

Seeding the Universe with Life: Securing Our Cosmological Future

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Appendix: Some Formulas and Mission Parameters

A1. Launch by Solar Sails

A1. Navigation and Probability of Arrival at the Target

For aiming the vehicles, the positions of the targets when the missions arrive must be predicted. The positional uncertainty at the time of arrival, δy , is expressed by Eq. (1), where α_p is the resolution of proper motion of the target object, d is the distance from Earth, and v the velocity of the vehicle.

$$\delta y = \alpha_p (d^2/v) \quad (1)$$

Angular proper motion resolutions of 0.00001 arcsec/yr can be anticipated. The positional uncertainties of the various targets considered upon the arrival of solar sail based ($v = 0.0005 c$) missions are listed in Table 1 in the text.

The probability that the vehicle will arrive at the targeted zone is determined by the ratio of the cross-sectional areas of the targeted region and that of the targeting scatter.

$$P_{(\text{target})} = A_{(\text{target})} / \pi (\delta y)^2 = r_{\text{target}}^2 v^2 / \alpha_p d^4 \quad (2)$$

Values of $P_{\text{target}} \geq 1$ mean unit probability. Equation (2) yields the P_{target} values in Table 1 as shown. For large cloud cores the targeting uncertainty is smaller than the radii of these objects and arrival at these targets is practically certain.

For planetary targets within a habitable zone of radius R_{hz} and width $w_{\text{hz}} = 0.4_{\text{hz}}$, the area of the target habitable zone is equal to that of a circle with radius $r = 0.89 r_{\text{hz}}$. For arrival at a zone in an interstellar cloud, equation (2) applies for a spherical target with a radius r_{cloud} with a $A_{\text{target}} = \pi r^2$ area cross-sectional.

A2. Deceleration, and Capture at the Target Zone

For solar sails missions to planets, deceleration is achieved by solar radiation acting in reverse of the original acceleration at launch. Once decelerated to orbital velocities, the payload is captured into orbits intersecting those of planets and they are dispersed and captured by planets.

Deceleration by drag in the viscous gas medium can be modelled numerically using Eqs. (3) and (4). This allows designing the capsule geometry (size) for selective capture in the desired zones of interstellar clouds, based on drag by the medium as given by equation (3) for elastic collisions with gas molecules.

$$dv/dt = -2(\rho_m v^2 A_c / m_c) \quad (3)$$

Here ρ_m is the density of the medium; v is the velocity, A_c the area and m_c the mass of the capsule. For a spherical object, $\sigma_a = (4/3)\rho_c r_c$, where σ_a is the density of the capsule material, assumed to be 0.001 kg/m^3 for a biological payload, and r_c is radius of the capsule.

$$dv/dt = -(3v^2/2\rho_c) \rho_m/r_c \quad (4)$$

The radius is a variable in Eq. (4) which was used for numerical integration.

A3. Delivery to Planets

The panspermia capsules captured in accretion disks or interstellar clouds will mix with the dust and will be delivered to planets in the same ratio as the total dust/ delivered dust. The probability of delivery of a captured capsule to the planet is then given by Eq. (5).

$$P_{(\text{entry})} = m_{(\text{total dust})} / m_{(\text{delivered dust})} \quad (5)$$

The total probability that a capsule that was launched originally is delivered to a planet is then given by Eq. (6).

$$P_{(\text{planet})} = P_{(\text{target})} / P_{(\text{entry})} \quad (6)$$

If the probability for a launched capsule to reach a target planet is small, then sufficiently large numbers of capsules n_{capsule} must be launched to assure a probability of landing on a planet near unity, as given by Eq. (7).

$$n_{(\text{capsules})} = 1 / P_{(\text{planet})} \quad (7)$$

If each capsule carries $m_{(\text{capsule})}$ of microbial biomass then the required biomass for a successful mission is given by Eq. (8).

$$M_{(\text{biomass})} = m_{(\text{capsule})} \times n_{(\text{capsules})} = m_{(\text{capsule})} / P_{(\text{planet})} \quad (8)$$

For a reasonable probability of success we may aim to deliver 100 capsules to the planet, each of carrying 100,000 microorganisms with a biomass of 1.1×10^{-10} kg with a total biomass of 1.1×10^{-8} kg. The biomass required for successful missions in Table 1 was derived on the basis of these considerations.

A4. Mission Parameters to Individual Stars

Consider a mission to the habitable zone of a star. We consider launching a 10 kg payload of microorganisms, launched by solar sails (Fig. 1). The sail-ship is placed in a solar orbit at 1 au and launched by unfurling a sail that cancels solar gravitation. To achieve the current level of monitoring of spacecraft attitudes to 0.01 arcseconds, the launch window is 0.2 seconds. For a target at 10 ly this will allow entry into an orbit defined with 0.024 au if the position of the star was defined accurately.

In order to arrive at the area of a habitable zone about a Sun-like star, we must target an area with a size of about 1 au (about $1e11$ meters). If the resolution in the proper motion of the target star is 0.01 milli-arcseconds/year and the target star is 10 light-years away, then the uncertainty in the speed of the star is 0.000031 au/year. After a transit at 0.0005 c for 20,000 years the uncertainty in the position of the star and its habitable zone will be 0.6 au and the microbial capsules should be dispersed over an area with this radius.

Finally, the payload must be captured by the target planet. For this purpose, a payload of 1 kg containing $1e15$ microorganisms will be dispersed by a propellant of 0.46 kg into $1e10$ capsules each weighing $1e-10$ kilograms containing 100,000 microorganisms and shielded against UV radiation. The capsules will disperse in twenty years into a ring with a density of $3.5e-15$ capsules/cm², in a ring from 0.9 to 1.1 au. A planet with a gravitational radius of 10,000 km will capture 11000 capsules with 33 million microorganisms when it passes the capsule ring. Coating the capsules with reflective materials will sweep them out from the star or allow them to oscillate in various orbits to seed further planets.

A5. Mission Parameters to Star-Forming Clouds

We consider missions to the Rho Ophiuchus interstellar cloud 520 ly away, using millimetre size, milligram microbial capsules launched by 35 cm solar sails at 0.0005 c to penetrate the cloud to high-density planetary accretion zones with densities of $1e-17 \text{ kg/m}^3$ where they are stopped by viscous drag.

The Rho Ophiuchus cloud forms long-lived low and medium mass stars. As described by Mezger (1994), the overall cloud with a mass over $3,000 M_{\text{sun}}$ (solar mass $M_{\text{sun}} = 2e30 \text{ kg}$) extends to about 50 ly ($< 1.7e-18 \text{ kg/m}^3$), which contains a 6x6 ly dense fragment of $\sim 500 M_{\text{sun}}$ with a density of $1.7x1e-11 \text{ kg/m}^3$ containing 78 young stellar objects. Within this cloud are four cores with diameters of over 1 ly and densities of ($1.7e-15 \text{ kg/m}^3$) and masses of 1 - 15 M_{sun} . One of these cores shows four protostellar condensations with radii of $\gg 3e14 \text{ m}$, densities of ($1.7e-14 \text{ kg/m}^3$) and masses of 0.4 to 3 M_{sun} and dust temperatures of 15 - 20 K.

We may consider spherical capsules entering the cloud with a velocity of $1.5e5 \text{ m s}^{-1}$, and their velocity becomes homogenized with the medium when they are decelerated to 2000 m/s, a typical internal velocity of grains in a cloud. The deceleration of spherical objects with radii of 35 μm and 1 mm, injected with an initial velocity of 0.0005^4 c shows that both size objects penetrate fully the Ophiuchus cloud fragment. The 35 μm object is stopped in the dense core, but the 1 mm object can penetrate it to the even denser protostellar condensations.

Even with the current resolution of $10^{-4} \text{ arcsec/yr}$ of the proper motion of the cloud, the dense core can be targeted reliably. However, even with α_p of 0.00001 arcsec/yr, targeting a 100 au radius dust sphere about an embedded star or accretion disk P_{target} is then 0.0036, and for targeting a 1 au habitable zone about a star P_{target} is only $3.9e-7$ for a star in the cloud, the small values resulting from the d^{-4} dependence of the P_{target} function.

Equation 2 yields the P_{target} values as shown in Table 1 for arrival at various zones of the cloud. The microbial packets are then dispersed as 20 micrometer 0.1 microgram capsules each carrying 100,000 microorganisms, where they become part of the cold 15 – 20 K dust.

The captured capsules will mix with the dust in the cloud and will be delivered to planets in the same ratio as the dust. Considering the typical masses of the various cloud zones, about 0.001 of the launched mass captured in the overall cloud will be captured in each protostellar condensation, and from its $1e30$ kg mass about $1e17$ kg dust will be captured by a planet during a billion year prebiotic period. By the same ratio, about $1e-13$ of the microbial capsules that were captured in the protostellar condensation will be delivered to the planet. Altogether, $1e-16$ of the originally launched biomass will be captured by the planet. The probability of capture from other zones of the cloud may be estimated similarly. These results and the required biomass for success are shown in Table 1 in the text.