters a planetary atmosphere. MHD Braking is a novel method being explored by a consortium of European researchers. Under the project name MEESST (Magnetohydrodynamic Enhanced Entry System for Space Transportation), researchers Manuel Betancourt et. al describe how the project plans to develop and demonstrate the concept in their latest paper [1].

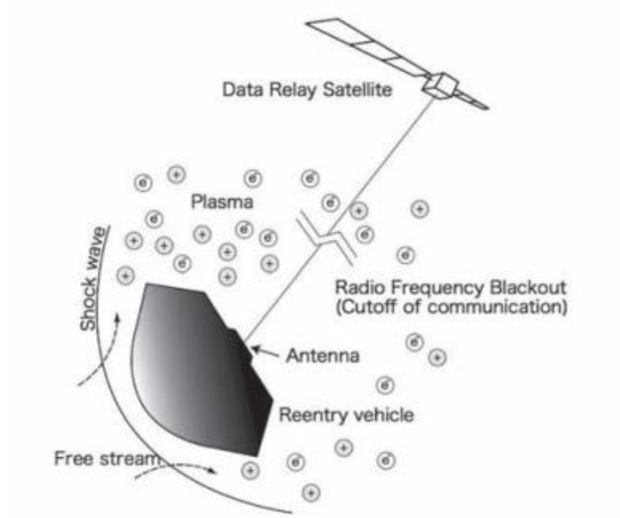

Image: Illustration of re-entry conditions [1]

Through the use of high temperature-rated superconducting wires, an electromagnetically created magnetic field can be formed at the tip of the spacecraft to adjust the location of the "bow shock." The further the distance of the bow shock from the spacecraft's nose, the lower its temperature loads. This technology has only recently become more feasible thanks to the development of more economic "Type 2G" superconducting wires: Wires which are needed for other applications such as power transmission and storage.

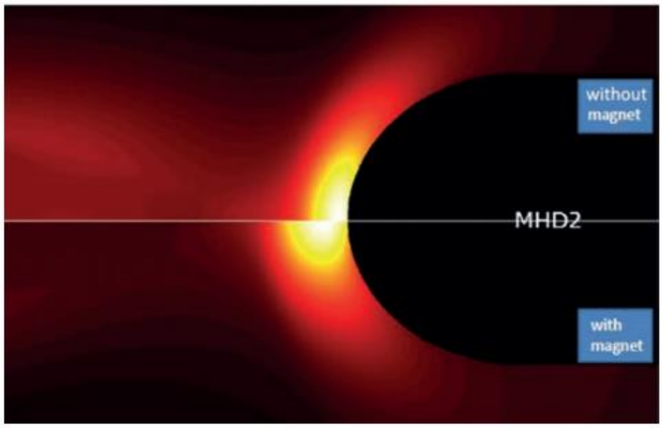

Image: Effect on bow shock location under the influence of a magnetic field.

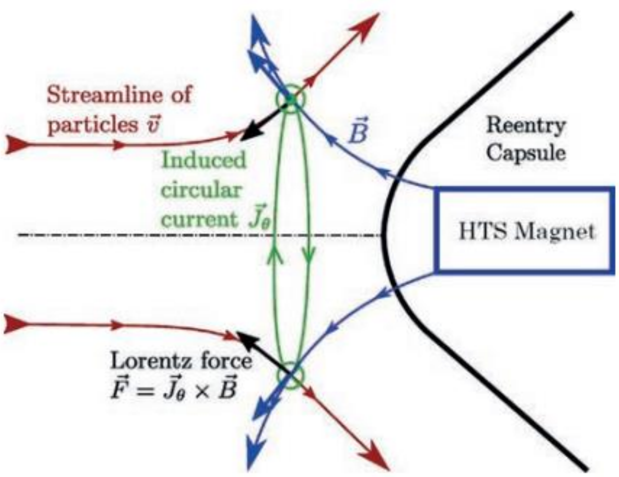

Image: Magnetic field configuration [1]

I had the privilege of asking Manuel a few questions regarding this project, and about some of the further reaching applications of this technology. You can see my correspondence with him below, and can find out more about the MEESST Consortium's work at their website: https://meesst.eu/

Colin: Your entry system seems to create a magnetic dipole by running current through a solenoid made out of superconducting materials. If the description of how you generate the magnetic field is correct, how do you plan to generate current for this wire? Could you couple generation of the current through the wire to the ionized plasma streaming past the spacecraft (i.e. magnetohydrodynamically generate the power in the wire from the streaming plasma?)

Manuel: We plan to generate the current using solar photovoltaic panels and feeding the current DC to the coil whereas the current consumption is not continuous. Once you have loaded the coil you just need to keep it cryocooled the real power consumption will be coming from the cryocooler. The second way to load the coil is by means of inducing the current through the use of a proprietary device that can induce currents on the superconducting coil. In any case the power budget required to operate the coil is minimal compared with savings in mass and increase of safety by using this approach.

Colin: At what speeds does this technology work? Could you use MEESST as a means of slowing down a Formula 1 car or a supersonic jet for instance? If it's only limited to objects moving at significant Mach numbers, could one "seed" the air thermionically with electrons to reduce the speed needed to ionize the surrounding neutral air to be able to brake magnetohydrodynamically?

Manuel: Hypersonic reentries MACH 20 or more, whereas the verifications and validations are being conducted in chambers that operate with plasma fluxes a much lower speed. MACH 2. You can apply aerobraking maneuvers to an object traveling at hypersonic speeds like a nuclear ballistic missiles or hypersonic airplanes. You will need to measure in-situ plasma characteristics to do so. The MACH numbers must match physics for MHD equations otherwise it is not possible to apply it. Whether you can brake or slow down the object will depend on the strength of the magnetic field applied and the aerodynamics of the object.

[1] Manuel La Rosa Betancourt et al. (2021). Magnetohydrodynamic Enhanced Entry System for Space Transportation (MEESST) as a Key Building Block for Low-Cost Interplanetary Missions. Journal of the British Interplanetary Society. 74. 448–453.

UPCOMING INTERSTELLAR AND SPACE EVENTS

Summer 2022. NASA's James Webb Space Telescope starts performing scientific observations, peering deeper into the cosmos than ever before.

24 July 2022. Chinese Wentian laboratory module launch.

August 2022. NASA Artemis 1 launch.

18-22 September 2022. Paris, France. International Astronautical Congress 2022. www.iafastro.org

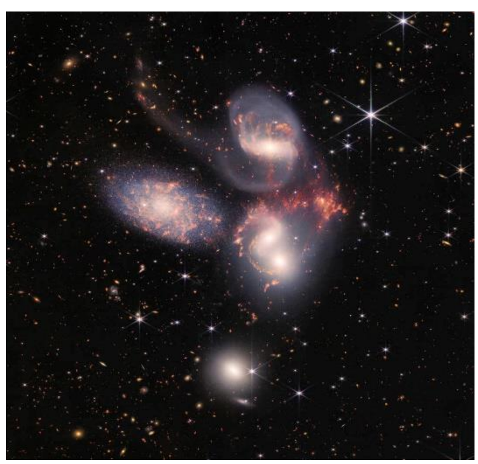

Image: One of the first images from the James Webb Space Telescope

Credit: NASA, ESA, CSA, and STScI