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EVOLUTIONARY LIGHTSAILING MISSIONS FOR THE 100-YEAR STARSHIP

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Incremental milestones towards interstellar flight can be achieved in this century by building on first steps with lightsailing, the only known technology that might someday take us to the stars. That this is now possible is enabled by achievements of first solar sail flights, the use of nano-technology for miniaturization of spacecraft, advances in information processing and the decoding of our genomes into transportable form. This paper quantifies a series of robotic steps through and beyond the solar system that are practical and would stimulate the development of new technologies in guidance, navigation, materials, communication, sensors, information processing etc. while exploring ever-more distant, exciting space objectives at distances impractical for classical rocket-based technologies. There robotic steps may be considered as precursors to human interstellar flight, but they may also be considered as evolutionary steps that provide for a different future: One of virtual human interstellar flight that may bypass the ideas of the past (big rockets launching heavy people) in favour of those of the future – networking amongst the stars with information, and the physical transport of digital and biological genomes.

Keywords: LightSails, Interstellar Precursors, Solar sail

1. ARCHITECTURE FOR EVENTUAL INTERSTELLAR FLIGHT

The vision of interstellar flight is a crucial part of space exploration and aerospace technology. Public fascination and financial support, as well as the participation of the space-faring technical and scientific teams are, in a large part, motivated by the big questions of the extent and nature of life in the universe. For all of human history this has been a theoretical or philosophical question, but now – with discoveries in our solar system and of planets in other solar systems it is a question of scientific exploration and discovery.

Incremental milestones towards interstellar flight can be achieved in this century by building on the first steps with the only known technology that might someday take us to the stars – lightsailing, a solar sail that uses photons as propulsion. That this is now possible is enabled by achievements of first solar sail flights, the use of nano-technology for miniaturization of spacecraft, advances in information processing and the decoding of our genomes into transportable form.

This paper quantifies a series of robotic steps through and beyond the solar system that are practical and will stimulate the development of new technologies in guidance, navigation, materials, communication, sensors, information processing etc. while exploring ever-more distant, exciting space objectives at distances impractical for classical rocket-based technologies. There robotic steps may be considered as precursors to human interstellar flight, but they may also be considered as evolutionary steps that provide for a different future – one of virtual human interstellar flight that may bypass the ideas of the past (big rockets launching heavy people) in favor of those of the future – networking amongst the stars with information, and the physical transport of digital and biological genomes.

The robotic steps provide interesting mission achievements that can sustain public interest as well as technical milestones that sustain the vision of interstellar flight. They also provide specific and more immediate technological benefits that serve space programs. Public engagement will also be enabled by refining the vision of interstellar flight with the advances in technology and the achievements of flight – further in distance and time into the unknown.

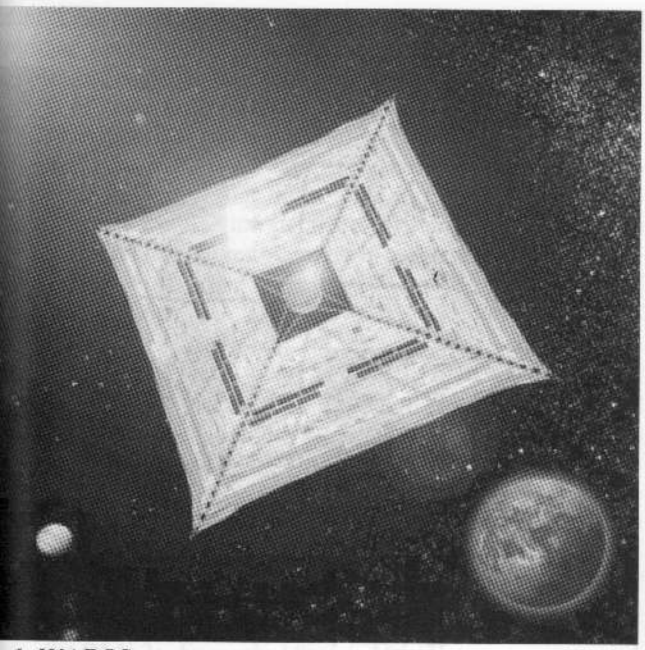
2. FIRST STEPS ON THE PATH

Lightsailing projects, shown in Figs. 1-5 have been undertaken by NASA, Japan and The Planetary Society. The first solar sail flight was successfully achieved by Japan's IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) spacecraft (Fig. 1). It was launched May 20, 2010 and flew successfully towards Venus, hitching a ride on the Japanese Venus mission, Akatsuki [1]. A photo, taken from a deployed camera in space of IKAROS with its deployed sail is shown in Fig. 2.

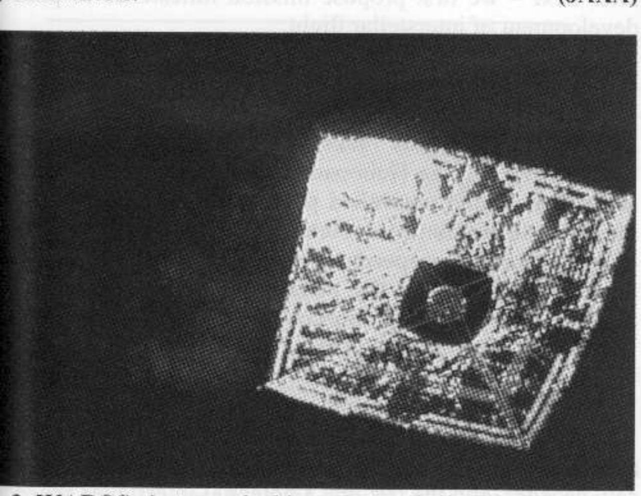
NASA launched its Nanosail-D spacecraft piggy-backing on the FASTSAT spacecraft in Nov.2010. After delays and uncertainty about its separation, it has now been confirmed that Nanosail-D (Fig. 3) did separate from FASTSAT and deployed its sail [2]. It did not fly as a solar sail, but in the Earth's atmosphere testing drag properties of the sail.

The Planetary Society's Cosmos 1 solar sail spacecraft

This paper was presented at the 100 Year Starship™ Study Symposium, 30 September - 2 October 2011, Orlando, Florida, USA. It was presented in the Time Distance Solutions technical track.



. 1 IKAROS. (JAXA)



. 2 IKAROS photographed in space by deployed camera. (JAXA)

s launched on July 20, 2004, but did not reach orbit when Russian Volna rocket first stage failed [3]. The Society reloped a nano-spacecraft, LightSail®-1, based on NASA's nosail but fully instrumented and controllable (Figs. 4 and The spacecraft was completed and put in storage, awaiting econdary launch opportunity out of the Earth's atmosphere a minimum altitude of 825 km [4]. In the meantime NASA iated Sunjammer, a larger solar sail built by the L'Garde rporation – it is scheduled for a launch into interplanetary ce in 2014.

Thus, after years of paper studies, we now can carry out tsailing missions to accelerate spacecraft without the use propellant, and thus take the first steps on the path to the rs. The development of technologies along the way will vide near-term benefits to the aerospace community. The omplishments of mission objectives along the way will vide near-term interest and engagement for the public taining the goals of long-term space exploration and seeking inderstand humankind's place in the universe.

Future interstellar payloads – even for human exploration y be genetic or cellular. The Planetary Society planned to

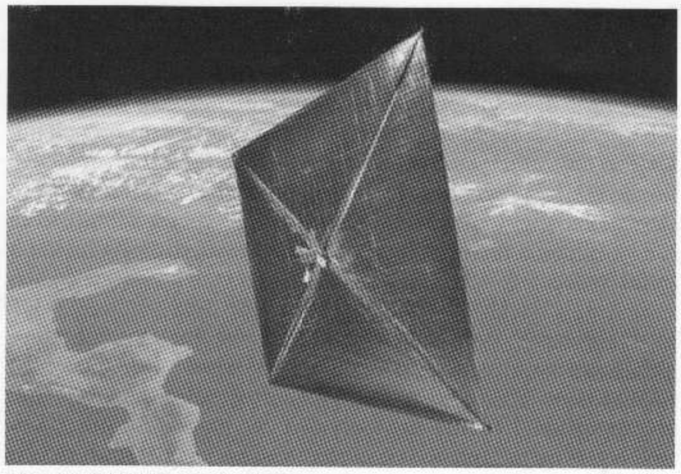


Fig. 3 NASA Nanosail-D. (NASA)

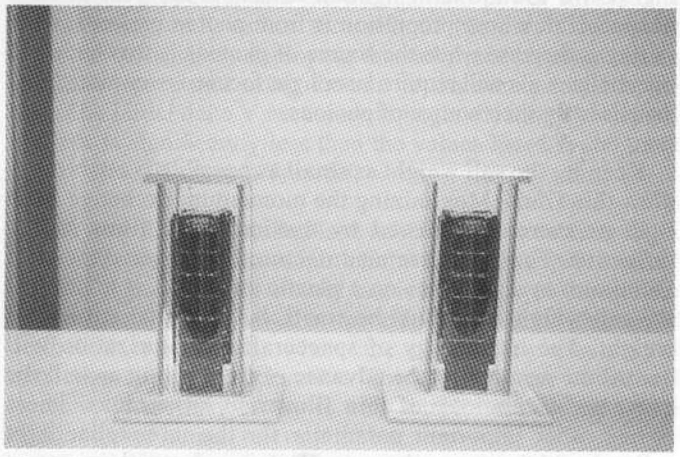


Fig. 4 TPS LightSail®-1 flight model and spare in storage.

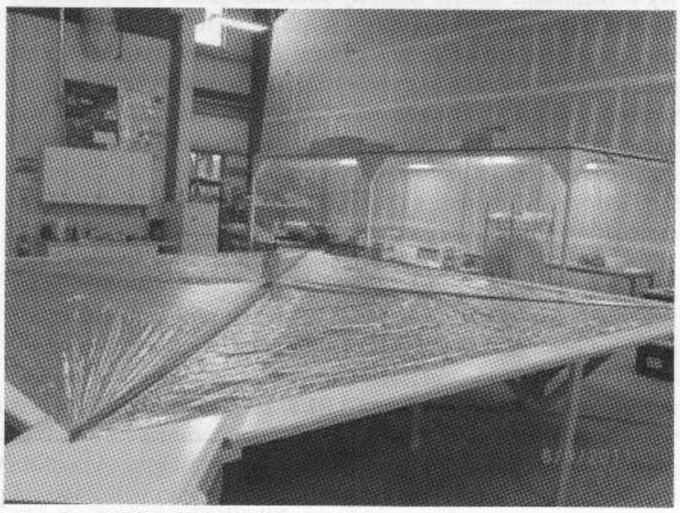


Fig. 5 TPS LightSail®-1 flight model spacecraft during development.

send the first-ever directed life from Earth on an interplanetary mission with a living interplanetary flight experiment on the Russian Phobos sample return mission in 2011 [5]. Unfortunately that mission failed before leaving Earth orbit. The experiment carried microbes. Future travelers might also be more intelligent microbes or, as Craig Ventner and Freeman Dyson have suggested, encoded ones to re-create life at the destination planet and transmit information back to us. Future robotic and human spacecraft might be 1 gram payloads on 1000 x 1000 meter sails.

3. LIGHTSAILING & NANOSATS – INTERSTELLAR FLIGHT TECHNOLOGIES

The single distinguishing characteristic that makes lightsailing the interstellar flight technology is that it carries no propellant. Unlike any other known technology lightsails will not have to carry a large mass that will be consumed in order to reach interstellar flight speeds. Interstellar flight speed is built from the continuous force of light pressure transferring momentum to the spacecraft.

The pressure from light derives from the energy of photons, and thus a large area for collecting photons is a key spacecraft requirement. Since the momentum imparted to the spacecraft is proportional to the area divided by mass, the other key spacecraft requirement is low mass. The acceleration of the several already developed solar sail spacecraft is shown in Fig. 6. We use the term lightsail to denote the general class of spacecraft whose propulsion is from photon pressure; solar sailing is the case when the source of photons is the Sun. True interstellar sails will require laser light focused over interstellar distances for their source of photons.

Keeping the sail weight as small as possible is enabled by ultra-thin films. Maximizing the momentum exchange from light pressure is achieved by making those films highly reflective. Thus sails are manufactured by a thin deposit of aluminum or silver ions on a plastic substrate. It is not just the sail weight that must be small, but the total spacecraft weight. The technology of spacecraft miniaturization will contribute as much to the advance of lightsailing as will the gossamer technology of thin films and large areas. There is one other important parameter for the interstellar light sailor besides area and mass. That is – how close can it fly to the Sun? Since velocity increase to an interplanetary spacecraft is most efficiently applied at its perihelion, and because obviously the light force is greatest near the Sun, we want to approach the Sun as close as possible while sailing. That defines the other key technology – material thermal resistance.

These technologies – gossamer large areas, ultra-low mass spacecraft components, and materials thermal and radiation resistance are those which will enable sailing to the stars, and they are also those of major interest to the aerospace community for advanced spacecraft with near- and deep-space applications. This is the connection between starships and the

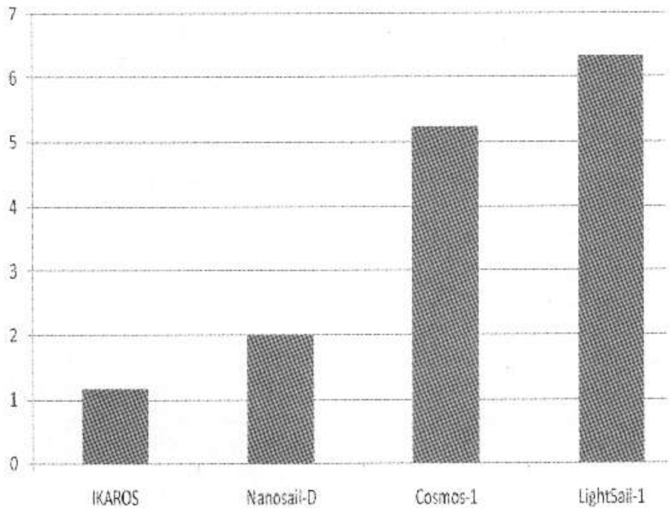


Fig. 6 Characteristic acceleration (at 1AU) in micro-g.

present. Technology development is discussed in the section after next – we first propose mission milestones to pace the development of interstellar flight.

4. MISSION MILESTONES

Lightsailing velocities make missions to the outer planets, the Kuiper Belt, the Heliopause, the Oort cloud and beyond, achievable within unrivalled practical flight times and within modest total mission costs. Achieving such milestones of flight, with ever increasing speed and distance records and technology advances will engage the public and sustain interest in the Starship enterprise. Examples of future spacecraft acceleration that we can imagine are given in Table 1.

These lower rows are concepts –one might be an interplanetary spacecraft foreseeable in the next decade, the next something that could escape the solar system in the next few decades, and the last one a potential interstellar spacecraft achieving Alpha Centauri in approximately 500 years (without laser propulsion!).

This bottom line in the table shows both the possibility and difficulty of interstellar flight. We can achieve enormous speeds with solar sails, and yet interstellar flight remains at the edge of feasibility. The "characteristic acceleration" cited is

TABLE 1: *Examples of Future Spacecraft Accelerations.*

Mission	Area in sq meters	Mass in kg	Char. accel. in micro-g (at 1AU)
Cosmos 1	600	105	5.2
IKAROS	400	315	1.1
Nanosail-D	10	4.6	1.6
LightSail®	32	4.6	6.4
Sunjammer	1200	34	32
JPL Halley design ca. 1975	800 × 800	900	640
Interplanetary concept	100 × 100	100	91
Nano-interplanetary concept	45 × 45	8	231
Pico-Interstellar concept	100 × 100	1	9133

that at 1 AU from sunlight pressure. If we maneuver the sail to pick up major velocity increment from a low perihelion, the acceleration is much larger. In the next section we present an analysis of solar sailing trajectories and find the trip times to potential milestones beyond the solar system. It suggests that there might be a Moore's law of spacecraft development to enable ultimate interstellar flight. This equivalent Moore's law for deep space exploration details a 10:1 increase in distance for every incremental improvement in technology.

5. ANALYSIS

To demonstrate the utility and effectiveness of a solar sailing for interstellar precursors, we analyzed key milestones that were scientifically interesting and relevant for demonstrating the long duration/distance exploration technologies. Example target milestones are listed in Table 2. They suggest that a step-by-step steady progression of scientifically significant missions exist at the outer edge and beyond the solar system that could advance both our knowledge and capability on the interstellar path.

TABLE 2: *Example Mission Milestones.*

Milestone	Approx. Dist – AU
Neptune	30
Kuiper Belt	50-500
Heliopause	150
Solar Gravity Lens Focus	600+
TAU	1,000
Oort Cloud	5,000-50,000
1 Light-Year	63,000
Alpha Centauri	300,000

Our analysis examined the ability to achieve these milestones over a 50 and 100 year timeline. The 50 year timeline mimics the success of Pioneer and Voyager probes for maintaining both the infrastructure and continued operations over decades of flight. This 50 year timeline is also relevant for potentially achieving its mission objectives during the career of the designers and initial operators of the system for continuity and corporate memory for the overall interstellar effort.

Using these two programs as exemplars, our analysis of the astrodynamics defines the potential performance parameters and system requirements to reach extra-solar system destinations in fifty years. The second timeline in the data and figures shown later in the paper is a century of operations. Extrapolating the ability to maintain the infrastructure and continued operations of these deep space probes from 50 to 100 years is a difficult task. There are few examples (i.e. power, sewer and rail) of infrastructure elements that persist from 1913 to today. The existence of such a robust functioning infrastructure is assumed in this paper to demonstrate the kinematic potential of a solar sail vehicle over a century of flight where even significant fractions of the distance to Alpha Centauri are achieved.

For either timeline, our analysis consisted of high fidelity modeling of the solar sail vehicle, solar radiation pressure and the gravitational n-body effects. As previously mentioned, for this effort the effects of planetary flybys and gravity assists were neglected to demonstrate the unbiased potential of solar sailing. For the same rationale, other propulsion technologies and techniques were also not considered as part of this base effort. Key to this trajectory modeling was how best to demonstrate and exploit the near-limitless delta V potential of the sail while within the orbit of Jupiter.

To this end two sail deployment scenarios were developed to bound the problem. The lower bound is marked by a vehicle precluding sail deployment until a specific perihelion distance is reached at which time the sail deploys and the vehicle accelerates away from the sun. This trajectory is achieved by a Hohmann transfer from the Earth to the target perihelion on the farside of the Sun. Table 3 details the delta V for departure at the Earth, transit time and the resulting heliocentric velocity at perihelion.

The three perihelion distances selected also represent realistic targets and challenges for the overall system in terms of material properties and the thermal and power subsystems for operating well within the orbit of Mercury. The upper bound is modeled by deploying the sail immediately while in cis-Lunar space and using the sail to decelerate towards the Sun. The initial delta V necessary to begin the long slow spiral inwards is significantly less than the values listed in the table for the direct Hohmann Transfer.

The only delta V required is to achieve escape velocity from the Earth which from Low Earth Orbit (LEO) is approximately 11 km/s. Again a simple control law is used to force the vehicle to continue to spiral inwards toward the Sun until the target perihelion is achieved, where the control law changes to maximize outward acceleration. This dynamic use of the sail to manipulate its trajectory is what enables these deep space missions over human relevant time scales.

Figures 7 and 8 depict the respective system and inner solar system trajectory plots for a 100 m^2/kg solar sail system following each of these scenarios. The dotted green curve is the path of the Hohmann transfer, subsequent perihelion passage and outbound passage at a velocity of approximately 6 AU per year. The purple trajectory is the resulting buildup and resulting expulsion of the sail following the initial spiral inward from the earth. The net velocity of the sail is greater than 8.5 AU per year following its final perihelion passage and ~20 AU/year as it leaves the solar system.

An interesting aspect of the spiral scenario is the fact that it outperforms the direct case in both initial delta V required and maximum distance. For this case, despite the direct probe reaching Saturn in less than 2 years, a feat that requires a further 14 years of travel for the spiral probe, the spiral probe ultimately surpasses the direct probe with its increased velocity. This celestial race runs counter to conventional wisdom, where the tortoise beats the hare.

The reason for this is that even with a simple control law the sail is able to add energy to the orbit over multiple years. The continued elongation of aphelion and resulting increase in perihelion velocity is analogous to winding up a spring. The final turn through perihelion results in a significant hyperbolic excess velocity over the Earth initiated Hohmann transfer trajectory enabling the initially slow spiral orbit to achieve even the distant interstellar milestones in only 50 years.

The spiral scenario also provides an ancillary benefit of enabling a total solar system survey mission during the years of slowly building up the vehicle's velocity.

TABLE 3: *Delta-V for Various Distances.*

Target Perihelion Distance (AU)	Delta V to Initiate Hohmann Transfer From Earth to Sun's Farside (km/s)	Transfer Orbit Time (Days)	Heliocentric Velocity at Perihelion (km/s)
0.1	16.8	210	123.9
0.15	14.4	224	99.7
0.2	12.4	239	84.8

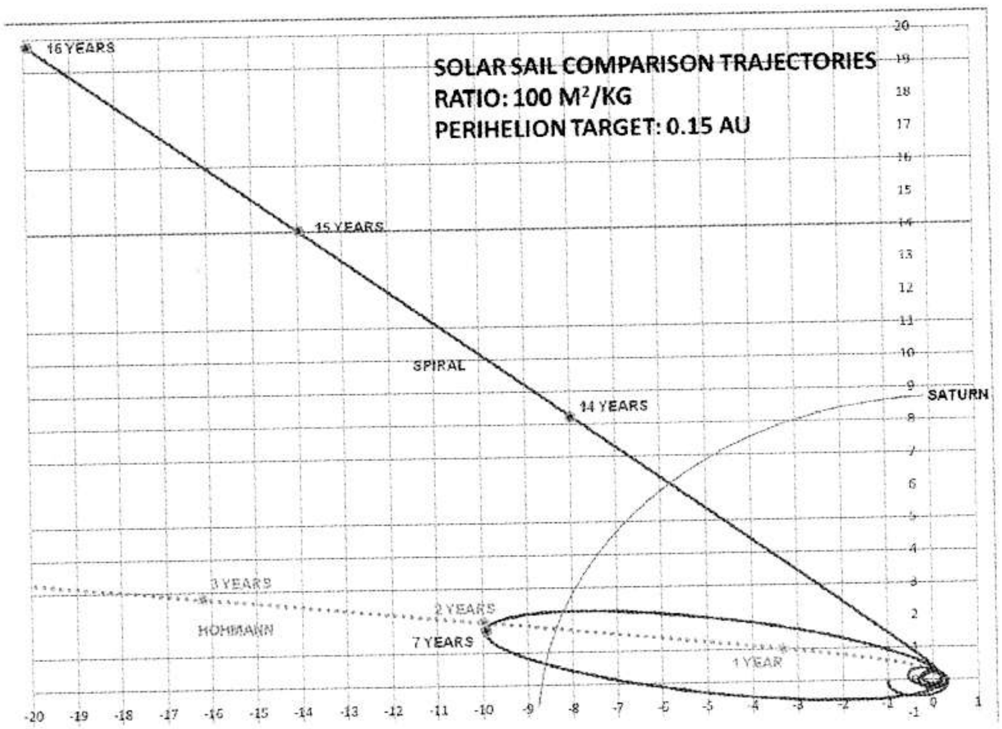


Fig. 7 Solar sail comparison trajectories (broad view).

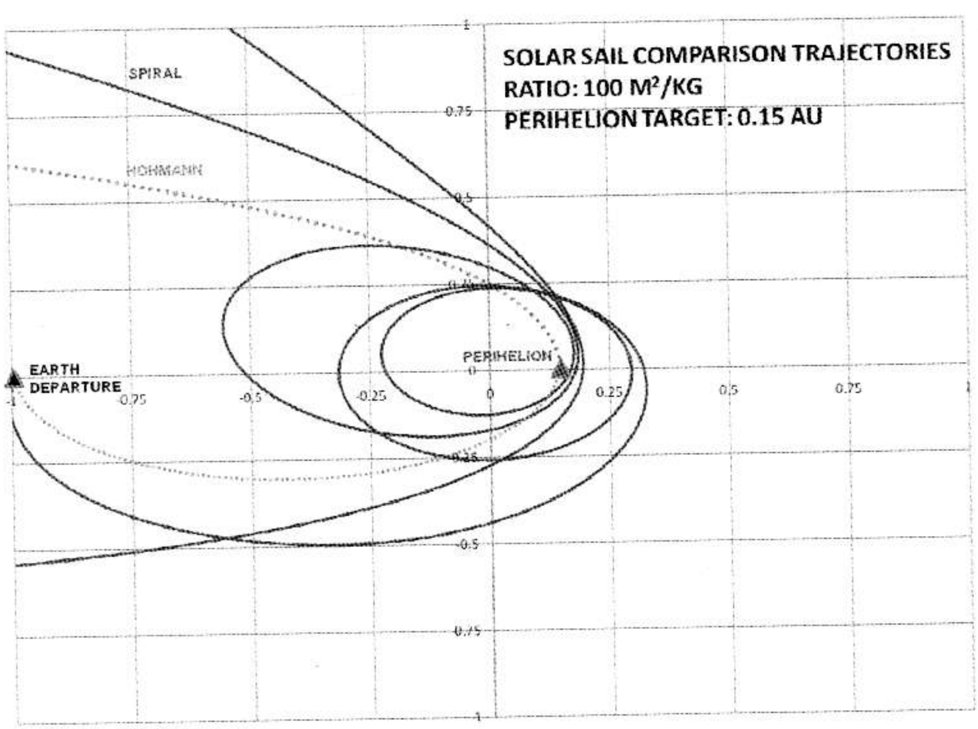


Fig. 8 Solar sail comparison trajectories (close view).

clusion of planetary flybys and ancillary propulsion ms further increases the utility, cost effectiveness and ancy of this approach to provide interesting and unique ific data over the course of its travels through the inner uter solar system.

gregating the results of both techniques is detailed dually in Figs. 9 and 10 and combined for both 50 00 years. The superior ability of the spiral trajectory hieve the requisite velocity necessary over the direct fer orbit for a given vehicle configuration is clearly ted.

ese plots detail the significant gains that can be made a characteristic vehicle with an area to mass ratio of 100 is achieved. Whether a 50 or 100 year timeline, the spiral trajectory provides the mechanism to efficiently achieve the target interstellar milestones.

Over a nominal 50 or 100 year mission, Figs. 11 and 12 provide the distance and vehicle requirements to achieve a specific target milestone. Also clearly depicted is the first order linear relationship between how increasing the vehicle's area to mass ratio results in clearly decreasing the time of flight to previous milestones.

This clear relationship between area to mass ratio and time of flight provides a simple metric for designers and mission planners for performing trades on overall system performance and allocations.

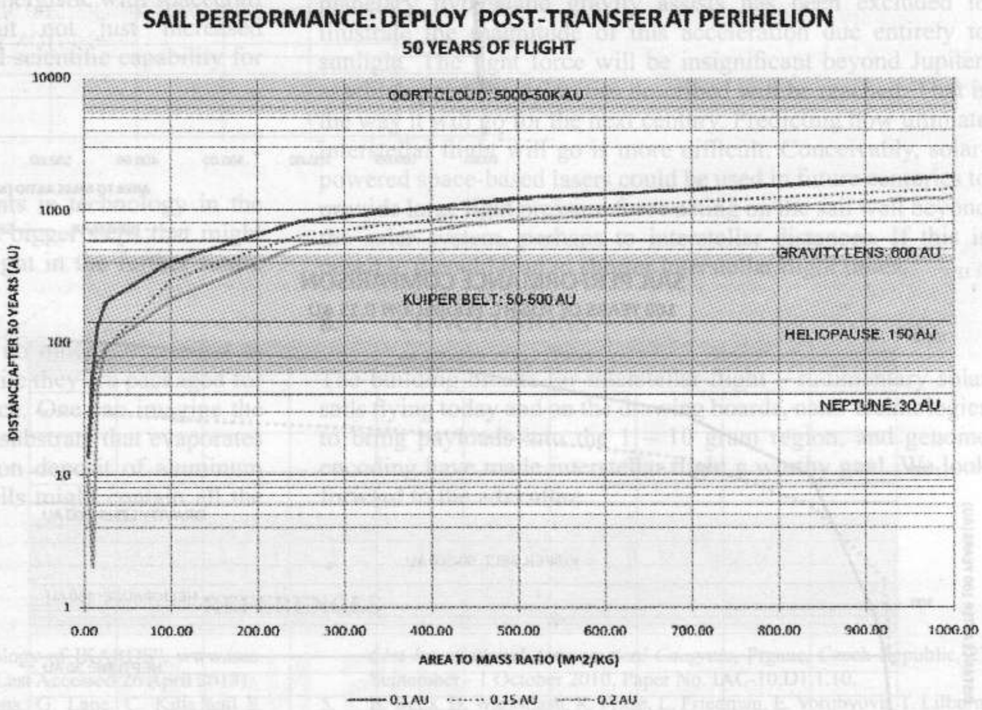
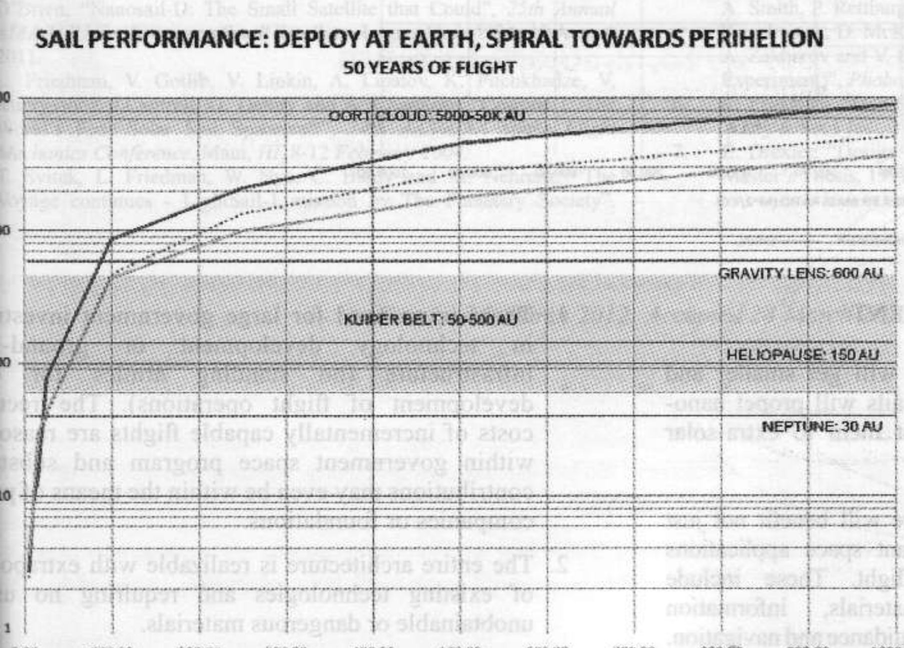


Fig. 10 Sail performance (deploy solar sail at perihelion).



9 Sail performance (deploy sail at perihelion).

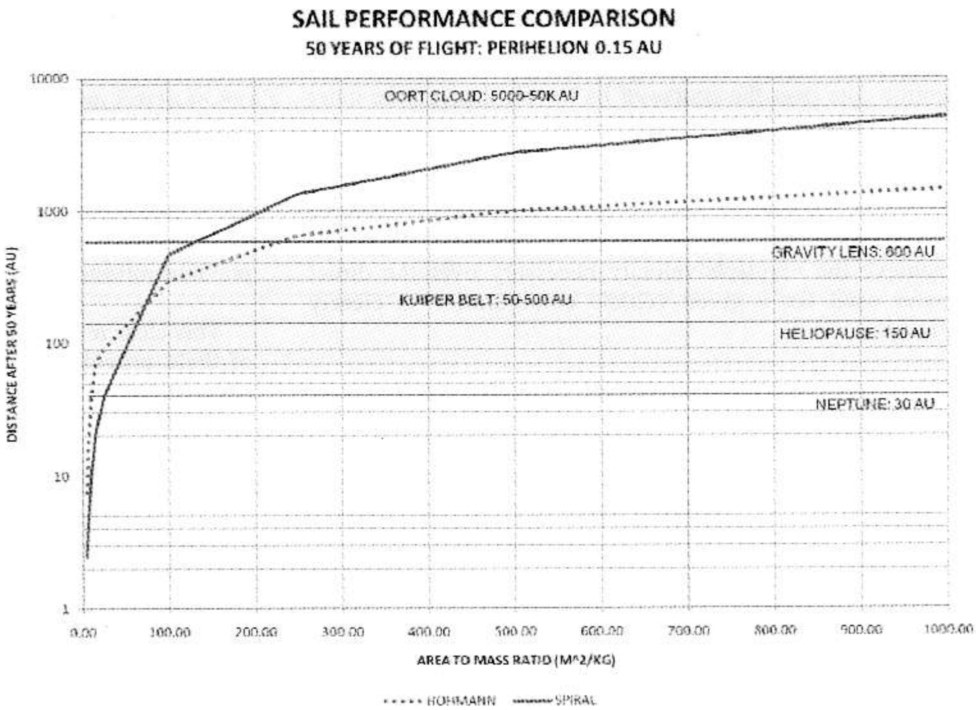


Fig. 11 Sail performance comparison for 50 years of flight.

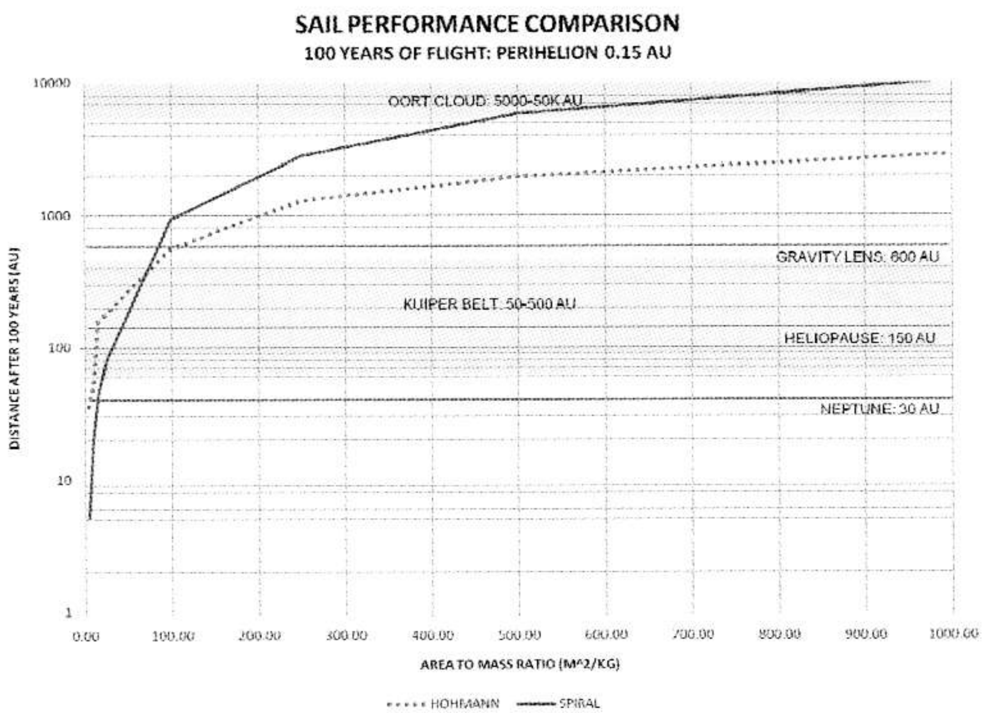


Fig. 12 Sail performance comparison for 100 years of flight.

6. TECHNOLOGY DEVELOPMENT

Solar sails will get bigger, spacecraft will get smaller and materials will get better so that huge sails will propel nano-spacecraft close to the Sun and shoot them to extra-solar distances – in this century.

The improvements in this architecture will benefit not just Starship development, but also important space applications in Earth orbit and interplanetary flight. These include communications, miniaturization, materials, information processing, sensors and instrumentation, guidance and navigation.

The technical advantages of an evolutionary solar sailing architecture are manifold:

1. There is no need for large government investments in technology development or ground-based infrastructure (no standing armies for either development of flight operations). The recurring costs of incrementally capable flights are reasonable within government space program and substantial contributions may even be within the means of private companies or foundations.

2. The entire architecture is realizable with extrapolation of existing technologies and requiring no use of unobtainable or dangerous materials.

3. The approach is scalable and modular, growing in capability as technologies mature and are inserted into the evolving solar sailing architecture. Achievements in

flight can be steadily increased moving closer and closer to interstellar flight.

4. The solar sails, once finishing their propulsive part of the mission can be reconfigured into ultra high gain antennas to transmit data back to Earth, even from enormous distances.
5. As the flight systems are scalable, they require no booster development, and can fly on whatever rockets are available at the time.
6. As propulsion is entirely derived from a near pass to the sun, missions can be launched at any time, in any direction, towards any objective.
7. Advanced in nano-technology, information processing and perhaps even biological sensors can be incorporated concurrent and synergistic with spacecraft miniaturization so to permit not just increased performance but also increased scientific capability for interstellar precursor missions.

7. THE FAR FUTURE

Beyond the extrapolated improvements in technology in the described evolutionary plan there are bigger steps that might ultimately aid practical interstellar flight in the further future [6].

For example, the substrate serves no other purpose but to hold the photon reflectors together while they are packaged for transportation and deployment in space. One can imagine the evolution of technology to produce a substrate that evaporates in space – leaving only the submicron deposit of aluminum for ultra-ultra-thin sails [7]. These sails might contain all the elements of spacecraft – computers, communications, attitude control, power, etc. in ways suggested by today's innovative first steps: the LEDs and solar cells imbedded in the IKAROS sail, printable spacecraft and trickle charge ultra-thin batteries.

If we can indeed incorporate the advanced payload and technology ideas we might find virtual human interaction with our nano-spacecraft just as satisfying and far more practical than human interstellar flight – something that would change the paradigm for long-range space exploration.

Thus far all of the technology and mission milestones described in this paper have been based on building up enormous speeds in the solar system by large gossamer spacecraft flying close to the Sun with ultra-light spacecraft mass. The entire propulsive force has come from the Sun and the benefits of planetary flybys and gravity assists has been excluded to illustrate the magnitude of this acceleration due entirely to sunlight. The light force will be insignificant beyond Jupiter, at which point the velocities described will be reached. That is the way it will go for the next century. Predicting how ultimate interstellar flight will go is more difficult. Conceivably, solar-powered space-based lasers could be used in future centuries to provide large light pressure force acting on the sail well beyond the solar system, perhaps to interstellar distances. If this is possible it could lead to shorter interstellar flight times.

8. CONCLUSIONS

The building blocks for interstellar flight – rudimentary solar sails flying today and on the drawing boards, nano-technologies to bring payloads into the 1 – 10 gram region, and genome encoding have made interstellar flight a worthy goal. We look forward to the adventure.

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