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Have Starship, Will Travel

The Newsletter of the Interstellar Research Group

Newsletter Contents

GAME CHANGER: AN EMERGING PARADIGM FOR DEEP SPACE
BY PAUL GILSTER

We need to get to the ice giants. We have limited enough experience with our system's larger gas giants, although orbital operations at both Jupiter and Saturn have been highly successful. But about the ice giants, their formation, their interiors, their moons (and even the possibility of internal oceans on these objects), we draw on only a single mission, Voyager II. Which is why the April 2022 decadal study ("Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032") recommended a Uranus mission, complete with orbiter, to be launched in the late 2030s.

Can we do this under our existing paradigm for space exploration? A new paper titled "Science opportunities with solar sailing smallsats," written by the Jet Propulsion Laboratory's Slava Turyshev and co-authored by major proponents of solar sail technologies, makes the case for coupling our abundant advances in miniaturization with our growing experience in solar sails to achieve missions at significantly lower cost and substantial savings in time. Because staying within the traditional game plan, we are constrained by slow chemical propulsion (or low-readiness nuclear methods) as well as decades of mission planning, not to mention cruise times in the range of 15 years to reach Uranus. These are numbers that can and should be improved, and greatly so.

Fortunately, solar sailing is moving beyond the range of experiment toward practical missions that will build on each other to advance a new paradigm – smaller and faster. Much smaller and much faster. Consider: The Japanese IKAROS sail has already demonstrated the interplanetary possibilities of sails, while the success of The Planetary Society's LightSail-2 helped to energize the NEA-Scout mission NASA launched in 2022. Concept studies continue. Japan developed OKEANOS, a hybrid sail/ion engine design as an outer planet mission as a follow-on to IKAROS (the mission was a finalist for funding but lost out to a space telescope called LiteBIRD).

But sail technology must be wed with practical payloads, and spacecraft acceleration is proportional to the sail area divided by the spacecraft mass, which means that miniaturization and the use of smallsats win on efficiency. Here we're reminded of the recent success of the Mars Cube One (MarCO) smallsats, which worked in conjunction with the InSight Lander and demonstrated the practicality of the highly modular and integrated CubeSat format for missions well beyond Earth orbit. Let's remember too the advantage of smallsat launches as 'rideshare' payloads, significantly reducing the outlay needed.

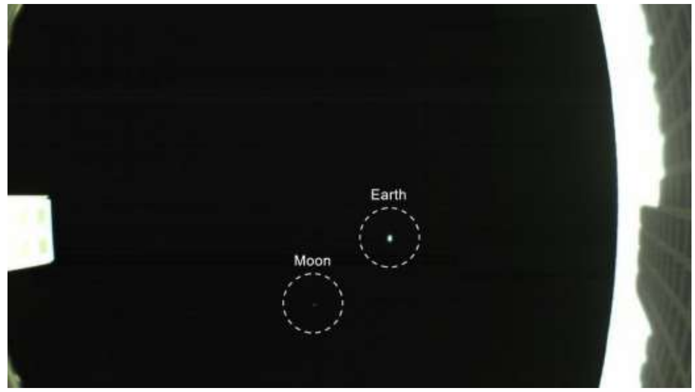


Image: The first image captured by one of NASA's Mars Cube One (MarCO) CubeSats. The image, which shows both the CubeSat's unfolded high-gain antenna at right and the Earth and its moon in the center, was acquired by MarCO-B on May 9, 2018. Credit: NASA/JPL-Caltech.

Solar sails are fast and, using the momentum of solar photons, require no onboard propellant, as both chemical and electrical methods do. Wedding sail propulsion to miniaturization in smallsats opens the way for spacecraft sent on 'sundiver' trajectories to harvest momentum from solar photons for the push to the outer Solar System. Here we're taking advantage of a sail's ability to change orbit by adjusting its attitude, another obvious plus. The authors believe that sailcraft built along these lines can achieve speeds of 33 kilometers per second, which works out to roughly 7 AU per year.

All of this leads to particular types of mission. From the paper:

> As the solar sailing smallsats will be placed on very fast trajectories, placing Sundivers in orbit around a solar system body will be challenging. However they naturally yield several mission types including fast flybys, impactors, formation flights, and swarms. As the weight of the system is constrained, any instruments on board need to be small, lightweight, and low-power. Given the ongoing e1orts in miniaturization of many instruments and subsystems, these challenges will be met by our industry partners who are already engaged in related technology developments.

As we continue to refine sail materials and advance deployment strategies, we are also learning how to harden smallsat computers for deep space while modularizing their components. Jupiter will be reachable with cruise times of two years, Saturn with three. What looms now is further development in the form of a technology demonstration mission (TDM) that has grown out of Turyshev and team's Phase III study for NASA's Innovative Advanced Concepts Office based on a sailcraft design that may one day reach the Sun's gravity lens, which for effective science begins at 550 AU and extends outward.

The TDM would further develop solar sail technologies with an eye toward the kind of 'sundiver' maneuver that would make such fast missions possible. It will be enabled by a series of preparatory solar sail flights that will validate the final TDM vehicle.

Coming back briefly to an ice giant mission, designing and building the kind of craft envisioned in the 2022 Decadal is at least a decade's work, and the cost of sending an orbiter to Uranus likely pushes beyond $4 billion. We're contemplating this at the same time that the Decadal Survey is recommending, as its second highest priority for the upcoming decade, an Enceladus orbiter/lander flagship mission. NASA's budget would be strained to the maximum to get even the Uranus mission off in the 2030s, which would push our next encounter with the ice giants back yet another decade.

The authors argue that we need to get realistic about what we can do with fast flybys not just to the ice giants but to numerous destinations in the Solar System. Let's explore the TDM mission as presented in the new paper, considering the mission concept and implications before moving on to look at the kind of destinations the combination of sails and smallsats will enable us to reach.

Building Smallsat Capabilities for the Outer System

'LightCraft' is the term used by Slava Turyshev's team at JPL and elsewhere to identify the current design of this ambitious mission. A Technology Demonstrator Mission (TDM) can be considered a precursor to what may become a mission to the solar gravitational lens. The mission concept is under active investigation, partly via a Phase III grant from NASA's Innovative Advanced Concepts Office. Reaching the focal region (for practical purposes, beyond 600 AU) in less than 25 years requires changes to our thinking in propulsion, not to mention payload size and the potential of robotic self-assembly enroute.

The TDM mission is conceived as a series of preparatory flights that allow the testing and validation of the technology and operational concepts involved in a mission to the focal region. The implications are hardly limited to the outer Solar System, for the smallsat/sail paradigm should be applicable to a wide range of missions in the inner system as well.

Let's pause for a moment on the term 'smallsat,' which generally refers to a spacecraft that is both small and lightweight, usually less than 500 kilograms, and sometimes much less, as when we get into the realm of CubeSats. Frequently in the news as we explore their capabilities, CubeSats can get down to less than 2 kilograms. What the authors have in mind is a demonstrator design that is scalable, the initial payload in the 1-2 kilogram range, but capable of moving up to between 36 and 50 kilograms.

The goal is a demonstrator mission that will perform a one to two-year test flight using a solar sail and a sundiver maneuver to achieve speeds greater than 5 AU per year. The figure works out to something on the order of 23.6 kilometers per second, an impressive feat given that Voyager 1, our current record holder, is moving at 17.1 kps. With the TDM demonstrating the capabilities of the sail's vane structure and the needed control for perihelion passage, the full solar gravitational lens mission contemplates still higher velocities, reaching 20 AU per year (roughly 95 kilometers per second).

The SGL mission concept is being built around in-flight cruise assembly of the full spacecraft through modules separately delivered as 20 kilogram or less smallsats. Given that overall design, you can see the need for the demonstrator mission to shake out both sail and sundiver concepts. Thus, while the TDM payload includes science instruments, the real focus here is on demonstrating the method: Use smallsat technologies with a highly maneuverable sailcraft to enable the fast travel times that will make reaching the focal region feasible.

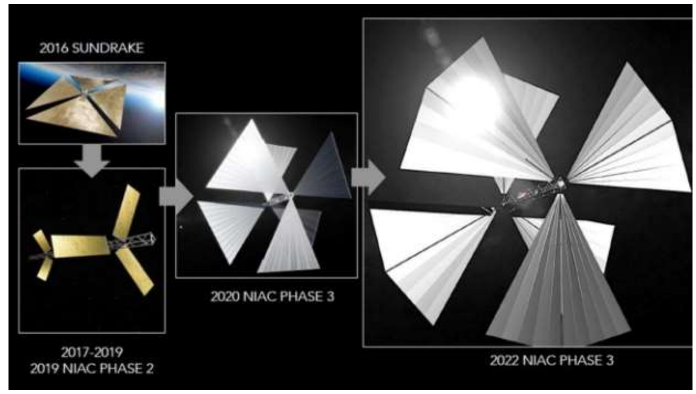


Image: This is from the paper's Figure 1, showing sailcraft design evolution during the period of 2016-2022.

The sail design is unusual, growing out of work at JPL in conjunction with L'Garde, further refined by space services company Xplore. The sail design draws on square panels aligned along a truss to provide the cumulative sail area needed for the mission. It's a striking object, not the conventional image of a solar sail. L'Garde has put together an eye-catching 1:3 scale model that hangs at the Xplore facility in Washington state.

The LightCraft TDM is envisioned as a 3-axis controlled spacecraft capable of the attitude control crucial for the Sundiver maneuver it will perform to reach cruise speed. Here are a few relevant details from the paper. Note the remark at paragraph close:

> Each sail element, or vane, can also be articulated to provide fine control to both the resultant thrust from solar radiation pressure and the vehicle's attitude. Each dynamic vane element is also a multifunctional structure hosting photovoltaics and communication elements with the requisite degrees of freedom to meet competing operational and mission requirements. The current TDM design total vane area is 120 m^2 and the mass of the integrated TDM vehicle is 5.45 kg, resulting in an area-to mass ratio of $A/m = 22\ m^2/kg$, or nearly 3 times the performance of other existing and planned sailcraft.

The mission concept relies on placing the sailcraft in a trajectory that takes it to solar perihelion – head first for the Sun, then leave it at high velocity, using the momentum of solar photons to push the craft, and again using the precise attitude control available through the SunVane design to adjust subsequent trajectory as needed. What this trajectory demands, then, is sail materials that can withstand a perihelion in the range of 15 to 20 solar radii, which the Phase III study research indicates will be available within the present decade.

This proof-of-concept demonstrator mission would aim at deployment through a rideshare launch, sharply reducing the cost in comparison with larger payloads, with checkout in a 'super-synchronous' orbit (meaning higher than geostationary orbit and moving faster than Earth's rotation). The paper describes an 'outspiral' into interplanetary space following the checkout phase, with a pivot at perihelion (listed here as 0.24 AU) to harvest the solar momentum needed to reach cruise velocity. The SunVane design allows the necessary maneuvering, as follows:

The trajectory is achieved with three simple control laws to maneuver the vehicle from geosynchronous orbit to perihelion and then egress: 1) maximum acceleration: align vanes perpendicular to the Sun to increase velocity; 2) no acceleration: align vanes edge-on to the Sun; and 3) maximum deceleration: align vanes so that the resultant force is opposite to the heliocentric velocity vector, to decrease orbital kinetic energy.

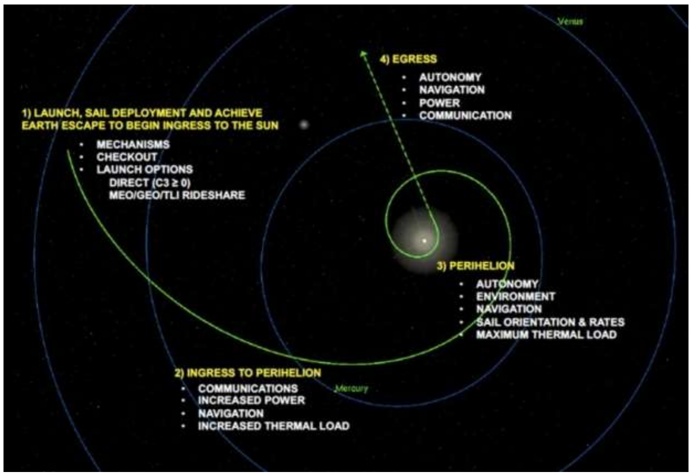


Image: This is Figure 2 from the paper. Caption: Common TDM mission phases and systems engineering objectives. Trajectory plot shown is for the SGL mission. Credit: Turyshev et al.

You would think the diciest part of the mission would be at perihelion (and of course it's crucial), but I was interested to see that the authors consider the most dynamic phase for the sailcraft is during the exit from Earth, where the vehicle alternates between acceleration and no-acceleration (factoring in eclipse periods). Reaching interplanetary space, the sail decelerates inward toward the Sun. The sail vanes are re-oriented at perihelion, with six degrees of freedom to ensure responsiveness to error.

All of this, the authors report, is well within the capabilities of the kind of onboard inertial sensors we already use in space operations. With the vanes used for propulsion, attitude determination and control are handled by reaction wheels, gyro, star tracker, sun sensors and accelerometers for yaw, pitch and roll. The preliminary studies reported in this paper show a sail area on the order of 100–144 m^2, with the overall spacecraft mass coming in between 4.2 and 6.4 kg. Note that the demonstrator would use photovoltaic elements on the sail vanes for power. Future missions to the outer system will also demand radioisotope power.

The paper presents further details about how the smallsat/sail concept can scale the TDM into future missions, such as sail material (currently Kapton but with other choices emerging), insulation for perihelion, and the various investigations re communications, batteries and the development of small radioisotope power sources.

So how likely is a Technology Demonstrator Mission to fly? The next steps are cited in the paper:

> The 2020 NIAC Phase III study concluded with a TDM Preliminary Design Review (PDR) on July 18, 2022 [7]. Next is pre-project mission development, which includes final design, hardware development, full-scale prototype construction, as well as hardware and software testing... Should funding be available, the TDM Critical Design Review (CDR) may be conducted in November 2023, when flight project commitment is expected, including a firm costing of the TDM. The total project cost will depend on the selected mission objectives, science payload, and experiments, and is expected to be in the range of $17–20M.

It's compelling to learn that a lightweight sundiver mission may be built at a cost of tens of millions (the authors cite $30-75 million), which is quite a contrast to the $2 to $5 billion cost of the typical flagship mission to deep space. Developing such technologies pushes us forward on the miniaturization of scientific sensors that will benefit all classes of future missions to deep space. But numerous opportunities would also open up for targets closer to home in the Solar System.

Self-Assembly: Reshaping Mission Design

It's interesting to contemplate the kind of missions we could fly if we develop lightweight smallsats coupled with solar sails, deploying them in Sundiver maneuvers to boost their acceleration. Getting past Voyager 1's 17.1 kilometers per second would itself be a headline accomplishment, demonstrating the feasibility of this kind of maneuver for boosting delta-v as the spacecraft closes to perhaps 0.2 AU of the Sun before adjusting sail attitude to get maximum acceleration from solar photons.

The economic case for smallsats and sails is apparent. Consider The Planetary Society's LightSail-2, a solar sail in low Earth orbit, which demonstrated its ability to operate and change its orbit in space for multiple years before reentering Earth's atmosphere in November of 2022. Launched in 2018, LightSail-2 cost $7 million. NASA's Solar Cruiser, a much larger design still in development despite budging hiccups, weighs in at $65 million. Turyshev and team at the Jet Propulsion Laboratory independently verified a cost model, with the help of Aerospace Corporation, of $11 million for a one-year interplanetary flight based on their Technology Demonstrator design.

Those numbers go up with the complexity of the mission, but can be reduced if we take advantage of the fact that spacecraft like these can be repurposed. A string of smallsat sailcraft sent, for example, to Uranus to conduct flybys of the planet, its moons and rings, would benefit from economies of scale, with successive missions to other outer system targets costing less than the ones that preceded them. Here the contrast between dedicated flagship missions (think Cassini or the Decadal Survey's projected Uranus Orbiter) could not be greater. Instead of a separately developed spacecraft for each destination, the modular smallsat/sail model creates a base platform allowing fast, low-cost missions throughout the Solar System.

To the objection that we need orbiters at places like Uranus to get the best science, the answer can only be that we need both kinds of mission if we are not to bog down in high-stakes financial commitments that preclude targets for decades at a time. Of course we need orbiters. But in between, the list of targets for fast flybys is long, and let's not forget the extraordinary range of data returned by New Horizons at Pluto/Charon and beyond. As the authors of the recent paper from the JPL team note, heliophysics can benefit from missions sent to various directions in the heliosphere:

> The shape of the heliosphere and the extent of its tail are subject to debate and the new model of the heliosphere—roughly spherical with a radius of ~100 AU—needs confirmation. Of course, every mission out to >100 AU will test it, but a series of paired missions (nose and tail, and in perpendicular directions) would provide a substantial improvement in our understanding of ISM/solar wind interactions and dynamics. High-velocity, low-cost sailcraft could probe these questions related to the transition region from local to pristine ISM sooner and at lower cost than competing mission concepts. Since the exact trajectory is not that crucial, this would also provide excellent opportunities for ad hoc trans-Neptunian object flybys.

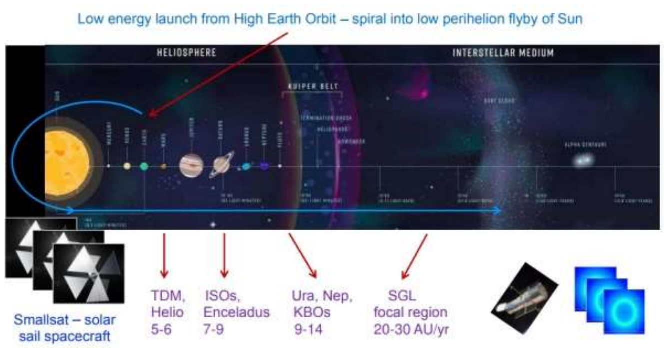


Image: This is Figure 5 from the paper. Caption: New paradigm – fast, low-cost, interplanetary sailcraft with trajectories unconstrained to the ecliptic plane. Note the capability development phases from TDM (at 5–6 AU/yr) to the mission to the focal region of the SGL (20–30 AU/yr). Credit: Turyshev et al.

What is emerging, however, is a new model not just for flyby missions but for the kind of complicated mission we've gotten so much out of through spacecraft like Cassini. We are on the cusp of the era of robotic self-assembly, which means we can usefully combine these ideas. Ten fast smallsats capable of flying considerably faster than anything we've flown before can, in this vision, self-assemble into one or more larger craft enroute to a particular destination. The Solar Gravitational Lens mission as designed at JPL relies on self-assembly to achieve the needed payload mass and also draws on the ability of smallsats with sails to achieve the needed acceleration.

We can trace robotic self-assembly all the way back to John von Neumann's self-replicating probes, but as far as I know, it was Robert Freitas who in 1980 first took the idea apart in terms of a serious engineering study. Freitas applied self-assembly to a highly modified probe based on the Project Daedalus craft. Freeman Dyson considered robotic methods using robot swarms to build large structures and also proposed his famous 'Astrochicken,' a 1 kg self-replicating automaton that was part biological and was conceived as a way of exploring the Solar System. Eric Drexler is well known for positing nanomachines that could build large structures in space.

So the idea has an interesting past, and now we can consider the Turyshev paper we've been looking at as the outline of an overall rethinking of the classic one-destination-per-mission concept, one that allows cheap flybys but also alternate ways of putting larger instrumented craft into the kind of orbits the 2022 Decadal has recommended for its putative Uranus mission. Modular smallsat design might incorporate self-assembly including propulsion modules for slowing the encounter speed of a mission to the outer planets. Here is what the paper says on the topic as it relates to a possible mission to search for life in the plumes of Enceladus:

> Another mission type may rely on in-flight aggregation [8], which may be needed to allow for orbital capture. For that, after perihelion passage and while moving at 5 AU/yr (~25 km/s), the microsats would perform inflight aggregation to make a fully capable smallsat to satisfy conditions for in situ investigations. One such important capability may be enhanced on-board propulsion capable of providing the Δv needed to slow down the smallsat. In this case, before approaching Enceladus, the spacecraft reduces its velocity by 7.5 km/s using a combination of on-board propulsion and gravity assists. Moving in the same direction with Enceladus (which orbits Saturn at 12.6 km/s) it achieves the conditions for in situ biomaterial collection.

We might, then, consider the option of either multiple flybys of small probes or larger payloads in self-assembling smallsat craft of the ice giants and other targets in the outer reaches of the system. The paper names quite a few possibilities. Among them:

The so-called 'interstellar ribbon,' evidently determined by interactions between the heliosphere and the local interstellar magnetic field.

Indirect probing of sailcraft trajectory in search of information about the putative Planet 9 and its gravitational effects somewhere between 300 and 500 AU of the Sun (Breakthrough Starshot has also discussed this). And if Planet 9 is found, target missions to a world much too far away to study with chemical propulsion methods.

The Kuiper Belt and beyond: KBOs and dwarf planets like Haumea, Makemake, Eris, and Quaoar within roughly 100 AU of the Sun, or even Sedna, whose orbit takes it well beyond 100 AU.

Observations of Earth as exoplanet, observing its transits across the Sun and improving transit spectroscopy.

Missions to interstellar objects like 1/I 'Oumuamua, which are believed to occur in substantial numbers and likely to be a rich field for future discovery.

Studies of the local interplanetary dust cloud responsible for the zodiacal light.

Exoplanet imaging through self-assembling smallsats, the JPL Solar Gravitational Lens mission.

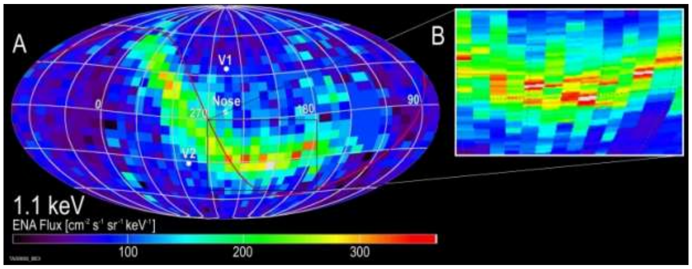


Image: This is Figure 9 from the paper. Caption: IBEX ENA Ribbon. A closer look suggests that the numbers of ENAs are enhanced at the interstellar boundary. A Sundiver spacecraft will go through this boundary as it travels to the ISM. Credit: SwRI.

As examined in JPL's Phase III study for the SGL mission (the term 'microsat' below refers to that category of smallsats massing less than 20 kilograms):

The in-flight (as opposed to Earth-orbiting or cislunar) autonomous assembly [8] allows us to build large spacecraft from modules, separately delivered in the form of microsats (<20 kg), where each microsat is placed on a fast solar system transit trajectory via solar sail propulsion to velocities of ~10 AU/yr. Such a modular approach of combining various microsats into one larger spacecraft for a deep space mission is innovative and will be matured as part of the TDM flights. This unexplored concept overcomes the size and mass limits of typical solar sail missions. Autonomous docking and in-flight assembly are done after a large Δv maneuver, i.e., after passing through perihelion. The concept also offers the compelling ability to assemble different types of instruments and components in a modular fashion, to accomplish many different mission types.

To say that robotic assembly is an 'unexplored concept' underlines how much would have to be resolved to make such a daring mission work. The paper goes into more details, of which I'll mention the high accuracy demanded in terms of trajectory. Remember, we're talking about flinging each microsat into the outer system after perihelion on its own, with the need for successful rendezvous and assembly not in Earth orbit but in outbound cruise. Docking technologies for structural, power and data connections would go far beyond those deployed on any missions flown to date.

Even so, I'm persuaded this concept is feasible. It's also completely brilliant.

Autonomous in-space docking has been demonstrated, while proximity operation technologies specific to such missions can be developed with time. I've referred before in these pages to NASA's On-Orbit Autonomous Assembly from Nanosatellites (OAAN) project, and note that the agency has followed with a CubeSat Proximity Operations Demonstration (CPOD) mission. Needless to say, we'll keep an eye on these and other efforts. I'm reminded of the intricacies of JWST deployment and have to say that from this layman's view, we are building the roadmap to make self-assembly happen.

Image: An early artist's impression of OAAN. Credit: NASA.

Alex Tolley, a contributor to my Centauri Dreams website, has been looking into self-assembly issues and noted the question of redundancy. Quoting Alex:

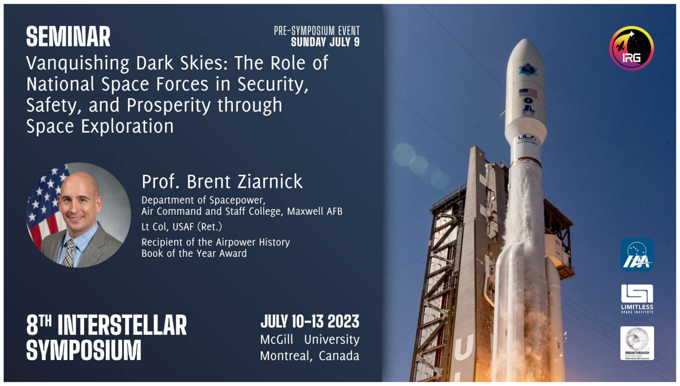
"Normally, a swarm of independent probe sails would o5er redundancy in case of failure. A swarm of flyby sail probes can afford the odd failure. However, this is not the case with probes that must be combined into a functioning whole. Now we have a weakest link problem. Any failure could jeopardize the mission if a failed probe has a crucial component needed for the final combined probes. That failure could be with the payload, or with the sail system itself. A sail may fail with a malfunctioning blade, which prevents being able to rendezvous with the rest of the swarm, or more subtly, be unable to manage fine maneuvering for docking."

Self-assembly is complex indeed, making early missions that can demonstrate docking and assembly a priority. Success could re-shape how we conceive deep space missions.

For a more detailed look at how the JPL team views self-assembly in the context of the SGL mission, see Helvajian et al., "A mission architecture to reach and operate at the focal region of the solar gravitational lens" (abstract at https://arxiv.org/abs/2207.03005). The Turyshev et al. paper is "Science opportunities with solar sailing smallsats," available as a preprint at https://arxiv.org/abs/2303.14917.

Montreal Seminars

If you can make it to Montreal a day early, please sign up for our seminar program. Seminars are 3-hour presentations on a single subject, providing an in depth look at that subject. Seminars are held before the Symposium begins, on Sunday, July 9, 2023, with morning and afternoon sessions. The content must be acceptable to be counted as continuing education credit for those holding a Professional Engineer (PE) certificate.



If Loud Aliens Explain Human Earliness, Quiet Aliens Are Also Rare: A Review.

BY DAVE MOORE

What can we say about the appearance and spread of civilizations in the Milky Way? There are many ways of approaching the question, but Dave Moore focuses on a recent paper from Robin Hanson and colleagues, one that has broad implications for SETI. Dave was born and raised in New Zealand, spent time in Australia, and now runs a small business in Klamath Falls, Oregon. He adds: "As a child, I was fascinated by the exploration of space and science fiction. Arthur C. Clarke, who embodied both, was one of my childhood heroes. But growing up in New Zealand in the '60s, such things had little relevance to life, although they did lead me to get a degree in biology and chemistry." Discovering like-minded people in California, he expanded his interest in SETI and began attending scientific conferences. We hope he will join us in Montreal this summer, but until then, here is his thinking on a controversial topic indeed.

I consider the paper "If Loud Aliens Explain Human Earliness, Quiet Aliens Are Also Rare," by Robin Hanson, Daniel Martin, Calvin McCarter, and Jonathan Paulson, a significant advance in addressing the Fermi Paradox. To explain exactly why, I need to go into its background.

Introduction and History

The Fermi paradox hangs over all our discussions and theories about SETI like a sword of Damocles, ready to fall and cut our assumptions to pieces with the simple question, where are the aliens? There is no reason not to suppose that Earth-like planets could have formed billions of years before Earth did and that exosolar technological civilizations (ETCs) could not have arisen billions of years ago and spread throughout the galaxy. So why then don't we see them? And why haven't they visited us, given the vast expanse of time that has gone by?

Numerous papers and suggestions have tried to address this conundrum, usually ascribing it to some form of alien behavior, or arguing that the principle of mediocrity doesn't apply, and intelligent life is a very rare fluke.

The weakness of the behavioral arguments is that they assume universal alien behaviors, but given the immense differences we expect from aliens—they will be at least as diverse as life on Earth—why would they all have the same motivation? It only takes one ETC with the urge to expand, and diffusion scenarios show that it's quite plausible for an expansive ETC to spread across the galaxy in a fraction (tens of millions of years) of the time in which planets could have given rise to ETCs (billions of years).

And there is not much evidence that the principle of mediocrity doesn't apply. Our knowledge of exosolar planets shows that while Earth as a type of planet may be uncommon, it doesn't look vanishingly rare, and we cannot exclude from the evidence we have that other types of planets cannot give rise to intelligent life.

Also, modest growth rates can produce Kardashev III levels of energy consumption in the order of tens of thousands of years, which in cosmological terms is a blink of the eye.

In 2010, I wrote a paper for *JBIS* modeling the temporal dispersion of ETCs. By combining this with other information, in particular diffusion models looking at the spread of civilizations across the galaxy, it was apparent that it was just not possible for spreading ETCs to occur with any frequency if they lasted longer than about 20,000 years. Longer than that and at some time in Earth's history, they would have visited/colonized us by now. So, it looks like we are the first technological civilization in our galaxy. This may be disappointing for SETI, but there are other galaxies out there—at least as many as there are stars in our galaxy.

My paper was a very basic attempt to deduce the distribution of ETCs from the fact we haven't observed any yet. The Robin Hanson et al paper, however, is a major advance in this area as it builds a universe-wide quantitative framework to frame this lack of observational evidence and produces some significant conclusions.

The paper starts with the work done by S. Jay Olsen. In 2015, Olson began to bring out a series of papers assuming the expansion of ETCs and modeling their distributions. He reduced all the parameters of ETC distribution down to two: (α), the rate at which civilizations appeared over time, and (v) their expansion rate, which was assumed to be similar for all civilizations as ultimately all rocketry is governed by the same laws of physics. Olsen varied these two parameters and calculated the results for the following: the ETC-saturated fraction of the universe, the expected number and angular size of their visible domains, the probability that at least one domain is visible, and finally the total expected fraction of the sky eclipsed by expanding ETCs.

In 2018, Hanson et al took Olsen's approach but incorporated the idea of bringing in the Hard Steps Power Law into modeling the appearance rate of ETCs, which they felt was more accurate and predictive than the rate-over-time models Olsen used.

The Hard Steps Power Law

The Hard Steps power law was first introduced in 1953 to model the appearance of cancer cells. To become cancerous an individual cell must undergo a number of specific mutations (hard steps i.e. improbable steps) in a certain order. The average time for each mutation is longer than a human lifetime, but we have a lot of cells in our body, so 40% of us develop cancer, the result of a series of improbabilities in a given cell.

If you think of all the planets in a galaxy that life can evolve on as cells, and the ones that an ETC arises on being cancerous, you get the idea. The Hard Steps model is a power law, so the chance of an outcome happening in a given period of time is the inverse of the chance of a step happening (its hardness) to the power of the number of steps. Therefore the chance of anything happening in a given time goes down very rapidly with the number of hard steps required.

In Earth's case, the given period of time is about 5.5 billion years, the time from Earth's origin until the time that a runaway greenhouse sets in about a billion years from now.

The Number of Hard Steps in our Evolution

In 1983, Brandon Carter was looking into how likely it was for intelligent life to arise on Earth, and he thought that due to the limitations on the time available this could be modeled as a hard step problem. To quote:

> This means that some of the essential steps (such as the development of eukaryotes) in the evolution process leading to the ultimate emergence of intelligent life would have been hard, in the sense of being against the odds in the available time, so that they are unlikely to have been achieved in most of the earth-like planets that may one day be discovered in nearby extra-solar systems.

Carter estimated that the number of hard steps it took to reach our technological civilization was six: biogenesis, the evolution of bacteria, eukaryotes, combogenisis [sex], metazoans, and intelligence. This, he concluded, seemed the best fit for the amount of time that had taken for us to evolve. There has been much discussion and examination of the number of hard steps in the literature, but the idea has held up fairly well so Hanson et al varied the number of hard steps around six as one of their model variables.

The Paper

The Hanson paper starts out by dividing ETCs into two categories: loud aliens and quiet aliens. To quote:

> Loud (or "expansive") aliens expand fast, last long, and make visible changes to their volumes. Quiet aliens fail to meet at least one of these criteria. As quiet aliens are harder to see, we are forced to accept uncertain estimates of their density, via methods like the Drake equation. Loud aliens, by contrast, are far more noticeable if they exist at any substantial density.

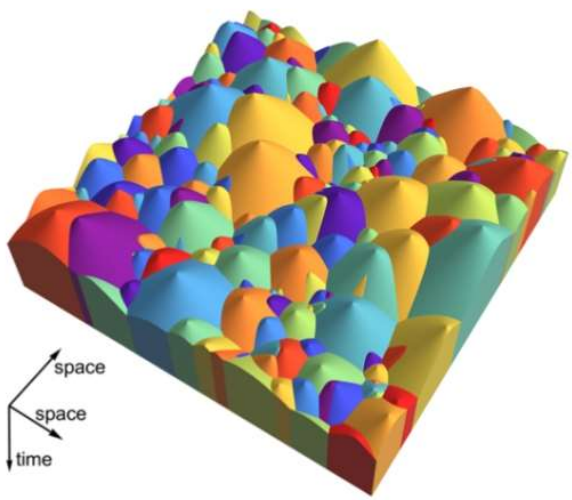
The paper then puts aside the quiet aliens as they are, with our current technology, difficult to find and focuses on the loud ones and, in a manner similar to Olsen, runs models but with the following three variables:

i) The number of hard steps required for an ETC to arise.

ii) The conversion rate of a quiet ETC into a loud, i.e. visible, one.

iii) The expansion speed of a civilization.

In their models, (like the one illustrated below) a civilization arises. At some point, it converts into an expansive civilization and spreads out until it abuts a neighbor at which point it stops. Further civilizations in the volume that is controlled are prevented from happening. Results showing alien civilizations that are visible from our point of view are discarded, narrowing the range of these variables. (Note: time runs forward going down the page.)



Results

In a typical run with parameters resulting in them not being visible to us, expansive civilizations now control 40-50% of the universe, and they will finish up controlling something like a million galaxies when we meet one of them in 200 million year's time. (Note, this paradoxical result is due to the speed of light. They control 40-50% of the universe now, but the electromagnetic radiation from their distant galaxies has yet to reach us.)

From these models, three main outcomes become apparent:

Our Early Appearance

The Hard Step model itself contains two main parameters, number of steps and the time in which they must be concluded in. By varying these parameters, Hanson et al showed that, unless one assumes fewer than two hard steps (life and technological civilizations evolve easily) and a very restrictive limit on planet habitability lifetimes, then the only way to account for a lack of visible civilizations is to assume we have appeared very early in the history of civilizations arising in the universe. (In keeping with the metaphor, we're a childhood cancer.)

All scenarios that show a higher number of hard steps than this greatly favor a later arrival time of ETCs, so an intelligent life form producing a technological civilization is at this stage of the universe a low probability event.

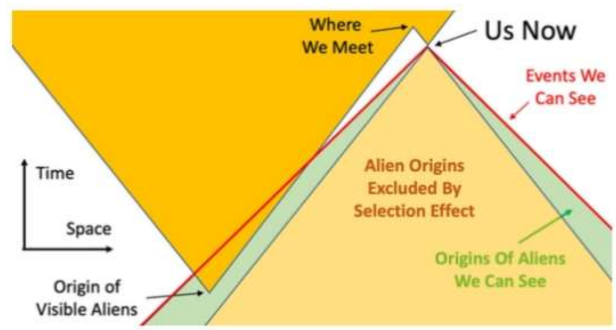
Chances of other civilizations in our galaxy

Another result coming from their models is that the higher the chance of an expansive civilization evolving from a quiet civilization, the less the chance there is of there being any ETCs aside from us in our galaxy. To summarize their findings: assuming a generous million year average duration for a quiet civilization to become expansive, very low transition chances (p) are needed to estimate that even one other civilization was ever active anywhere along our past light cone ($p < 10^{-3}$), or existed in our galaxy ($p < 10^{-4}$), or is now active in our galaxy ($p < 10^{-7}$).

For SETI to be successful, there needs to be a loud ETC close by, and for one to be close by, the conversion rate of quiet civilizations to expansive, loud ones must be in the order of one per billion. This is not a good result pointing to SETI searches being productive.

Speed of expansion

The other variable used in the models is the speed of expansion. Under most assumptions, expansive civilizations cover significant portions of the sky. However, when taking into account the speed of light, the further distant these civilizations are, the earlier they must form for us to see them. One of the results of this relativistic model is that the slower civilizations expand on average, the more likely we are to see them.



This can be demonstrated with the above diagram. The orange portion of the diagram shows the origin and expansion of an ETC at a significant proportion of the speed of light. We—by looking out into space are also looking back in time—can only see what is in our light cone (that which is below the red line), so we see the origin of our aliens (say one billion years ago) and their initial spread up to about half that age. After which, the emissions from their spreading civilization have not yet had time to reach us.

The tan triangle represents the area in space from which an ETC spreading at the same rate as the orange aliens would already have arrived at our planet (in which case we would either not exist or we would know about it), so we can assume that there were no expansive aliens having originated in this portion of time and space.

If we make the spread rate a smaller proportion of the speed of light, then this has the effect of making both the orange and tan triangles narrower along the space axis. The size of the tan exclusion area becomes smaller, and the green area, which is the area that can contain observable alien civilizations that haven't reached us yet, becomes bigger.

You'll also notice that the narrower orange triangle of the expansive ETC crosses out of out of our light cone at an earlier age, so we'd only see evidence of their civilization from an earlier time.

The authors note that the models rely on us being able to detect the boundaries between expansive civilizations and unoccupied space. If the civilizations are out there, but are invisible to our current instruments, then a much broader variety of distributions is possible.

Conclusions

We have always examined the evolution of life of Earth for clues as to the distribution of alien life. What is important about this paper is that it connects the two in a quantitative way.

There are a lot of assumptions build into this paper (some of which I find questionable); however, it does give us a framework to examine them and test them, so it's a good basis for further work.

To quote Hanson et al:

> New scenarios can be invented and the observable consequences calculated immediately. We also introduce correlations between these quantities that are obtained by eliminating dependence on α [appearance rate], e.g. we can express the probability of seeing at least one domain as a function of v [expansion velocity] and the currently life-saturated fraction of the universe based on the fact we haven't see or have encountered any.

I would point out a conclusion the authors didn't note. If we have arisen at an improbably early time, then there should be lots of places (planets, moons) with life at some step in their evolution, so while SETI searches don't look promising from the conclusions of this paper, the search for signs of exosolar life may be productive.

This paper has given us a new framework for SETI. Its parameters are somewhat tangential to the Drake Equation's, and its approach is to basically work the equation backwards: if N=0 (number of civilizations we can communicate with in the Drake equation, number of civilizations we can observe in this paper), then what is the range in values for f_i (fraction of planets where life develops intelligence), f_c (fraction of civilizations that can communicate/are potentially observable) and (L) length of time they survive. The big difference is that this paper factors in the temporal distribution of civilizations arising, which is not something the Drake Equation addressed. The Drake equation, for something that was jotted down before a meeting 61 years ago, has had a remarkably good run, but we may be seeing a time where it gets supplanted.

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REMEMBERING JIM EARLY (1943-2023)
BY PAUL GILSTER

I was saddened to learn of the recent death of James Early, author of a key paper on interstellar sail missions and a frequent attendee at IRG events (or TVIW, as the organization was known when I first met him). Jim passed away on April 28 in Saint George, UT at the age of 80, a well-liked figure in the interstellar community and a fine scientist. I wish I had known him better. I ran into him for the first time in a slightly awkward way, which Jim, ever the gentleman, quickly made light of.

What happened was this. In 2012 I was researching damage that an interstellar sail mission might experience in the boost phase of its journey. Somewhere I had seen what I recall as a color image in a magazine (OMNI?) showing a battered, torn sail docked in what looked to be a repair facility at the end of an interstellar crossing. It raised the obvious question: If we did get a sail up to, say, 5% of the speed of light, wouldn't even the tiniest particles along the way create significant damage to the structure? The image was telling and to this day I haven't found its source.

I think of the image as 'lightsail on arrival,' and if this triggers a memory with anyone, please let me know. Anyway, although our paths crossed at the first 100 Year Starship symposium in Orlando in 2011, I didn't know Jim's work and didn't realize he had analyzed the sail damage question extensively. When I wrote about the matter on *Centauri Dreams* a year later, he popped up in the comments:

> I presented a very low mass solution to the dust problem at the 100 Year Starship Symposium in a talk titled "Dust Grain Damage to Interstellar Vehicles and Lightsails". An earlier published paper contains most of the important physics: Early, J.T., and London, R.A., "Dust Grain Damage to Interstellar Laser-Pushed Lightsail", *Journal of Spacecraft and Rockets*, July-Aug. 2000, Vol. 37, No. 4, pp. 526-531.

I was caught by surprise by the reference. How did I miss it? Researching my 2005 *Centauri Dreams* book, I had been through the literature backwards and forwards, and *JSR* was one of the journals I combed for deep space papers. Later, at a TVIW meeting in Oak Ridge, we talked, had dinner and Jim kidded me about my research methods. As I saw it, his paper was a major contribution, and I should have known about it. Yesterday I asked Andrew Higgins (McGill University) about the paper and he had this to say in an email:

> Jim Early's paper (written with Richard London in 1999) on dust grain impacts addressed one of the

bogeys of interstellar flight: The dust grain impact problem when traveling at relativistic speeds. Their analysis showed—counterintuitively—that the damage caused by a dust grain on an interstellar lightsail actually decreases as the sail exceeds a few percent of the speed of light. While the grain turns into an expanding fireball of plasma as it passes through the sail, the amount of thermal radiation deposited on the sail decreases as the fireball is receding more quickly from the sail. This was a welcome result suggesting sails might survive the interstellar transit, and their study remains the seminal work on dust grain interactions with thin structures at relativistic speeds.

Image: Dinner after the first day's last plenary session in Oak Ridge in 2014. That's Jim Benford at far left, then James Early, Sandy Montgomery and Michael Lynch.

The family has set up a website honoring Jim and offering photos and an obituary (https://memorialsource.com/memorial/jim-early). He got his bachelor's degree in Aeronautics at MIT, following it with a master's degree in mechanical engineering at Caltech, and a PhD in aeronautics and physics at Stanford University. He was involved with development activities for the Delta launch vehicle while obtaining his bachelor's degree by working at NASA Goddard Space Flight Center in the summers and then at McDonnell-Douglas after finishing his master's degree. He joined Lockheed and Hughes aircraft for a time before finally ending up at the Lawrence Livermore National Laboratory working on laser physics until he retired.

Sail in Flight

So let's look at Jim's paper on sails, a subject he continued to work on for the next two decades. Although Robert Forward came up with sail ideas that pushed as high as 30 percent of the speed of light (and in the case of Starwisp, even higher), Jim and his co-author Richard London chose 0.1 *c* for cruise velocity in their paper, which provides technical challenges aplenty but at least diminishes the enormous energy costs of still faster missions, and certainly mitigates the problem of damage from dust and gas along the way. Depending on the methods used, the sail as analyzed in this paper may take a tenth of a light year to get up to cruise velocity. It's worth mentioning that the sail does not have to remain deployed during cruise itself, but deceleration at the target star, depending on the methods used, may demand redeployment. Breakthrough Starshot envisions stowing the sail in cruise after its sudden acceleration to 20 percent of *c*.

Early and London use beryllium sails as their reference point, these being the best characterized design at this stage of sail study, and assume a sail 20 nm thick. In terms of the interstellar medium the sail will encounter, the authors say this:

> Local interstellar dust properties can be estimated from dust impact rates on spacecraft in the outer solar system and by dust interaction with starlight. The mean particle masses seen by the Galileo and Ulysses spacecraft were 2×10^{-12} and 1×10^{-12}g, respectively. A 10^{-12}g dust grain has a diameter of approximately 1 μm. The median grain size is smaller because the mean is dominated by larger grains. The Ulysses saw a mass density of 7.5×10^{-27}g cm^{-3}. A sail accelerating over a distance of 0.1 light years would encounter 700 dust grains/cm^2 at this density. The surface of any vehicle that traveled 10 light years would encounter 700 dust grains/mm^2. If a significant fraction of the particle energy is deposited in the impacted surface in either case, the result would be catastrophic.

The question then becomes, just how much of the particle's energy will be deposited on the sail? The unknowns are all too obvious, but the paper adds that neither of the Voyagers saw dust grains larger than 1 μm at distances beyond 50 AU, while a 1999 study on interstellar dust grain distributions found a flat distribution from 10^{-14} to 10^{-12} g with some grains as large as 10^{-11} g. Noting that a 10^{-12} g dust grain has a diameter of about 1-μm, the authors use a 1-μm diameter grain for their impact calculations.

The results are intriguing because they show little damage to the sail. Catastrophe averted:

> At the high velocities of interstellar travel, dust grains and atoms of interstellar gas will pass through thin foils with very little loss of energy. There will be negligible damage from collisions between the nuclei of atoms. In the case of dust particles, most of the damage will be due to heating of the electrons in the thin foil. Even this damage will be limited to an area approximately the size of the dust particle due to the extremely fast, one-dimensional ambipolar diffusion explosion of the heated section of the foil. The total fraction of the sail surface damaged by dust collisions will be negligible.

The torn and battered lightsail in its dock, as seen in my remembered illustration, may then be unlikely, depending on cruise speed and, of course, on the local medium it passes through. Sail materials also turn out to offer excellent shielding for the critical payload behind the sail:

> Interstellar vehicles require protection from impacts by dust and interstellar gas on the deep structures of the vehicle. The deployment of a thin foil in front of the vehicle provides a low mass, effective system for conversion of dust grains or neutral gas atoms into free electrons and ions. These charged particles can then be easily deflected away from the vehicle with electrostatic shields.

And because the topic has come up in a number of past discussions here, let me add this bit about interstellar gas and its effects on the lightsail:

> The mass density of interstellar gas is approximately one hundred times that of interstellar dust particles though this ratio varies significantly in different regions of space. The impact of this gas on interstellar vehicles can cause local material damage and generate more penetrating photon radiation. If this gas is ionized, it can be easily deflected before it strikes the vehicle's surface. Any neutral atom striking even the thin foil discussed in this paper will pass through the foil and emerge as an ion and free electron. Electrostatic or magnetic shields can then deflect these charged particles away from the vehicle.

Consequences for Sail Design

All of these findings have a bearing on the kind of sail we use. The thin beryllium sail appears effective as a shield for the payload, with a high melting point and, the authors conclude, the ability to be increased in thickness if necessary without increasing the area damaged by dust grains. Ultra-thin foils of tantalum or niobium offer higher temperature possibilities, allowing us to increase the laser power applied to the sail and thus the acceleration. But Early and London believe that the higher atomic mass of these sails would make them more susceptible to damage. Even so, "…the level of damage to thin laser lightsails appears to be quite small; therefore the design of these sails should not be strongly influenced by dust collision concerns."

Dielectric sails would be more problematic, suffering more damage from heated dust grains because of their greater thickness, and the authors argue that these sail materials need to be subjected to a more complete analysis of the blast wave dynamics they will experience. All in all, though, velocities of 0.1 *c* yield little damage to a thin beryllium sail, and thin shields of similar materials can ionize dust as well as neutral interstellar gas atoms, allowing the ions to be deflected and the interstellar vehicle protected.

These are encouraging results, but the size of the problem is daunting, and given the apparent cost of the classically conceived interstellar probe, the prospect of impact damage calls for continued analysis of the medium through which the probe would pass. This is one of the advantages of sending not one large craft but a multitude of smaller 'chipsat' style vehicles in the Breakthrough Starshot model. Send enough of these and you can afford to lose a certain percentage along the way. I can only wish I could sit down with Jim Early again to kick around chipsat concepts, but what a fine memorial to know that your paper continues to influence evolving interstellar ideas.

The paper is Early, J.T., and London, R.A., "Dust Grain Damage to Interstellar Laser-Pushed Lightsail," *Journal of Spacecraft and Rockets*, July-Aug. 2000, Vol. 37, No. 4, pp. 526-531.