PRINCIPIUM

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Scientia ad sidera
Knowledge to the stars

Editorial

Welcome to issue 33 of Principium, the quarterly magazine of i4is, the Initiative and Institute for Interstellar Studies. Our lead feature this time is *Practicalities and Difficulties of a Mission to 1I/'Oumuamua*, by Adam Hibberd. Oumuamua remains a mystery and Harvard astronomer sticks to his ET theory in *Extraterrestrial*, reviewed with some scepticism by Patrick Mahon in this issue.

We return to practicalities with *Project Pinpoint: Pushing the Limits of Miniaturization* by Andrew Broeker, technical lead of this i4is chipsat project.

Another substantial piece by Michel Lamontagne

Self Replicating Factories is a work in progress following up his *Worldship and self replicating systems* in our last issue. One of our regular collaborators delivering to the International Space University, Strasbourg is Simone Caroti and in this issue his original work on the subject, The Generation Starship in SF, is reviewed by John Davies.

Our front cover image is the weirdest of our own gas giants, Uranus, envisaged by a good friend of i4is, David Hardy - the first among space artists.

The back cover image is inspired by an amateur astronomers imaging the International Space Station silhouetted against the moon but derived in this case from a public domain NASA image.

We have 21 items of Interstellar News including an i4is team paper, the first of a series on the nature, origin and frequency of interstellar objects (ISOs), ideas for a dark energy ramjet, locating possible deep space communication nodes and a positive energy warp drive, news of the recent Breakthrough Discuss 2021 and the upcoming IRG 7th Interstellar Symposium (and more news from IRG), a deep space discovery "FarFarOut" and deep space technology including the current New Horizons, ESA's deep space communications, China's aims beyond the Solar System, the JWST first programme, a revised 2I/Borisov mission paper and ideas for extreme metamaterial solar sails, near-term self-replicating probes and photonic phase sensing and control for laser propulsion. We report the i4is chief exec briefing the German Federal Ministry of the Environment and round up with summaries of a bumper set of recent interstellar papers in the Journal of the British Interplanetary Society (JBIS).

The regular Members Page asks members to help with outreach and schools contact, tells of our 2020 Annual Report to members and summarises out recent members newsletters and the new videos available to members.

Our next issue, August 2021, will include a summary of interstellar topics at the October International Astronautical Congress in Dubai and more about the September IRG 7th Interstellar Symposium in Tucson. We plan two pieces on interstellar downlink communications, the "heavy brigade" based on the Icarus Firefly downlink and its predecessor the BIS Daedalus downlink, and the (very) "light brigade" the ideas of David Messerschmitt et al for swarming micro-probes.

If you have any comments on Principium, i4is or interstellar topics more generally, we'd love to hear from you!

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Back issues of Principium, from number one, can be found at www.i4is.org/Principium.

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Please print and display our posters - our general poster on pages 30 (black background) and 42 (white) - and a student poster on page 47 (black).

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The views of our writers are their own. We aim for sound science but not editorial orthodoxy.

Contents

Practicalities and Difficulties of a Mission to 'Oumuamua

LEAD FEATURE

Adam Hibberd

Our i4is colleague Adam Hibberd has driven the computational thinking behind our proposals for missions to interstellar objects (ISOs) such as the still-mysterious 1I/'Oumuamua. Here he considers some broader issues in reaching and investigating this asteroid-like object - or is it just a very weird comet? Astronomers remain divided and some have even suggested that this, our first observed, ISO, will remain a mystery forever. The i4is Project Lyra team have shown that this need not be so. But what are the challenges for an intercept mission?

So we have discovered this very weird object, how do we get to it? I have researched the general theoretical feasibility of trajectories to ‘Oumuamua using some software I developed called OITS (Optimum Interplanetary Trajectory Software (Ref.1) and everything is looking fine as far as that is concerned, see Hibberd et al, Hein et al (Ref. 2 & 3) – it seems doable.

However what about the practicalities? What are the main details to address and are there any limitations which could render the mission infeasible and deny us our scientific prize? The following is a peek at some of these - with a focus on trajectory considerations - which are not addressed by the Project Lyra papers (spoiler alert – generally speaking it’s all looking rather rosy).

Let us recount the story of the spacecraft’s (s/c) journey to ‘Oumuamua:

1) First there is a launch from Earth.

2) There then follows a long drawn-out 3 year near-elliptical orbit (actually two hemiellipses stuck together) which results in the s/c returning to its home planet, Earth. As we shall see, this phase is just the quiet before the storm. A Deep Space Manoeuvre (DSM) at the farthest point from the sun on this ellipse (aphelion) slows the s/c down and alters the return encounter kinematics with respect to the Earth. You may ask, what is the possible benefit in such a journey if the s/c merely ends up where it started off? Well to mission designers it is known as a ‘V_∞ Leveraging Manoeuvre’ and amplifies the s/c’s kinetic energy relative to the Earth, and reduces the velocity increment, ΔV* (and so rocket fuel) required to get to Jupiter.

3) Arriving at Jupiter is where the action starts. With a reverse gravitational assist (GA), the s/c is dramatically slowed by the pull of Jupiter’s immense gravity to such an extent as to be almost brought to a halt relative to the sun. The purpose of this reverse-GA is to allow the s/c to start falling towards the sun in a free-fall, gradually accelerating more and more as the sun is approached.

4) A very close approach to the sun then ensues and so it is a matter of ‘hang on to your hats’ (or maybe your parasols) over this hazardous segment of the trajectory, where the awesome mass and might of the sun in its proximity exert their terrifying influences. Its huge mass is the very reason this hazardous approach is necessary, because in a gravitational well, the maximum benefit of a ΔV kick occurs at the point of closest approach (perihelion). This is the Oberth effect and this whole slingshot manoeuvre is known as an Oberth manoeuvre. The power of the sun, although of course fundamental to life on Earth, is of no help to us whatsoever, as unshielded this would create huge thermal problems for the s/c. We therefore need a heat shield.

5) There is then a long coast before we arrive at ‘Oumuamua 22 years after the launch from Earth and at a distance from the sun of around 200 AU, outside the heliopause and into the pristine Interstellar Medium.

* ΔV here is in normal font. This is the standard convention for a scalar quantity. But velocity has both magnitude and direction so change in velocity is shown in bold font **ΔV**. The magnitude of **ΔV** is |**ΔV**| = ΔV in normal font (ie not **bold**) since it is a scalar, a value with only magnitude, not direction.

For this article, two of the 'Oumuamua mission trajectory options A & B are summarised in Tables 1 & 2 respectively. We shall concentrate on Trajectory A, refer to Figure 1. Trajectory B is the same sequence of encounters as A but with a lower Solar Oberth of 4 Solar Radii.

Table 1: E-DSM-E-J-6SR-1I Trajectory A **ΔV** Analysis

Encounter Number	**Planet**	**Date**	**Arrival Speed (km/s)**	**Departure Speed (km/s)**	**ΔV at encounter (km/s)**	**Cumulative ΔV (km/s)**	**Periapsis Altitude (km)**
1	Earth	2030 JUN 09 18:53:14	0	7106.2	7.1062	7.1062	N/A
2	DSM	2031 NOV 25 11:39:06	11.5701	11.0052	0.6593	7.7656	N/A
3	Earth	2033 APR 17 17:26:14	11.9715	12.4288	0.3395	8.1051	200.0
4	Jupiter	2034 JUL 12 11:54:56	14.6104	14.4661	0.0674	8.174	262748.9
5	6 Solar Radii	2036 FEB 24 04:32:46	251.2642	258.338	7.171	15.3434	N/A
6	'Oumuamua	2052 JUL 29 04:32:46	30.6801	30.6801	0	15.3434	N/A

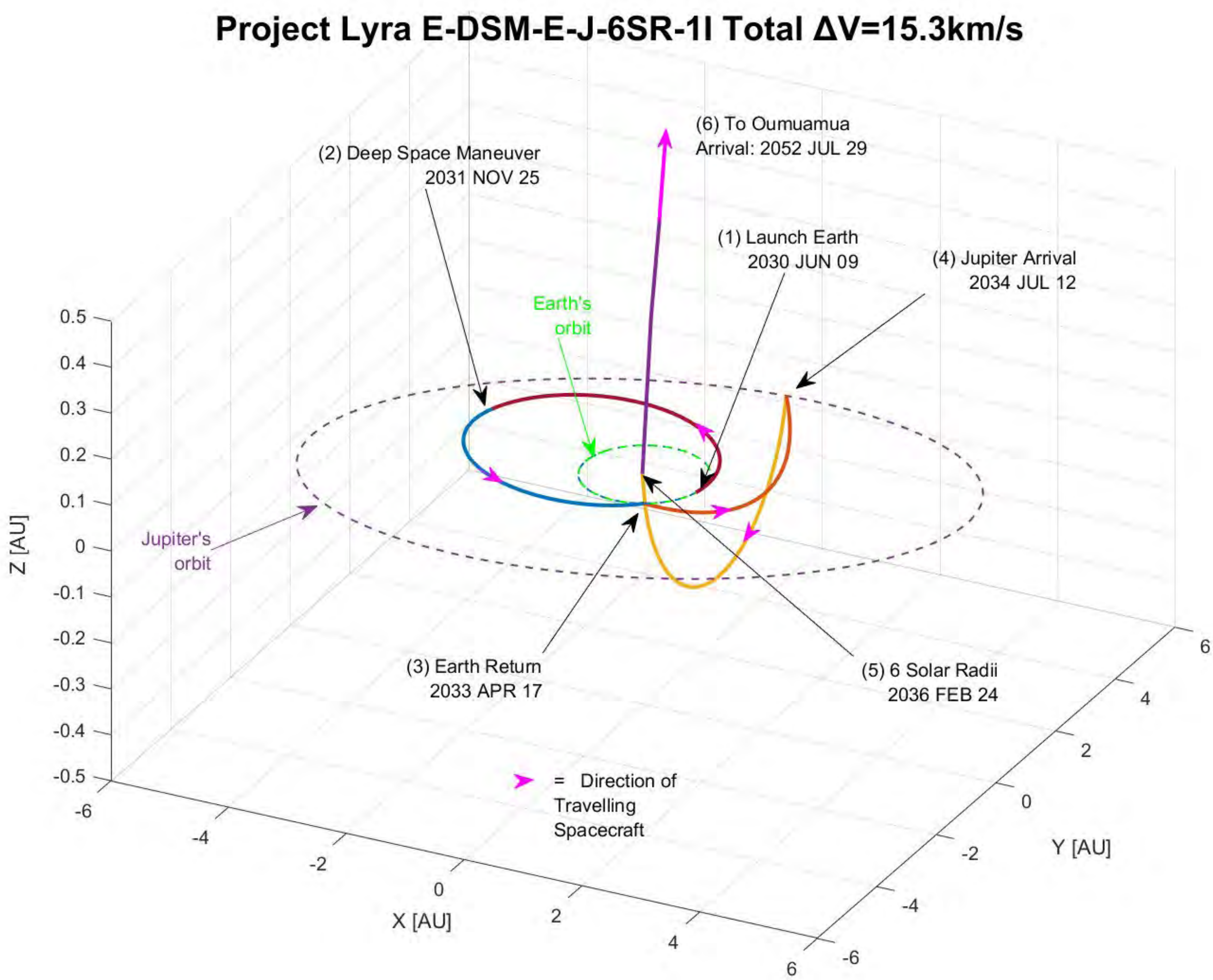

Figure 1: Trajectory A (see text) to 'Oumuamua with launch in 2030.

Table 2: E-DSM-E-J-4SR-1I Trajectory B **ΔV** Analysis

Encounter Number	Planet	Date	Arrival Speed (km/s)	Departure Speed (km/s)	ΔV at encounter (km/s)	Cumulative ΔV (km/s)	Periapsis Altitude (km)
1	Earth	2030 APR 11 03:44:11	0	7.0054	7.0054	7.0054	N/A
2	DSM	2031 OCT 29 00:02:21	11.4996	11.1093	0.500	7.5054	N/A
3	Earth	2033 MAY 21 18:33:07	10.7061	11.8454	0.8149	8.3203	200
4	Jupiter	2034 JUL 12 16:06:40	15.1624	19.2138	1.2396	9.5599	17204.3
5	4 Solar Radii	2035 JUL 17 15:18:59	308.294	313.6442	5.388	14.9479	N/A
6	'Oumuamua	2051 DEC 20 15:18:59	29.6896	29.6896	0	14.9479	N/A

So let us negotiate each of the challenges (1) to (5) above one at a time, assessing their feasibility on the way.

1) Launch Earth

When addressing the issue of launch, the necessary conditions must be referenced to the Earth, so rather than a heliocentric reference frame, we need to relate everything to a geocentric reference frame. We know that first of all, the s/c must embark on an interplanetary trajectory and this necessitates departing Earth's gravitational sphere of influence (SOI). Therefore an Earth escape orbit (also known as a hyperbolic orbit) is required, and the transition between this Earth-referenced escape orbit into the sun-referenced interplanetary elliptical orbit can be assumed to be at this departure point. In addition, the speed relative to Earth on leaving its SOI can be assumed equivalent to the 'hyperbolic excess', the theoretical speed at infinity of the escape orbit. Generally speaking the lower the magnitude of this hyperbolic excess, the greater the payload mass capability of a particular launch vehicle. As we are necessarily trying to maximise this mass, we are equivalently attempting to minimise this hyperbolic excess.

To this end, let us denote the velocity on departing the SOI as **ΔV**, the magnitude of which is the hyperbolic excess speed ΔV. From Table 1 we see that the hyperbolic excess required at Earth is 7.106 km/s. As a fundamental requirement then, we need a powerful enough launcher to achieve an escape orbit with this value of hyperbolic excess. The payload capability of a particular launch vehicle to an escape mission is usually provided in its user guide and is generally not given as a function of hyperbolic excess, but usually the square of this, designated 'C3', or the 'Characteristic Energy'. We shall assume that the launcher utilised for the 'Oumuamua mission is either the mighty still-not-yet-operational NASA Space Launch System (SLS), or the significantly-less-mighty (at least for escape missions) SpaceX Falcon Heavy, both of which can achieve the C3 value of $7.106^2 = 50.5\ km^2/s^2$. Note as well that the payload mass for the SLS would be significantly higher than for the Falcon Heavy.

The escape asymptote – the direction the s/c should ultimately head off in - is in the direction of **ΔV**. For an escape mission, a particular launcher will need to achieve an orbit with a launcher-dependent perigee distance R_p (closest approach to Earth) greater than the Earth's radius. The distance R_p and excess speed ΔV combine together to define the angle, η, between the escape asymptote and the injection point (which can usually be assumed to be at R_p).

Theoretically, ignoring launch vehicle considerations, the plane and therefore orbital inclination of the escape orbit can be any value as is illustrated in Figure 2. This results in a theoretical locus of points which an unspecified hypothetical launcher could target for orbital insertion.

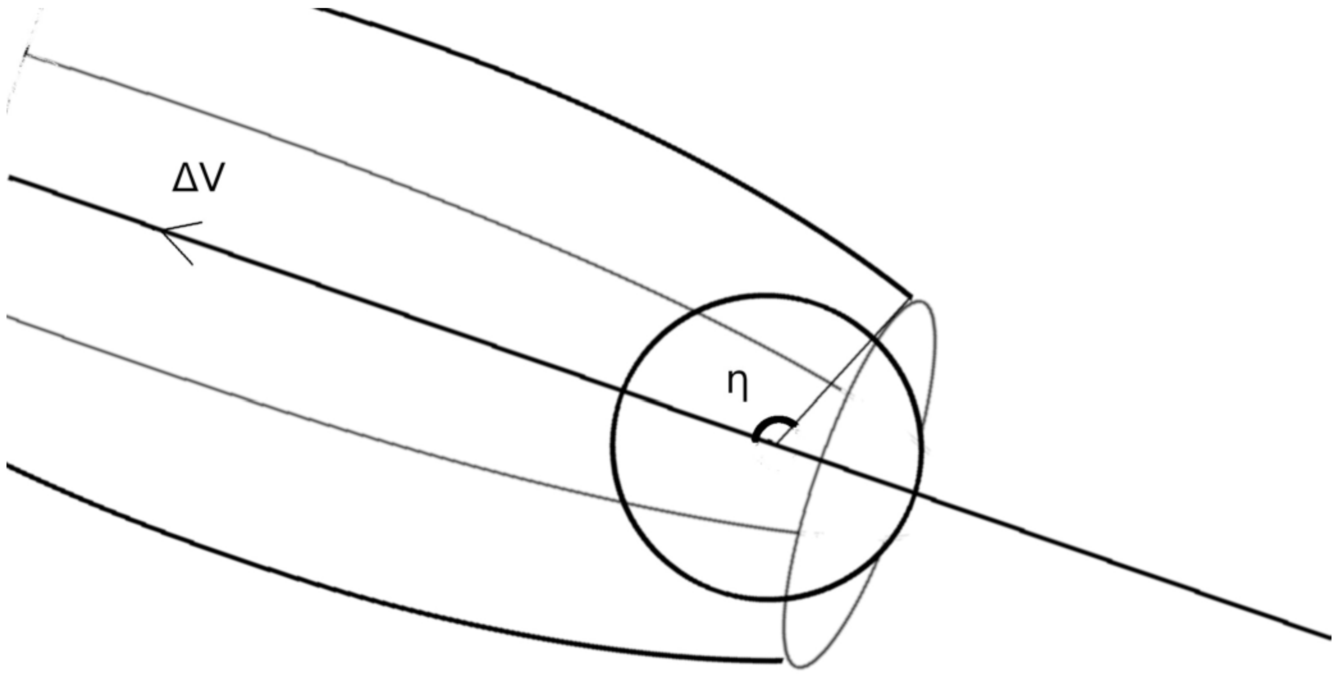

Figure 2: Possible Escape Orbits Around Earth, All Resulting in the Same Required Escape Asymptote.

Figure 3 shows a 3D image of the Earth in a reference frame with origin at the centre of the Earth and looking from a vantage point perpendicular to the meridian of the launch site. The geocentric launch site latitude φ is provided.

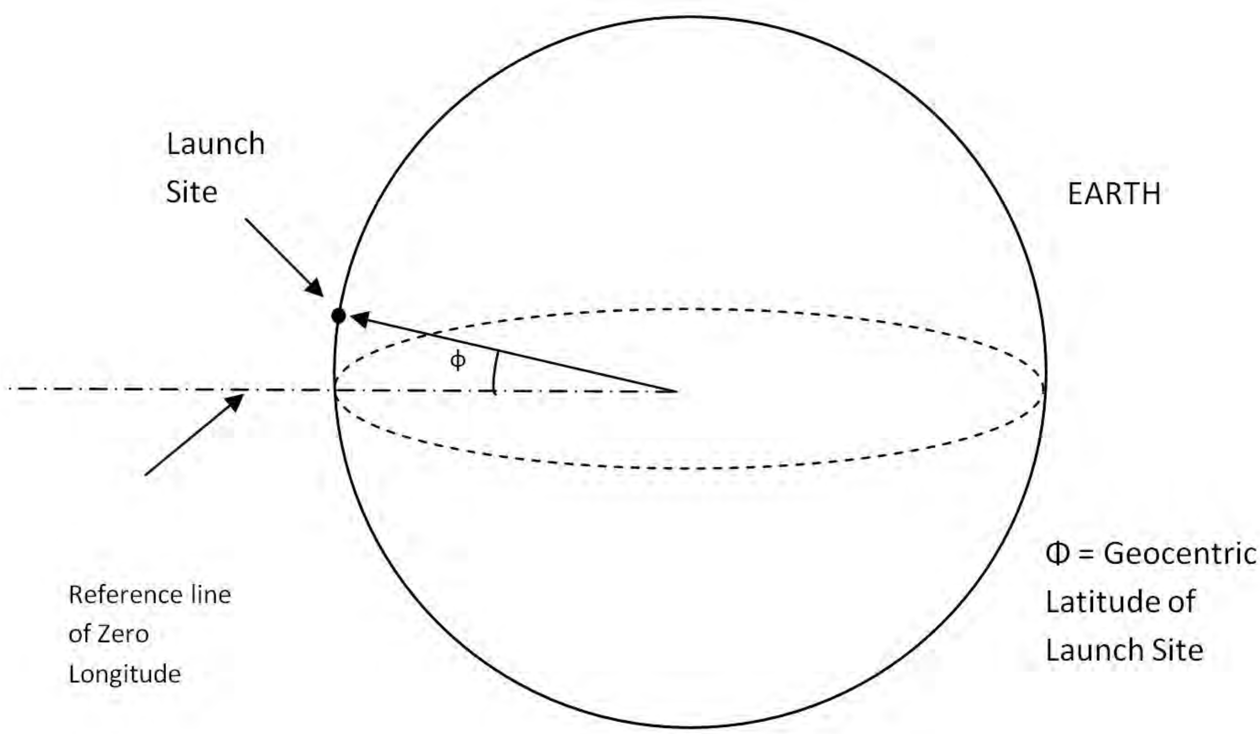

Figure 3: The Earth in 3D - Looking from an Angle Perpendicular to the Launch Site Meridian.

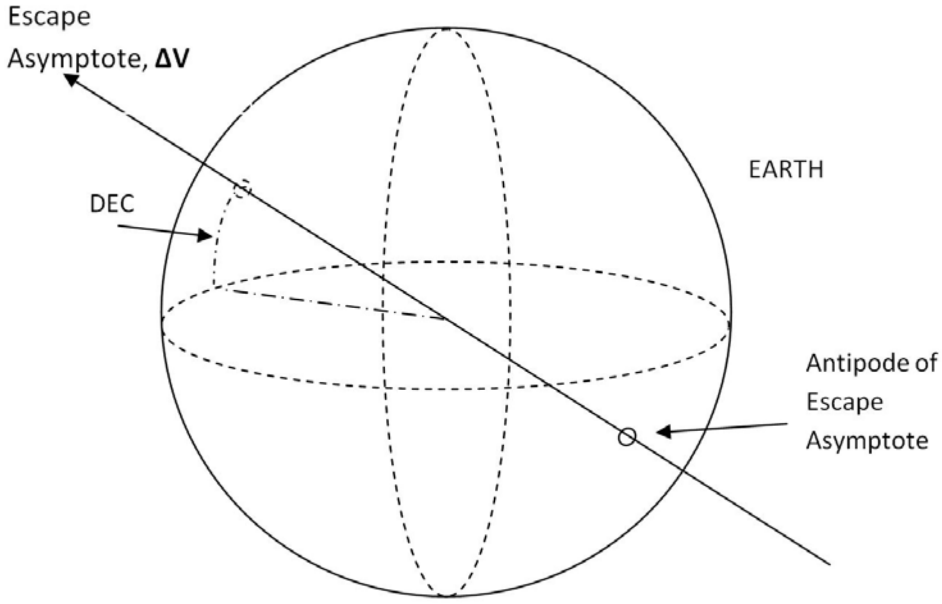

Figure 4: The Escape Asymptote Direction and its Declination.

Figure 4 shows a required escape asymptote with respect to the Earth and the direction of this can be completely specified by two parameters - Right Ascension (RA) and Declination (DEC), the latter is provided in the diagram and to all intents and purposes is equivalent to the latitude of the escape asymptote. The antipode of the escape asymptote is provided in this figure as well.

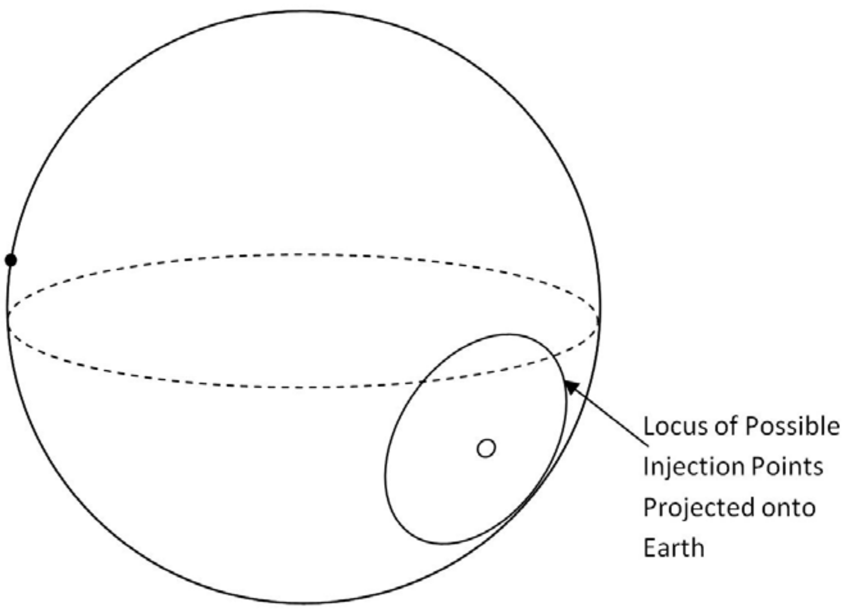

Figure 5: Locus of Possible Orbital Insertion Points Which would Allow Acquisition of the Required Escape Asymptote.

Figure 5 shows the locus of orbital insertion points projected onto the Earth assuming the inclination of the target escape orbit can be free. Ideally the orbit achieved by a particular launcher must pass through the antipode of the escape asymptote. Therefore, in order to avoid wasting precious fuel in changing the plane of the launcher's trajectory, the ground track of the launcher ascent trajectory (ie the projection of the launcher's trajectory onto the Earth) must also pass through this point. This constrains the possible inclinations of escape orbits viable for a particular launch vehicle. Furthermore, ideally we wish the inclination of the target orbit to equate to the latitude of the launch site because then the thrust direction at launch (the thrust azimuth) is to the east which reaps maximum benefit from Earth's rotational velocity.

The arc between launch site and injection is provided in Figure 6, and we'll denote it here as ψ. Figure 7 shows the ground track of the launcher's trajectory in 2D.

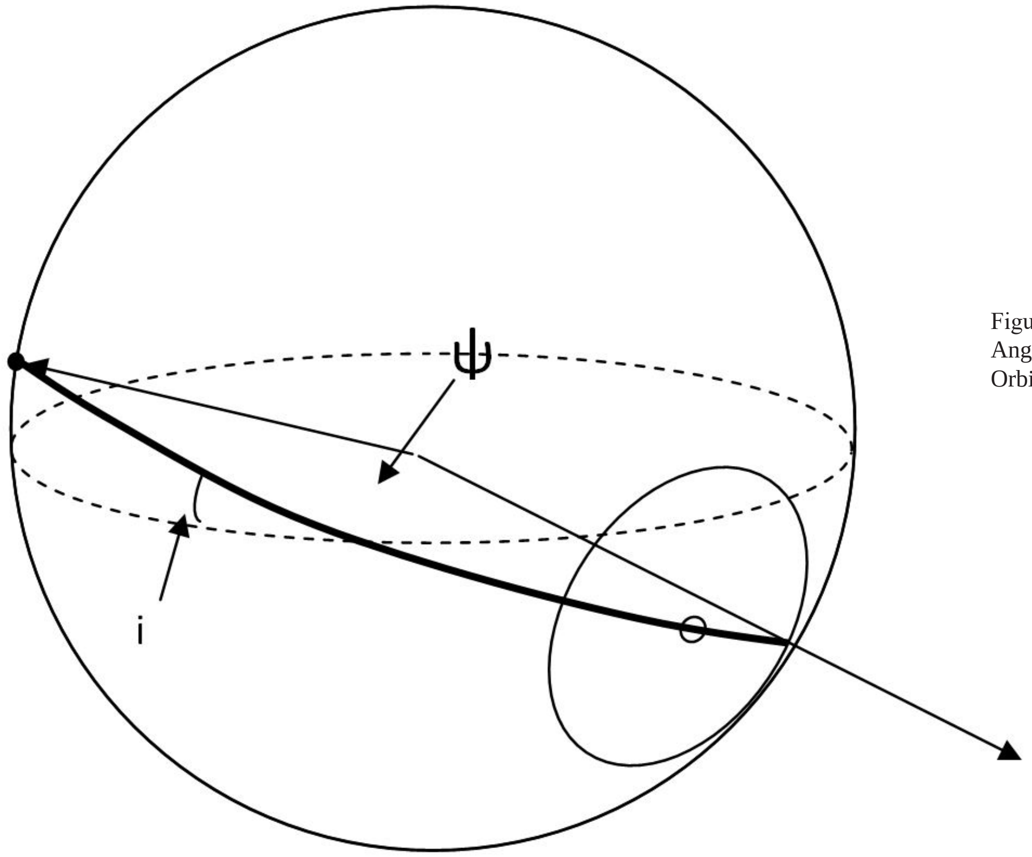

Figure 6: Definition of ψ, the Angle Between Launch and Orbital Insertion.

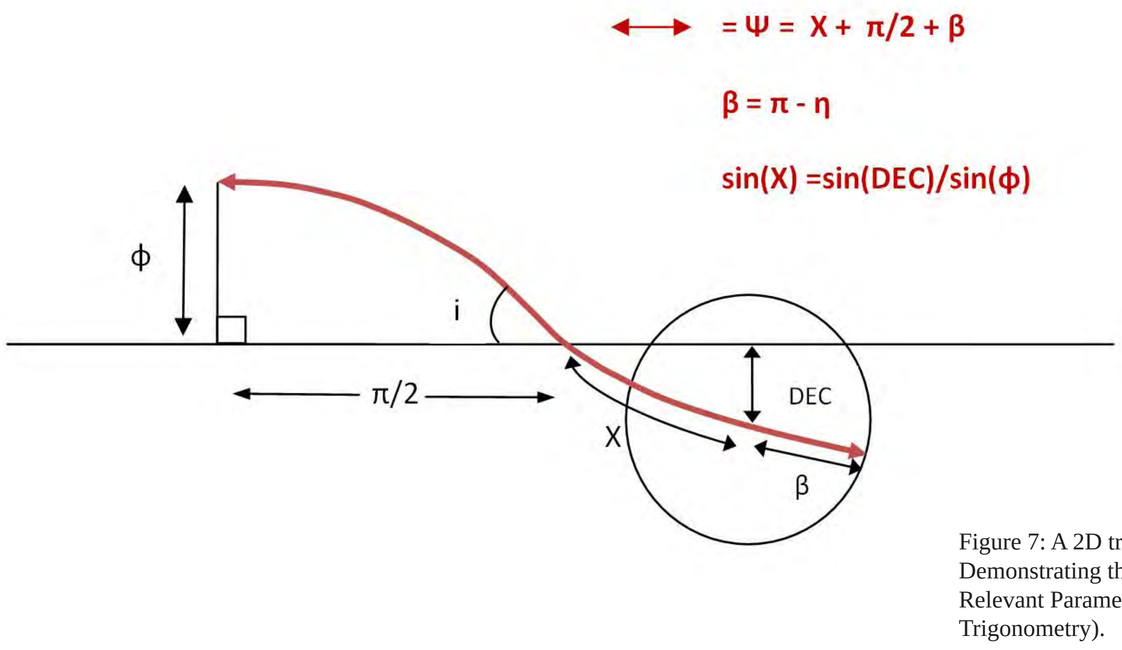

Figure 7: A 2D transformation of Figure 6, Demonstrating the Relationships Between Relevant Parameters (Using Spherical Trigonometry).

We have enough information now to do some number crunching – using the equations provided in Figure 7 - for both of the two selected vehicle options SLS and Falcon Heavy. We shall assume in both cases that R_p has an altitude of 185 km (though the results don't change much for a wide range of possible perigees) and also in both cases that the geocentric launch latitude is about 28.6°. It can be calculated that η = 112.1° for the escape asymptote. From Table 3 (next page) we have DEC= -5.319°. This gives a value of ψ = 146.7°.

Table 3 Detailed Data on Each of the Encounters in Turn (Trajectory A)

	Units	Earth	DSM	Earth	Jupiter	6 Solar Radii	'Oumuamua
Distance from Sun	AU	1.015	3.2	1.004	4.959	0.028	199.509
Longitude	degrees	-101.433	72.526	-152.446	0.973	180	8.637
Latitude	degrees	0.004	0.014	0.002	-1.285	4.566	23.231
True Anomaly	degrees	37.696	180	36.455	66.225	180	145.186
Angle between departure and arrival velocities	degrees	N/A	1.726	33.651	79.882	0.265	N/A
Angle between arrival velocity and periapsis	degrees	N/A	N/A	107.287	129.771	N/A	N/A
Angle between departure velocity and periapsis	degrees	N/A	N/A	106.364	130.112	N/A	N/A
Periapsis Radius	km	N/A	N/A	6578	334241	N/A	N/A
Impact Parameter	km	N/A	N/A	8727	299948	N/A	N/A
Miss Distance	km	N/A	N/A	8937	713054	N/A	N/A
Arrival Velocity Right Ascension (RA)	degrees	N/A	161.073	0.678	340.112	285.856	358.321
Arrival Velocity Declination (DEC)	degrees	N/A	7.823	0.211	-7.913	82.807	24.475
Departure RA	degrees	345.339	162.747	333.81	257.417	287.86	358.321
Departure DEC	degrees	-5.319	7.347	-20.829	-27.862	82.727	24.475

Thus we have discovered that for both launchers, the injection into the required escape orbit must occur at a significant distance downrange – in other words at a significant angular displacement - from the launch site. To be clear, this is feasible but obviously would require a significant coast arc in the 2nd Stages of both the Falcon Heavy and the SLS. Fortuitously both 2nd stages are indeed restartable.

But what is the direction of this hyperbolic excess, **ΔV**? What defines it? Well actually this requires stepping back a bit and looking at the situation from a heliocentric standpoint. In order to understand the situation we are presented with at launch, we need to look into the precise heliocentric orbit – ie the orbit around the sun - we are trying to escape into.

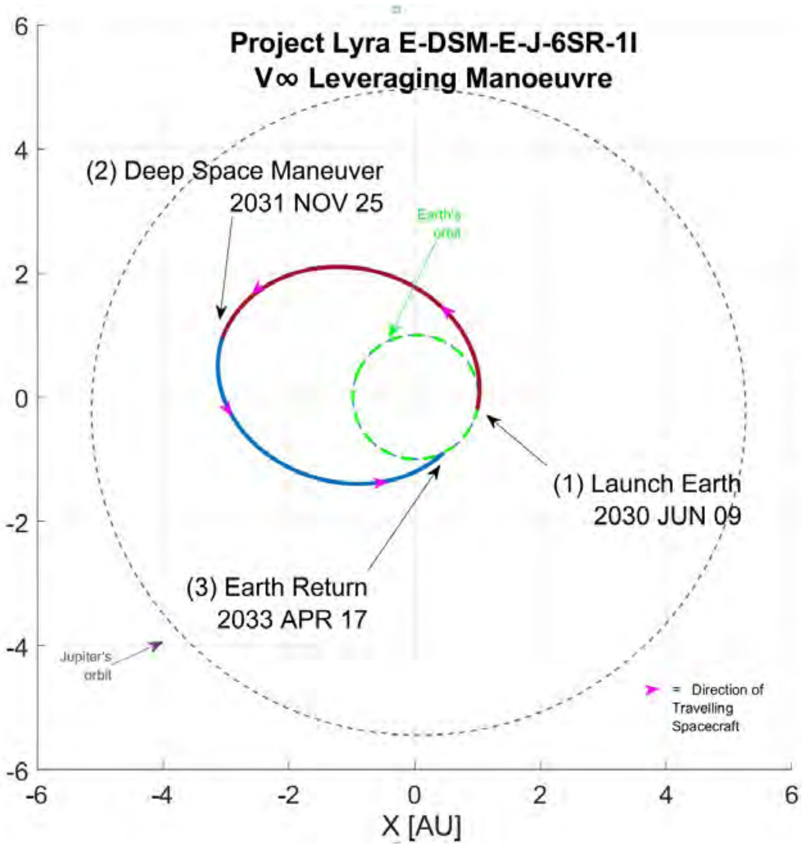

Figure 8: The Required Heliocentric Near-Elliptical Orbit - The V∞ Leveraging Manoeuvre.

Figure 8 shows the target heliocentric ellipse (actually two hemiellipses stuck together at a DSM) required for the V∞ Leveraging Manoeuvre. Figure 9 is the same as Figure 8 but shows the required heliocentric velocity vector (in pink) needed at Earth in order to follow this heliocentric ellipse. This pink velocity vector - let's call it **VDEP** - is relative to a sun reference frame. Observe that this direction is just about in line with Earth's orbital velocity, ie tangential to Earth's orbit. This makes sense because then we can best exploit Earth's own motion (**VE**) which has a considerable magnitude of around 30 km/s relative to the sun in this direction.

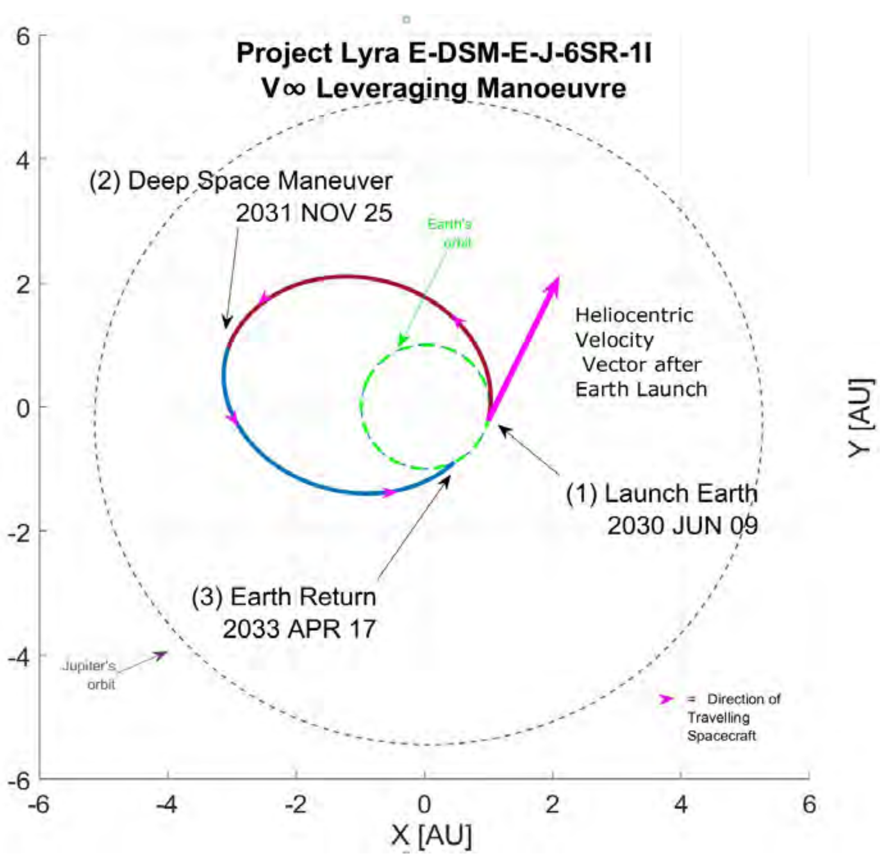

Figure 9: The Pink Arrow Shows the Required Heliocentric Velocity, VDEP, Needed at Earth to Achieve the V∞ Leveraging.

The desired **ΔV** at Earth in the heliocentric reference frame is the change in velocity relative to Earth needed to acquire a heliocentric velocity **VDEP**. It follows quite straightforwardly that:

ΔV = VDEP – VE

VDEP and **VE** are virtually aligned with each other and so **ΔV** will be aligned with them also. Because the Earth is orbiting the sun, the direction of **VE** is changing, by almost 1°/day, Thus the direction of heliocentric velocity we wish to acquire, **VDEP**, will also change with launch date in order to maintain co-linearity (and optimality) with **VE**. This means that due to Earth's orbital motion around the sun, RA will recede to the East with each day of launch delay.

So we have the direction of **ΔV** in the sun-centred reference frame (along Earth's direction of motion), we now need to transform this into an Earth-centred frame. It turns out this direction is lined up to the Earth's sun/shadow terminator. Figure 10 illustrates what is happening. As Earth spins on its axis, the location on Earth which points in this direction changes, but the time associated with this point will approximately be 6 am apparent solar time.

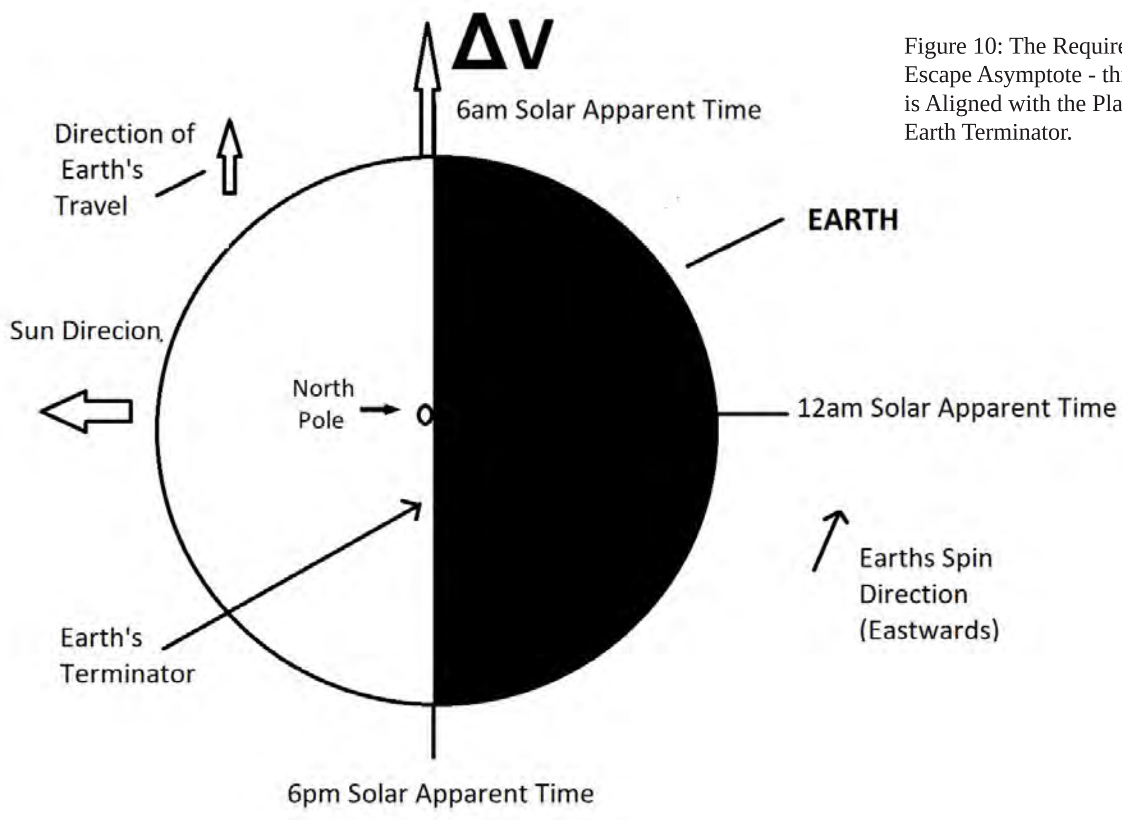

Figure 10: The Required Earth Escape Asymptote - this Direction is Aligned with the Plane of the Earth Terminator.

2) V∞ Leveraging Manoeuvre

Figure 8 gives a clear view of the V∞ Leveraging Manoeuvre from above the solar system projected onto the ecliptic – it is a near-elliptical heliocentric orbit with a return to Earth after approximately 3 years of uneventful travel. There is also a Deep Space Manoeuvre (DSM) in the middle of this (after 1 ½ years) where the s/c slows down with respect to the sun (another ΔV is applied, though from now onwards we shall define **ΔV** as an impulsive change in velocity, not the hyperbolic excess).

The natural question is what is the purpose of this manoeuvre? Well as I see it, there are three key advantages to this leveraging:

1) It reduces the total mission ΔV, by reducing the ΔV needed to get to Jupiter.

2) It extends the launch window compared to a direct mission to Jupiter.

3) It reduces the C3 at launch.

Figure 11 provides the evidence in plot form for the claims (1) & (2) above. It shows the total ΔV for a mission to 'Oumuamua with the V∞ Leveraging (the blue line) and without the Leveraging (the red line). The horizontal x-axis is the launch date compared to the theoretically optimal launch date – this optimal launch date being 9th June 2030 for the trajectory with leveraging, and 8th May 2033 without. Clearly the former scenario has a significantly lower mission ΔV of 15.3 km/s (at its optimal value) compared to 18.3 km/s for the latter (that's point (1) demonstrated). Furthermore the former scenario has a much more gradual rise in ΔV either side of the optimal launch date (which demonstrates point (2)) – particularly prior to this date. For (3) above, the C3 at the respective optimal launch dates are 50.5 km^2/s^2 with leveraging as compared to 120 km^2/s^2 for the direct to Jupiter trajectory. These are three significant performance enhancements and allow an appreciable improvement in the payload mass we can eventually get to 'Oumuamua. The theory behind how this manoeuvre actually works is rather beyond the remit of this article, but is explained in detail by Sims and Longuski Ref 6.

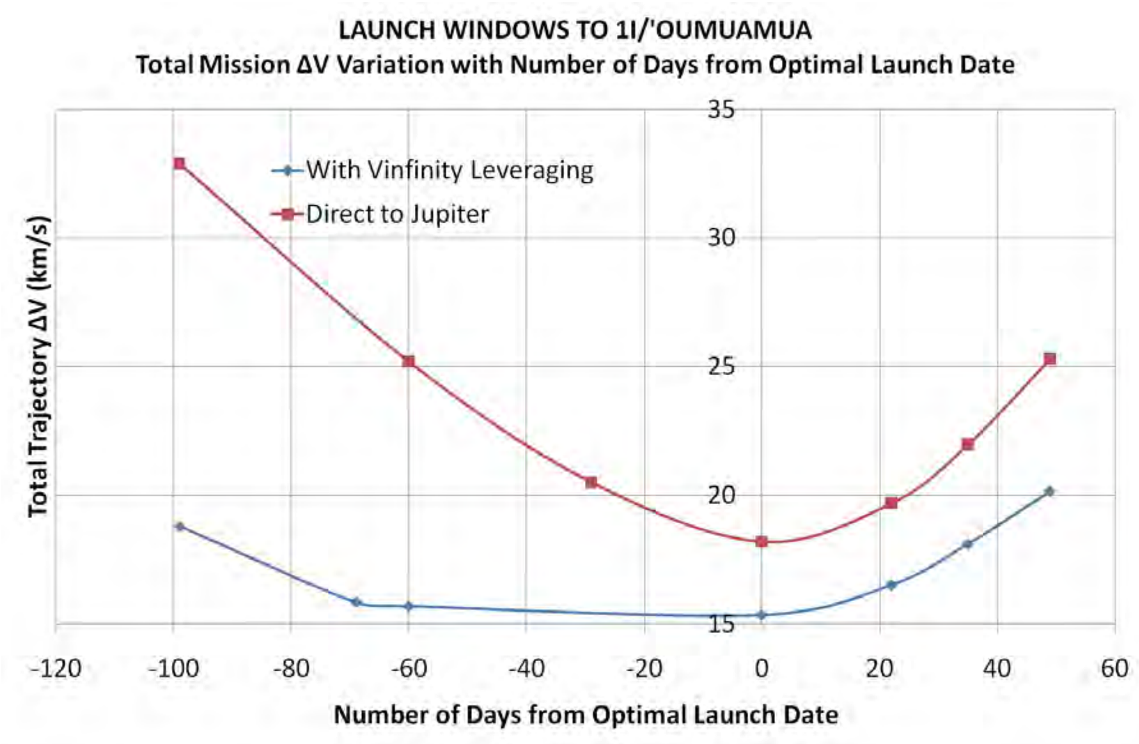

Figure 11: Plot of ΔV Dependency on Launch Date Showing the Clear Improvements of V∞ Leveraging.

It has to be said this is not an interesting phase of the overall journey. However note that the near-ellipse followed by the s/c is very close to the ecliptic plane. As a result of this low inclination, the spacecraft is obstructed by the sun for two separate windows of time, firstly on the out-bound leg of the journey (to aphelion) and then again on the in-bound leg (back towards perihelion - the Earth). The window opening and closing times for these two communication outages are from 2031 6th May 18:06 to 7th May 14:36 and from 2032 30th June 17:12 to 1st July 14:22 respectively.

A note on the aphelion distance of the DSM. The placement of this DSM is modelled in my software by an 'Intermediate Point' which allows the user to specify a distance from the sun, so then the heliocentric longitude and latitude can be optimized by the NOMAD optimizer (see Ref 1). In researching missions to 'Oumuamua, I set the value of this heliocentric distance at 3.2 AU. You may ask what was the reasoning behind this? Well the clue is we need the overall ellipse to have a time period of around 3 years. Kepler's third law relates the time period of an orbit to its semi-major axis (the semi-major axis is defined as half the distance between the perihelion and the aphelion points). The perihelion is taken as Earth's distance, which by definition is 1.0 AU, and so it is quite straight forward to calculate the required aphelion distance for the Intermediate Point from all this.

This ellipse will take the s/c right though the heart of the asteroid belt, no doubt affording plenty of opportunity for pictures.

Let us move onto the return encounter with Earth, where the s/c will come extremely close to the Earth, at a perigee altitude of 200 km. On the face of it this would seem a perilous approach, and what's more the speed of approach from infinity relative to Earth, VA, (the arrival hyperbolic excess) is 12.0 km/s. This is an alarmingly high speed for such a close approach to the planet - but how do we quantify the degree of danger?

Well Figures 12 & 13 show the definition of two important parameters for this encounter. Given a Perigee R_p a speed of approach, VA, and the mass of Earth, there is a straight forward equation which provides what we shall call here the 'miss distance', or R_{MISS} – defined as the nearest the s/c would have come to the Earth, assuming Earth had no gravitational pull. The second parameter to consider is the impact parameter, R_{IMP}, and is the minimum value of 'miss distance' needed to avoid collision with Earth. Clearly, we wish $R_{MISS} > R_{IMP}$.

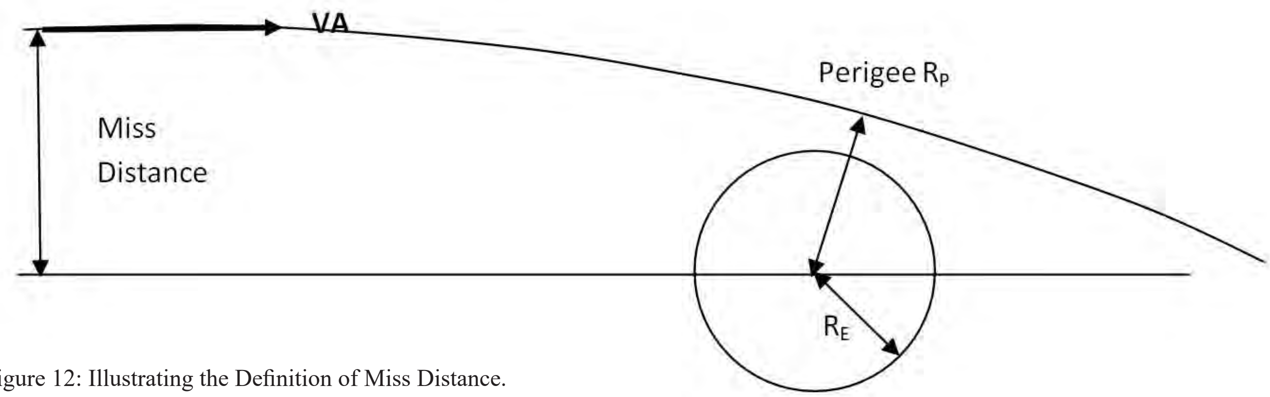

Figure 12: Illustrating the Definition of Miss Distance.

For the trajectory we are analysing here, we have:

R_P = 6,578 km, R_{MISS} = 8,937 km, R_{IMP} =8,727 km

Thus there is indeed a narrow corridor – of around 210 km - which the s/c must travel through in order to avoid an impact with the Earth. Now at the time of writing this article, the Perseverance lander to Mars had arrived at Mars and missed its planned target in the Jezero crater by a mere 5 m. I think we can assume therefore, with all the navigational apparatus available in close proximity to the Earth (which are not available at Mars), that this is an entirely feasible fly-by of Earth. In addition there is a thrust of the on-board engines at perigee with ΔV of magnitude 0.3 km/s making this a powered fly-by of Earth. A small adjustment it would seem, but this would have been entirely unnecessary had there been sufficient scope for an even closer approach.

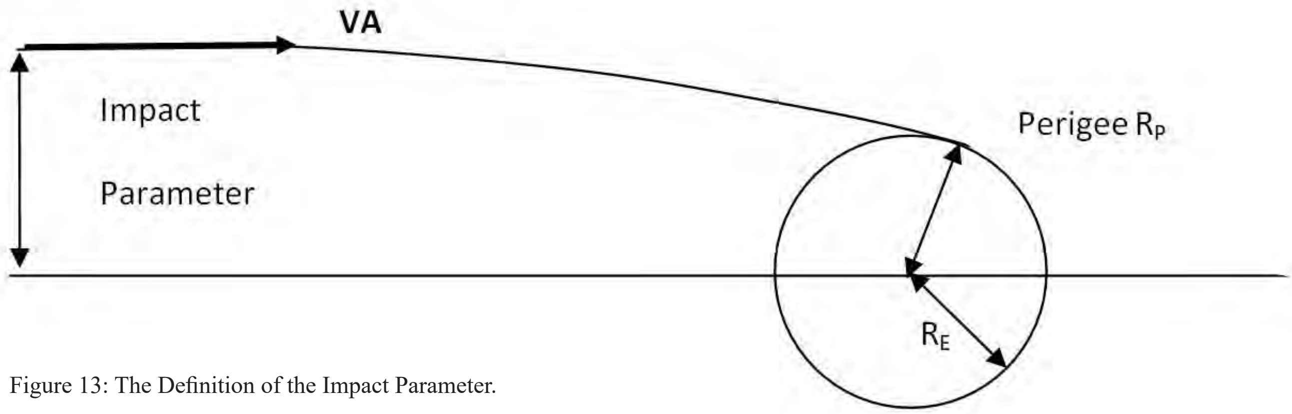

Figure 13: The Definition of the Impact Parameter.

3) Jupiter Encounter

What now of the encounter with Jupiter? This is a gravitational assist which doesn't accelerate the spacecraft, but quite the opposite, slowing it down dramatically from a heliocentric velocity of 15.7 km/s to one of 3.5 km/s.

How does it do this? Look at Figures 14-17. The key is that the s/c arrives at Jupiter's SOI ahead of Jupiter in its orbit around the sun. Observe that the component of the arrival heliocentric velocity perpendicular to the line to the sun is less than Jupiter's tangential velocity of 13.7 km/s, hence Jupiter catches up with the s/c and in effect ploughs into it.

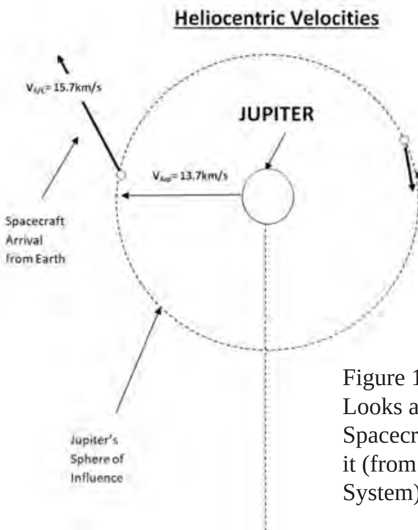

Figure 14: How Jupiter Looks at the Time of the Spacecraft's Encounter with it (from Above the Solar System).

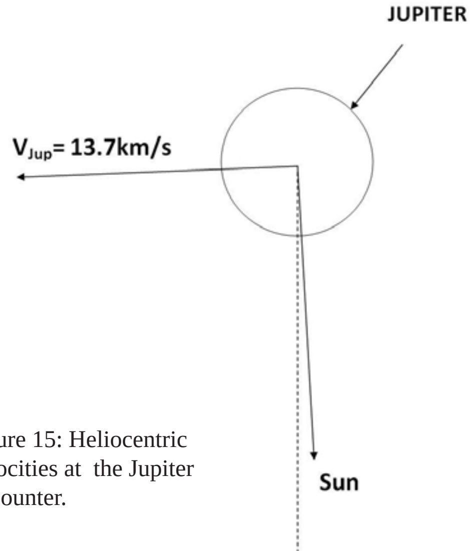

Figure 15: Heliocentric Velocities at the Jupiter Encounter.

If we subtract Jupiter's heliocentric velocity from the arrival velocity and departure velocity, we get everything relative to Jupiter, so we get a look at how Jupiter sees the encounter. As far as Jupiter is concerned, its gravitational pull is bending the approach velocity to eventually spit the s/c out backwards - in a direction almost tangential, but opposite, to Jupiter's motion.

By so doing, when Jupiter's heliocentric velocity is added back on in order to return to the sun-referenced frame, the s/c has actually slowed down quite dramatically.

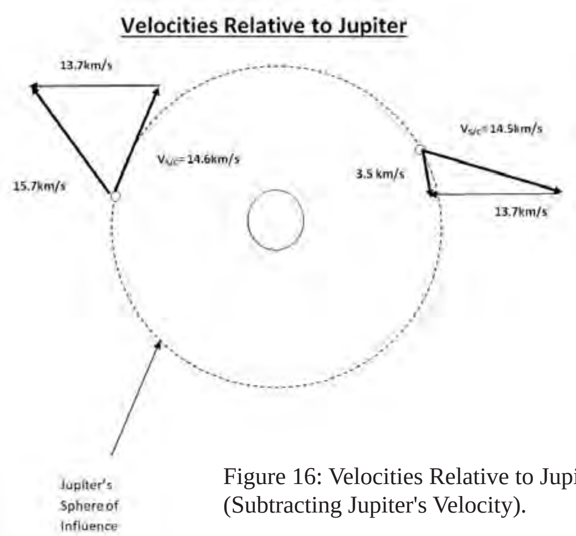

Figure 16: Velocities Relative to Jupiter (Subtracting Jupiter's Velocity).

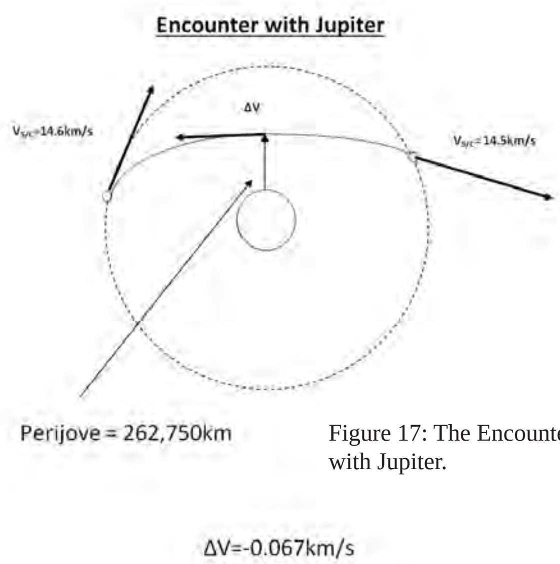

Figure 17: The Encounter with Jupiter.

The perijove altitude turns out at 262,750 km and one Jupiter radius is around 71,490 km, so the s/c will come within 4 Jupiter radii of Jupiter. We can perform the same analysis with Jupiter's encounter as we did with the Earth encounter in the previous section, we get the following:

R_P= 334.241 km, R_{MISS}= 713.054 km, R_{IMP}=299.948 km

Thus the arrival corridor to avoid a Jupiter collision is a fairly large value of 413,000 km.

4) Solar Oberth

Having encountered Jupiter, the s/c leaves Jupiter's SOI with a helpful nudge towards the sun of 3.5 km/s. As the sun is approached, so the acceleration of the s/c increases and is in fact proportional to the inverse square of the sun distance (of course by Newton's law of gravity). This free-fall phase of the trajectory lasts altogether just over 1½ years from leaving Jupiter, ample opportunity to develop a huge heliocentric speed higher than 250 km/s. At the time of writing, the Parker Solar Probe has yet to reach its maximum speed, which apparently will be around 200 km/s, and so the 'Oumuamua s/c would smash this record by a considerable amount.

Since the s/c will come within close proximity of the sun (a distance of 5 solar radii from the sun's surface), there is an inevitable question as to the possibility of the s/c being at some point obstructed by the sun, or alternatively transiting in front of the sun with respect to observers on Earth (and therefore the Deep Space Network), both of which would affect the communications link. Such an eventuality during this crucial period of the mission (after all, the success of the entire mission hinges on success here) would be extremely problematic and could compromise the mission. The news is good, however, serendipitously the Earth and the s/c are favourably aligned during the Solar Oberth, and no obscurations or transits arise. This is shown in Figure 18 which shows a view of the s/c, as seen by an observer in the northern hemisphere of the Earth, from slightly before until slightly after the Solar Oberth, the horizontal and vertical axes are in units of solar radius (696,342 km).

What is certain is that things will get hot, with a solar flux at perihelion of 1850 times that of the solar flux incident on Earth. The latter solar flux is 1.37 kW/m^2 (on the order of a tenth of the heat flux of your average

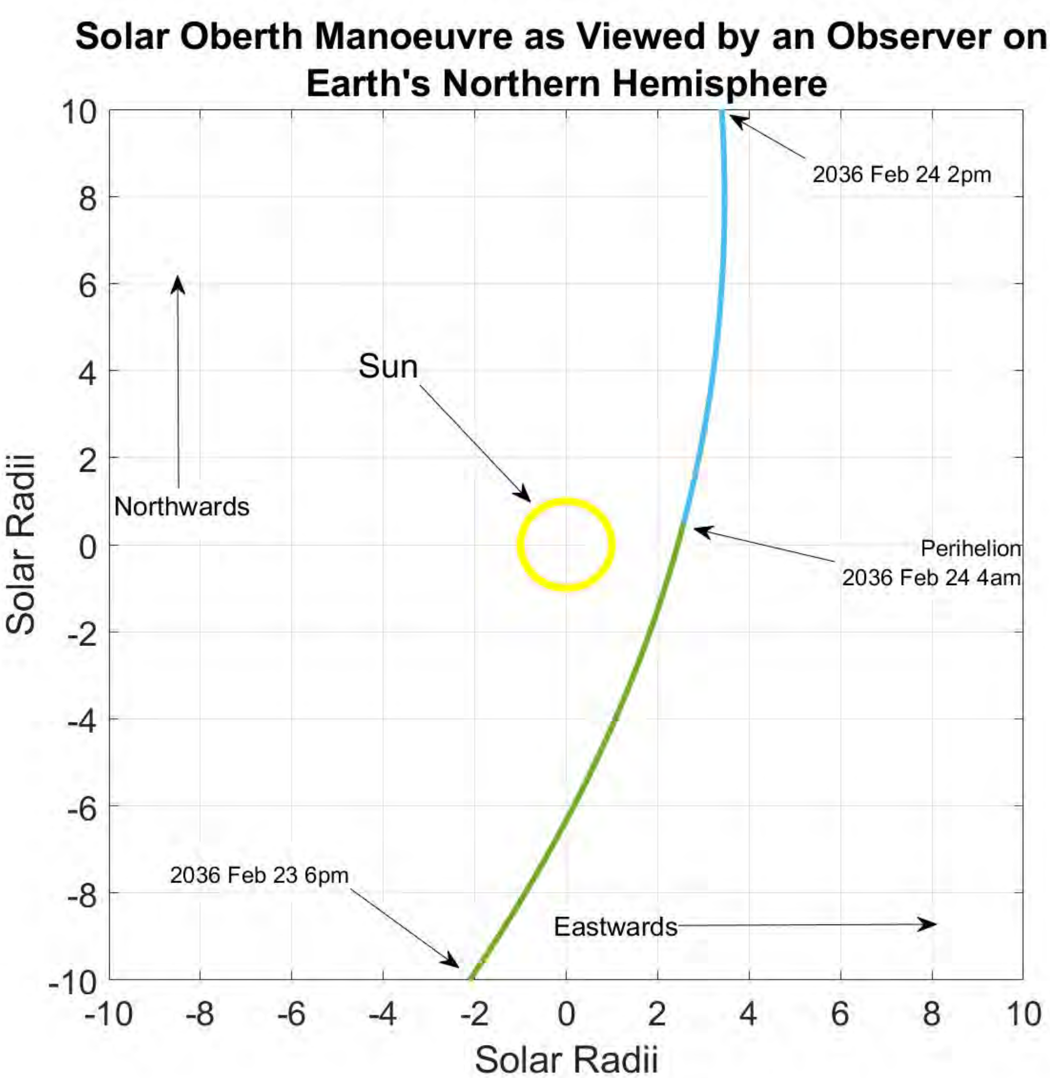

Figure 18: The Solar Oberth as viewed from Earth.

toaster) giving a value at the Solar Oberth of 2.534 MW/m². This enormous level of solar flux necessitates a heat shield to protect the precious payload. A study into Solar Oberth manoeuvres with Solar Thermal Propulsion – STP - (but aiming for the interstellar medium rather than specifically 'Oumuamua) has been conducted and is provided in Sauder et al *System Engineering a Solar Thermal Propulsion Mission Concept for Rapid Interstellar Medium Access* (2020), Ref 7. For our purposes, the long stretch to 'Oumuamua will indeed take us into the pristine interstellar medium, and we also need to get there fast. There is some mention in the Sauder et al study of a heat shield which is composed mainly of the same carbon-carbon composite material utilised for the Solar Parker Probe. However it also mentions there is an issue with this in that this material alone would quickly heat up to high temperatures when close and exposed to the sun. The solution is to coat this C-C composite with a thin layer of something highly reflective like Barium Fluoride, which also has an almost ideal low absorption profile in the most intense part of the solar spectrum.

A ΔV kick of around 7.2 km/s is required at the Solar Oberth and the original Project Lyra paper went into some detail as to how a similar kick could be delivered using, not STP (which has a relatively low Technical Readiness Level) but by the tried and trusted solid propellant rocket. That paper however only dealt with the 2021 mission which is now practically speaking infeasible due to time constraints.

For Trajectory A, which is considered here (and explored in the second Project Lyra paper), there is an issue in that one single stage solid rocket would not be able to deliver such a kick, so we ideally need two stages (or even three). There are plenty of candidates for powerful solid rockets, including the Thiokol STAR 48B, 63F and 75, in order of increasing ΔV kick. For our Solar Oberth burn we could try some combination of these for our two stage solid rocket boost, or even better, why not calculate the optimal ratio of stage masses and construct two bespoke solid rockets with this ratio of masses especially for the mission? I have done some analysis into all of this and Table 4 and Figure 19 are the results. Referring to Table 4, the liquid propellant motor present is there to apply all the ΔVs on the s/c from encounters 2 to 4 in Table 1. Note it is assumed the popular combination of hydrazine and nitrogen tetroxide is used, but this is likely to be phased out in the future, due to health and environmental concerns, and there are plenty of alternatives. Column 7, the theoretical minimum exhaust velocity needed for the liquid propellant motor is a calculation of the Specific Impulse which would result if a perfect liquid rocket stage were used to apply all the ΔVs for the encounters 2 to 4, assuming all the spare capacity in the column 6 could be used as fuel.

Table 4: Payload Masses achievable to 'Oumuamua Using 2 Stages for the Solar Oberth and a NASA SLS.

Payload to 'Oumuamua (including heat shield mass)	Traj	1st Rocket Motor (Location)	2nd Rocket Motor (Location)	Minimum SLS Config. Needed	Spare Capacity for Liquid Propellant Rocket Motor (LPRM)	Minimum Exhaust Velocity (Ve) Required for LPRM	Possible Liquid Propellant Oxidiser+Fuel (N2O4+MMH Has Ve = 3.347km/s)
200kg	A	STAR 48Bs (SO)	STAR 48Bs (SO)	Block 1	5.5mt	1.252km/s	N2O4+MMH
427kg	A	STAR 63F (SO)	STAR 63F (SO)	Block 1B	8.4mt	1.591km/s	N2O4+MMH
541kg	A	STAR 75 (SO)	STAR 48B (SO)	Block 1B / 2	7.2mt / 12.2mt	1.958km/s / 1.323km/s	N2O4+MMH/ N2O4+MMH
639kg	A	STAR 75 (SO)	STAR 75 (SO)	Block 2	6.2mt	3.184km/s	N2O4+MMH
640kg	A	STAR 75 (SO)	STAR 63F (SO)	Block 1B / 2	4.7mt / 9.7mt	3.305km/s / 1.826km/s	N2O4+MMH?/ N2O4+MMH
711kg	B	STAR 63F extended (PJ)	STAR 75 (SO)	Block 2	9.1mt	2.581km/s	N2O4+MMH
296kg (3 Stages: 378kg)	A	Liquid Propellant Used	Liquid Propellant Used	Block 1	N/A	N/A	N2O4+MMH
532kg (3 Stages: 681kg)	A	Liquid Propellant Used	Liquid Propellant Used	Block 1B	N/A	N/A	N2O4+MMH
680kg (3 Stages: 870kg)	A	Liquid Propellant Used	Liquid Propellant Used	Block 2	N/A	N/A	N2O4+MMH

SO = Solar Oberth   PJ = Perijove

For Table 4 and Figure 19, the Block 1 data assumed is based on an older design spec for the SLS. Since that time the power of Block 1 has evolved and become much closer to what was then known as the Block 1B variant. The vertical lines show the total payload capacity for each of the SLS versions Block 1, Block 1B and Block 2. The stars indicate what mass payload can be delivered to ‘Oumuamua (the vertical axis) against the total mass combined of the payload and solid booster stages 1 & 2 just prior to the Solar Oberth. The available mass for the liquid propellant stage (for encounters 2 to 4) is therefore the horizontal difference between a star and the vertical bar of the SLS version of interest. The diagonal line represents the capability for an optimal ratio of Solar Oberth stage masses. Masses of 711 kg are achievable to ‘Oumuamua by a Block 1B and the old Block 1 could easily have delivered masses of 200 kg.

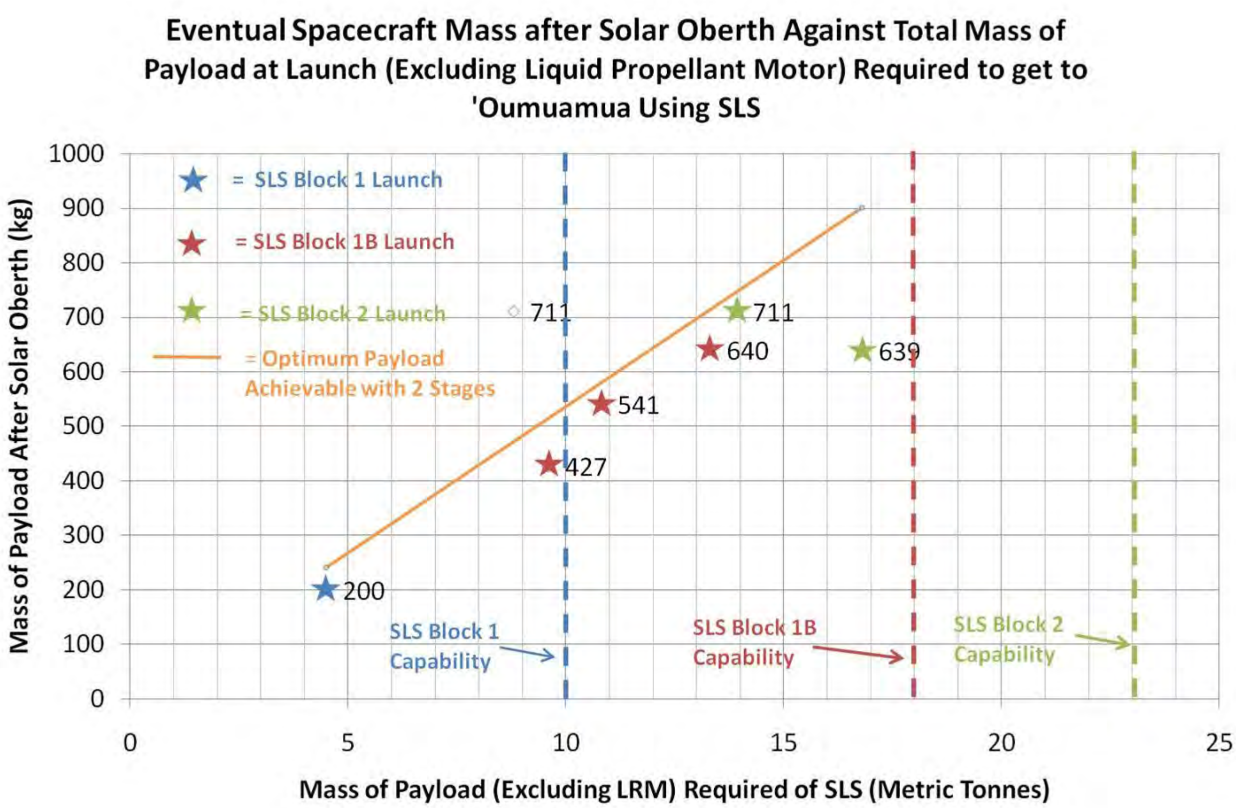

Figure 19:: Graphic of Possible Payload Masses to 'Oumuamua Using the NASA SLS..

5) Coast to ‘Oumuamua and Arrival

Nominally it will take 16 years after the Solar Oberth to get to ‘Oumuamua making the overall mission duration 22 years (arriving in 2052). This is a long wait and begs the question as to whether we can reduce this duration. The straightforward answer would be yes if we were to use an alternative to chemical propulsion, for example the emerging NTP, Nuclear Thermal Propulsion. But this, like STP, has a low TRL* and hasn’t actually been flight tested yet - so let us stick to chemical for the moment.

* Technology Readiness Level https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

What happens to the size of ΔV needed at the Solar Oberth as we reduce the flight duration from the Solar Oberth to 'Oumuamua? Figure 20 shows clearly that as this duration is reduced, so the ΔV increases, moving from right to left in the plot. On the far right of this curve, it is equivalent to trajectory A, ie a 16 or so year flight and a ΔV impulse of 7.2 km/s. As we move to the left, so the flight duration reduces and as one would expect, the impulse goes up. Initially the rise is quite gradual but if we try to shorten the duration too much, say by 3 years or more, we start to enter infeasible territory.

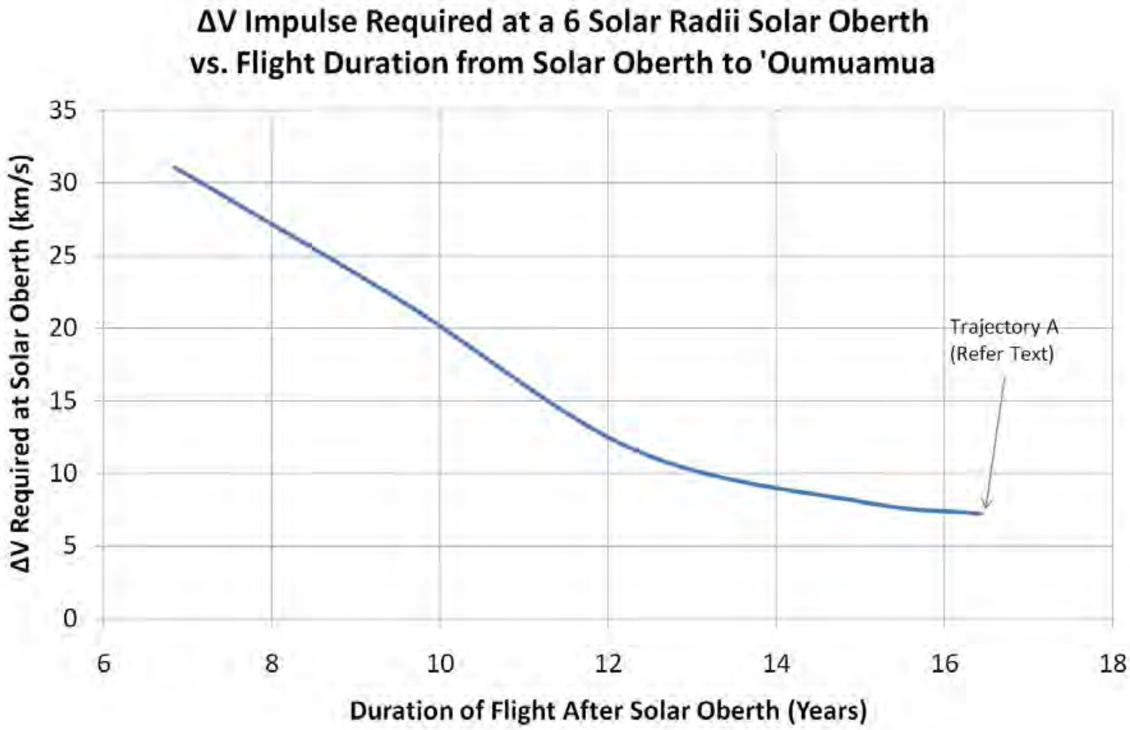

Figure 20: How ΔV at the Solar Oberth Varies with Flight Duration after the Solar Oberth.

There is an issue with arriving at 'Oumuamua in that there is a fair degree of uncertainty in its precise direction – the asymptote direction - which it is heading in relative to the sun. There are two prime reasons for this. Firstly 'Oumuamua was detected fairly late as it encountered the inner solar system – after perihelion in fact – and as a consequence the number of observations of it from ground telescopes and the Hubble space telescope was relatively low. Secondly when 'Oumuamua's trajectory was analysed, a non-gravitational force was discovered to be present, influencing and perturbing its motion Micheli et al (Ref 4). Both of these factors mean we don't have an accurate fix on the orbit of 'Oumuamua. One can do the calculations and we find that for an intercept distance of 200 AU, 'Oumuamua could be laterally displaced by as much as 1 or 2 million km from the best estimate of its orbital path.

This seems to be a real issue for any single spacecraft. The solutions suggested in the i4is Interstellar Now paper (Ref 8) are -

- An onboard telescope should be able to detect an object from within a range of around (1/R) AU where R is the distance from the sun in AU. We know that R=200 AU, so we find this distance turns out at around 750,000 km. So a single spacecraft could quite easily pass 'Oumuamua by without even noticing it!
- The other solution elaborated in the Interstellar Now paper is to send a single spacecraft which, at a significant distance from 'Oumuamua's predicted position, deploys a swarm of chipsats in a random scatter around 'Oumuamua's estimated asymptote direction. With a sufficient number of chipsats, statistically at least one should detect 'Oumuamua and be able to communicate back to the mother craft 'Oumuamua's precise position and velocity. It should then be a simple question of the mother craft applying a corresponding adjustment to its velocity vector to ensure an intercept.

Clearly it would be helpful if we had solutions to this terminal guidance issue which were not so demanding upon telescopic pattern matching or as-yet unproven chipsat technology.

The next issue of Principium will examine terminal guidance in detail.

In future we will also consider the science payload possible with a number of probe scenarios - flyby, impactor and rendezvous - and configurations including single, multiple and swarm spacecraft.

6) Final

You may have noticed the entire mission duration is extremely extended – over 20 years. Furthermore this mission would stretch the limits of current human scientific and technological understanding. Is the scientific prize worth all this? I guess I end this whole analysis with a call to arms not just to scientists and engineers, but to the whole of humanity.

Just as a young software engineer should regularly be asked by their supervisor, “where do you see yourself in the future? What are your goals?” Should not humanity be asked the same question? However in our case there is no supervisor, there is no overseer to steer us. Is it not therefore incumbent upon us collectively to ask ourselves this question? When an opportunity arises, surely it would be folly not to grasp it and seek to climb the ladder of promotion. And who knows where interstellar travel may bring us? To a Kardashev Type III species maybe? Such grand ambitions start with small steps and as luck would have it an opportunity has indeed arisen, let us all now unite in this common goal. Objective: ‘Oumuamua.

7) References

1 Github repository for OITS - https://github.com/AdamHibberd/Optimum_Interplanetary_Trajectory

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8 A. M. Hein, T. M. Eubanks, M. Lingam, A. Hibberd, D. Fries, N. Perakis, J, Schneider. “ Interstellar Now: Missions to and Sample Returns from Nearby Interstellar Objects”, 2020, arXiv e-prints, https://arxiv.org/abs/2008.07647

About The Author

Adam was educated at a state school in Coventry and attended the University of Keele, gaining a joint honours degree in physics and maths. He worked in the ‘90s as a software engineer on the on-board flight program for the European Ariane 4 launch vehicle - including the production, maintenance, real-time testing and post-flight analysis, his expertise being the guidance algorithm. He is also a pianist and composer and, as a member of musical trio ‘Superheroes Dream’, produced a vinyl under the Coventry Tin Angel Record Label (tinangelrecords.bandcamp.com/album/waiting-or-flying). He developed his Optimum Interplanetary Trajectory Software, ‘OITS’ in 2017 as a personal challenge to learn the MATLAB programming environment and language. He then used it to investigate missions to interstellar objects (the work being published in Acta Astronautica) and now is a research volunteer for the ‘Initiative for Interstellar Studies’.

Interstellar News

John I Davies reports on recent developments in interstellar studies

i4is prediction - Up for Refutation!

A paper from the i4is Project Lyra team and associates fluttered a few dovecotes in the science press recently - though its implications are much wider than the headlines.

In universetoday.com "There Should be About 7 Interstellar Objects Passing Through the Inner Solar System Every Year" -

www.universetoday.com/150478/there-should-be-about-7-interstellar-objects-passing-through-the-inner-solar-system-every-year/

> What they found was that in an average year, the Solar System would be visited by up to 7 ISOs that are asteroid-like. Meanwhile, objects like 2I/Borisov (comets) would be rarer, appearing around once every 10 to 20 years.

And from *New Scientist* "Seven alien space rocks should pass through our solar system each year" -

www.newscientist.com/article/2271307-seven-alien-space-rocks-should-pass-through-our-solar-system-each-year/

> An average of seven interstellar objects pass by the sun every year, potentially close enough for us to observe and even visit, according to a new analysis.

This was echoed by a number of other, less scientific, news sources.

The paper in question is - *Interstellar Objects in the Solar System: 1. Isotropic Kinematics from the Gaia Early Data Release 3*, Eubanks et al.

A brief extract from the abstract makes the conjecture about the frequency of interstellar objects (ISOs) very clear -

> Finding additional ISOs and planning missions to intercept or rendezvous with these bodies will greatly benefit from knowledge of their likely orbits and arrival rates. Here, we use the local velocity distribution of stars from the Gaia Early Data Release 3 Catalogue of Nearby Stars and a standard gravitational focusing model to predict the velocity dependent flux of ISOs entering the solar system. With an 1I-type ISO number density of ~ 0.1 AU−3, we predict that a total of ~ 6.9 such objects per year should pass within 1 AU of the Sun.

The Gaia astrometry vehicle has produced a wealth of information about our interstellar neighbourhood. More in *News Feature: The 10 parsec sample in the Gaia era* elsewhere in this issue.

The paper by Eubanks et al paper also examines the possible results obtainable from an impactor ejected by a fast flyby vehicle intercepting an ISO.

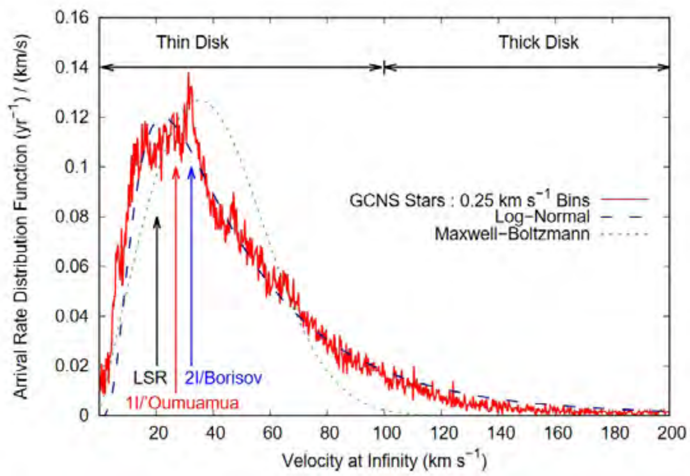


Figure 5. The differential ISO arrival rate at the Earth's orbit (LSR - Local Standard of Rest - the mean motion of near parts of the galaxy).

Credit: T Marshall Eubanks (Space Initiatives Inc and Institute for Interstellar Studies), Andreas M Hein (Initiative for Interstellar Studies), Manasvi Lingam (Florida Institute of Technology and Harvard University), Adam Hibberd (Initiative for Interstellar Studies), Dan Fries (University of Texas at Austin and Initiative for Interstellar Studies), Nikolaos Perakis (Initiative for Interstellar Studies and Technical University of Munich), Robert Kennedy (Institute for Interstellar Studies), W P Blase (Space Initiatives Inc) and Jean Schneider (Observatoire de Paris) arxiv.org/abs/2103.03289.

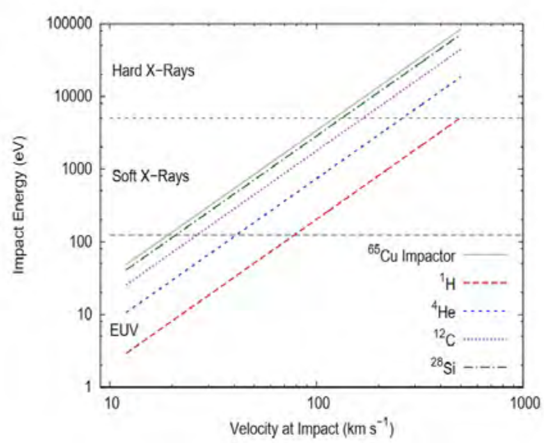


Figure 7: Prompt impact energies as a function of the impact velocity for various atomic species. Credit:Eubanks et al.

The Wormship: A Dark Energy Ramjet

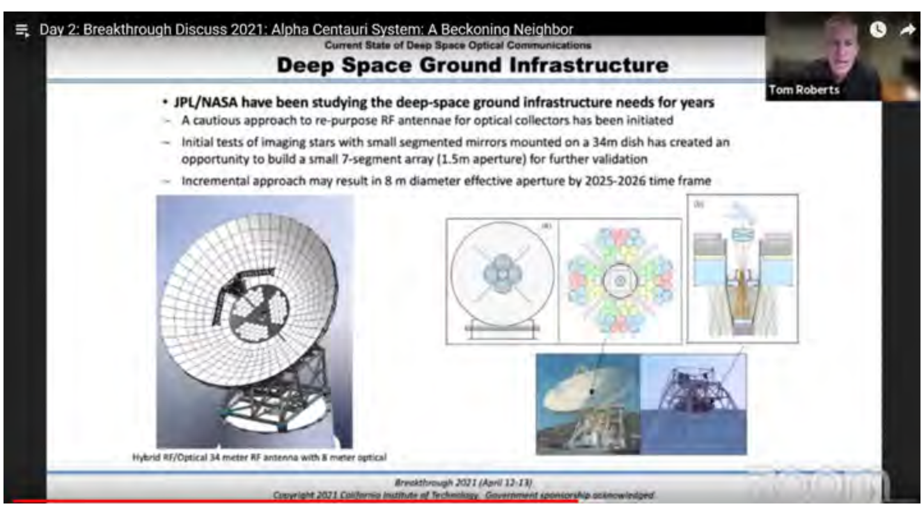
Dr Stephen Baxter is a physicist and science fiction writer. He has made major contributions to interstellar studies notably *Artificial Intelligence for Interstellar Travel* (JBIS 2019 arxiv.org/abs/1811.06526 with Dr Andreas Hein of i4is) and 18 other papers in the Journal of the British Interplanetary Society as far back as 2001, most on interstellar subjects.

Stephen will be presenting his idea, *The Wormship: A Dark Energy Ramjet* to BIS West Midlands on 20 November 2021(www.bis-space.com/event/the-wormship-a-dark-energy-ramjet-by-stephen-baxter/).This is based on his paper with the same title in JBIS V74 #2 February 2021. The abstract announces "a tentative dark energy ramjet design" and cautiously suggests that "this is highly speculative, and depends on the nature of dark energy" but "if it could be built, such a vessel would be well suited to journeys in intergalactic space, and indeed between galactic clusters, where alternate potential fuel media, baryonic and dark matter, reach very low densities". Such propulsion might also provide a technosignature for SETI. This looks like a fascinating talk from a major innovator in interstellar studies.

Breakthrough Discuss 2021

Breakthrough Discuss is an annual academic conference focused on life in the Universe and novel ideas for space exploration. This year the topic was "The Alpha Centauri System: A Beckoning Neighbor" held on April 12-13. The speakers and timetable are at - breakthroughinitiatives.org/initiative/5/discuss2021. All three sessions are available on Youtube [1] - an example below.

Tom Roberts, JPL, on *Current State of Deep Space Optical Communications* on day 2 of Breakthrough Discuss 2021. Watch out for the first ever joke about dB (that I am aware of!)



Roberts mentioned near term experiments (*Psyche*), pulse-position modulation (see Breakthrough Starshot thinking in Principium 27 page 28, P28 page 17 P31 page 38), forward error correction (FEC), interleaving to combat deep fades and experimental re-purposing a radio dish as a mirror-tiled optical receiver (see his slide, left). The day-night downlink performance differences are striking - order of 10 better at night - but there was no mention of the use of space telescopes - which would not have this handicap.

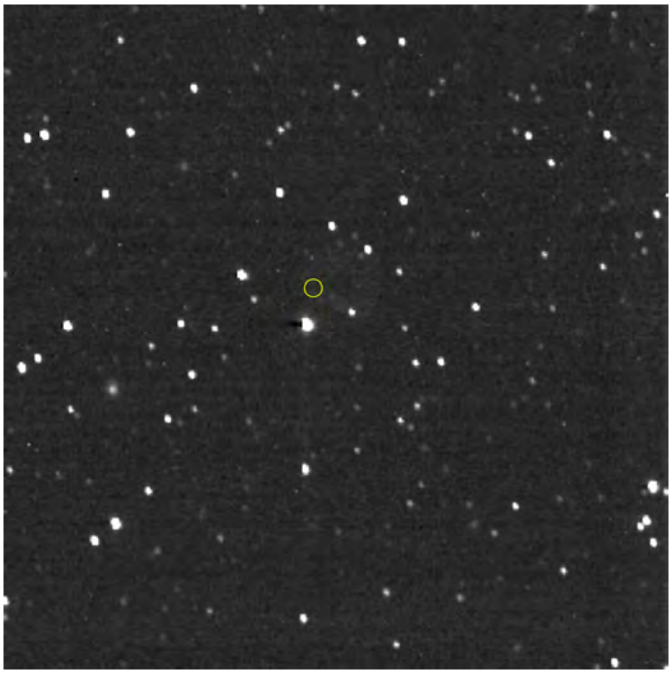
IRG 7th Interstellar Symposium

Principium readers may need no reminding of this year's main event from our friends and colleagues at the Interstellar Research Group (IRG) - the Tennessee Valley Interstellar Workshop, as it was formerly known. Famous speakers announced for the event include Professor Avi Loeb (see the review of his book, *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth* by Patrick Mahon elsewhere in this issue) and Esther Dyson (investor and visionary). The Symposium will be in Tucson, Arizona September 25-27, 2021 (with pre-symposium seminars taking place on the 24th). Details and registation at irg.space/.

[1] Breakthrough Discuss 2021 www.youtube.com/playlist?list=PLyF3OMOiy3nGgq35b5FVqCqSl6CrvHERg

Even at 50 AU New Horizons is "Gonna need a bigger telescope"!

Having recently watched *Jaws* again I'm reminded of Chief Brody's remark to Quint when NASA pointed the telescope on New Horizons in the direction of Voyager 1 but said it was "about 1 trillion times too faint to be visible ". NASA's New Horizons probe is now 50 times as far from the Sun as Earth (ie 50 AU) and took the opportunity to point its telescope, the Long Range Reconnaissance Imager (www.boulder.swri.edu/pkb/ssr/ssr-lorri.pdf), towards the location of its predecessor Voyager 1's position. Voyager is now at 152 AU. The image cannot, of course, include Voyager 1. By my calculation it is ten billion (10^9) times too far away - and as always the dreaded inverse square law applies.



Hello, Voyager! From the distant Kuiper Belt at the solar system's frontier, on Christmas Day, Dec. 25, 2020, NASA's New Horizons spacecraft pointed its Long Range Reconnaissance Imager in the direction of the Voyager 1 spacecraft, whose location is marked with the yellow circle. www.nasa.gov/sites/default/files/thumbnails/image/voyager1look_4x4_041421.png.

Voyager 1 was 11.2 billion miles (18 billion kilometers) from New Horizons when this image was taken. Voyager 1 itself is about 1 trillion times too faint to be visible in this image.

Image and caption credit: NASA

China aims beyond the Solar System

As reported in Space Daily and elsewhere, China intends to send two spacecraft to 100 AU, about 2/3 of the distance currently achieved by Voyager 1. The target arrival date, 2049, is the centenary of the founding of the current state, the Peoples Republic of China. These Interstellar Heliosphere Probes (IHPs) are planned to launch around 2024 (meetingorganizer.copernicus.org/EPSC-DPS2019/EPSC-spacenews.com DPS2019-1986-1.pdf), one towards the leading edge of the heliopause and the other in the opposite direction. This looks like a rival, or possibly complement, to the Johns Hopkins University - Applied Physics Lab (APL) project for a near-term, "pragmatic" Interstellar Probe aiming to launch around 2030 with the more ambitious target of 2,000 AU (interstellarprobe.jhuapl.edu/) - as reported in several previous issues of Principium. The JHU-APL probe aims to use a solar Oberth manoeuvre to achieve a much higher final velocity - as explained by Adam Hibberd in *The Equation used in the Benkoski Paper* in Principium 28.

More about the China proposal at spacenews.com (spacenews.com/china-to-launch-a-pair-of-spacecraft-towards-the-edge-of-the-solar-system/.

Expanding ESA's Deep Space Communications

The European Space Agency (ESA) has announced plans to build a second deep space dish at New Norcia, Western Australia. It will be ESA's second 35-metre antenna at the site and its fourth in total. The three sites of the ESA deep space ground station network are in Spain, Argentina and Australia - about 120° apart in longitude to provide continuous coverage as the Earth rotates. All are controlled from the European Space Operations Centre (ESO) at Darmstadt, Germany. Missions currently supported include the Gaia astrometry observatory at the Earth-Sun L2 point, Mars Express, Exomars and the European-Japanese Bepi-Colombo mission to Mercury.

Positive Energy Warp Drive

In *Positive Energy Warp Drive from Hidden Geometric Structures* (arxiv.org/abs/2104.06488), Shaun D B Fell and Lavinia Heisenberg challenge the assumption that negative energy densities are a requirement of superluminal motion. They claim a tremendous improvement on the classical configurations with their numerical analysis of a set of example configurations finding total energy requirements three orders of magnitude smaller than the solar mass.

This remains a staggering energy requirement but if these physicists at ETH Zurich have found a way of achieving such a massive reduction of the warp drive energy requirement then perhaps, one day, we may find solutions that would allow Scotty to tell Captain Kirk that he is no longer asking his chief engineer to change the laws of physics!

Extreme Metamaterial Solar Sails for Breakthrough Space Exploration

In a recent paper Artur Davoyan, UCLA, (www.nasa.gov/directorates/spacetech/niac/2020_Phase_I_Phase_II/Extreme_Metamaterial_Solar_Sails/) suggests that extreme metamaterial solar sails may enable numerous low cost and high speed missions to be launched at speeds >60 AU/year when coupled to low mass spacecraft and diving to extreme proximity to the sun (2-5 solar radii). His NASA NIAC study challenges the limits of materials, paving the way for development of high endurance ultrathin film architectures that can handle extreme environments manifested by solar radiation and plasma in addition to providing spacecraft control. Potentially Jupiter in 5 months, Neptune in 10 months, surpassing Voyager 1 in 2.5 years and getting to the solar gravity lens location in 8.5 years.

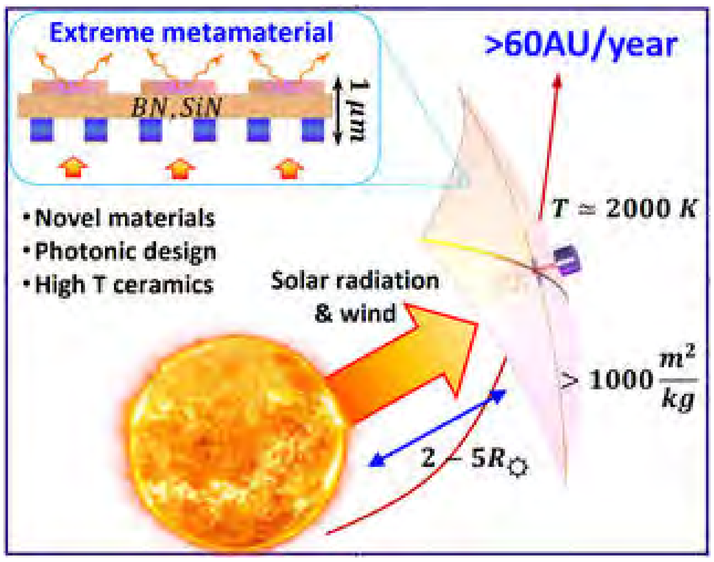


Image credit: Artur Davoyan

FarFarOut is a long way away

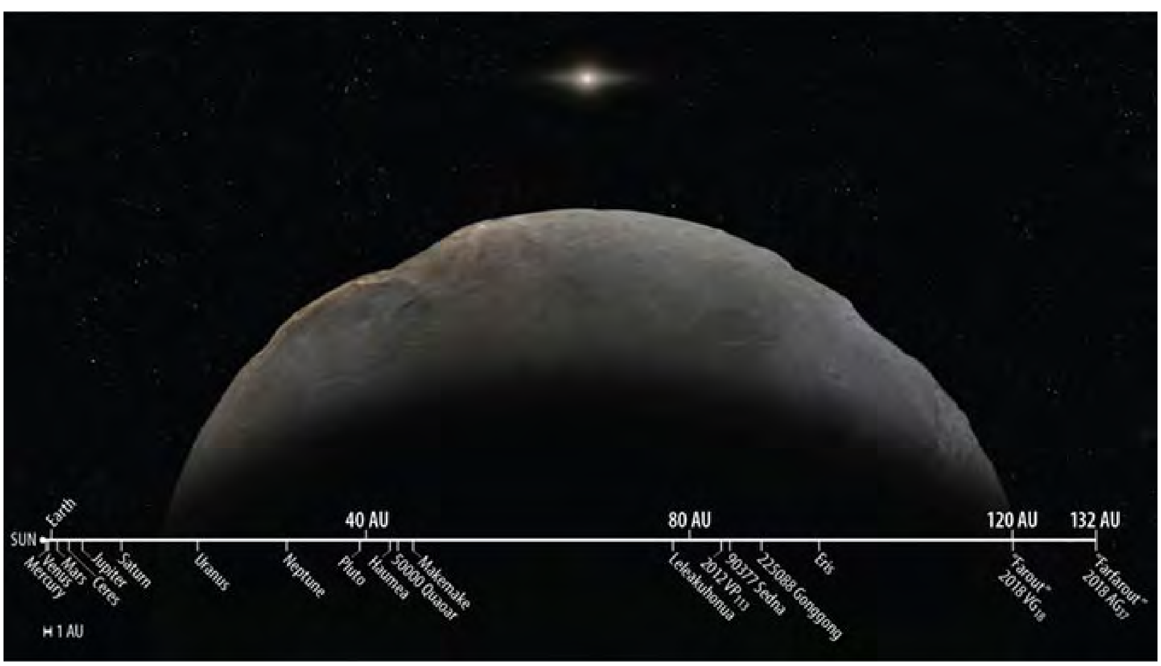
A team of researchers including Carnegie astronomer Scott Sheppard have confirmed the most distant object ever observed in our Solar System (epl.carnegiescience.edu/news/farfarout-officially-added-count-dwarf-sized-planets-distant-solar-system). The dwarf planet officially named 2018 AG37, but nicknamed FarFarOut, is 132 AU away and the researchers have kindly provided a nice visualisation of the distance (below). Note how the planets are crammed into less than one quarter of this linear scale.

Latest news from IRG

Our friends at the Interstellar Research Group (IRG, formerly TVIW) have published their latest newsletter (irg.space/wp-content/uploads/2021/03/IRG_Newsletter_N22.pdf) featuring a review of *Dark Skies: Space Expansionism, Planetary Geopolitics, and the Ends of Humanity* in which Daniel Deudney, a political scientist at Johns Hopkins University, argues that humanity’s expansion into space will decrease the probability of human survival. Reviewer Ken Roy tells us that most of Deudney's arguments cite technologies that have no direct connection with expansion into space.

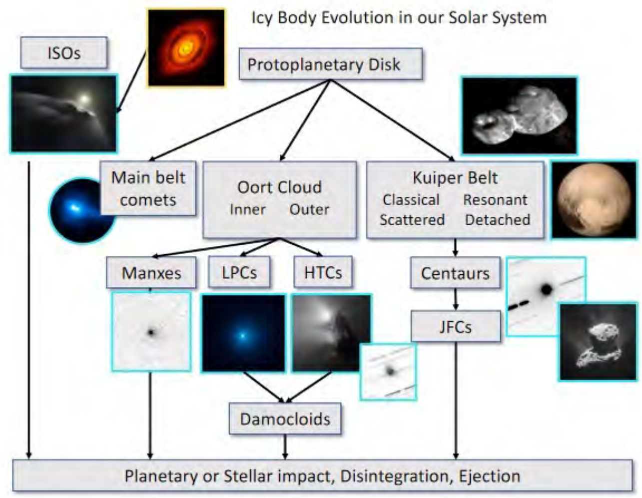
And David Fields laments what we have lost with the demise of the Arecibo telescope and argues not for a direct replacement but for creating better instruments based on the Arecibo experience.

FarFarOut - image credit: Roberto Molar Candanosa, Scott S. Sheppard from Carnegie Institution for Science, and Brooks Bays from University of Hawai‘i



Oort Comet Objects - InSitu Exploration

A paper, *In-Situ Exploration of Objects on Oort Cloud Comet Orbits: OCCs, Manxes and ISOs* (baas.aas.org/pub/2021n4i282/release/1) by lead authors Karen J Meech, University of Hawai'i and Julie Castillo-Rogez, JPL, points out that NASA's competitive mission calls are not compatible with missions that are responsive to new discoveries such as potentially hazardous Near Earth Objects (Oort Cloud comets or OCCs and Manx comets) and interstellar objects (ISOs). They report two suggested responses; spacecraft in storage, ready to launch, and spacecraft in standby orbit such as the ESA Comet Interceptor. They explore both the science needed for quick reaction missions and the technologies to achieve them.



Meech/ Castillo-Rogez target object taxonomy - caption quote - Figure 1: Genetic relationships of early solar system planetesimals. The Oort cloud is the largest reservoir of objects that has not been explored with an in situ mission. HTC = Halley Type comet, JFC = Jupiter Family Comet, ISO = Interstellar Object, arriving from another solar system.)

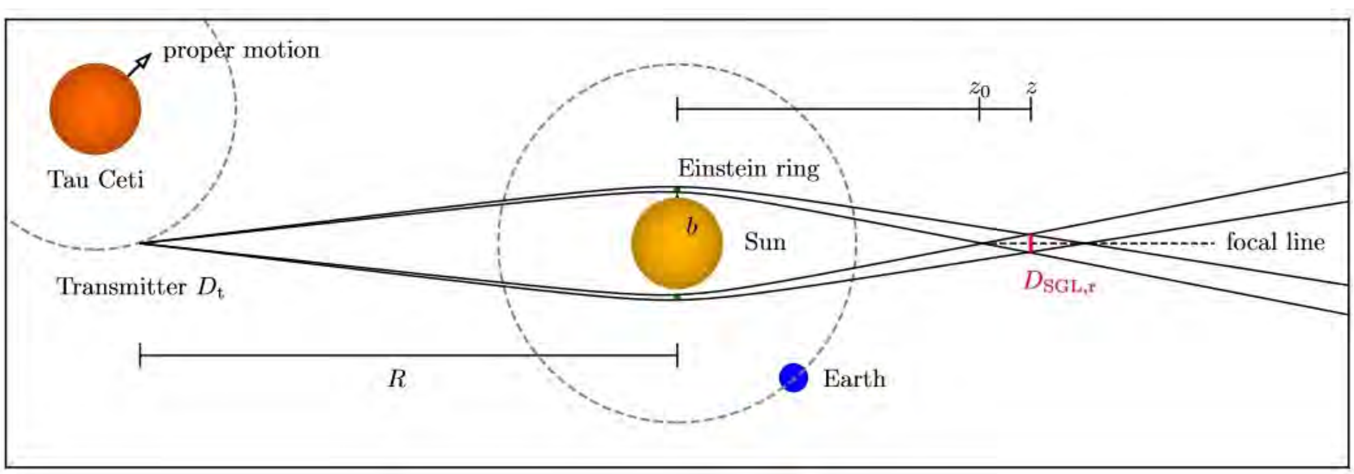
Locating deep space nodes

Michael Hippke presents *Interstellar communication network. III: Locating deep space nodes* he suggests that an interstellar communication network would benefit from relay nodes placed in the gravitational lenses of stars (arxiv.org/abs/2104.09564). The signal gains would be of order 10^9 with optimal alignment, allowing for GBit/sec connections at kW power levels with metre-sized probes over parsec distances. He asks - If such a network exists, there might be a node in our solar system: where is it? His paper suggests that, with some assumptions on the network topology, candidate sky positions can be calculated.

Andreas Hein briefs German Federal Ministry of the Environment

i4is Executive Director Dr Andreas M Hein was invited to a discussion on space resource utilization with the German Federal Ministry of the Environment, Nature Conservation, and Nuclear Safety (BMU) on the 25th March 2021. He presented the prospects of space resource utilization and space settlements. The results of the discussion will inform future German federal government policy-making.

Hippke - caption quote- Figure 1. Cartoon diagram of the solar gravitational lens configuration. The receiver with aperture $D_{SGL,rn}$ on the focal line (right) observes the flux at distances from the sun which comes through the Einstein ring from the transmitter at distance.



KEEP AN EYE ON OUR FACEBOOK PAGE

Our Facebook page at - www.facebook.com/InterstellarInstitute - is the place for up to date announcements of our work and of interstellar studies in general. It's a lively forum much used by our own Facebookers and others active in our subject area.

If you prefer a more professionally focused social network then our LinkedIn group provides this - www.linkedin.com/groups/4640147

Introducing physical warp drives

Longer term Principium readers will be familiar with the ideas of Miguel Alcubierre [1] A new paper in *Classical and Quantum Gravity* by Alexey Bobrick and Gianni Martire of the Advanced Propulsion Laboratory at Applied Physics, New York (appliedphysics.org), titled *Introducing physical warp drives*, observes that, since it allows for superluminal travel at the cost of enormous amounts of matter with negative mass density, the Alcubierre solution has been widely considered unphysical. They aim to show that their model of a general warp drive spacetime in classical relativity encloses all existing warp drive definitions and allows for new metrics without the most serious issues present in the Alcubierre solution. There is an open access version of their paper at - arxiv.org/abs/2102.06824.

Does their idea work? And, if so, is the result significant enough to bring Alcubierre's ideas nearer to feasibility?

JWST first programme announced

scientificamerican.com examines the proposals selected for the General Observer (GO) programs for the first year of operation of the James Webb Space Telescope (www.scientificamerican.com/article/the-james-webb-space-telescopes-first-year-of-extraordinary-science-has-been-revealed/). This will start after deployment of the 6.5-meter segmented mirror and even larger sun shield and a subsequent six-month phase of commissioning its instruments. SciAm reports that study items were chosen by panels of scientists in a double-blind process with about 1,200 proposals received and 266 selected, a third of them led by women, and about a third from ESA member states but the majority from US scientists.

It's worth noting that this will be one of the last launches by the European Ariane 5 rocket before it is superseded by the more economically efficient Ariane 6. Ariane 5 has been one of the most reliable launchers so far developed but there is only one JWST. So a lot of people worldwide, including the i4is team, will have fingers crossed for a flawless launch (and, of course, deployment).

JWST in Ariane 5 - launch currently (20/5/21) uncertain
Credit: Arianespace - ESA - NASA

Revised 2I/Borisov mission paper

Adam Hibberd has revised the i4is mission planning paper, *Sending a Spacecraft to Interstellar Comet 2I/Borisov*, arxiv.org/abs/1909.06348 ([v2] Sat, 1 May 2021 10:10:54 UTC) using more up-to-date orbital data. It has a more detailed examination of the viability of a mission, including the calculation of the declination of the escape asymptote at Earth, a parameter with implications for a launch trajectory.

Near-term self-replicating probes

In Acta Astronautica, a paper by Olivia Borgue and Andreas M Hein of i4is, *Near-term self-replicating probes - A concept design* (www.sciencedirect.com/science/article/abs/pii/S009457652100117X) demonstrates that 70% replicability is already practicable and provides a technology roadmap to achieving full replication and interstellar exploration. Open publication arxiv.org/abs/2005.12303.

Photonic phase sensing and control for laser propulsion

In the Journal of the Optical Society of America B Bandutunga et al have *Photonic solution to phase sensing and control for light-based interstellar propulsion* (Vol. 38, Issue 5) www.osapublishing.org/josab/fulltext.cfm?uri=josab-38-5-1477&id=450064.

Breakthrough Starshot proposes a ground-based laser array to accelerate a gram-scale spacecraft. This requires around 100 GW and the coherent combination of many lasers to achieve. The paper presents a photonic solution for optical phase sensing and control to enable the coherent combination of many lasers (scalable to 10^8), including the ability to sense and compensate for atmospheric distortions. The proposed solution avoids the limitations of previous methods based on sensing backscatter from the sail. This is increasingly impractical for solutions envisaging a large distance between laser array and sail because of the delays involved. They suggest use of multiple satellite-based laser "guide-stars" to detect the effects of the part of the optical path within the Earth's atmosphere.

Of course a space based laser array would not require this.

[1] see Twaites, *Warp drive is possible*, P13 May 2016, and Mehta, *Is the Alcubierre Drive the answer to Interstellar Travel?* P17 May 2017, several reports in our *News Feature: Foundations of Interstellar Studies Workshop 2019* in P26 August 2019 and *News feature: FISW2 videos and presentations on the i4is website* in P30 August 2020. See also the report of propulsion technology presentations by Dan Fries, Deputy Director of the i4is Technical team to i4is-led masters electives at the International Space University in P31 November 2020 and upcoming reports from this year's elective.

A philosopher looks at Oumuamua

In *The 'Oumuamua Encounter: How Modern Cosmology Handled Its First Black Swan*, (www.mdpi.com/2073-8994/13/3/510) Les Coleman of the Department of Finance, The University of Melbourne, gives a comparative study of techniques used by cosmologists versus those used by financial economists in qualitatively similar situations where data conflict with the current paradigm. Coleman invokes the Duhem-Quine (DQ), or joint test, problem of interpreting observations relying on untested theory. One example he suggests is the refusal of a contemporary philosopher to look through Galileo's telescope - essentially because he distrusted the ability of this new-fangled device to tell him the truth.

The issue is underdetermination. For example the Stanford Encyclopedia of Philosophy quotes John Stuart Mill (plato.stanford.edu/entries/scientific-underdetermination/#FirLooDuhQuiProUnd) -

> ...an hypothesis...is not to be received as probably true because it accounts for all the known phenomena, since this is a condition sometimes fulfilled tolerably well by two conflicting hypotheses... while there are probably a thousand more which are equally possible, but which, for want of anything analogous in our experience, our minds are unfitted to conceive.

When dealing with partial knowledge as in the case of 1I/'Oumuamua, interstellar studies needs all the help it can get - and philosophical economists are a welcome addition to our intellectual team!

Recent Interstellar papers in JBIS

2021 has already been a bumper year for interstellar papers in the Journal of the British Interplanetary Society. There have been two General Interstellar Issues and at least one other paper of interstellar interest.


JBIS
Journal of the British Interplanetary Society

General Interstellar Issue

DEFINING INTELLIGENCE-FAVOURING GALACTIC PARAMETERS for targeted SETI searches
Gary S. Robertshaw

STRATEGIES FOR THE DETECTION OF ET PROBES Within Our Own Solar System
John Gertz

THE WORMSHIP: A DARK ENERGY RAMJET – Engineering, SETI Detectability, and Implications for Cosmic Expansion
Stephen Baxter

EXOTIC FLUIDS MATCHING THE STRESS-ENERGY TENSOR OF ALCUBIERRE WARP DRIVE SPACETIMES
Willie Bilatrix-Drouhet

HOW MANY ALIEN PROBES COULD HAVE COME FROM STARS PASSING BY EARTH?
James Benford

www.bis-space.com


JBIS
Journal of the British Interplanetary Society

General Interstellar Issue

GENETIC EVOLUTION OF A MULTI-GENERATIONAL POPULATION in the context of interstellar space travel
Frédéric Marin, Camille Beluffi & Frédéric Fischer

MULTI-PERCEPTUAL MODALITIES MESSAGE DELIVERY MODULE: MAILbox
Suchetan Mummigatti

FROM THE SPACEX STARLINK MEGACONSTELLATION TO THE SEARCH FOR TYPE-I CIVILIZATIONS
Z. N. Osmanov

WAS THE WOW! SIGNAL DUE TO POWER BEAMING LEAKAGE?
James Benford

www.bis-space.com


JBIS
Journal of the British Interplanetary Society

General Issue

SURVEYING THE LAUNCHER MARKET
Vadim Zakirov et al

ACCESS TO ORBIT FROM UNST – a worked example
Robin Brand & Scott Hammond

WHAT DO WE NEED TO ASK BEFORE SETTLING SPACE?
James Schwartz et al

QUENCHING-SUPERCONDUCTOR ROCKETS: Blasting to the Limits of Chemical Rocketry
David Negretti et al

TERRAFORMING MARS: an Investigation into the Feasibility of Transforming the Red Planet to Support a Biosphere
Benjamin Kanda

www.bis-space.com

Journal of the British Interplanetary Society

2021 covers V74.2, V74.4 and V74.5

Recent Interstellar papers in JBIS

V74 #2 Feb 2021			
Defining Intelligence-Favouring Galactic Parameters for targeted SETI searches	Gary S Robertshaw	Innovation Centre, York Science Park, UK	The dark matter (DM) dense galactic mid-plane (GMP) may cause cyclical extinction events (CEEs) on transiting life-bearing planets. This may foster the emergence of intelligent life. Robertshaw hypothesises that the probability of intelligent life emerging is proportional to the number of GMP transits concluding that the emergence of intelligent life is rare, cyclical and confined to specific host stars. Observations of signal beacons from specific types of stars could provide indirect evidence of alien transmissions.
Strategies for the Detection of ET Probes within our own Solar System	John Gertz	Zorro Productions, Berkeley, CA	Are ETs more likely send physical probes to our Solar System to communicate with Earth rather than to communicate from afar? An intentional hunt for those probes would sacrifice SETI sensitivity in favour of a widened field-of-view. The paper suggests strategies to detect local ET probes.
The Wormship: A Dark Energy Ramjet – Engineering, SETI Detectability, and Implications for Cosmic Expansion	Stephen Baxter	UK, contact via agent Selectric Artists, USA	Baxter suggests a tentative dark energy ramjet design, the Wormship. See BIS West Midlands talk 20 November, The Wormship: A Dark Energy Ramjet announced elsewhere in this Interstellar News.
Exotic Fluids Matching the Stress-Energy Tensor of Alcubierre Warp Drive Spacetimes	Willie Béatrix-Drouhet	Paris	Seeking insights into the source of the Alcubierre warp drive, this paper looks for an orthogonal basis from the metric expression finding that exotic fluids can produce the same stress-energy tensor as the Alcubierre warp drive. Some configurations exhibit non-exotic equations of state for warp velocities smaller than 0.004c and seem able to sustain warp velocities up to 2,200c with exotic equations of state.
How Many Alien Probes Could Have Come From Stars Passing By Earth?	James Benford	Microwave Sciences, CA, USA	The paper tells us that about two stars per million years come within a light year of our solar system and a passing ET civilisation, seeing our ecosystem, would send probes to investigate. The estimated probe frequency from passing stars, and their current locations, suggests close inspection of bodies at the Moon and the Earth Trojans in a Search for Extraterrestrial Artefacts (SETA).

In JBIS V74 #4 Apr 2021 Schwartz et al asks *What do we need to ask before Settling Space?* Advocating a "humanitarian review" of proposals, examining the cultural and ethical questions raised by five rationales/objectives for settlement (long-term human survival, resources, scientific knowledge, adventure and spiritual insights) and asking who will participate - arguing for thorough scrutiny of cultural and ethical questions during all phases of settlement.

V74 #5 May 2021			
Genetic Evolution of a Multi-Generational Population in the context of interstellar space travel	Frédéric Marin, Camille Beluffi & Frédéric Fischer	Université de Strasbourg, CASC4DE Strasbourg, Université de Strasbourg	Updating the agent based Monte Carlo code HERITAGE simulating human evolution within restrictive environments such as interstellar, sub-light speed spacecraft to include effects of population genetics incorporating a simplified representative model of the human genome, each individual with his/her own diploid genome. Mimicking gamete production (sperm and eggs), simulating meiosis and mutation of the genetic information from cosmic ray bombardments. A second paper will demonstrate how genetic patrimony of multi-generational crews can be affected by genetic drift and mutations and demonstrating that Hardy-Weinberg equilibrium[1] is reached for starting crews >100 people with larger departing crews (500) showing more stable equilibria over time.
Multi-Perceptual Modalities Message Delivery Module:MAILbox	Suchetan Mummigatti	Cranfield University UK	Updating the idea of the Voyager Golden Records and Pioneer Plaque intended to carry basic information about humanity and planet Earth insights from astrolingusitics, astrosociology, astronautics, and astrobiology, this paper considers the design of a message delivery module: *Messaging All Intelligent Lifeforms box (MAILbox)* incorporating perceptual modalities avoiding assumptions that the species has similar senses to humans and spaceflight capability while not appearing intimidating, provocative, or misleading about humanity and the Earth.
From the Spacex Starlink Megaconstellation to the Search for Type-I Civilizations	Z N Osmanov	University of Tbilisi, Georgia	Extrapolating from the SpaceX's Starlink satellites to building planetary megastructures (solid objects or a web of satellites) by Type-I civilizations and the consequent detection of their techno-signatures. Showing that the Very Large Telescope Interferometer (VLTI) can potentially observe the emission patterns.
Was the WOW! signal due to power beaming leakage?	James Benford	Microwave Sciences, CA, USA	The Wow Signal, 1977, might credibly have been leakage from an interstellar power beam, perhaps from launch of an interstellar probe, explaining the power density, duration and frequency - and why the Wow source has not been observed again, Such power beams would be visible over interstellar distances but transient and non-repeating. All-sky surveys in both the microwave and laser bands might detect more power beam leakages.

[1] https://en.wikipedia.org/wiki/Hardy%E2%80%93Weinberg_principle

News Feature: The 10 parsec sample in the Gaia era

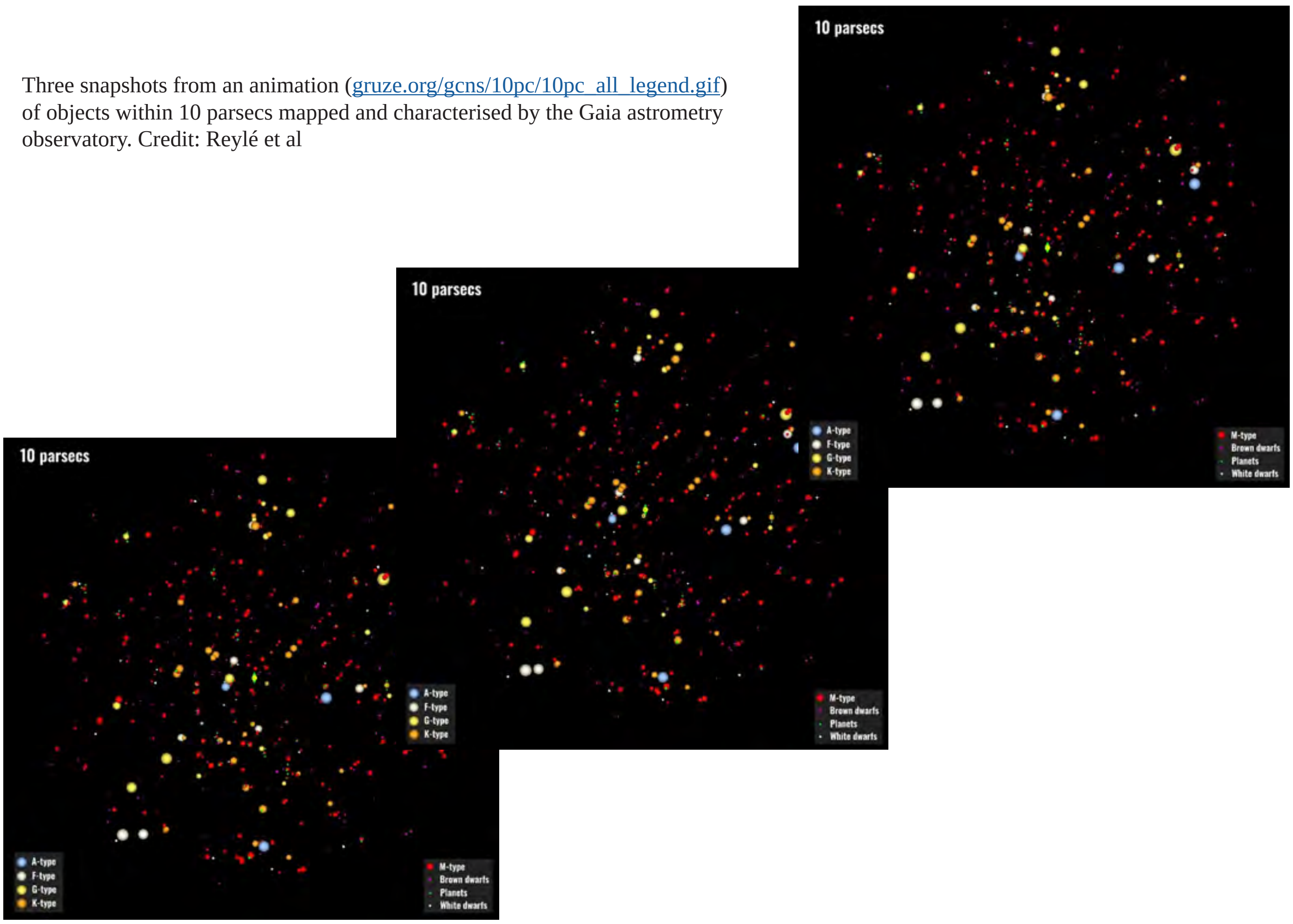
John I Davies

The Gaia astrometry observatory is a dual-telescope vehicle orbiting the Earth-Sun Lagrange 2 position (L2) which it will soon (we hope!) share with the James Webb Space Telescope. L2 is a favourite spot for astronomical missions and Gaia has mapped our interstellar neighbourhood to unprecedented accuracy. Here we introduce a recently organised set of results and a paper analysing them.

A recent paper, Reylé et al, *The 10 parsec sample in the Gaia era* [1] describes a nearer subset of the objects Gaia has found. A team including the lead author of the paper, Celine Reylé, has produced a corresponding online database of this subset [2]. This data is likely to prove a treasure trove for a significant proportion of Principium readers - astronomers both professional and amateur. A team including Marshall Eubanks and his colleagues are seeking collaborators to further refine this data. If you have time and expertise then contact John.Davies@i4is.org who can put you in touch.

And, of course, any initial exploration of nearby star systems is likely to be to the systems in this catalogue - see the log-log diagram later in this report.

Reylé et al, have also published data and some illustrative images of the results [3]. Here is a sample of them. We'll be reporting progress by Marshall and his colleagues in subsequent issues of Principium.

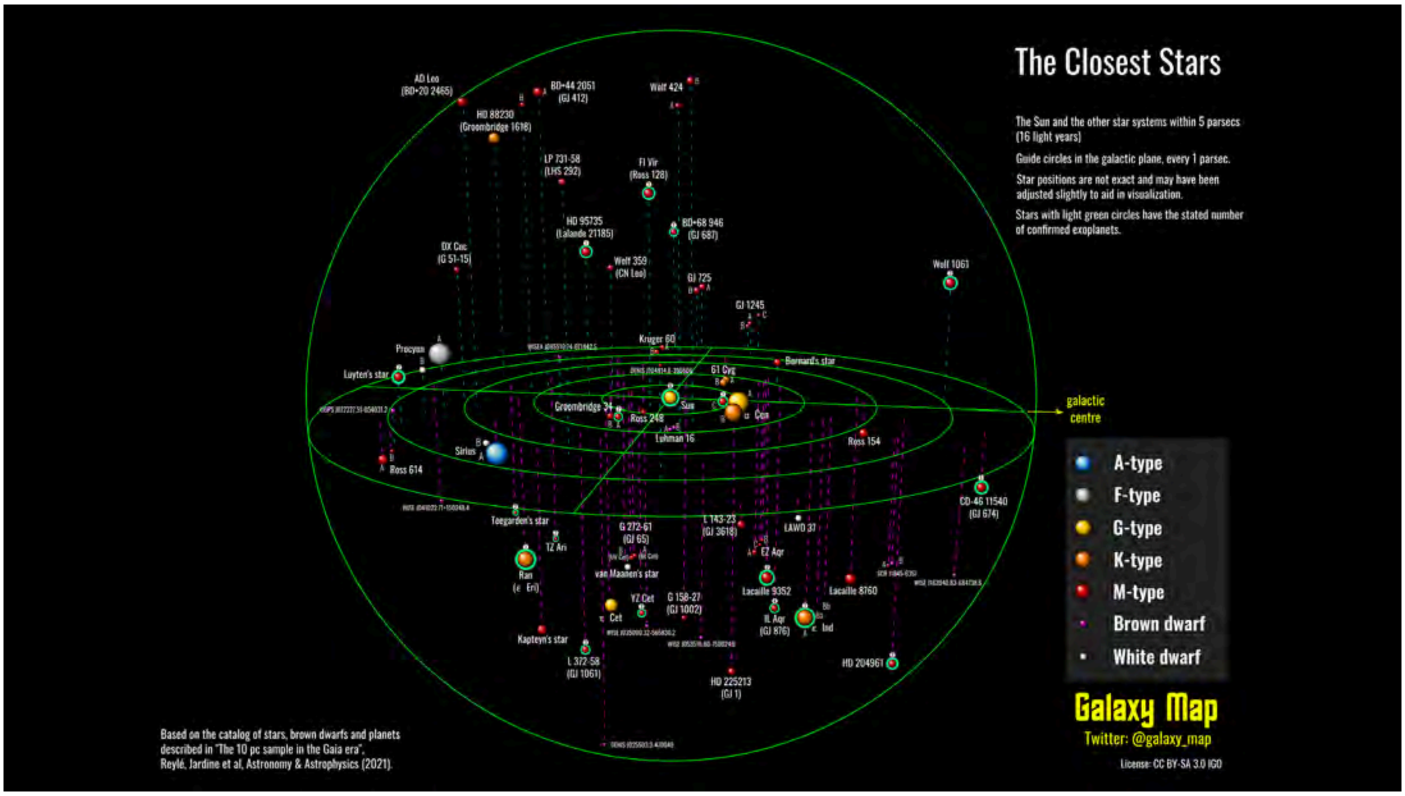


Three snapshots from an animation (gruze.org/gcns/10pc/10pc_all_legend.gif) of objects within 10 parsecs mapped and characterised by the Gaia astrometry observatory. Credit: Reylé et al

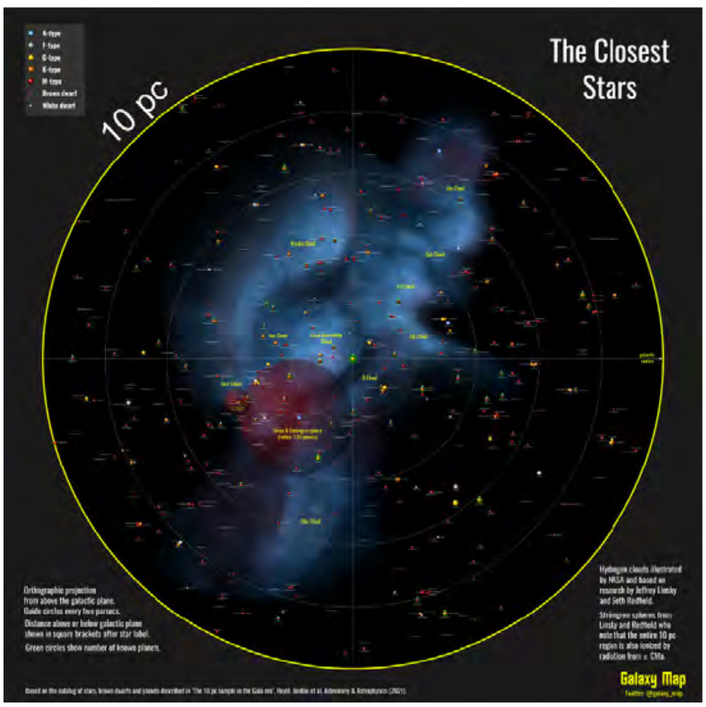
[1] *The 10 parsec sample in the Gaia era*, for epublication in Astronomy & Astrophysics, gucds.inaf.it/GCNS/The10pcSample/The_10_parsec_sample_in_the_Gaia_era.pdf

[2] gucds.inaf.it/GCNS/The10pcSample/

[3] gruze.org/gcns/10pc/resources

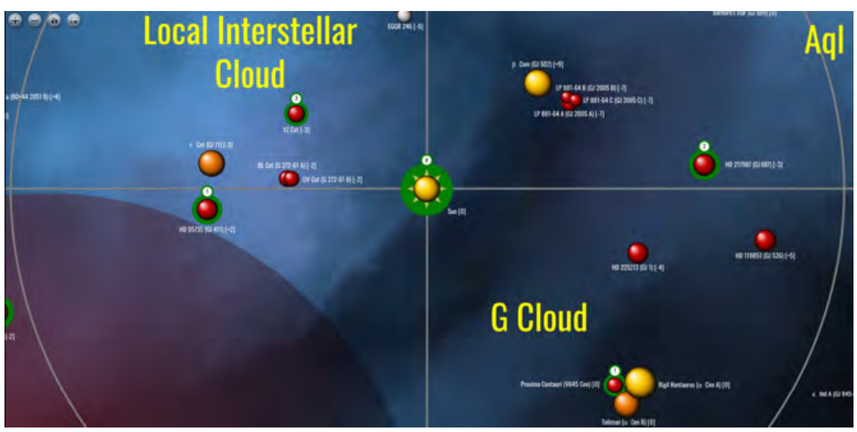


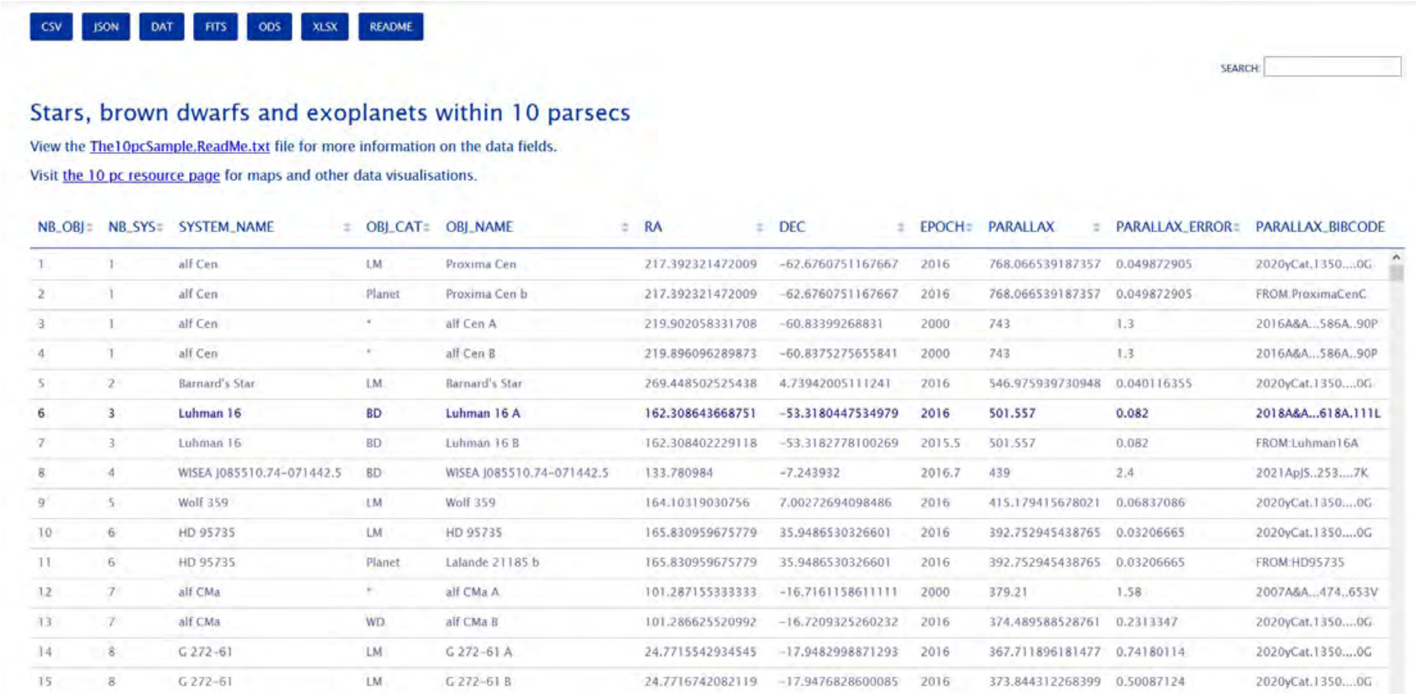
All star systems within 5 parsecs. Credit: Reylé et al gruze.org/gcns/10pc/resources



Two snapshots from a zoomable top down 10 parsecs map. Credit: Reylé et al gruze.org/galaxymap/10pc/

Ten parsecs is about 32 light years or 2 million AU.





CSV JSON DAT FITS ODS XLSX README

SEARCH:

Stars, brown dwarfs and exoplanets within 10 parsecs

View the The10pcSample.ReadMe.txt file for more information on the data fields.

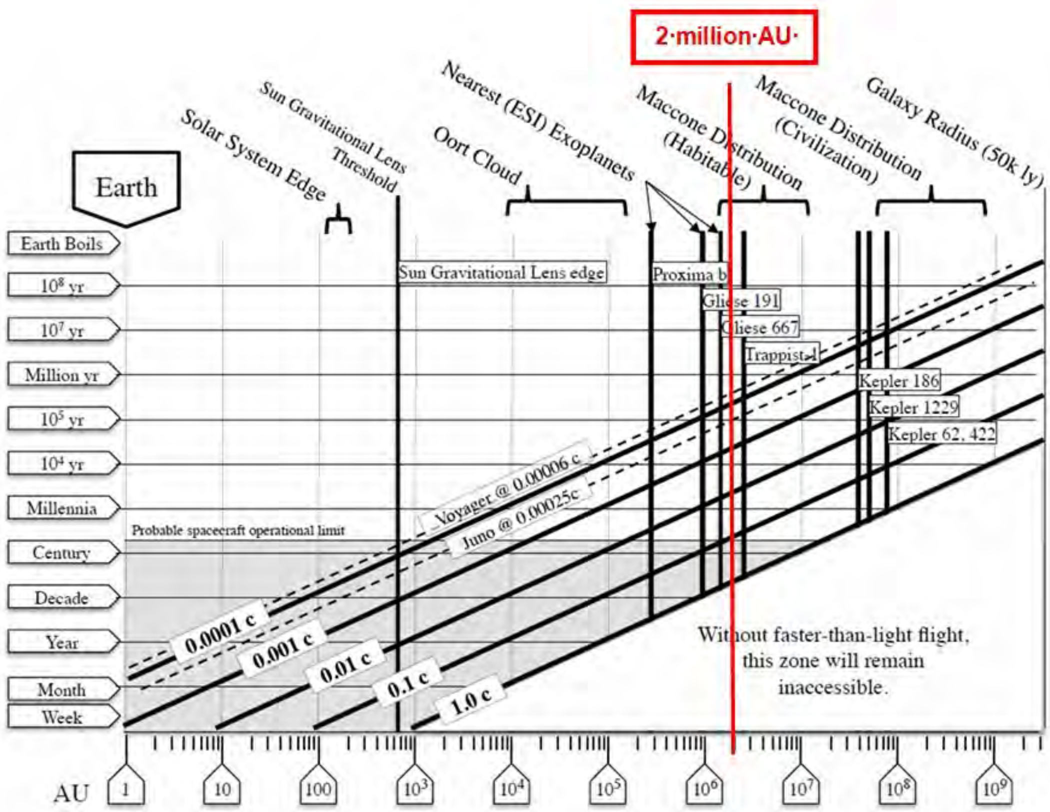
Visit the 10 pc resource page for maps and other data visualisations.

NB_OBJ	NB_SYS	SYSTEM_NAME	OBJ_CAT	OBJ_NAME	RA	DEC	EPOCH	PARALLAX	PARALLAX_ERROR	PARALLAX_BIBCODE
1	1	alf Cen	LM	Proxima Cen	217.392321472009	-62.6760751167667	2016	768.066539187357	0.049872905	2020yCat.1350....0G
2	1	alf Cen	Planet	Proxima Cen b	217.392321472009	-62.6760751167667	2016	768.066539187357	0.049872905	FROM:ProximaCenC
3	1	alf Cen	*	alf Cen A	219.902058331708	-60.83399268831	2000	743	1.3	2016A&A...586A..90P
4	1	alf Cen	*	alf Cen B	219.896096289873	-60.8375275655841	2000	743	1.3	2016A&A...586A..90P
5	2	Barnard's Star	LM	Barnard's Star	269.448502525438	4.73942005111241	2016	546.975939730948	0.040116355	2020yCat.1350....0G
6	**3**	**Luhman 16**	**BD**	**Luhman 16 A**	**162.308643668751**	**-53.3180447534979**	**2016**	**501.557**	**0.082**	**2018A&A...618A.111L**
7	3	Luhman 16	BD	Luhman 16 B	162.308402229118	-53.3182778100269	2015.5	501.557	0.082	FROM:Luhman16A
8	4	WISEA J085510.74-071442.5	BD	WISEA J085510.74-071442.5	133.780984	-7.243932	2016.7	439	2.4	2021ApJS..253....7K
9	5	Wolf 359	LM	Wolf 359	164.10319030756	7.00272694098486	2016	415.179415678021	0.06837086	2020yCat.1350....0G
10	6	HD 95735	LM	HD 95735	165.830959675779	35.9486530326601	2016	392.752945438765	0.03206665	2020yCat.1350....0G
11	6	HD 95735	Planet	Lalande 21185 b	165.830959675779	35.9486530326601	2016	392.752945438765	0.03206665	FROM:HD95735
12	7	alf CMa	*	alf CMa A	101.287155333333	-16.7161158611111	2000	379.21	1.58	2007A&A...474..653V
13	7	alf CMa	WD	alf CMa B	101.286625520992	-16.7209325260232	2016	374.489588528761	0.2313347	2020yCat.1350....0G
14	8	G 272-61	LM	G 272-61 A	24.7715542934545	-17.9482998871293	2016	367.711896181477	0.74180114	2020yCat.1350....0G
15	8	G 272-61	LM	G 272-61 B	24.7716742082119	-17.9476828600085	2016	373.844312268399	0.50087124	2020yCat.1350....0G

snapshot of - Searchable and sortable data table downloadable in different formats https://gruze.org/10pc/

Accessibility of the 10 parsec sphere

The 10 parsec sphere = 2 million AU (about 206,000 AU per parsec)



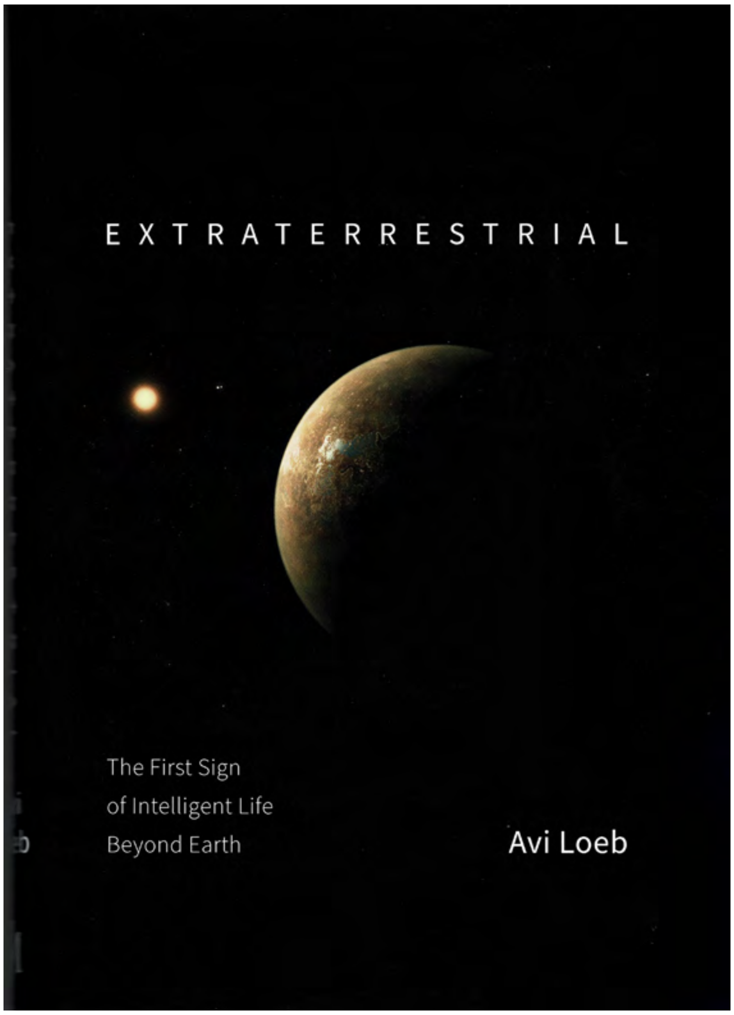
How far can we reach in the 10 parsec sphere? To appreciate the distances and times involved we need to think in powers of ten.

This log-log diagram is adapted from the "Maccone Distribution" in C Maccone, *The Statistical Drake Equation*, 59th International Astronautical Congress, Glasgow, 2008.

Book Review: *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth*, Avi Loeb

Patrick Mahon

Professor Avi Loeb's views on the possible nature of 1I/'Oumuamua have been controversial for some time and his recent book has both stoked controversy and set out his views in detail, Here Principium Deputy Editor Patrick Mahon gives us his analysis of the book and the views it articulates.



Credit: UK Publisher: John Murray Press, 2021

Regular readers of Principium may recall the excitement, some three and a half years ago, as the scientific community announced the first ever detection of an interstellar object flying through our solar system [1]. What became known as 1I/'Oumuamua made worldwide news in October 2017 when astronomers announced its unusual nature: it appeared to be five to ten times as long as it was wide, famously being portrayed in an artist's impression as a long, thin cigar-like shape, not unlike the alien spacecraft portrayed in Arthur C Clarke's 1973 novel *Rendezvous with Rama*. This prompted me to speculate on the apparent parallels between 'Oumuamua and Rama in a review of that novel published in Principium issue 21 [2], while i4is colleagues quickly created Project Lyra, which explores the possibilities for sending a scientific probe to 'Oumuamua, despite its high velocity as it leaves our solar system [3].

Someone else who found the nature of 'Oumuamua particularly intriguing is Professor Abraham (Avi) Loeb of the Centre for Astrophysics at the University of Harvard. Loeb is a decorated scientist with five books and over 800 published papers to his credit, as well as being a member of the President's Council of Advisors on Science and Technology. Of most relevance to this story, however, is his role as Chair of the Advisory Committee to Breakthrough Starshot, the $100 million programme to send tiny laser sail-powered probes to Alpha Centauri at one-fifth of the speed of light.

In the year following the detection of 'Oumuamua, Loeb read the scientific papers which set out the observational data that had been collected over a brief 11 day period between the first observation and the point at which the object became too faint to detect. Like many others, he noted the various anomalies which marked 'Oumuamua out as unusual. But while most other professional astrophysicists eventually concluded that, though unusual, 'Oumuamua was an entirely natural asteroid or comet that just happened to have come from outside our solar system, Loeb reached a different conclusion.

In *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth* [4], Loeb explains how he came to a profound difference of view with the vast majority of his colleagues in the scientific community, and why he thinks it is so important that all of us consider seriously not just the radical hypothesis he puts forward, but the implications that follow from it.

In summary, Loeb's argument goes like this: there is general agreement in the astrophysics community that the observations made of 'Oumuamua display several unusual features. This makes it unlike 2I/Borisov, our second interstellar visitor, which travelled through the solar system in 2019. Borisov is universally agreed to be interstellar in origin, but otherwise looks very similar to a normal comet [5]. 'Oumuamua doesn't. Loeb highlights four of 'Oumuamua's features in particular:

• The aspect ratio (the ratio of length to width) was high, indicating that the object was either shaped like a cigar or, alternately, a pancake;

• Even when relatively close to the Sun, it was cold (as the Spitzer Space telescope could not detect it in the infrared), so must be small, perhaps only 100 metres long by 10 metres in width;

• It was very bright – up to ten times brighter than a typical solar system asteroid or comet – suggesting something that was highly reflective; and

• As it travelled through the solar system, its trajectory deviated slightly from the hyperbolic orbit that would have been expected if it was purely moving under the influence of the Sun's gravity. Instead, there was a small excess acceleration which diminished with the square of the object's distance from the Sun.

It is this fourth feature that Loeb found most intriguing. The reasons why are two-fold. On the one hand, the various explanations put forward by his colleagues for this deviation from the expected trajectory seemed to get ever more convoluted over time. The first explanation was outgassing from the object as the Sun heated it up, as you'd expect if it were a comet. Yet no outgassing was detected, and Loeb calculated that to achieve the excess acceleration that had been measured, the object would have had to lose about 10% of its mass in outgassing, which surely would have been observed? Then it was proposed that 'Oumuamua was made of pure hydrogen ice, something never seen before. Next, the suggestion was made that the object had broken up when it got to its closest approach to the Sun, changing its trajectory as it retreated. But as far as Loeb could see, none of these theories seemed to fit all of the observational evidence.

On the other hand, Loeb and his postdoctoral fellow Shmuel Bialy did some calculations, based on Loeb's work with Breakthrough Starshot, and found that the excess acceleration could be reproduced if 'Oumuamua was a highly reflective, extremely thin disc-like object which was reflecting solar radiation. In other words, something that looked an awful lot like a solar sail. They did not conclude that it had to be artificial, but it was difficult to conceive of any natural mechanism that would produce an object with the required characteristics of high reflectivity and extreme thinness. Thus, the paper they published in late 2018 included the phrase 'one possibility is that 'Oumuamua is a lightsail, floating in interstellar space as debris from advanced technological equipment' [6].

Clearly, Loeb's hypothesis is extremely exotic. And many other scientists insist that they have been able to generate natural explanations for all of the anomalies that Loeb highlighted. Indeed, Emeritus Professor Alan Aylward gave an extended explanation of the 'case for the defence' in the last issue of Principium [7]. If you haven't yet read it, I'd urge you to do so.

However, Loeb's argument, on my reading, is not that he thinks he's definitely right and everyone else is definitely wrong. Rather, he thinks that the evidence is sufficiently indefinite that both hypotheses remain possible. And in his view, those putting forward a 'natural' explanation are having to go to extreme lengths to account for all the anomalies simultaneously. He believes that Occam's Razor favours his simpler alternative hypothesis, if you're only able to get over what he sees as an unhelpful conservatism within the mainstream of career scientists, which biases them against any explanation that requires an, admittedly huge, leap of the imagination.

Carl Sagan's phrase 'extraordinary claims require extraordinary evidence' is often raised at this point, the implication being that any hypothesis that depends on the existence of an intelligent alien civilisation (the creators of the lightsail that Loeb has hypothesized) needs to be able to produce a 'smoking gun' if it's to be taken seriously.

Loeb's response to this is to note that different standards of proof seem to apply to several other areas of physics, including string theory and the theory of the quantum multiverse, where physical proof appears unlikely if not impossible to obtain. Yet this does not seem to prevent work in these areas. On the other hand, he points to historical examples where radical hypotheses were initially rejected by the mainstream, yet later turned out to be correct. Examples include Galileo's observations of Jupiter's moons in 1610, which he used as evidence that the Earth was not the centre of the Universe, and for which he was put under house arrest by the Catholic church. More recently, Einstein's 1905 Theory of Special Relativity was rejected in the UK physics community for several years because it directly contradicted the existence of the ether, the hypothetical medium that British scientists believed at that time to fill all of space.

Much of the second half of Loeb's book is taken up with an exploration of what might happen if more people – not just scientists, but the general public too – were to take his hypothesis seriously. So just for a second, let's suppose that 'Oumuamua really is an alien solar sail. How might that change what we think and what we do?

For starters, we would surely want to invest more in the technologies that would allow us to take a closer look at any further interstellar interlopers that enter our solar system in the future, following on from 'Oumuamua and Borisov. The team at i4is certainly wouldn't disagree with this, as our work on Project Lyra attests.

Equally, accepting 'Oumuamua as potential proof that life has emerged elsewhere than on the planet Earth would surely attract a lot more money and attention to the study of exoplanets and the science of astrobiology. Indeed, we might see more money made available for missions to the various places in our own solar system where primitive life may exist, including Jupiter's moon Europa and Saturn's moon Enceladus.

More radically, projects like Breakthrough Starshot and our own Project Dragonfly might be accelerated, so that we could find out whether the exoplanet orbiting the nearest star to our own Sun, Proxima Centauri, harbours life, not in a few hundred years, but in the next few decades.

So that's Avi Loeb's argument. Does he make it well?

To be honest, when I started reading this book, I was ready to side with the scientific mainstream, who have labelled Loeb as yet another formerly respectable physicist who is suffering from a very public mid-life crisis. I'd rather got that impression from the discussion of Loeb's position in the popular science media. But that's not how he comes across in this book.

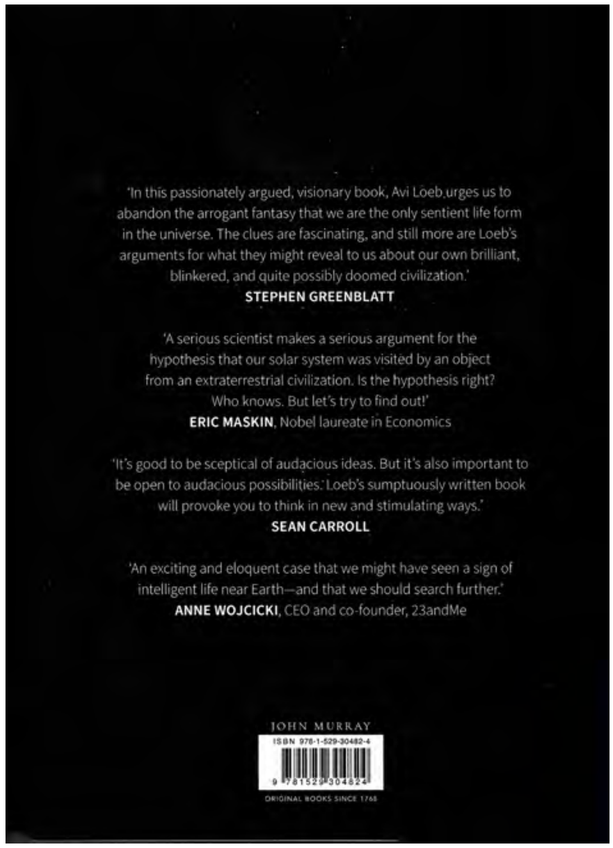
There are some points I could find fault with here. On several occasions, the book's narrative over-simplifies the conflict between Loeb's view and the more mainstream alternative. I don't know whether Loeb wrote it that way originally, or whether the publisher, wanting to maximise the book's potential audience, has taken out some of the subtleties.

On the right - Avi Loeb, Frank B Baird Jr Professor of Science, Harvard University - at the public announcement of Breakthrough Starshot , April 12, 2016 with Yuri Milner, Stephen Hawking, and Freeman Dyson.
Credit: Harvard University lweb.cfa.harvard.edu/~loeb/Loeb_Starshot.pdf

Taken as a whole, though, the book suggests an author who is calm, thoughtful, reflective and self-aware. He knows that the hypothesis he's putting forwards is radical. He just thinks that it explains the data better than the rival ideas that have been proposed. And on that basis, he thinks that the hypothesis – and its implications – are worthy of serious consideration, even though he's well aware that saying so in public is likely to result in criticism from many of his peers, due to the inherent conservatism of the scientific establishment.

I have a lot of sympathy with this aspect of Loeb's argument. As someone who has worked in and around large bureaucracies for most of my professional life, I'm well aware of the difference between the open and nuanced discussions which fellow professionals may be prepared to have in private, and the carefully worded and conventional statements that they and their institutions are prepared to have ascribed to them on the record.

Do I believe, after reading this book, that 'Oumuamua is an alien solar sail? Honestly, I don't know. I still think it's unlikely. But Loeb is right to point out that our current understanding of planetary formation, revolutionised by the extraordinary variety of exoplanets that have been discovered in the last quarter of a century, suggests that potentially habitable planets may be common across our galaxy. Even if only a tiny proportion of these turned out to be able to support life, that's still lots of opportunities for non-human lifeforms to evolve. Perhaps one (or more) such species has advanced as far as humanity, or even beyond. Is that inconceivable? Surely not.



Rear cover with publisher's quoted reviews

If you're reading this review, then you are presumably interested in what is to be found outside our solar system. We're lucky enough to live at a time when our observational equipment is good enough to detect an object flying through our solar system from outside it, for the very first time. Perhaps 'Oumuamua is just an asteroid or a comet of a rather unusual kind. Or perhaps it's the first piece of evidence to cross our path, demonstrating that our solar system is not the only source of life in the universe.

If that last sentence intrigues you, then I'd urge you to read Avi Loeb's book. You probably won't agree with everything he says – I certainly didn't – but I found him a credible author with a reasonable story to tell. And while the implications of his hypothesis are revolutionary, I think they are ones that many Principium readers will find worthy of serious consideration.

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[2] Review of Rendezvous with Rama, Principium issue 21, pp.30-32 (May 2018).

[3] 'Project Lyra: Sending a Spacecraft to 1I/'Oumuamua (former A/2017 U1), the Interstellar Asteroid', A.M. Hein et al., Acta Astronautica 161, pp. 552-561 (Aug 2019). arxiv.org/abs/1711.03155

[4] Extraterrestrial: The First Sign of Intelligent Life Beyond Earth, Avi Loeb (John Murray, London, 2021).

[5] 'Comet 2I/Borisov', NASA Solar System Exploration, April 2020. solarsystem.nasa.gov/asteroids-comets-and-meteors/comets/2I-Borisov/in-depth/

[6] 'Could solar radiation pressure explain 'Oumuamua's peculiar acceleration?', S. Bialy and A. Loeb, Astrophysical Journal Letters (12 Nov 2018). iopscience.iop.org/article/10.3847/2041-8213/aaeda8/pdf

[7] 'An interstellar visitor: sorting the fact from the speculation', Alan Aylward, Principium issue 32, pp.53-59 (Feb 2021).

News Feature: The 2021 ISU Masters Elective and Masters Projects

John I Davies

This year the International Space University and i4is have again offered a two week interstellar elective to students taking Masters of Space Studies (MSS) at ISU. A number of ISU students have also completed substantial studies on interstellar topics with the support of i4is experts. Here we summarise this year's work.

Interstellar Elective

As before, the elective consisted of one week of presentations by i4is and other experts as introduction to substantial assignment course work on this year's topic, Worldships -

- Professor Chris **Welch**
- Rob **Swinney**
- John **Davies**
- Dr Andreas **Hein**
- Olivia **Borgue**
- Michael **Madsen**
- Dr Frédéric **Marin**
- Michel **Lamontagne**
- Simone **Caroti**
- Dr Dan **Fries**

Presentations and videos are available in the members area of the i4is website. The programme -

	Monday 26 April	Tuesday 27 April	Wednesday 28 April	Thursday 29 April	Friday 30 April
9:00 to 10:00	M8-ISR-L01 Introduction to Elective + Interstellar Studies	M8-ISR-L05 Precursor Missions + Destinations	M8-ISR-L09 Advanced Propulsion Systems 1	M8-ISR-L13 The Case for Interstellar	M8-ISR-L17 Our Interstellar Future
	Welch/Swinney	Swinney	Swinney	Welch	Davies
10:15 to 11:15	M8-ISR-L02 Introduction to Worldships	M8-ISR-L06 Worldship Systems	M8-ISR-L10 Advanced Propulsion Systems 2	M8-ISR-L14 Worldship Documentary	Group Meeting
	Hein	Hein	Borgue	Madsen	
11:30 to 12:30	M8-ISR-L03 Introduction to Assignment	M8-ISR-L07 Artificial Intelligence for Worldships	M8-ISR-L11 Worldship Population Dynamics	M8-ISR-L15 Interstellar Missions and Concepts	Assignment work
	Hein	Davies	Marin	Swinney	
14:00 to 15:00	M8-ISR-L04 Worldship Design 1	M8-ISR-L08 Worldship Design 2	M8-ISR-L12 Worldships in Science Fiction	M8-ISR-L16 Advanced Propulsion Systems 3	Assignment work
	Lamontagne	Lamontagne	Caroti	Fries	

Assignment work took up the remainder of each day in this first and the whole of the following week with students presenting their results on Thursday 6 May. We'll be reporting on the results of the course work in the next issue of Principium.

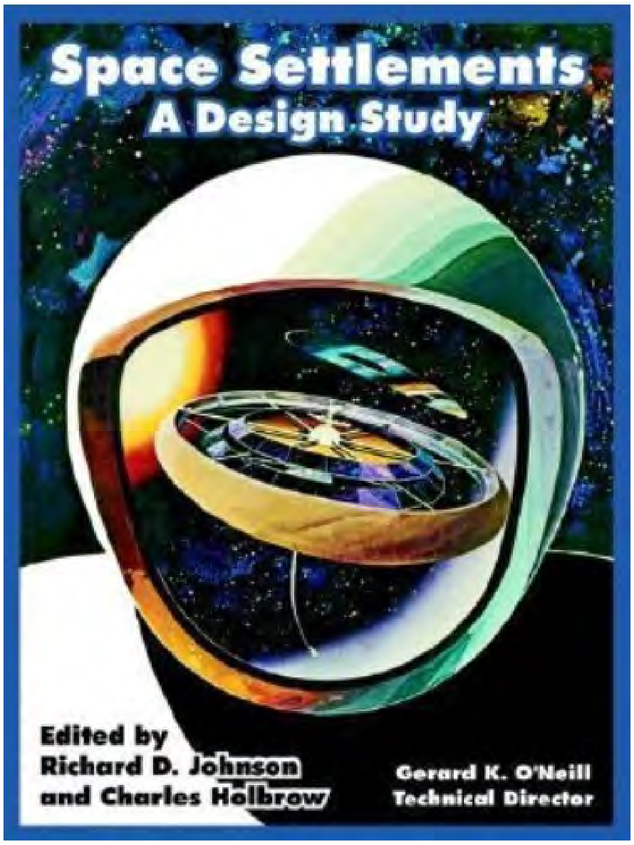
Studies on Interstellar Topics

The topics suggested for substantial investigation by MSS students were developed by Dr Andreas Hein (Initiative for Interstellar Studies). Professor Chris Welch (International Space University) and Rob Swinney, i4is Director of Education.

All of these are likely to be entered for peer-reviewed publication and we will, of course, report further when they are published.

McKendree world ship

A McKendree cylinder is an upscaled version of an O'Neill colony with a length of 4,600 km and a radius of 460 km, introduced by Tom McKendree. Its internal surface area is roughly the size of Russia. It is, therefore, considerably larger than the largest O'Neill colonies (length ~30 km) and world ship habitats (~200 km). The goal of this project is to assess, if a world ship based on a McKendree cylinder could be built (eg required propellant mass, propulsion system) and if yes, to propose a high-level conceptual design for a McKendree world ship.



Cover of *Space Settlements: A Design Study*, Richard D Johnson, Gerard K O'Neill, University Press of the Pacific, 2004. Report of a 10-week program in engineering systems design held at Stanford University and the Ames Research Center of the National Aeronautics and Space Administration during the summer of 1975. Cited by McKendree.

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Bond, A, & Martin, A R (1984). World ships-an assessment of the engineering feasibility. Journal of the British Interplanetary Society, 37, 254.

Do we need space settlements as precursors for world ships?

World ships contain large habitats in which its inhabitants need to survive over centuries. In order to minimize risk for the inhabitants, it may be expected that such habitats have already been tested over extensive durations within our solar system. This has been proposed, for example, by Gerard K O'Neill. A more recent assessment on what can and cannot be proven via a space habitat in our solar system regarding a world ship has been provided by Hein et al. (2012). The objective of this project is to revisit this assessment and to extend it to planetary surface settlements, to provide a wider picture of how space habitat heritage can be accumulated within our solar system.

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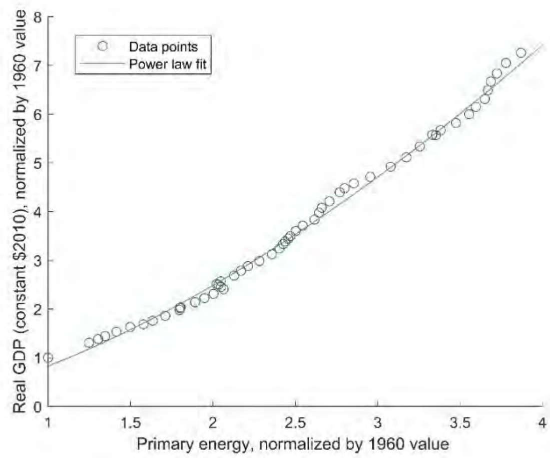
O'Neill, G K (1977). The High Frontier: Human colonies in space.

Economic preconditions for building world ships

A world ship requires an economy which is much larger than the currently existing one. At current growth rates of global wealth, expressed via the Gross Domestic Product (GDP), a world ship might become feasible in the year 2300 to the year 3000. However, GDP growth over such extended periods are expected to be problematic, due to energy limits (Hein & Rudelle, 2020) and their environmental impact in general. The objective of this paper is to assess various scenarios, for example, from Hein & Rudelle (2020) and their implications for the economic feasibility for world ships. An interesting conclusion from this research might be the first quantitative demonstration that world ship-type projects can only be realized via an in-space economy.



Data points for normalized world primary energy generation versus constant $2010 GDP from 1960 to 2015 and power law fit. Figure 1 from Hein/Rudelle (2020), Energy Limits to the Gross Domestic Product on Earth

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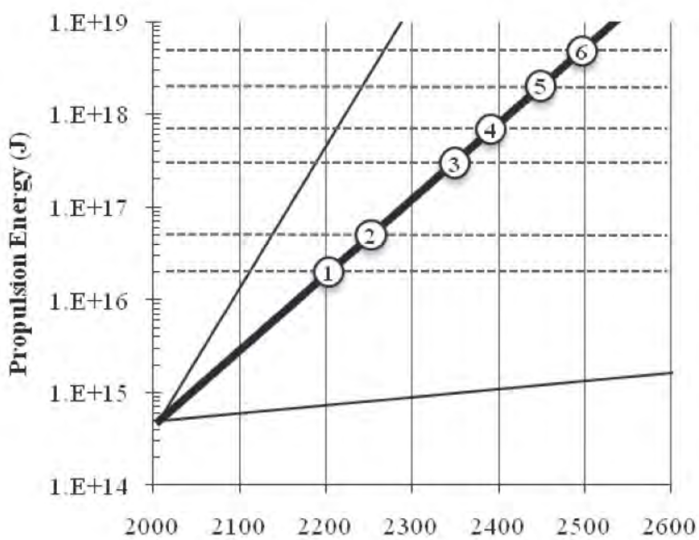


Correlation between growing propulsion energy availability (bold line) and energy thresholds (dashed horizontal lines). The narrower sloped lines represent ±1 standard deviations of growth. Based on the data shown in Tables 1, 2 and 4 the numbered intersections refer to these events: 1. Colony ship (10^7 kg) kinetic energy threshold reached, 2. Propulsion energy available when humanity achieves the equivalent of 100% of sunlight on the Moon (5 x 10^{16} J), 3. Centauri probe (10^3 kg) kinetic energy threshold reached, 4. Propulsion energy available when Kardashev Type I status attained (7 x 10^{17} J), 5. Centauri probe (10^3 kg) rocket energy threshold reached, 6. Colony ship (10^7 kg) rocket energy threshold reached. Figure 1 from Millis(2010)

Manufacturing infrastructure for world ships

Bond and Martin (1984) propose various manufacturing technologies for constructing a world ship. However, the infrastructure for manufacturing a world ship will be enormous and includes an entire supply chain, starting from resource extraction, processing, to component manufacturing, and assembly. The objective of this project is to map out the different steps of the infrastructure that is capable of manufacturing a world ship and proposing different technology alternatives for each step. If possible, high-level estimates for the capacities of each step should be provided,

References:

Bond, A, & Martin, A R (1984). World ships-an assessment of the engineering feasibility. Journal of the British Interplanetary Society, 37, 254.

News Feature: The i4is Talk Series - 2020 and 2021

John I Davies

i4is is delivering a series of talks on interstellar topics. Some of these are Open to all and others are for i4is members only.

Members can see past talks via the members' page i4is.org/members/ and the presentations as PDFs at [i4is.org/members/member-events/.](i4is.org/members/member-events/)

Members and non-members can register for future talks by email to [talks@i4is. org](mailto:talks@i4is.org). The talks are -

2021 First Series

26th January — John Davies — The Interstellar Downlink — Open

Example -

6 Conclusions and ongoing

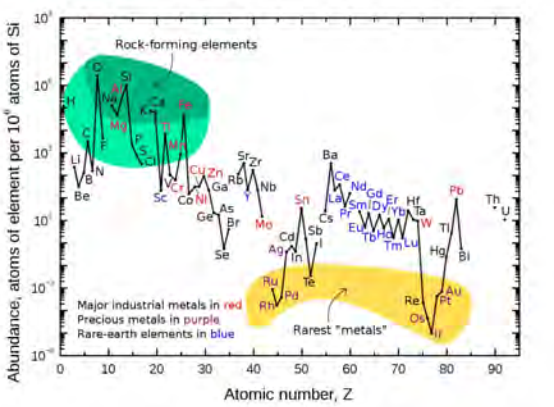
- Distance² is the main problem
- Even more challenging for tiny probes
- RF transmission difficult for tiny probes
- Optical more efficient but major problems with ground-based reception
- Several power source options
- Challenging link budget demands exceptional technology
- If pictures are important then use application-specific FEC?
- The transit time gap for receiver implementation - 4 light years means decades waiting for downlink data from target system

2nd February — Olivia Borgue — Advanced Propulsion 2 (Nuclear etc)

9th February — Adam Hibberd — 'Optimum Interplanetary Trajectory Software', from Interplanetary to Interstellar

16th February — Robert G Kennedy III —Assuring Humanity's Interstellar Mission Capability for Posterity, or, Learning from Bronze Age Mistakes

Example -



23th February — Dan Fries — Interstellar Travel using Einsteinian Physics — Open

2021 Second Series

The next talk series will run weekly from Tuesday 25th May at 8 pm (UK time). If you have previously registered for an earlier talk series, there is no need to do so again. Committed so far -

22nd June: John Davies, Visions of our Interstellar future

29th June: Terry Regan, Modelling Interstellar Spacecraft

2020 Series

The series began in October 2020 -

27th October — Rob Swinney — Introduction to Interstellar Studies

3rd November — Marshall Eubanks — Missions to Interstellar Objects - an i4is Initiative — Open

10th November — Dr Andreas Hein —Worldship Design

17th November — Dan Fries — An Introduction to Advanced Propulsion

24th November — Robert Swinney —Interstellar Precursor Missions

1st December — Patrick Mahon — Science Fiction Interstellar Starships — Open

News Feature: i4is wins major contract in Interstellar Studies

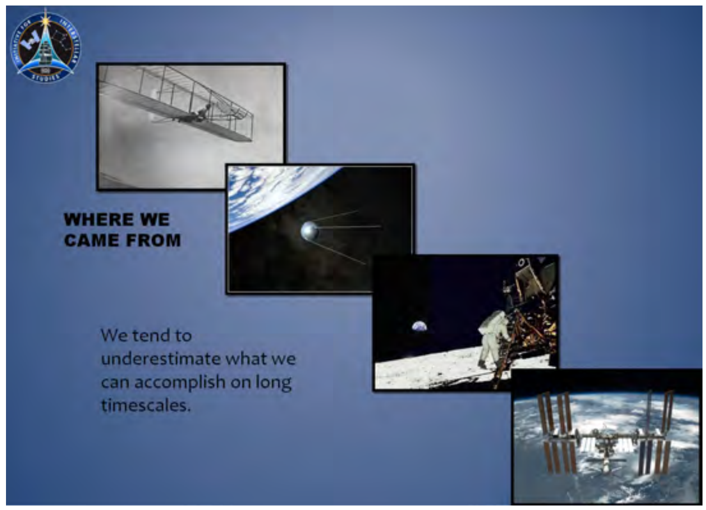
John I Davies

Since your last Principium in February i4is has agreed a highly significant contract for interstellar studies work. This is material for a course for the Limitless Space Institute, *Human exploration of the far solar system and on to the stars.* A poster for the first run of the course follows this news feature.

We hope and believe that this will advance both our subject and the reputation of the Initiative and Institute for Interstellar Studies as one of the leading organisations beating a path for humanity to the stars.

Interstellar Studies Summer Course - Human Exploration of the Far Solar System and on to the Stars

The Initiative for Interstellar Studies (i4is) has agreed to deliver a course package to the Limitless Space Institute (LSI) with the working title - *Human exploration of the far solar system and on to the stars*. The course will provide a fundamental appreciation and basic knowledge of principal subjects. The course will be predominantly, though not exclusively, a STEM-based course targeting freshman/first year university students with a particular interest in the most ambitious opportunities for human exploration of space. The course duration is anticipated to be 1 week. The i4is team will teach a virtual inaugural summer class this year commencing the week of 26 July 2021 (register interest with Janice Campbell at LSI jan@limitlessspace.org). The contract for this was signed on 30th March by Brian Kelly, President, on behalf of the Limitless Space Institute and by Dr Andreas Hein, Executive Director, on behalf of the Initiative for Interstellar Studies.



Humanity came from powered aviation, into space, to the Moon and established a permanent human presence in space in the course of a single century. Imagine our progress towards the stars within the coming one hundred years.

Brian “BK” Kelly, President. LSI. Credit: LSI

Andreas M Hein, Executive Director, i4is

Delivery will be coordinated by Dr Harold White for the Limitless Space Institute and by Robert W Swinney for the Initiative for Interstellar Studies with project management of the i4is team by Tam O'Neill, i4is.

Dr Harold “Sonny” White, Director of Advanced R&D, LSI. Credit: LSI

Robert Swinney, Deputy Director, Chairman Education Academy Committee, i4is

Tam ONeill, Project Manager, i4is

Interstellar Studies Summer Course

Human Exploration of the Far Solar System and on to the Stars
July 26 – 30th, 2021

To be delivered online by the Initiative for Interstellar Studies on behalf of Limitless Space Institute.

The Limitless Space Institute has commissioned the Initiative for Interstellar Studies to create a new course to educate and inspire the next generation to explore and travel beyond our solar system. With new material being developed, it will also incorporate material previously delivered to the International Space University and i4is' own 'Starship Engineer' courses.

The course will provide a fundamental appreciation and basic knowledge of principal subjects, from setting the background and context through to advanced propulsion, systems, concepts, and designs. The course will be predominantly (but not exclusively) a STEM-based course and specifically targeting the level of freshman/first year STEM university students. Attendees will need a suitable background and have a particular interest in the most ambitious opportunities for human exploration of space.

If you would like to know more, you should register your interest with Janice Campbell of LSI at jan@limitlessspace.org.

LIMITLESS SPACE INSTITUTE

www.limitlessspace.org
501.c.3 Non-Profit , Houston, TX

LSI Mission - Inspire and educate next generation to travel beyond solar system and support Research & Development of enabling technologies

www.i4is.org

I4is is a not-for-profit company founded in 2012, incorporated in the UK, but a world wide organisation.
The i4is education team envisage an optimistic future for humans on Earth and in space. The vision is to be a beacon of quality education in society over the next century and more, enabling and directed towards a sustainable space-based future, for exploration beyond the solar system and on towards the stars.

The i4is Members Page

The i4is membership scheme launched in December 2018 and we are now adding new members-only material to the website regularly. This page features currently available content and what is planned. Membership of i4is draws together all who aspire to an interstellar future for humanity. Your contribution, together with the voluntary work of our team and their donation of their own expenses helps us to take the vital early steps toward that goal.

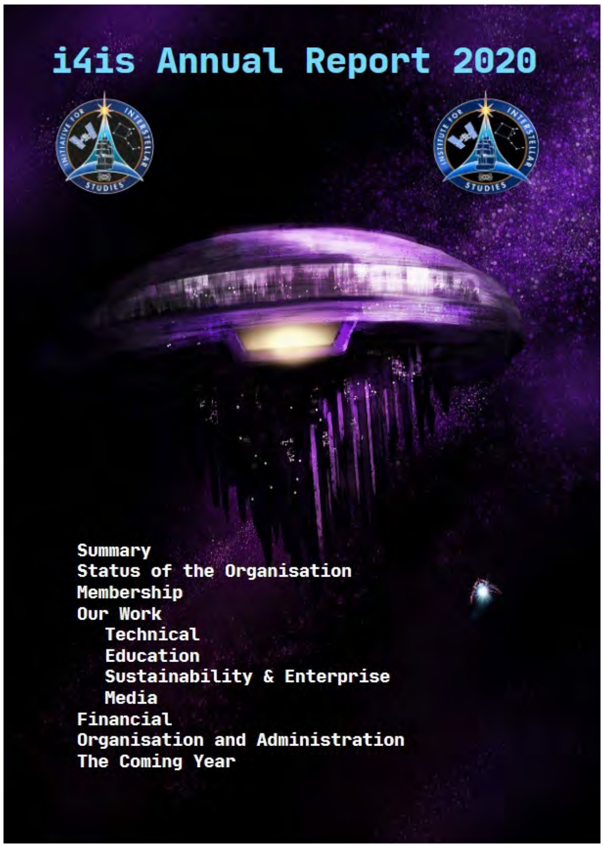
You need to login with your i4is identity to access members' content. If you are not yet a member you can sign up via - i4is.org/membership - or simply find out more about membership. We'll keep you up to date as we add to this content, both in the next issue of Principium and in our members' email newsletter.

Help our Education and Outreach Activities

You will see that we are increasingly reaching out to schools, astronomy societies and other groups. If you would like to think about delivering talks yourself and maybe even promoting them in your neighbourhood city or country then get in touch with Rob (rob.swinney@i4is.org) or John (john.davies:i4is.org) to talk about it. No commitment until you are ready!

2020 Annual Report to members

Our Annual Report to members for the year 2020 was published in our members area in April 2021. This is the second Annual Report to Members of the Initiative and Institute for Interstellar Studies. It reports our work in the past year, 2020. Our first report summarised our earlier work so this, the first report covering a single year, is somewhat shorter at 20 pages. It covers the Status of the Organisation, Membership, Our Work, Financial, Organisation and Administration, The Coming Year and Contacts for all our main activities.



Help us to grow!

Our membership is growing steadily worldwide but we can do better with your help. If you are somewhere where virus restrictions permit then print one or two of our posters from - i4is.org/i4is-membership-posters-and-video/

Or anywhere in the world just tell your friends and colleagues "like" us on social media, contact us with ideas. To members who have been with us for more than one year receive a single-use code that they can share with a friend, giving their friend a One Year Free Trial on their new membership of the Initiative for Interstellar Studies (i4is.org/members/free-trial/). We hope that many of you will take this up especially on behalf of the rising generation in full time education. In subsequent years their student membership will be £5, just over $6 and just under €5.

Just login and go to - i4is.org/members/free-trial/ - you will see -

Share the single-use code with a friend and they can join with a 1 year free trial.

You can either copy the code's link and share it with a friend, or give them the code and tell them to visit i4is.org/free-trial to redeem their free trial. They can sign up with any of the annual membership plans with a one year free trial. They will be charged for subsequent years after the trial period but they can cancel their subscription at any time during the trial period.

Members' Newsletter

i4is members have received two Members Newsletters since our last issue -

Newsletter: Debate — The Case for Interstellar - 27/02/2021

Tuesday 2nd March at 8 pm, as the last item of the current series, we are arranging, for i4is members only, not a talk but a structured debate between the for and the against the case for interstellar.

Videos for most of our previous talks.

New Videos and Presentations in the i4is Members Area!

Video: John Davies: *Concepts and Challenges of Interstellar Probes — How can we do it?* A talk by John Davies to the Loughton Astronomical Society on the 11th February 2021.

Newsletter: Interstellar Studies Summer Course, and Annual Report 2020 - 07/05/2021

Interstellar Studies Summer Course: Human Exploration of the Far Solar System and on to the Stars, The i4is education team announce a new summer course delivered by i4is on behalf of Limitless Space Institute (LSI) from 26th–30th July 2021.

Annual Report 2020. The report discusses all of i4is' activities during 2020, and highlights the vital and valued support that you, our members, provide to i4is.

Members Talk Series #3 The next talk series aimed at members will run weekly from Tuesday 25th May.

i4is talk for German Ministry of the Environment. i4is Director presents prospects of space resources and settlements to German Federal Ministry of the Environment.

Practicalities and Difficulties of a Mission to 'Oumuamua. A new Principium preprint by Adam Hibberd.

Videos and presentations

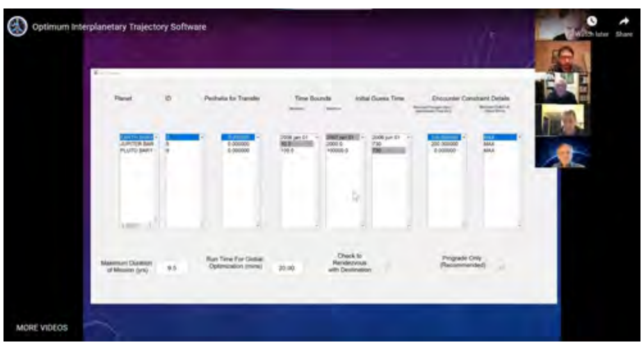
Lots of new videos and presentations - both public and "members only" are listed in our *Become an i4is member* page in this issue.

You can find them all at -

i4is.org/videos/

i4is.org/talks/

Register for future talks via the /talks/ link - both public and "members only" or just email talks@i4is.org.



Olivia explains the Warp Drive equation

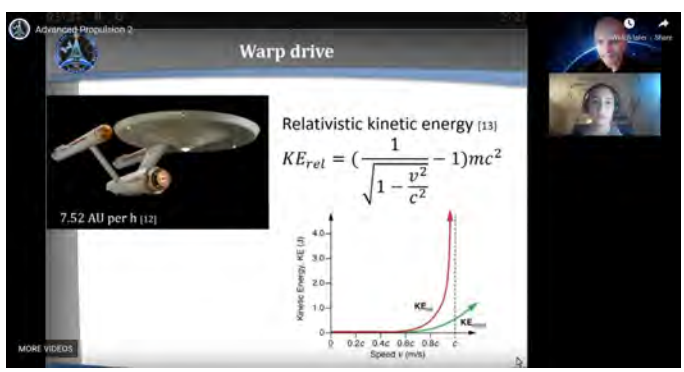
Talk Series: *Advanced Propulsion 2 (Nuclear etc.)*, 2nd February 2021

Presenter: Olivia Borgue

Adam optimises missions to Jupiter and Pluto

Talk Series: *'Optimum Interplanetary Trajectory Software', from Interplanetary to Interstellar* 9th February 2021

Presenter: Adam Hibberd



Become an i4is member

Patrick J Mahon

If you like what you see in Principium, and want to help us do more, why not become a member?

i4is formed in 2012. Nine years on, we're making great strides in our technical research, education and outreach programmes. We are a growing community of enthusiasts who are passionate about taking the first steps on the path toward travel beyond our solar system. Our ambitions are sky high, but to achieve them we need your support.

The best way you can support our mission is to become a subscribing member. If you want to, and have the time, we would love you to get actively involved with our projects. But we appreciate that not everyone who shares our interstellar vision can do this. Becoming a member is a great way to show your support and help us expand our activities.

Members have access to exclusive benefits, including:

- regular member-only talks on interstellar topics;
- early access to selected Principium articles before public release;
- regular newsletters keeping you up to date with the latest interstellar news;
- videos of i4is lectures and presentations; and
- copies of our corporate publications, including our annual report.

Recent highlights of the 2021 talk programme include:

- a debate on the case for interstellar travel;
- interstellar travel using Einsteinian physics;
- Assuring Humanity's Interstellar Mission Capability for Posterity, or, learning from Bronze Age mistakes; and
- A hands-on guide to using the 'Optimum Interplanetary Trajectory Software' package.

Our most recent newsletter gave members an early opportunity to register their interest in a new summer course on 'Human Exploration of the Far Solar System and on to the Stars', which will be delivered by i4is on behalf of Limitless Space Institute this July.

More details of the benefits of membership are on the i4is members' page, also in this issue of Principium.

If you would like to join, please go to i4is.org/membership.

Join i4is now and help us build the way to the Stars!

Keep an eye on the i4is blog

Go to i[4is.org/blog/](https://i4is.org/blog/) its updated frequently

You are here: **Home** / Blog

Blog

Newsletter: Interstellar Studies Summer Course, and Annual Report 2020

7 May 2021

The i4is education team announce a new summer course delivered by i4is on behalf of Limitless Space Institute (LSI) from 26th–30th July 2021.

ISU World Ship Module

2 May 2021

We are very pleased to be back to the International Space University (ISU) for this year's MSS21 elective on Interstellar World Ships with several i4is researchers such as Andreas Hein, Rob Swinney, John Davies, Dan Fries, Olivia Borgue. The 2-week elective will provide the students with in-depth knowledge on world ships and they will work […]

i4is Interstellar Object Article makes Headlines

2 April 2021

i4is, in collaboration with researchers from the Florida Institute of Technology, Harvard, and Paris Observatory published a paper, in which they estimate that about 7 interstellar objects are entering the solar system per year. The article has been featured in numerous media outlets: Science Alert, Phys.org, Astrobites, Universe Today, Mashable India, Republic World, Fred Zone. […]

The Self Replicating Factory: a work in progress

Michel Lamontagne

Following up his piece, Worldship and self replicating systems, in our last issue, Michel Lamontagne brings us his latest thinking on large scale self-reproduction.

Summary

The self replicating factory has been an ideal pursued by technological society for nearly 100 years. Many of its elements were present in the Ford Rivière Rouge plant in the early 20th century[1]. Its likely form has not changed significantly since the nineteen eighties, in particular the large form factory that Drexler dubbed 'The clanking self reproductive factory'[2]. Recent progresses is deep learning and automation for vehicles have advanced multi purpose robots to at least the advanced prototype phases.

Fundamental problems remain. On Earth, with the local ecosystem and planetary conditions, humans are significantly better than multi purpose robots for a large number of tasks. "Lights out factories"[3], that operate with minimal human intervention remain marginal, but are progressing. Rigidly designed factories have proven disappointing economically[4]. The existence of specialized production units with Just on Time distribution has mostly superseded the vertical integration of large multipurpose plants.

However, renewed development of low cost to orbit rocket systems are in the process of creating an easier environment for space development. In a few years, it will be possible to land a 100 tonnes equipment package on the Moon for a fraction of the present cost. Combined with some limited human presence and the creation of seed packages that provide the essential elements than the factory is unable to make itself, largely self replicating factories might become available soon. Perhaps less perfect than the original visions, but certainly useful in creating a future in space rather than confined to the Earth.

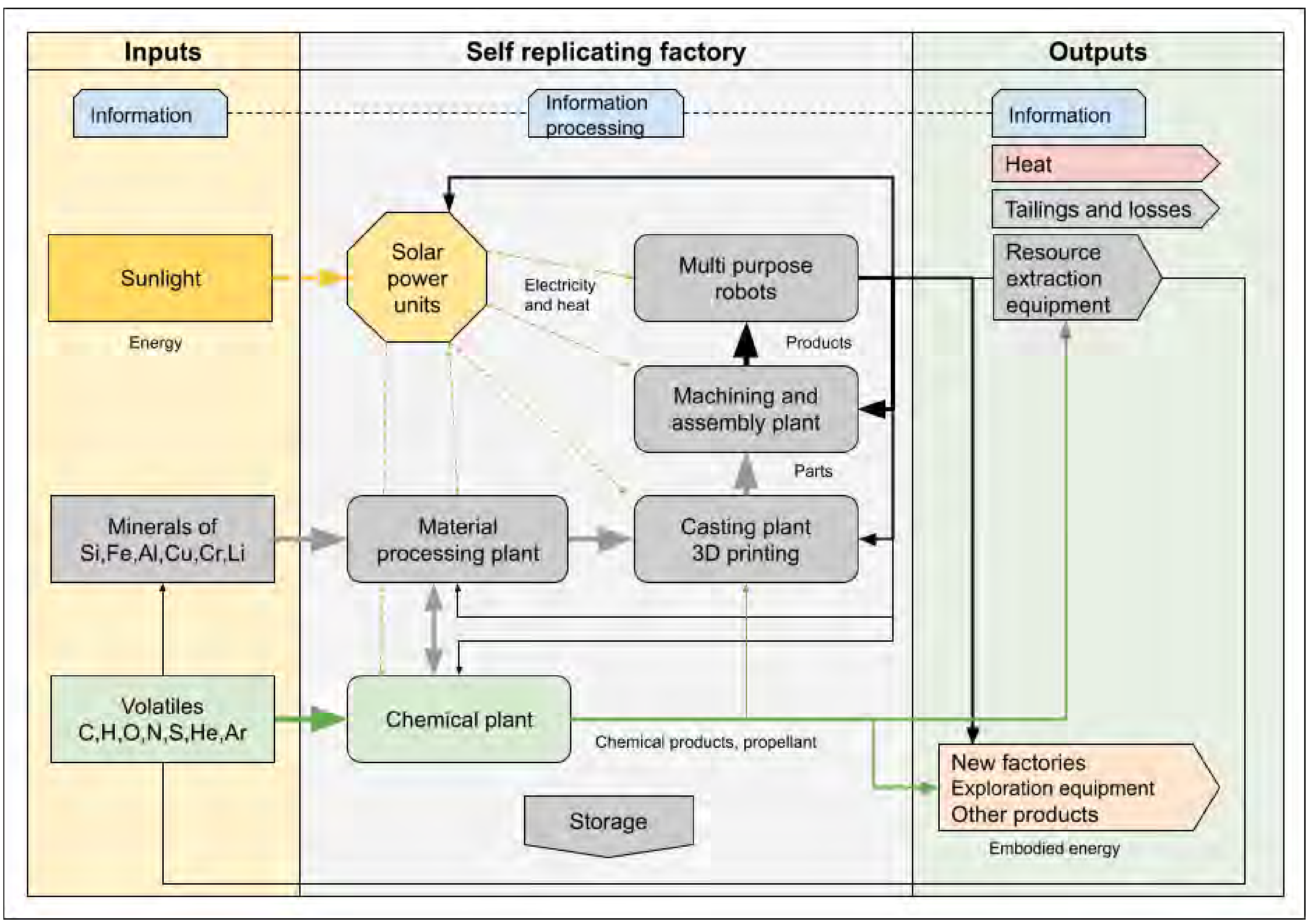


Diagram 1- A self replicating factory. Solid lines represent transportation of materials (all images by the author unless otherwise noted).

General description

At the heart of the diagram, as well as at the heart of a self replicating factory, you will find the multi purpose robot. Meet RG-132, the level 5 self driving car, oups, multi-purpose robot:

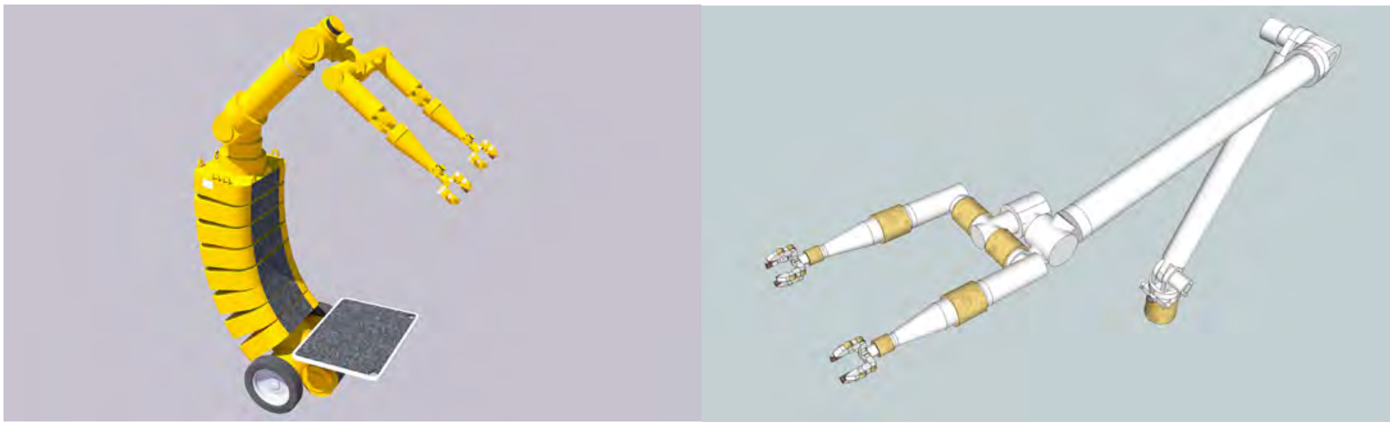


Image 1 - Ground version and zero-G version.

The requirements for a self driving vehicle are essentially the same as those of a multipurpose robot, as regards to its mobility in the environment. However, the robot also needs to be self loading and to be able to do fine manipulations, functions that are not required of cars but that have been available for decades from industrial robots.

As in today's deep learning systems, only part of the intelligence resides in the vehicle/robot. Most of the deep learning takes place in a central server system.

The multi purpose robot morphs naturally into an even closer analog to the self driving vehicle in the self driving truck and its space equivalent, the space tug.

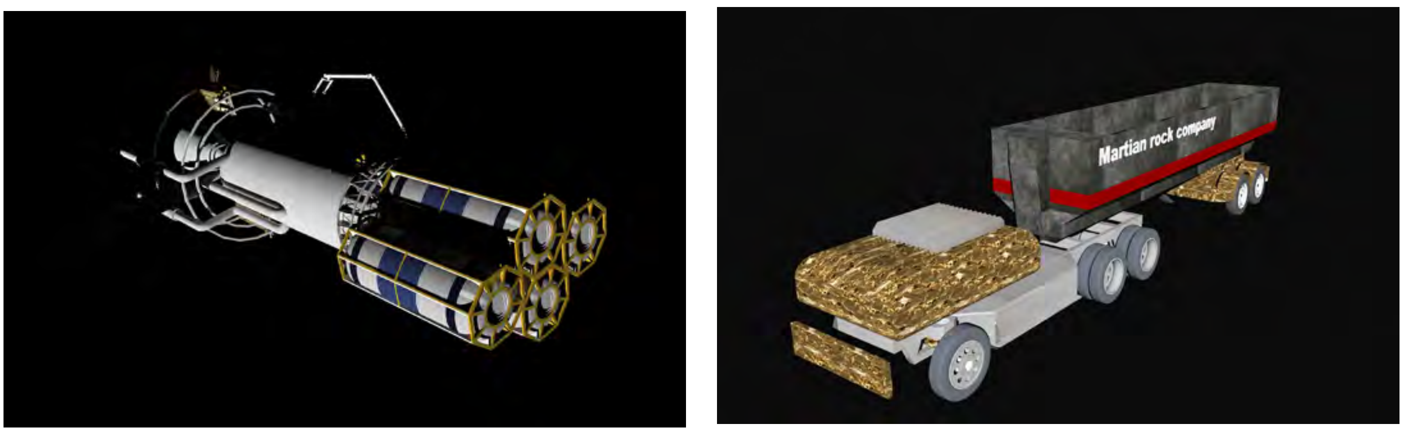


Image 2- Space tug with some ore tanks and autonomous truck with a ore trailer

These find their purpose both in hauling materials and in moving extraction and separation equipment to where the ore is found. To feed the material separation units, at the beginning of the supply chain, are the digging machines, such as these orbital diggers of surface roadheaders.

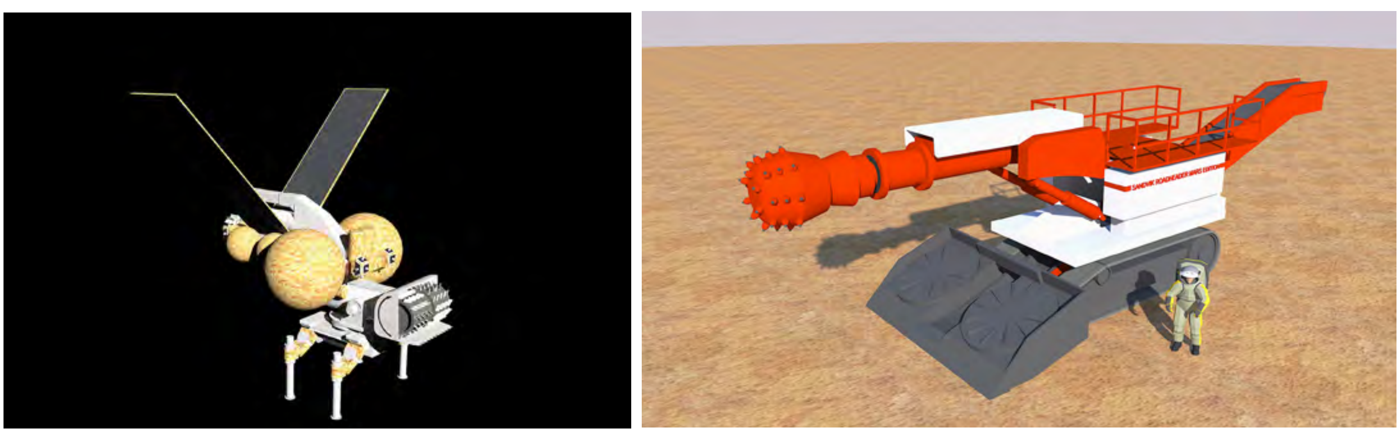


Image 3- An ice extractor for a low gravity moon, and a Martian regolith digging machine.

The first level of mineral extraction is generally to remove steriles from the ore. Ideally this is done on the mining site itself to reduce transportation. Mineral concentration by crushing and separation is commonly done at the mine site as well.

Image 4- Space tug and concentrator and ground version of same.

Finding the best location for the concentrator is the business of the geologist. Either on wheels or as a small autonomous probe. Capable of some on the spot analysis, most of the analysis would be done in a laboratory at the factory, that would double as a process laboratory.

Image 5- Geologist, ground and space versions. Commonality reduces the number of parts required for production. A modern reference would be the NASA MMSEV.

All of these machines are products of the factory. These are complex vehicles, but only represent a small mass of the production from the factory. Except for structural elements and ground preparation, the most common product of the factory will be solar power units.

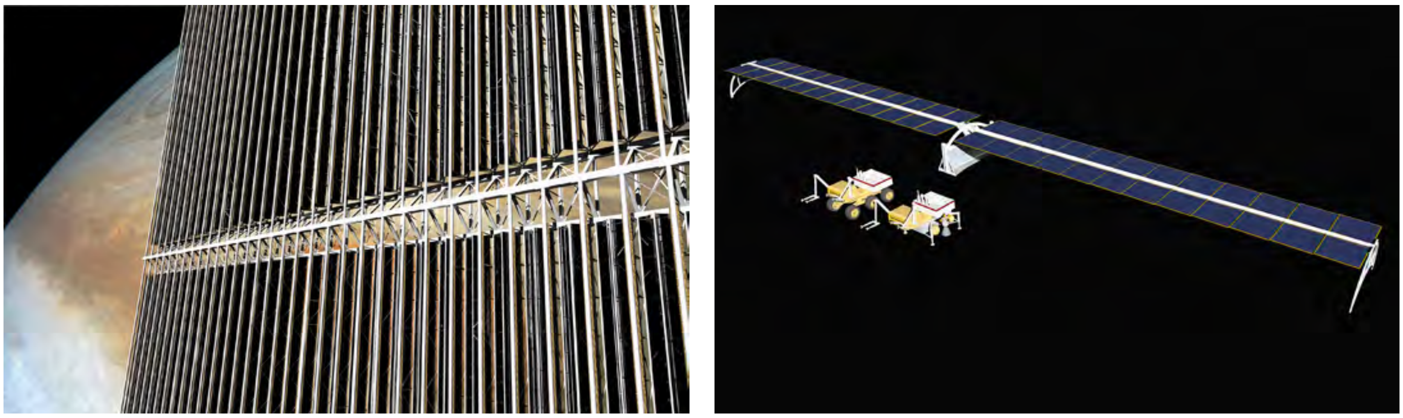


Image 6- A solar array with concentrators for a gas giant orbital installation, and a surface type deployable and orientable array for surface installation

Solar arrays give the possibility of local energy production, reducing the need for a large scale energy distribution infrastructure and of an extensive supporting civilization.

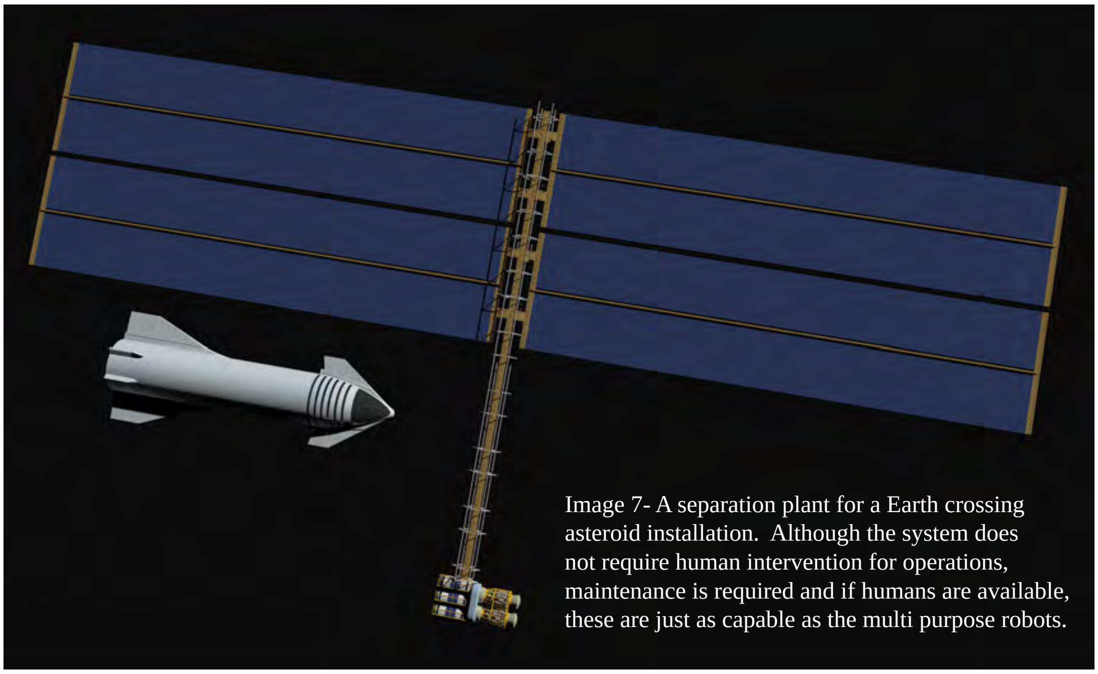


Image 7- A separation plant for a Earth crossing asteroid installation. Although the system does not require human intervention for operations, maintenance is required and if humans are available, these are just as capable as the multi purpose robots.

Trucks also operate on the mining sites, moving steriles to tailing areas and ore to concentrators.

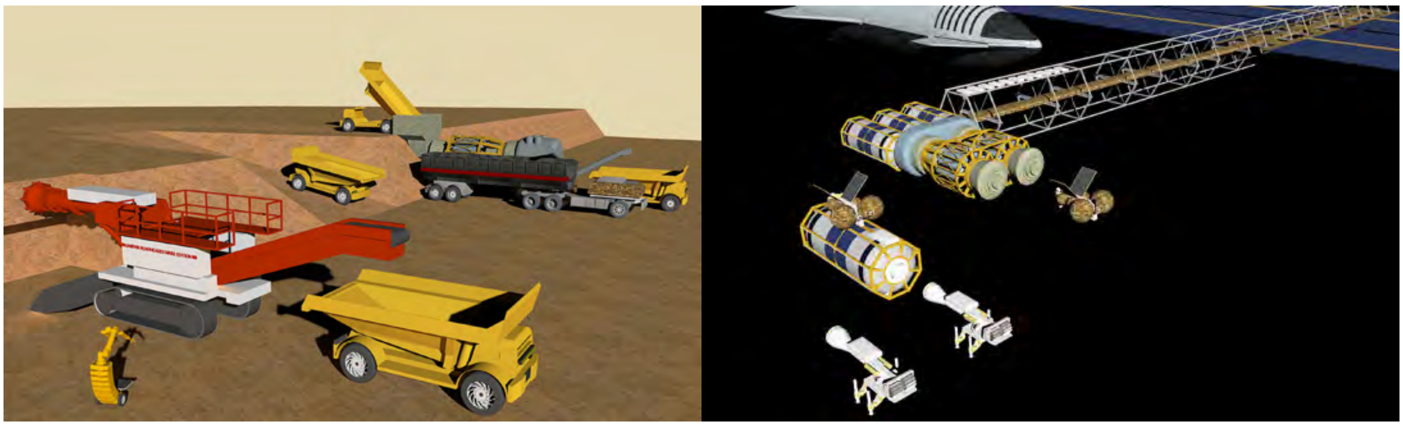


Image 8 - A mining site on Mars. Mining trucks that restrict themselves to the mine site and long haul trucks are shown. Self driving mining trucks already exist[5]. And the space equivalent.

The trucks and tugs feed the factory input areas, where storage silos store the materials required for the first stages of transformation, separation and reduction. Refineries that produce the first grade of products required for the factory.

If Martian settlements take off, Mars may not see self replicating factories, but rather apply the model of the extended production systems and Just in Time existing on Earth. Automation will provide high productivity, and will also be applied on Earth.

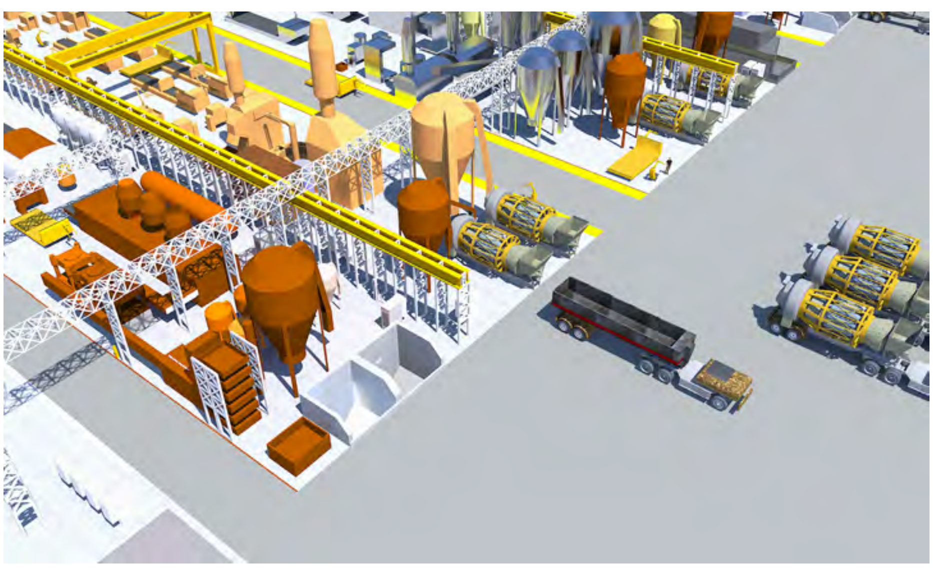


Image 9- View in the materials input area for the Silica, Iron and Aluminum production lines, lunar or martian surface factory. If you search a bit you will find the human to scale.

The silica is crushed and graded to different dimensions, while the iron ore is separated to Fe_2O_3 by centrifugal separation. The Alumina needs to be separated chemically from the ore that contains it in more complex forms, such as clays or olivine.

In the factory material handling takes many forms: autonomous lifts and carriers, automated storage systems and various cranes.

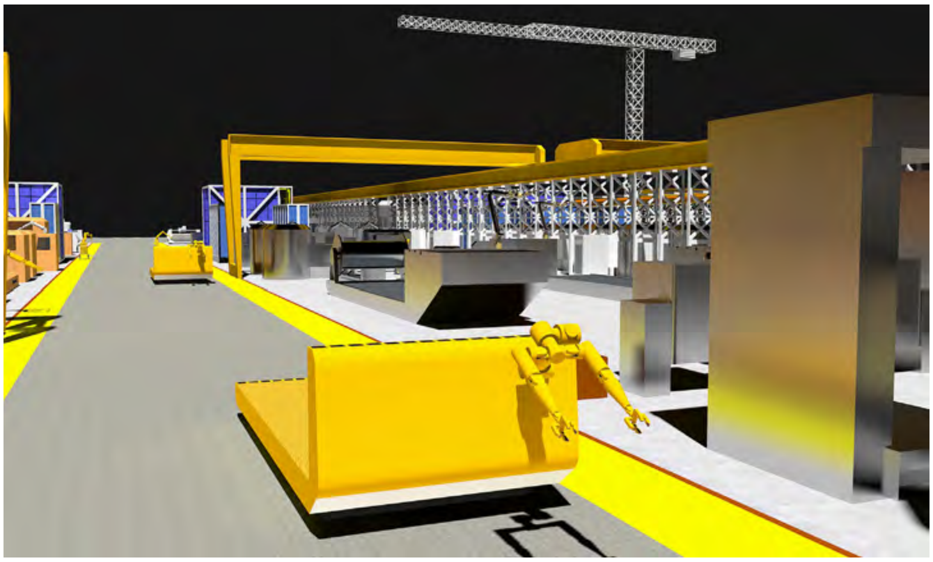


Image 10- An autonomous carrier moves in front of some aluminium shaping equipment and remelting furnaces. Overhead cranes handle large parts, while the tall crane in the background carries out final assembly of the larger equipment.

The single floor plan simplifies the maintenance and operations, and is more compatible with the wheeled robots. A few special multi handed/legged robots would be required in case of work in elevated areas.

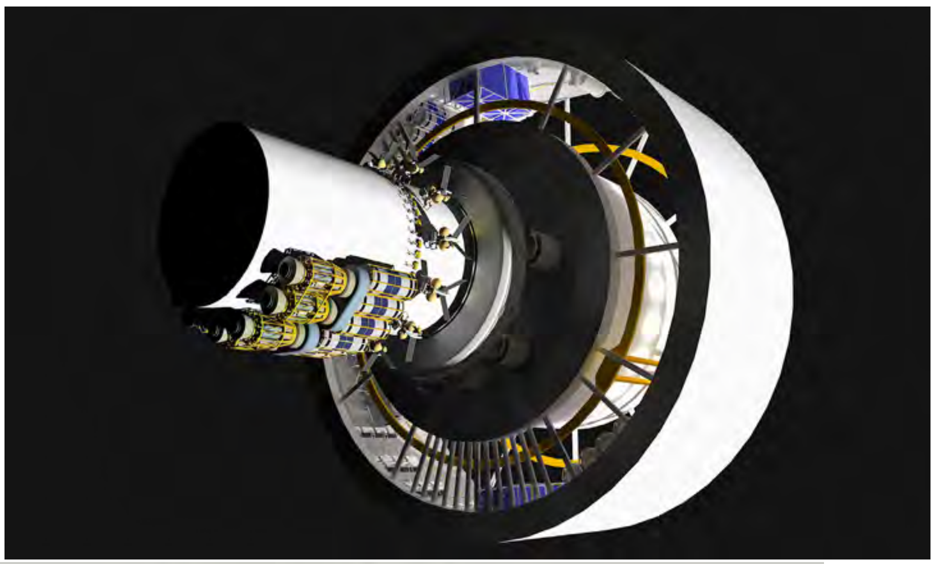
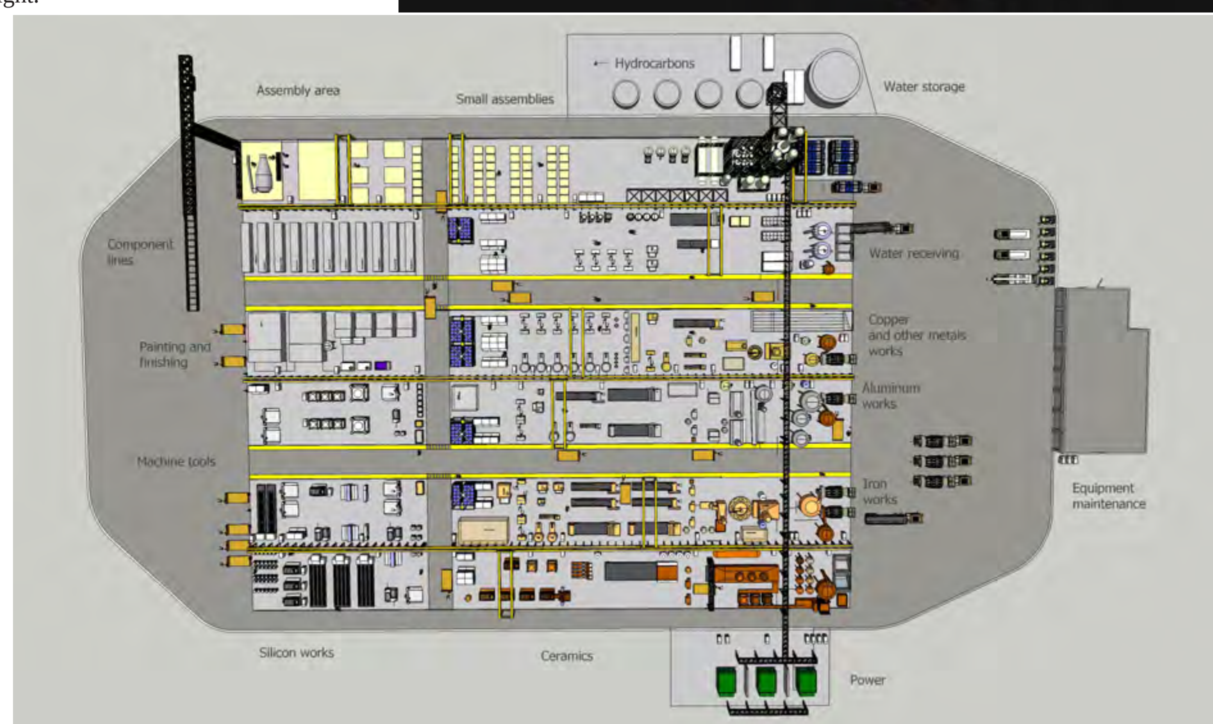


Image 11 - A smaller orbital version of the factory. Part of the factory would rotate to facilitate processes and handling

Image 12- Factory plan. A roof carrying solar cells would almost certainly be required, in particular on the Moon. The roof would be closed with insulated panels, for the long lunar night.



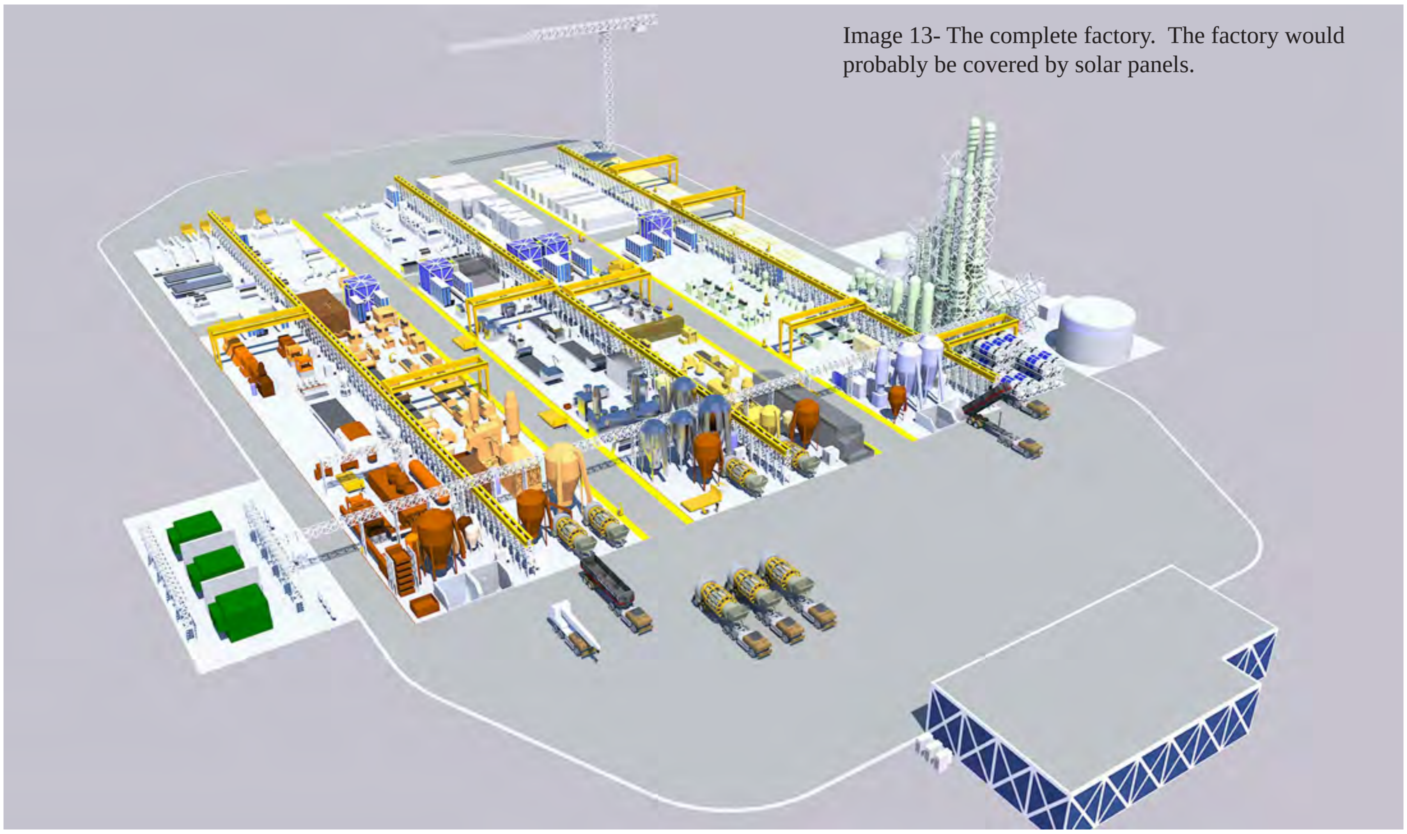


Image 13- The complete factory. The factory would probably be covered by solar panels.

There is nothing new in all this. In fact, the factory shown here is just a different version of the similar work done in the early eighties. But we are a lot closer to building it than we were then.

Image 14- 1980 version of the self replicating moon factory.
Credit: NASA

An even earlier vision can be found in the 1941 Ford River Rouge plant. Vertical integration went from raw material supply to a manufactured car on a single site, very close to what is proposed for self replicating factories.

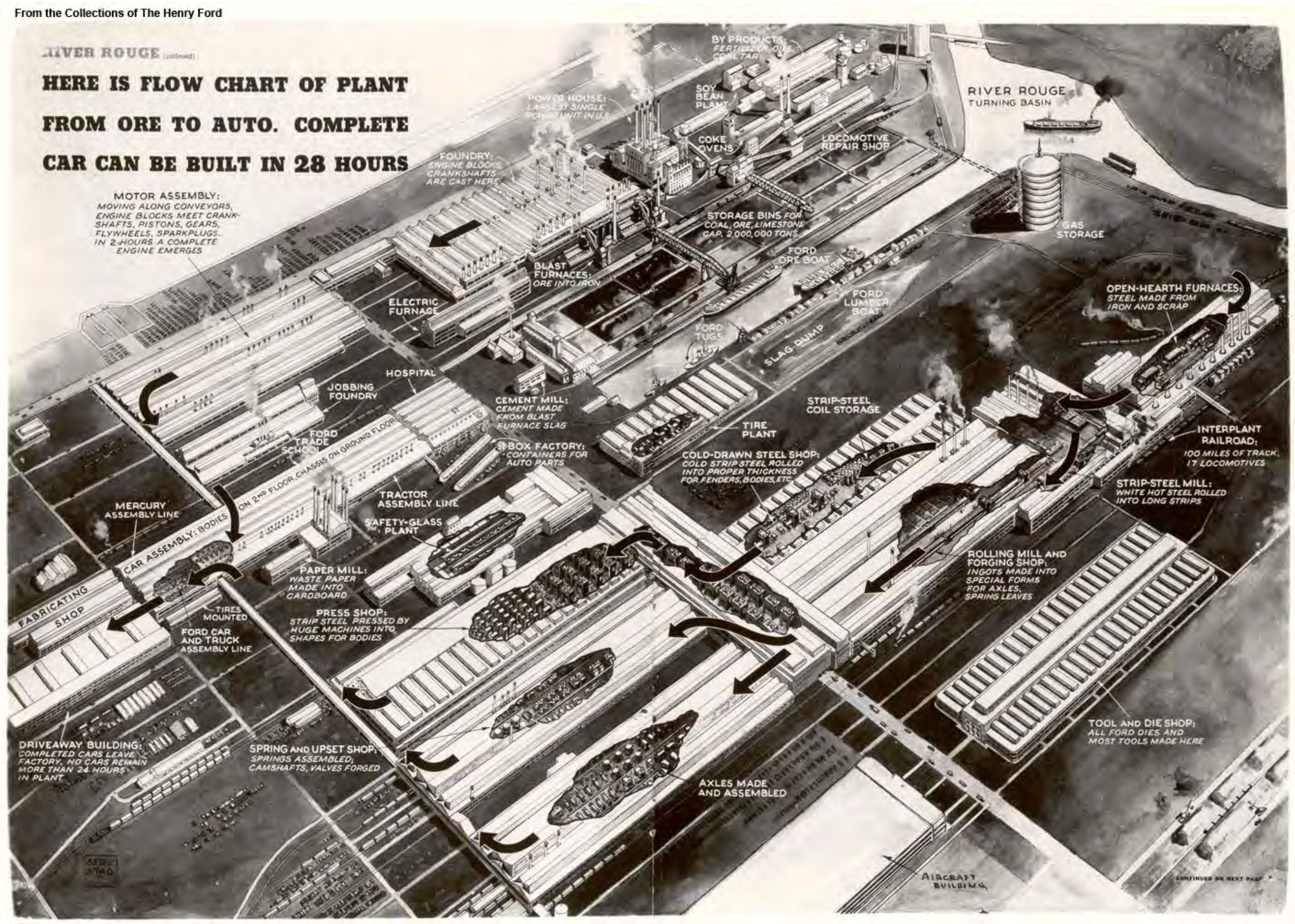


Image 15 - The Ford Rivière rouge plant in 1941.
Perhaps one of the most complete implementation of the vertically integrated factory in history.

Credit: University of Michigan-Dearborn - *Automobile in American Life and Society* www.autolife.umd.umich.edu/
"From the Collection of The Henry Ford. 1) P.833.75060"
www.autolife.umd.umich.edu/Labor/L_Overview/FlowChart_RougePlant_FullSize.htm

Operations

The self reproducing factory illustrated here is based on a production rate of 10,000 tonnes of steel per year, with ratios for other materials drawn from World production numbers for minerals and metals of 2020[6]. These numbers are for a self replicating factory on the Moon.

Self replicating factory	million T/year reference	Tonne per year	t/day	ratio ore to metal	total ore required per year	Ore, t/day	Embodied energy	Power
	Earth	Factory					kWh/t	kW
Water, factor of 6		60,000	200	1	60,000	200	140	1,750
Hydrogen from electrolysis		125	0.4	8	1,000	3	50,400	1,313
Carbon, from CO2		500	2	4	2,000	7	280	29
Slag, factor of 4		40,000	133	1		133	280	2,333
Cement	4,000	13,333	44	1		44	420	1,167
Steel and iron	3,000	10,000	33	4	40,000	133	9,800	20,417
Aluminium (doubled from Earth)	64	427	1.4	12	5,120	17	61,600	5,476
Magnesium	29	96	0.3	12	1,148	4	61,600	1,228
Copper	20	67	0.2	100	6,667	22	39,200	544
Manganese	19	63	0.2	100	6,270	21	39,200	512
Chromium	44	147	0.5	100	14,667	49	33,600	1,027
Silicon for solar cells		140	0	2	280	1	560,000	16,333
Polymers		500	1.7	1		2	22,400	2,333
Other metals/resources	110	363	1.2	150	54,450	182	42,000	3,176
Total		**11,801**	**419**		**191,602**	**818**		**57,638**

Table -1 Production numbers for a 10,000 tonnes of steel per year nominal self replicating factory.

The two most energy intensive productions are structural steel and silicon for solar cells. The power values are for continuous production during a year. Actual power could vary significantly depending on emplacement, resource accessibility and orbital characteristics of the location. The factory could reproduce itself about every two years, and produce about its mass of equivalent equipment in the ratio shown in the table. Added emphasis on solar cells, for example, would reduce mass output as these are high energy, low mass items. The factory is essentially energy limited, but probably also operationally limited as regards to the complexity of the manufactured parts.

It might be possible to optimise this factory to a smaller dimension, ideally to a point where the entire seed material required for a new factory could fit inside a 100 tonnes payload. This might be enough for a factory massing about 2,000 tonnes. At this point the unmounted solar cells might come from Earth, considerably reducing the energy required for the production of power systems.

For a lunar self replicating factory the lack of volatiles, such as water, CO2 and carbon as well as nitrogen might limit the capabilities of the factory considerably, although some volatiles are available from polar sources.

Recent developments

Some recent technological developments are moving industry towards the capability for self reproducing factories, notable elements are:

● Additive manufacturing; flexible production lines, use of simple materials for production for both plastics and metals. Additive manufacturing can also be used to produce dies for extrusion machines and various specialized small runs tooling, making the maintenance and modifications of conventional production machines easier. Extrusion fabrication remains orders of magnitude faster than additive manufacturing for many applications, and the combination of the two may be a winning approach.

● Deep learning; the development of much more independent robotic systems, with real world applications such as self driving cars drives a rapid development of these technologies; human input remains essential for deep learning training, however, and this still prevents the development of fully autonomous systems that might be required for Interstellar exploration.

● Minimal fabs; this is a manufacturing system for producing small runs of microprocessors. The technology is promising but may not survive the fierce competition from multi billion dollar fabs.

● The rapid evolution of cheaper space access, first from SpaceX and next from all of their waking up competition, is poised to deliver now markets than are likely to require in situ resources development, that in turn requires highly autonomous systems for production.

Some other factors that are still obstacles to total autonomy, and in particular make the use of fully automated factories on Earth unlikely, are the following:

● The low cost of human labor, and the high efficiency and flexibility of humans compared to robots.

● The low cost of transportation vs the cost of warehousing.

● The lower cost of large scale specialized factory products.

The first world economy seems to have started divorcing itself from the constant growth of energy production. Quality products take less and less energy to produce and to operate. On the other end of the economic spectrum, the increase in productivity may have started to outstrip the ability to consume the products in certain markets. This might grow into the capability of space production to create materials resources that can be used for entirely new ways of life, such as space settlements.

Image 16 - An early factory, with a number of SpaceX Starships serving as basic construction elements

Evolution of the factory

Starting with a first factory on the Moon, the precursor factories might be a small version of the Ford River Rouge vertically integrated plant. Deep learning could be carried out in simulation on Earth. The space environment of a lunar factory should be much simpler to navigate than a modern city road.

The factory would evolve towards the larger, more autonomous surface version explored in this article, and eventually move to interplanetary space. These factories would then follow humanity to the Stars, after having helped to build the infrastructure required for the occupation of the solar system and for Interstellar travel.

The single unit self replicating machine may remain far in the future, but a self replicating factory, part of a larger technological system, may soon exist. Rather like a plant or a tree is an individual system within the larger framework of an ecosystem.

On Earth, despite the abundance of mineral resources and energy sources, the self replicating factory may never come to be, outcompeted by more specialized elements of technological civilization. And humans are still hard to beat as far as autonomous robots go.

On the Moon, the lack of volatiles may handicap the long term development of the factories. However, factories on the Moon would be very useful for the fabrication of some of the elements for habitats in Earth orbit, as has been known for decades.

Self replicating factories might find wide use on Mars, in particular if the planet turns out to be impossible to settle. The factories could be operated from orbit in a fly-in fly-out type of operation. Mars is the closest large scale source of volatiles to the Earth, and use of in-situ propellant manufacturing may reduce the deltaV cost from the surface to orbit to a very low level.

The asteroid belt may be the ultimate resource for space settlement construction. However, volatile rich asteroids are in the outer limits of the belt, where the solar resource is getting rarer. Fusion power might then supplant solar power, but fusion remains a speculative technology.

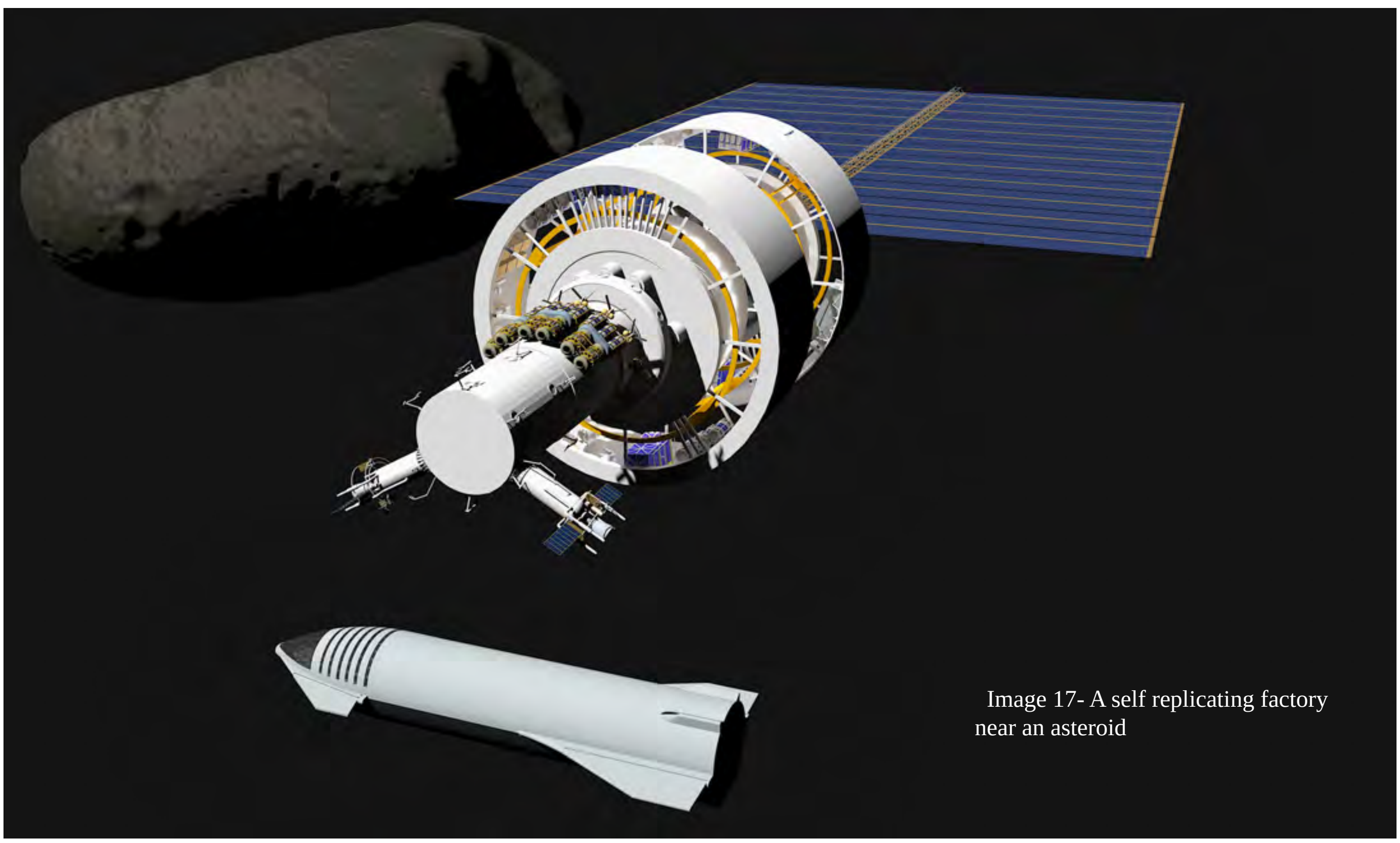


Image 17- A self replicating factory near an asteroid

Interstellar applications

Self replicating factories bypass the paradigm of limited resources often applied in the development of tiny probes and miniature exploration systems. In effect, any self replicating factory can eventually produce systems of any size, it is just a matter of time. Giving the exponential nature of the self replicating factory's output, waiting a few generations allows for much larger equipment. The resources available in the solar system, both in energy and matter, are stupendously large. Even the largest of worldships is an infinitesimal piece of equipment compared to a small moon, not to mention a full planet.

Conclusion

A large increase in the efficiency of autonomous production is likely in the near future. This increase should be applied to the creation of factories for the development of in situ resources for the exploration and development of the solar system. Additive manufacturing and high volume process tooling will combine into factories capable of flexible production runs and multiple outputs with very low modification costs. Combined with exploration and efficient resource acquisition, all the ingredients seem available for the creation of self replicating factories that can open up to solar system to occupation. Even if completely autonomous self replicating factories never come to pass, partially self replicating factories can be used to create habitats for humans in space. The inhabitants of these habitats can then participate in the operations of the factories, blurring the line between a self replicating factory and a self replicating civilization.

References

1 - River Rouge Ford motor plant, Ford archives

2 - Drexler, K E (1986). *Engines of creation.* Anchor books.

3 - Lee, Noah K *Total Automation: The Possibility of Lights-Out Manufacturing in the Near Future.* Missouri S&T's Peer to Peer 2, no. 1 (2018): 4. scholarsmine.mst.edu/peer2peer/vol2/iss1/4/

4 - *Lights-Out Automation: Fact or Fiction? Humans are the most flexible "machine" for assembly tasks*, 2019, Austin Weber. www.assemblymag.com/articles/94982-lights-out-automation-fact-or-fiction

5 - Hyder, Zeshan, Keng Siau, and Fiona Nah. *Artificial intelligence, machine learning, and autonomous technologies in mining industry.* Journal of Database Management (JDM) 30, no. 2 (2019): 67-79. www.researchgate.net/profile/Keng-Siau-2/publication/325934538_Use_of_Artificial_Intelligence_Machine_Learning_and_Autonomous_Technologies_in_the_Mining_Industry/links/5b97332e92851c78c4190e83/Use-of-Artificial-Intelligence-Machine-Learning-and-Autonomous-Technologies-in-the-Mining-Industry.pdf

6 - *All the World's Metals and Minerals in One Visualization*, March 1, 2020, Nicholas LePan www.visualcapitalist.com/all-the-worlds-metals-and-minerals-in-one-visualization/

About The Author

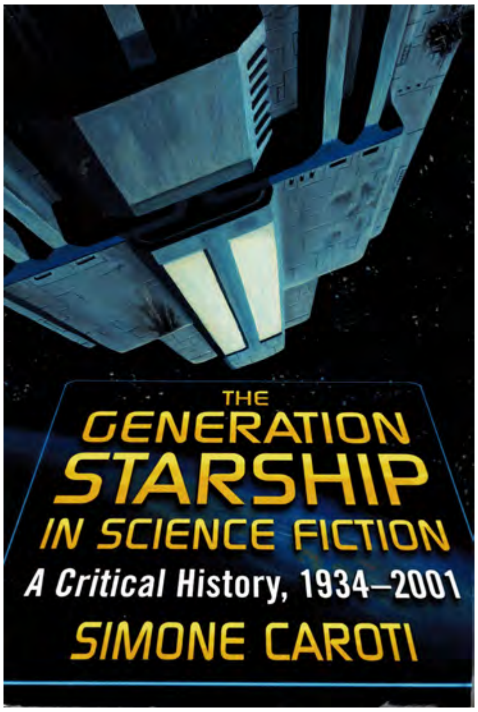
Michel Lamontagne is one of the two principal developers, with Robert Freeland, of the Firefly interstellar probe design for Project Icarus (see Patrick Mahon's discussion of the basics of its propulstion in *Reaching the Stars in a Century using Fusion Propulsion: A Review Paper based on the 'Firefly Icarus' Design* in Principium 22 August 2018 and at i4is.org/reaching-the-stars-in-a-century-using-fusion-propulsion/. Michel is a French Canadian engineer living near Montreal. He works in mechanical engineering, mainly in building systems: plumbing and HVAC. As you will see from the illustrations here, and his cover art for P22, P30 and P31, Michel is an artist as well as an engineer. He mostly worked in comic art in his earlier years; you can find examples of this earlier work (up till 2014) on the web site: sites.google.com/site/bdespace /Home - use the side menu for most images. His more recent work is on Deviant Art: www. deviantart.com/michel-lamontagne/gallery/.

Book Review: The Generation Starship In Science Fiction A Critical History, 1934-2001

Simone Caroti

reviewed by John I Davies

Dr Simone Caroti has now delivered his presentation on *The Generation Starship In Science Fiction* to students taking the i4is-led interstellar elective at the International Space University in both 2020 and 2021. Here John Davies reviews his 2011 book based on his PhD work at Purdue University*.



Published: McFarland 2011 mcfarlandbooks.com
Image credit: Bill Knapp, *Arrival* www.artprize.org/bill-knapp

Within an overall chronological plan the major themes in Dr Caroti's book seem to me to be -

- The conflict between the two conceptions of a worldship. Is it a world which happens have an artificial "substrate" or is it a ship with a mission which happens to require a multi-generation crew.
- How can the vision of dreamers like Tsiolkovsky, J D Bernal and Robert Goddard be made to inspire the source civilisation, for whom this is a massive enterprise, the initial travellers, their intermediate descendants and those who must make a new world at journeys end?
- And, more practically, how can culture, science and technology be sufficiently preserved over many generations?

Opening Chapters

The book sees the development of the worldship as a fictional theme in six overlapping eras - the first worldship ideas (not all as fiction), The Gernsback Era, 1926-1940 , The Campbell Era, 1937-1949, The Birth of the Space Age, 1946-1957, The New Wave and Beyond, 1957-1979 and The Information Age, 1980-2001.

Caroti read a lot of science fiction and speculative non-fiction before beginning his PhD at Purdue University. He mentions Vernor Vinge, Iain M Banks and Carl Sagan (and returns to them later). Another early mention is critic John Clute [1].

His Introduction gives some historical context to worldship ideas with the key scientific event of the discovery of the first ideas of the true scale of the universe and the unattainability of light speed in 1905 as the founding premise for the worldship concept. Tsiolkovsky, as (almost) always, sets the problem and suggests a solution in *The Future of Earth and Mankind* in 1928. In the following year J D Bernal in *The World, the Flesh & the Devil* [2] suggests a hollowed asteroid as a worldship.

In the chapter "Fathers" he again cites Tsiolkovsky and Bernal and adds Robert W Goddard, who wrote some notes, *The Last Migration*, and a précis *The Ultimate Migration*, in 1918 - a year before his seminal idea *A Method of Reaching Extreme Altitudes* [3] in 1919. Caroti sees Tsiolkovsky as having a "purer vision" than Goddard. But Goddard's envisaged *Last Migration* was not published in the USA until 1972 [4].

* *The generation starship in science fiction, 1934-1977* **docs.lib.purdue.edu/dissertations/AAI3379320/**

[1] *Encyclopaedia of Science Fiction*, edited by John Clute, David Langford, Peter Nicholls (emeritus) and Graham Sleight (managing). www.sf-encyclopedia.com/entry/world_ships

[2] J D Bernal, *The World, the Flesh & the Devil, An Enquiry into the Future of the Three Enemies of the Rational Soul*, Verso Books, www.versobooks.com/ and www.marxists.org/archive/bernal/works/1920s/soul/

[3] NATURE 26 August 1920 www.nature.com/articles/105809a0.pdf

[4] www.centauri-dreams.org/2013/05/06/robert-goddards-interstellar-migration

The Ultimate Migration *https://web.archive.org/web/20191102193806/https://www.bis-space.com/2012/03/23/4110/the-ultimate-migration*

Caroti sees parallels between an aristocracy of scientific knowledge in Bernal and Gene Rodenberry's vision of our interstellar future. "Strange bedfellows" indeed given that Bernal was a lifelong convinced communist [1]. Bernal was certainly very "modern" - conceiving of his habitats as having a "metabolic" existence with no clear organic/mechanical distinction. Caroti compares the visions of Tsiolkovsky, Goddard and Bernal and is optimistic about the influence of science on both capitalist and socialist[2] societies. Would he still be so optimistic now - ten years after publication?

The Gernsback Era

The first of Caroti's overlapping eras is *The Gernsback Era, 1926-1940*. Gernsback recruited Verne and Wells into his category of "scientific-ition" using it to proselytise for science and engineering solutions to human problems and the advance of technical civilisation. But Caroti agrees with the later view of Brian Aldiss that Gernsback "ghetto-ised" science fiction (SF) while also arguing that he was unconsciously following the more articulate techno-optimism of Bernal, Tsiolkovsky and Goddard. Curiously he does not mention *Things to Come*, a 1936 film written by H G Wells, which pitched technological progress against the local demagogue, The Boss, and shot a nubile young couple to the Moon with the last words uttered by Raymond Massey in his full pomp "All the universe or nothing? Which shall it be?".

Cover of the first edition. Image credit: Frank R Paul

Gernsback published *The Living Galaxy*, Laurence Manning, in 1929 which Caroti cites as "the first fully fledged generation starship narrative". An 8 page story covering an 800 million year future history (which he later contrasts with the brief time span of Gene Wolfe's multi-novel "Long Sun" sequence). Manning writes in the Victorian "dear reader" style. For a story about the ship rather than future history he introduces *The Voyage that lasted 600 years*, a 1940 short story by Don Wilcox, The crew, just 16 couples to start, are guided by an intermittently hibernating "Keeper of Tradition". The "Keeper" has little success in preserving culture after his second 100 year hibernation and Caroti sees the lessons of Jared Diamond's much later meditation on civilisation *Guns, Germs and Steel* played out. He also sees strong parallels with the Eloi and Morlocks of Wells' earlier *The Time Machine* in the stark social dualism which arises[3]. The general tendency of pulp-era science fiction to pit an evil monster or robot against a white male hero and his defenceless female companion might be present here? Caroti suggests that Wilcox is simulating a perceived decline in contemporary American culture. Caroti devotes 25 pages to analysing this story, more that 10% of his main narrative.


The Voyage That Lasted 600 Years

by DON WILCOX

Thirty generations would live and die before the *Flashaway* reached its destination. Could the one man who was to live on keep them to their purpose?

THEY gave us a gala send-off, the kind that keeps your heart bobbing up at your tonsils.

"It's a long, long way to the Milky Way!" the voices sang out. The band thundered the chorus over and over. The golden trumpaphones blasted our eardrums wide open. Thousands of people clapped their hands in time.

There were thirty-three of us—that is, there was supposed to be. As it turned out, there were thirty-five.

We were a dazzling parade of red, white and blue uniforms. We marched up the gangplank by couples, every couple a man and wife, every couple young and strong, for the selection had been rigid.

Captain Sperry and his wife and I—I being the odd man—brought up the rear. Reporters and cameramen swarmed at our heels. The microphones stopped us. The band and the crowd hushed.

"This is Captain Sperry telling you good-by" the amplified voice boomed. "In behalf of the thirty-three, I thank you for your grand farewell. We'll remember this hour as our last contact with our beloved Earth."

The crowd held its breath. The mighty import of our mission struck through every heart.

82

Grimstone gripped his automatic tightly as he stepped from the animation machine

83

Opening pages of *The Voyage that lasted 600 years*, Don Wilcox. Credit: Amazing Stories, 1940. https://classicsofsciencefiction.com Images- Julian S Krupa

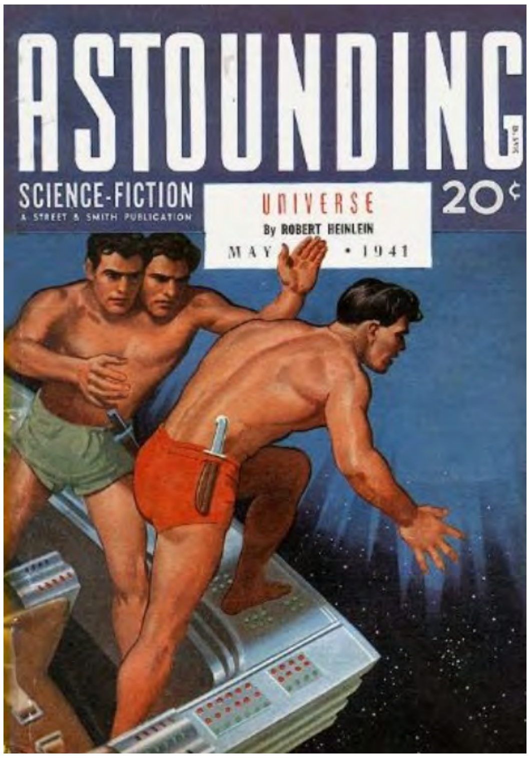
[1] Bernal maintained his support for the Soviet model of communism until his death in 1971. He also stretched his intellectual embrace as far as the anti-Mendelian genetics of Lysenko. In political jargon he was a "tankie" - one of those who supported the suppression of the 1956 Hungarian uprising by Soviet tanks.

[2] By "socialist" I believe he means communist in the Soviet sense - thus leaving out both the post-communist oligarchies of Russia and China and the social democracy which has been either dominant or highly influential in western Europe.

[3] Plot spoiler - It may be worth noting the limits of this parallel. The Eloi are, it turns out, eaten by the Morlocks.

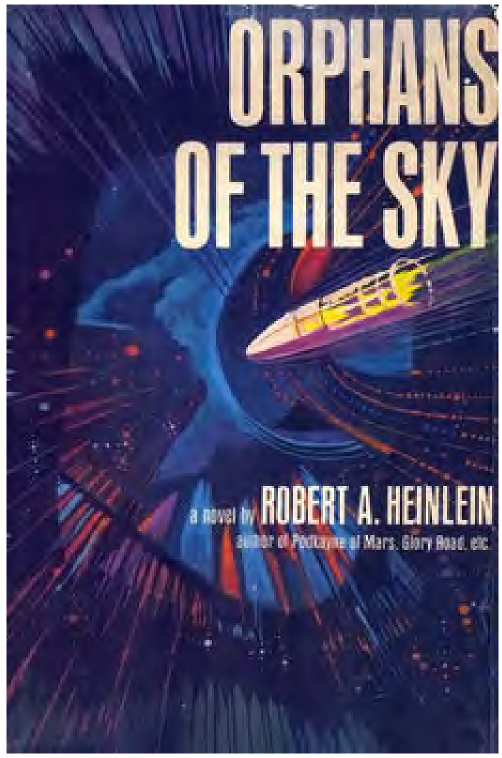
The Campbell Era

Caroti tells us that John W Campbell's *Astounding* magazine attempted to make SF more about engineering than "bug-eyed monsters". The recovery from the '29 crash and the technological supercharger of the Second World War offered scope for more optimistic SF. He sees the technical race between Germany, Japan and the US as a main driver. Presumably the Soviets and the Brits were less influential? He also sees Robert Heinlein as Campbell's virtual alter-ego. Heinlein attempted a technology driven "history of the future" with his linked worldship stories "Universe" and "Common Sense" occupying the latter part of his timeline. In fact this pair of 1941 magazine stories became a novel, *Orphans of the Sky*, more than 20 years later (1963).

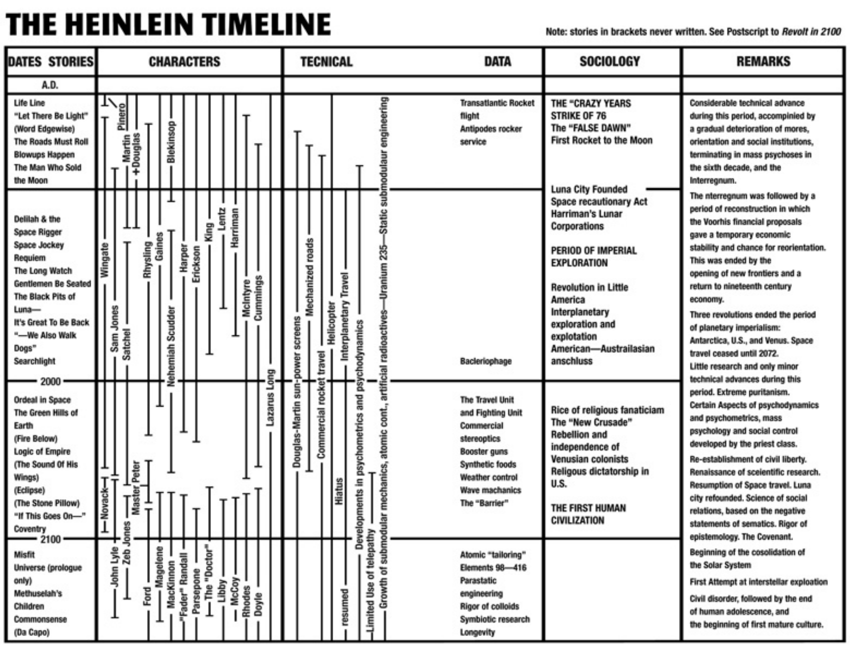


1941 to 1963. A contrast in covers between the same stories in *Astounding* magazine and the book 20 years later.

Credits: Astounding and Putnam (+ book cover artist Irv Docktor) respectively



Heinlein envisaged a cylindrical worldship - and again it had lost its way. Heinlein gives us the guided tour in typical explanatory style. A regressed culture within a very advanced technology with a ritualising scientific elite [1]. The degenerate "muties" Caroti sees as protestants in late medieval Europe with the prophetic character Hyland as Galileo leading them out of interstellar darkness to planetfall [2]. Again Caroti discusses a story at length, 25 pages.



The Heinlein timeline from *Revolt in 2100*. Credit: SFFWorld https://www.sffworld.com/2019/02/revolt-in-2100-by-robert-a-heinlein/

[1] The ritualisation of science seems to me to parallel the humorous parody of science as religion in Bester's *The Stars My Destination*. The "Scientific People" are effectively marooned on an asteroid worshipping "The Holy Darwin", anticipating "The arrival of the fittest" and approving good actions as "most scientific".

[2] The second story "Common Sense" evokes Thomas Paine and I suspect Heinlein used it consciously but Caroti does not mention the parallel between the title and another rationalist persecuted for challenging religious orthodoxy. See the *Book Review: Religions and Extraterrestrial Life* by David A Weintraub in Principium 29. May 2020.

Birth of the Space Age

Dr Caroti characterises the period 1946-1957 as The Birth of the Space Age, He cites the influence of the members of the German Rocket Society, the VfR [1] notably Willy Ley, who fled the Nazi regime, and Werner Von Braun, who led the design of the V2 missile. A minor error here - Caroti refers to the V2 as "the first true ICBM". From the US point of view it was most fortunate that the A4, propaganda name V2, was not a "true ICBM". There was an intercontinental ballistic missile on the drawing board, the A9/A10 two stage vehicle, but the war ended before it could be built.

Arthur C Clarke appears in 1946 with his Astounding magazine story "Rescue Party", of a worldship fleet evacuating a dying Earth. Gernsback is still active, publishing the non-fiction "Interstellar Flight" by Les Shepherd of the British Interplanetary Society[2]. Caroti commends Shepherd (with Tsiolkovsky) for examining the worldship as a system, though neglecting the psychology of the travellers, and for addressing the question "Why go?". The systems approach is extended to hydroponics in Clifford Simak's "Spacebred Generations" in 1953.

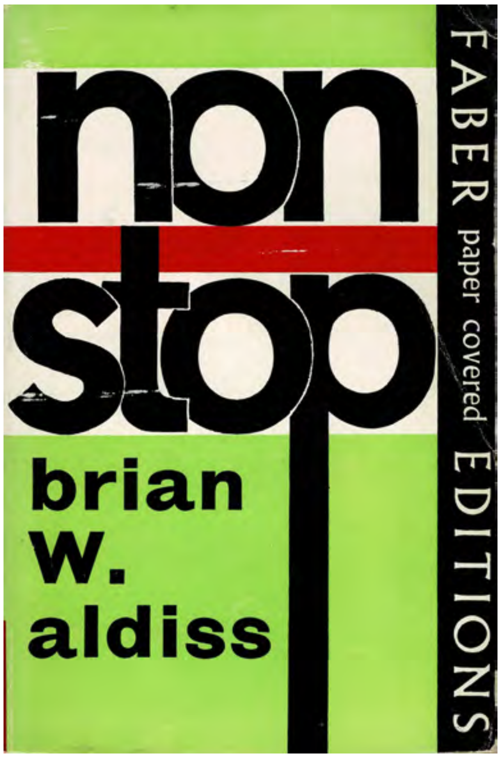
Caroti examines Frank M Robinson's "The Oceans are Wide" at some length. Themes include the 'loneliness of command' and the choice of destination - leadership rejecting a paradise planet and preferring a challenging environment despite having fled a conflict-ridden Earth.

Another minor error, Caroti briefly mentions James Blish's "Cities in Flight" series and mentions the cities operating "billions of years after our planet's demise". At the conclusion of *Earthman Come Home* they do just that but the Earth cops don't welcome them!

The New Wave and Beyond

Caroti sets the beginning of the New Wave of SF in 1957 and sees it extending to 1979. 1957 seems to be chosen as the year of Sputnik 1 when Americans found a bleeping sphere orbiting over their heads every 90 minutes - and the advent of Mutually Assured Destruction (MAD)[3].

The most accepted beginning of the New Wave was in 1964, with Michael Moorcock's editorship of the magazine *New Worlds* and the stories of Harlan Ellison, J G Ballard and Brian Aldiss. But Caroti mentions an earlier story by John Brunner, "Lungfish", in 1957 with mutual alienation between the Earthborn and Tripborn generations. Population psychology dominates technology. Another example, "The Wind Blows Free" - also 1957, by Chad Oliver has a misfit "rebel without a cause" who tries to commit suicide by leaving the ship only to discover it has already arrived. A novel *NonStop*, Brian Aldiss 1958, describes a degenerated starship society of jungle tribes with limited access to more advanced weapons. The evolved social rituals and the partitioning of the ship into elements paralleling human psychology are clear examples of the intervention of what became characterised as "inner space". Caroti deals at some length with the shift between Heinlein and Aldiss. Though their careers overlapped their anticipation of worldship societies diverged enormously. J G Ballard ventured into the field with the story "Thirteen to Centaurus". Here the plot revelation is the ship never left Earth and is an experiment in social psychology, precursor to a real mission[4]. Here Ballard's "inner space" is both psychological and literal.



Nonstop 1965 Faber edition cover.

SF has started to get serious by 1965

[1] Verein für Raumschiffahrt, Society for Space Travel 1927-1934

[2] More about this by the encyclopaedic Paul Gilster in The Worldship of 1953 https://www.centauri-dreams.org/2014/06/12/the-worldship-of-1953/

[3] Caroti characterises MAD as a "zero sum game" preventing World War III. This is doubtful. In a zero sum game every point I win is a point you lose so the sum of wins, pluses, and losses, minuses, comes to zero. Any game where both sides benefit as in the avoidance of World War III cannot be zero sum. However the views of experts would be welcome.

[4] Is this a variant of the great moral question of the worldship - who can decide for succeeding generations?. But we are all, to a degree, limited by our social backgrounds. It is very hard to leave a closed religious community or to avoid a military mindset in a military family.

The concept of Spaceship Earth has a natural relation to worldship ideas and Caroti mentions the thinking of Adlai Stevenson, Barbara Ward and R Buckminster Fuller - and later biological metaphor of James Lovelock's Gaia hypothesis.

An example of another worldship issue arises in Samuel R Delaney's *The Ballad of Beta-2*. Caroti here illustrates the Wait calculation but does not take it as a major theme - perhaps because it has received limited attention in fiction. Will a slow ship be overtaken by faster technology, making the sacrifice of generations perhaps pointless?[1]

Though the new wave encompassed "inner space", feminist SF and later cyberpunk and steampunk, Caroti quotes examples of the old style such as Poul Anderson's *Tau Zero*, a voyage almost infinitely prolonged by the unstoppable acceleration of a Bussard ramjet, and Clarke's *Rendezvous with Rama*, the alien worldship with no apparent inhabitants. But Harlan Ellison's brave attempt to introduce a worldship to television SF, *The Starlost*, was cancelled after a single series.

The Information Age

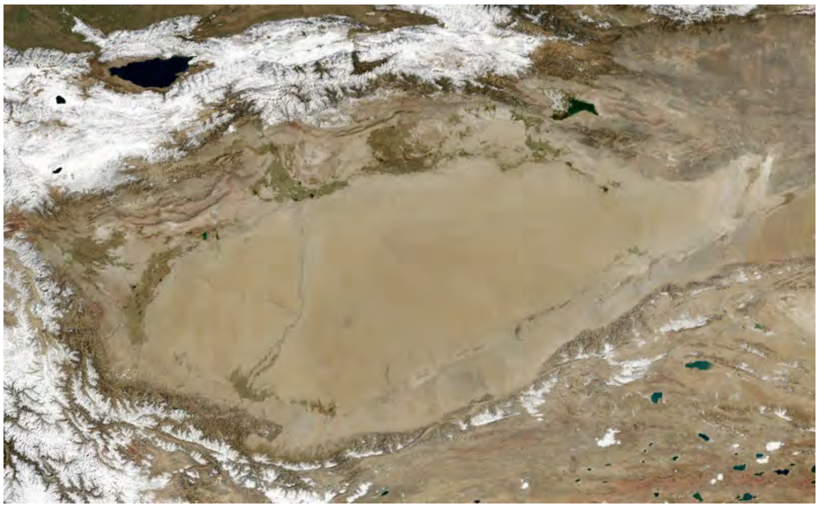
Caroti's last chronological phase is the period 1980-2001, The Information Age. Here we digress to the "Terminator" films but quickly come to trends in SF identified by John Clute in his article in *The Cambridge Companion to SF*, 2006 -

- relative decline in written SF versus films, TV and games
- the abandonment of the idea of the SF genre having a "life story", birth, maturity, etc
- the end of machine-oriented SF with the "end" of the space programme (written, of course, before the rise of private launchers, the development of "heavy" launchers outside NASA and lunar and Mars missions by India and China)
- new writers who are "citizens of the information revolution"

Caroti gives weight to the latter two but notes more Campbell-ian SF with Asimov and Clarke continuing to write stories in this style. I beg to differ in the case of Clarke who, perhaps influenced by his final home, Sri Lanka, embraced nature and even titled his space elevator story, a classic Campbell theme, *The Fountains of Paradise*.

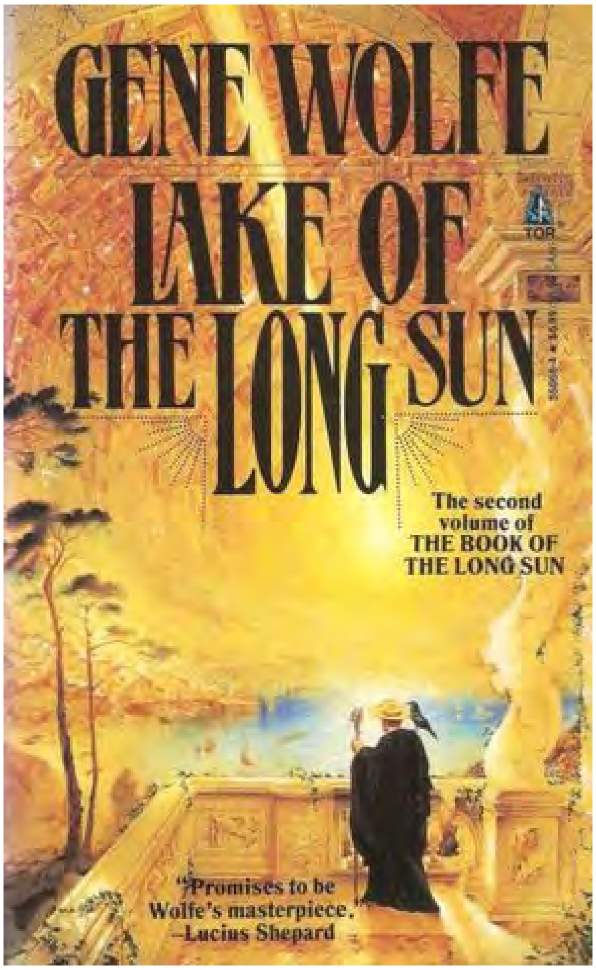
An exception, for Caroti, is Frank M Robinson with *The Dark Beyond the Stars*, in 1991. Here a worldship, 2,000 years into its voyage, has split into "go on" and "go back" factions with the "go on" faction all immortal. The viewpoint character discovers he is biologically immortal but is "mind wiped" every 20 years. When the ship does return to Earth it discovers an alien starship in orbit. Robinson wrote a 1954 story, "The Oceans are Wide" (briefly mentioned earlier in this review). The last survivors of Earth in a ship dominated by a visible "Director" and an unseen "Predictor". Caroti sees the decision, to settle a hostile world rather than a benign one to avoid decadence, as a contradiction. The voyagers are fleeing a nuclear holocaust arising from just the aggressive qualities sought in the destination planet - and thus a probable repeat of that history. In the later novel Robinson is saying "Earthman come home" 54 years after a story advocating the rebuilding of a "Heinlein tough" civilisation from nuclear ashes. He recommends reading the two stories in succession.

Another parable is Bruce Sterling's *Taklamkan*, a real desert providing the background of a story about the discovery of a monster cavern containing three fake starships populated by "undesirables".



NASA image of the Takla Makan Desert (setting of Sterling's *Taklamkan*) in north west China. 920 km by 420 km, mostly shifting sand.
www.britannica.com/place/Takla-Makan-Desert

[1] For a fairly recent examination of this see - *Interstellar Travel: The Wait Calculation and the Incentive Trap Of Progress*, Andrew Kennedy, JBIS, Vol. 59, 2006, open publication available via Google Scholar.



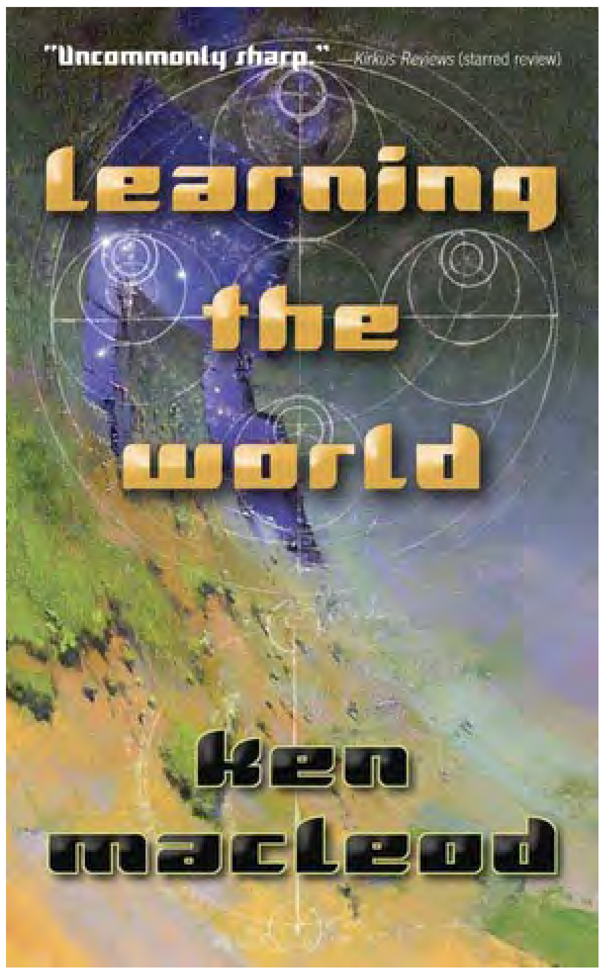
Caroti sees this as a relatively benign environment compared with our own outcast areas such as Gaza, Darfur and Afghanistan[1]. If we are to have what Caroti calls "generational entrapment" as in these unfortunate places then perhaps a worldship, even a simulated one, is preferable[2]?

Simone Caroti is clearly a Gene Wolfe fan. He looks at the worldship which forms part of his New Sun/Long Sun sequence of novels. From this long lived ship, the Whorl, he suggests Wolfe has a "painterly" approach, using SF tropes to examine concepts like Plato's cave[3]. The Long Sun is the extended illuminator of another cylindrical worldship with the population degenerating to worshipping the controlling artificial intelligences.

Cover 1995 Tor Books edition of Lake of the Long Sun, Gene Wolfe.
Illustrating the linear illuminator in Wolfe's cylindrical worldship

Conclusion. Trip's End

In the final part of the main thread of his book, Dr Caroti takes us beyond the final date in his title. His book was published in 2011 and he reports that a dozen worldship stories were published after 2001. He particularly commends Ken McLeod's *Learning the World*. The ship visits systems, planting settlements carrying Founders, Crew and Colonisers. The story is of First Contact, with a batlike species at about early 20th century stage of technology. A paradoxical situation arises with formerly peaceful travellers descending to civil war while the benign message they carry promotes peace amongst the "bat people". "A fight in front of the children" as one of the travellers puts it!



Ken McLeod's *Learning the World.*
US edition cover, Tor Science Fiction 2006

[1] a humorous treatment of this from Douglas Adams is the "B Ark", a real worldship populated by telephone sanitisers, hairdressers, personnel officers and management consultants in *The Restaurant at the End of the Universe* and the earlier radio and TV series.

[2] Reminiscent of President Donald Trump wanting to stop people coming to the US from "shithole countries" - as he told CNN in 2018 (edition.cnn.com/2018/01/11/politics/immigrants-shithole-countries-trump/index.html).

[3] Plato's cave - see Stanford Encyclopaedia of Philosophy, entry 13. Sun, Line and Cave of Plato's Middle Period Metaphysics and Epistemology https://plato.stanford.edu/entries/plato-metaphysics/#13

Conclusions

This is a massive piece of work, in terms of scope and thinking, fitted into a relatively modest 240 pages of main text. I suspect I have done it less then justice.

There is a substantial *Appendix. The Generation Starship: A Chronological Bibliography*, a general bibliography, chapter notes and a good index - though with a few flaws.

There are some inconsistencies between main text, the two bibliographies and the index. An example - Fritz Leiber's *Ship of Shadows* appears in the Chronological Bibliography with a detailed citation but not in the general Bibliography, the Index, or (as far as I can tell) the main text.

I have a few reservations -

- Inevitably such a short book, 240 pages of main text, on such a massive subject needs to concentrate to some extent and Caroti concentrates on the literary, political and social aspects of the subject with little on the science and engineering, either implied or explained, in the works described.
- The question of technological, scientific and cultural development on board, possibly informed and influenced by communication with Earth despite the delay, does not seem to be much treated either in worldships as described in the stories or analysed by Dr Caroti. But maybe I'm asking for more than the book sets out to achieve.
- The balance between the chronological periods suggests concentration on the first half of the century -
  - The Gernsback Era, 1926-1940 and The Campbell Era, 1937-1949 average 3 pages per year.
  - The Birth of the Space Age, 1946-1957, The New Wave and Beyond, 1957-1979 and The Information Age, 1980-2001 average 2 pages per year.
- The most significant omission, in this reviewers personal opinion, is the very brief mention of James Blish and his "Cities in Flight" series, notably *Earthman Come Home*, which imagines Manhattan as a worldship crewed by long-lived, but not immortal, 1950s-culture Americans, taking advanced technology around the galaxy with the slogan "Mow your Lawn, Lady?" emblazoned across City Hall. This looks like a prime target for the sort of cultural analysis that Caroti applies to what are, in my opinion, much lesser works. Blish has explicitly referenced Spengler's Decline of the West [1] as a primary inspiration for this series.

However I recommend Simone Caroti's book as the best coverage of the subject I have yet encountered and I believe it would merit an update and republication to a wider audience. In any case I will be reading it again.

Still from a video, Cities In Flight, by Charlie McCulloch (www.charliemcculloch.com/) UX Design Lead at Recast, Edinburgh, inspired by the James Blish stories

[1] Der Untergang des Abendlandes, Oswald Spengler, 1922-23. Spengler's ideas of the finite lifetime of civilisations were a clear theme in the Cities in Flight series www.britannica.com/biography/James-Blish. Blish even applied it to cosmology by implying a cyclical universe.

Project Pinpoint: Pushing the Limits of Miniaturization

Andrew Broeker

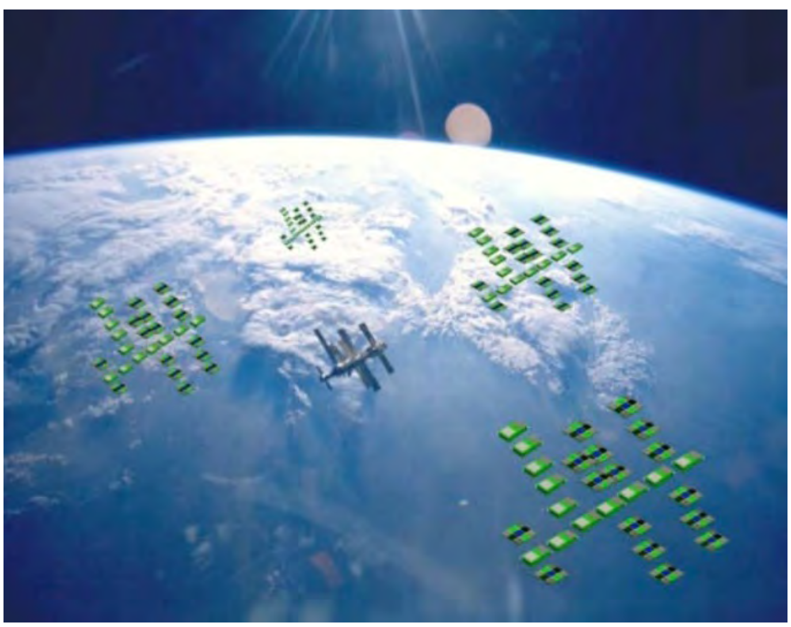
Project Glowworm has the objective of raising the orbit of a laser sail-equipped chipsat by 10 km - as a step on the way to interstellar probes at chipsat scale. The idea of a spacecraft so small acting as a (very) deep-space probe is an unprecedented technical challenge. With this in mind the Project Pinpoint team led by David Evinshteyn and Andrew Broeker are developing the first i4is chipsat, Project Pinpoint. Here lead designer Andrew Broeker explains how the team is addressing the challenge.

1.0 Introduction

I have been the Pinpoint Team's lead designer for about three years. With financial support from the Initiative for Interstellar Studies (i4is), we have been developing a 25x25 mm chipsat named Pinpoint. Chipsats, sometimes called femtosats, which are spacecraft that consist of a single circuit board with incorporated electronics. Pinpoint will advance chipsat design and develop production heritage for i4is and serve as a technology demonstrator for more capable and independent chipsats. Our focus is on developing a chipsat closer in computing, electrical power, and communications capability to what would be necessary for serious use of chipsats propelled by laser sails on missions exploring our own solar system and, ultimately, nearby stars. The development will also be applicable to near-term projects such as the chipsat for Project Glowworm[1].

So far, chipsats deployed in space have all operated in low-Earth orbit (LEO) and carried at most very simple sensors and have returned only small amounts of information to Earth, at least on a per-chipsat basis [2]. Laser-propelled chipsats used for space exploration beyond Earth orbit must surely feature more sophisticated communication systems and sensors if they are to be used for scientific inquiry or commercial purposes. Because the communications channel available to a several-gram spacecraft is quite small, it can be valuable to pre-filter its collected data for "useful" information before downlink. To further these ends, Pinpoint will feature a tiny 240x320 pixel color camera and use a low-resource machine vision algorithm to attempt to return only images of large, bright objects such as the Earth and Moon, with one image returnable per ~90-second communications window while passing over a ground station.

Achieving a sufficient volume of data return within the limited communication window with very low transmitted power necessitates a ground station more sophisticated than those used for other chipsat concepts [2]. A highly capable ground station aligns well with the overall concept of laser-propelled chipsats for space exploration, which primarily focuses on conserving resources by keeping as much of the mission infrastructure on or near Earth as possible [3].



Laser propulsion scale economies favour swarming and chipsat swarms are already under investigation here "SWIFT swarms mimicking the shape of the International Space Station" [4].

2.0 Mission Architecture

In its current conception, the Pinpoint mission hardware consists of one or more mobile radio ground stations and the Pinpoint chipsat, which is launched into LEO and either deployed to orbit freely via a launcher or permanently affixed to the exterior of a parent spacecraft.

2.1 Launch and Orbit

Despite previous launch offers, Pinpoint's launch and orbit are still in question, which presents obstacles for design. One possibility, which would simplify things for the launch provider and parent mission, is to simply attach Pinpoint permanently to the exterior of the parent craft. Options for spring-loaded deployment are also being considered.

A viable orbit will have both apoapsis and periapsis between 350 km and 750 km above Earth's surface and an inclination of at least 45 degrees. Higher inclination may be necessary if a collaborator wants to put a ground station at higher latitude.

2.2 Concept of Operations

Even if permanently affixed to a parent craft, Pinpoint will operate completely independently, with no power or data connections. Once sufficient energy is stored for camera operation, Pinpoint will begin to periodically capture images. These images will be assigned a score using criteria for identifying objects of interest, and due to limited onboard storage space, low-scoring images will be overwritten by new images. The selection criteria will select for images showing large objects such as the Earth and Moon.

The Pinpoint Team will drive to locations near Pinpoint's ground path throughout the mission. At the appropriate time, determined using satellite tracking services, the ground station will begin attempts to contact Pinpoint to request downlink. Once contact is established, Pinpoint will transmit data packets which, due to data storage constraints, will be encoded for forward error detection in real time. Upon receipt, the ground station will decode the packets and check for uncorrected errors in real time so that it may request that erroneous packets be resent. Once all packets for a given image are received and verified, the ground station will signal Pinpoint to overwrite the received image the next time it attempts image capture.

A mobile ground station will allow us to set up in remote locations closer to the ground path in order to maximize signal return and minimize interference, as Pinpoint will pass closer and be more directly overhead, keeping it in communications range for longer. Ideal locations will be elevated and away from sources of radio interference, but practicalities of time and travel will of course limit options. Exactly how close to the ground path we want to be will depend on the details of Pinpoint's orbit. Subsequent passes near the same area will be approximately 90 minutes apart, which is the amount of time we'll have to reposition if we are to attempt to receive consecutive passes on the same day with the same ground station. The minimum distance between subsequent passes is highly dependent on the inclination of Pinpoint's orbit and the latitude of the ground station's operating area, with lower-inclination orbits preferable so long as the inclination exceeds the desired latitude. In a polar or near-polar orbit it would be impossible for a mobile ground station to catch subsequent passes at likely latitudes.

The mission will end when Pinpoint ceases to function, or when the concept has been sufficiently demonstrated as workable. Eventually Pinpoint will be destroyed upon orbital decay and atmospheric reentry.

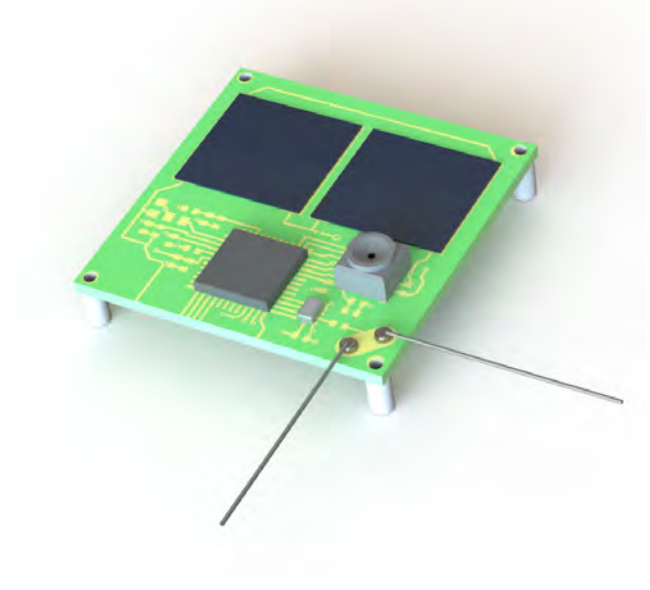


Figure 1: A 3D rendering depicting Pinpoint's current design. Small components not depicted.

3.0 Design

The primary challenges in chipsat design compared to the design of larger spacecraft are the extremely limited size and power supply, and the direct exposure of components to the space environment. These are, in essence, the same obstacles faced in the design of any spacecraft that is not self-propelled or self-stabilized, but exaggerated to the point of approaching the limits of being able to accomplish anything useful. As is often the case with spacecraft, some of these difficulties can be alleviated by improving the capability of supporting ground systems.

In the case of Pinpoint, the preliminary design is made more difficult by the uncertainties regarding its configuration in relation to the parent craft. Permanent attachment to the exterior of the parent craft could present issues with solar energy collection and signal transmission, depending on the attitude and rotation of the parent craft.

3.1 Surviving Space

Earth orbit is in many ways a more hostile environment than is interplanetary space. The Earth's magnetic field captures energetic charged particles, and while LEO is not nearly as bad in this regard as are high orbits, this radiation may still damage digital electronics. With no outer skin, the components are exposed directly to this radiation.

The thermal environment, too, is in some ways more extreme than in interplanetary space. When passing between Earth and the Sun, heating comes from both sides. When eclipsed by the Earth, temperatures plummet. In addition to potential issues with component operating temperatures, this fluctuation results in considerable thermal stress. With such a small thermal mass, no insulation, and high surface-to-volume ratio, chipsats suffer more intensely from this issue than do other spacecraft.

Micrometeorites are one threat for which chipsats have some advantage over larger spacecraft. Their small cross sections make them much less likely to be struck, though strikes are more likely to be catastrophic. Pinpoint's mission is quite short, but this is a definite consideration for more advanced projects.

Given the many other challenges faced, no special efforts are being made to avoid these problems. Components will undergo thermal vacuum chamber testing to ensure short-term function, but the necessarily limited life of Pinpoint due to radiation, thermal stress, and potentially rapid deorbiting are simply accepted as problems that may be alleviated in some applications and which can be addressed by future developments.

3.2 Size and Components

The limited size of Pinpoint makes it critical to minimize the number of distinct components. System on a Chip devices (SoCs) are extremely attractive in this role, as they combine diverse capability in computation and radio communications. In many cases, SoCs have low power consumption, sleep functionality, and integrated sensors. I selected a chip from Silicon Labs' Flex Gecko series primarily for its radio capability and operating voltages (Section 3.3). The full-wavelength V-antenna will be board-integrated.

Several instruments were considered for Pinpoint early on, including magnetometers, GPS receivers, and inertial measurement units. To conserve PCB space, I ultimately decided to focus on a single sophisticated instrument. Unlike a camera, positional instruments are often integrated into combined-function chips such as Flex Gecko's line, so they would be trivial to integrate into future chipsat projects once available components advance. A 240x320 pixel Galaxycore GC6123 color camera was selected, along with a Jiangxi Hongxin Optical Co. PM011 endoscopic camera lens and assembly. The captured images will be low-quality, distorted, and will only be able to image the very brightest stars. Purpose-made equipment of similar size would undoubtedly perform better, but this assembly will serve as a sufficiently sophisticated instrument for demonstration purposes.

All energy for Pinpoint will be collected by board-mounted solar cells, which will be protected from back-voltage by a MAX40200ANS+TC-ND integrated circuit ideal diode. Collected energy will be stored in several components that will each support specific functions. A 470 µF capacitor will store enough energy and discharge it at an appropriate voltage to operate the camera long enough to capture a single image and move it to memory. A MS920T-FL27E lithium battery provides 1 milliamp at 3 V in order to power the Flex Gecko in sleep mode and during low-rate processing. An 11 mF supercapacitor provides enough power to maintain radio communications during a 90-second ground station pass.

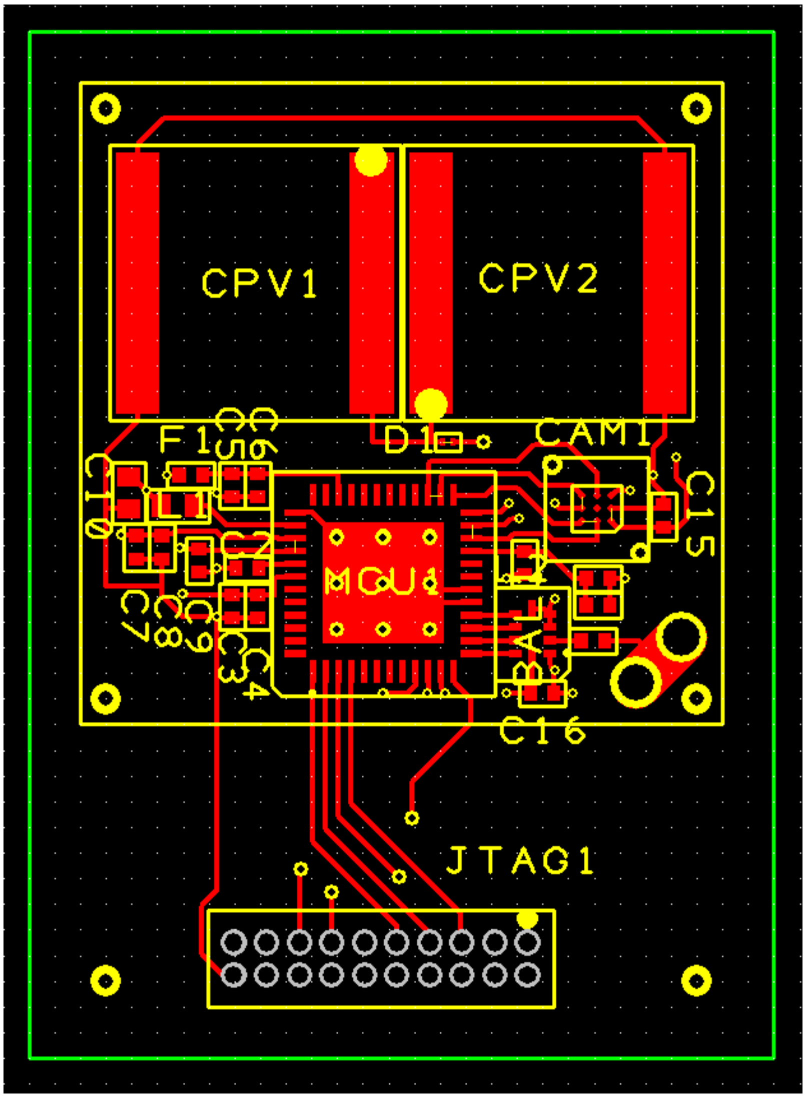


Figure 2: The front side of the preliminary PCB design, including JTAG connector for testing and software development. The PCB would be cut down to the yellow outline for flight.

Of these components, only the camera's power capacitor is mission-critical. This capacitor in conjunction with the solar cells will be able to power the other functions of Pinpoint, albeit at a lower rate, so a complete transmission may require multiple passes. These energy storage components have already been tested by Pinpoint Team member Sarah Friedensen of the University of Pennsylvania in a room-temperature vacuum chamber over a period of several months and continue to function satisfactorily. Thermal vacuum testing will occur at a later date.

We have already produced a tentative design for Pinpoint's PCB layout, with all components electrically decoupled according to manufacturer instructions. Assembly will mostly be performed by a specialist service, with only the camera lens, antenna, and energy storage components installed by the Pinpoint Team.

3.3 Downlink Plan

The downlink will necessarily have a low signal to noise ratio (SNR). The chipsat antenna needs to radiate close to uniformly in all directions at only around 20 mW over a distance of hundreds of kilometers. The directivity of the ground station antenna is limited since the short mission duration and quick on-site setup of the ground station make machine pointing an impracticality. The chipsat's signal will be less powerful than received thermal noise. The ground antenna choice does limit reception of interfering transmission originating from Earth, but cannot eliminate them entirely. The total data payload for one image is about 154 kB.

This low SNR necessitates a careful choice of radio protocol and equipment. Radio communication is further complicated by variations in Doppler shift and spacecraft orientation during radio contact windows. The 70 cm amateur band (~440 MHz) provides a good balance between antenna size, sensitivity to noise, and available bandwidth while requiring only a basic amateur radio license for use. Differential phase shift keying (DPSK) is an ideal modulation scheme for this application, as it is much less sensitive to ongoing continuous phase and frequency shifts than most other modulation schemes. Due to the low SNR, there is no benefit to using a higher-order modulation scheme than binary. [5]

Data packets will have cyclic redundancy check (CRC) error detection blocks computed in advance of downlink. These 24-bit blocks of high-order parity data will be appended to the ends of data packets and allow final confirmation that each packet is received correctly.

Bits will be encoded with a direct-sequence spread spectrum chipping scheme which encodes bits as chips (signal modulations) at a ratio of 16 chips per bit. This scheme allows error correction at the level of single bits and reduces susceptibility to radio interference. This scheme is hardware-implemented in the Flex Gecko's radio subprocessor.

Forward error correction by Pinpoint will be implemented by the main processor with a turbo encoder in real time as the message is passed to the radio during transmission. This will increase the number of transmitted bits by a factor of 3 or 4, but will allow bits received incorrectly by the ground station to be corrected in most cases.

3.4 Ground Station

The design of the ground station and its software is just as critical to the success of the Pinpoint mission as is the design of the chipsat itself. We have chosen the Ettus Research N210 USRP with WBX daughterboard, a software-defined radio (SDR) as the ground station transceiver. This SDR will provide a good noise floor as well as the capacity for software-defined modulation, signal subsampling, easy synchronization, real-time Doppler correction, and FPGA implementation of decoding. Because the power transmitted from Pinpoint and thus the SNR will be very low, computationally-intensive decoding schemes are necessary to ensure downlinks are accurate. An FPGA will excel at processing the decoding quickly during a satellite pass.

The rest of the ground station equipment will consist of a motor vehicle, a car battery or generator, a laptop for operating the SDR, a low-noise amplifier for enhancing receiving signals from Pinpoint, and a mast-mounted eggbeater antenna with ground plane from M2 Antenna Systems, optimized for use with satellites. A handheld Yagi antenna will be available as a backup option. I considered a concept for a handmade antenna with two parallel dipoles over a ground plane to create a planar main beam lobe which could be aligned with the sky path of the chipsat, but rejected it as it would be difficult to use and have issues with signal polarization which could dramatically reduce signal gain in some chipsat orientations.

As Pinpoint lacks the computational resources, receiver noise floor, and antenna directivity of the ground station, messages to Pinpoint from the ground station will pass through a signal power amplifier and employ a simple modulation and encoding scheme rather than using the same scheme that Pinpoint uses for transmission.

Ettus Research N210. Credit: Ettus Research

4.0 The Path Forward

The Pinpoint Team is currently acquiring hardware for software development and hardware testing.

Our next steps are to finalize the details of the radio scheme, test the camera, perform breadboard testing on a model device, and finalize the PCB layout. From there, we will produce a batch of ten Pinpoint chipsats for hardware testing and software finalization.

Personally, I'm most excited for beginning downlink testing, which should be starting quite soon. We'll be using real distance (a few kilometers perhaps) between the chipsat stand-in and ground station in addition to local testing with attenuators in order to evaluate the performance of different encoding schemes and hardware arrangements with real radio interference.

4.1 Glowworm

Project Glowworm's [1] laser sail chipsat could use many of Pinpoint's features, including a Flex Gecko SoC chip and similar power collection electronics. Pinpoint's planned energy storage components have far too much mass to meet the mass goal for the Glowworm chipsat, but the Glowworm chipsat does not need a camera and will have much smaller data transmission and computation requirements, so much less energy storage will be necessary. The Glowworm chipsat could also share significant segments of Pinpoint's radio and operational software.

5.0 How You Can Chip In

Our mission is much more likely to be successful if we can recruit other ground teams to help with downlink. Universities, hobbyists, and businesses which already have access to much of the required equipment for a ground station are ideal collaborators. Auxiliary ground stations would not need to be mobile or use identical hardware setups, though collaborators who would like to use other SDRs might need to write their own code based on our documentation in order to participate.

If you are interested in mission collaboration, please contact Pinpoint Team's project manager David Evinshteyn at evinshteyn@gmail.com. For technical discussion, you may contact me at andrewbroeker@gmail.com.

Citations

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Andrew Broker studied Physics and Mathematics at Gettysburg College and Drexel University. He got involved in spacecraft systems engineering through Drexel's relationship with i4is. His hobbies include bonsai and the keeping of exotic plants and animals. His HAM callsign is KC3NBI.

NEXT ISSUE

Interstellar topics at International Astronautical Congress 2021

More about IRG 7th Interstellar Symposium, Tucson, September

Interstellar downlink communications - the "heavy brigade" and the (very) "light brigade"

Cover Images

Front Cover

Uranus is another gas giant, smaller than Jupiter and Saturn, and blue-green in colour. Its most unusual feature is that instead of spinning upright, like a top, it 'rolls' around its orbit like a ball on its side, its axis being tilted at 98 degrees (Earth's axial tilt is 23.5). Once thought to have 5 moons, the latest count was 27…

www.astroart.org/uranus

Back Cover

International Space Station Transits the Full Moon

www.nasa.gov/image-feature/international-space-station-transits-the-full-moon

The International Space Station, with a crew of six onboard, is seen in silhouette as it transits the moon at roughly five miles per second on Tuesday, 30 Jan, 2018, from Alexandria, Va.

Onboard are NASA astronauts Joe Acaba, Mark Vande Hei, and Scott Tingle; Russian Cosmonauts Alexander Misurkin and Anton Shkaplerov, and Japanese astronaut Norishige Kanai.

Image Credit: (NASA/Bill Ingalls)

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The mission of the Initiative & Institute for Interstellar Studies is to foster and promote education, knowledge and technical capabilities which lead to designs, technologies or enterprise that will enable the construction and launch of interstellar spacecraft.

Vision

We aspire towards an optimistic future for humans on Earth and in space. Our bold vision is to be an organisation that is central to catalysing the conditions in society over the next century to enable robotic and human exploration of the frontier beyond our Solar System and to other stars, as part of a long-term enduring strategy and towards a sustainable space-based economy.

Values

To demonstrate inspiring leadership and ethical governance, to initiate visionary and bold programmes co-operating with partners inclusively, to be objective in our assessments yet keeping an open mind to alternative solutions, acting with honesty, integrity and scientific rigour.

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Front cover: Uranus 'rolls' around its orbit
Credit: © 2015 AstroArt by David A Hardy
Back cover: ISS Transits the Full Moon
Credit: NASA/Bill Ingalls

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