Starwisp: An Ultra-Light Interstellar Probe

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Starwisp is an interstellar flyby probe of wire mesh sail with microcircuits at each intersection. It is pushed by beamed microwaves at high acceleration and reaches a coast velocity near light speed while still close to the transmitting antenna. Upon arrival at the target star, the transmitter floods the star system with microwave energy. Using the wires as microwave antennas, the microcircuits collect energy to power their optical detectors and logic circuits to form images of the planets in the system. The phase of the microwaves at each point of the mesh is sensed and used to form a retrodirective phased array that beams a signal back to Earth. A minimal Starwisp would be a 1 km mesh sail weighing 16 g and carrying 4 g of microcircuits. It would be accelerated at 115 *g* by a 10 GW microwave beam, reaching one-fifth of the speed of light in one week. Upon arrival at Alpha Centauri 21 years later, Starwisp would collect sufficient microwave power to send back high-resolution television pictures during its flythrough of the system.

Nomenclature

a = acceleration of sail
a_0 = initial constant acceleration of sail
A = area of square sail
b = diameter of wire in mesh sail
B = diameter of transmitted beam
B_e = diameter of retroreflected beam back at Earth
B_* = diameter of transmitted beam at star
c = speed of light (3×10^8 m/s)
d = diameter of sail
D = diameter of transmitting Fresnel lens
e_a = absorptance of sail
e_b = fraction of energy in main beam of Fresnel lens
e_f = transmission efficiency of Fresnel lens
e_g = geometry factor of sail
e_h = ratio of maximum hole diameter to wavelength (h/λ)
e_i = inverse of signal to noise used to insure bit detection
e_m = efficiency of transfer of photon momentum to sail
e_p = propulsion efficiency of system
e_r = reflectance of sail
e_t = transmittance of sail
E = minimum energy needed to transmit one bit of information
F = microwave flux level
g = earth gravity (9.8 m/s^2)
h = maximum diameter of holes in mesh sail
k = Boltzmann's constant (1.38×10^{-23} J/K)
K = mesh reflectance parameter
L = total length of wire in square sail
m = mass of square sail
M = mass of circularized sail
n = number of wires across width of square sail
N = number of bits
N_p = number of bits in high resolution picture (8×10^6)
P_e = power received back at Earth
P_i = power incident on sail
P_t = power transmitted
P_* = power incident on sail at star
q = density of wire in mesh sail
r = spacing of wires in mesh sail
s = distance between transmitting lens and sail
s_0 = distance over which acceleration stays constant
s_* = distance to star
t_0 = time of constant acceleration
t_p = time to transmit one picture
T = temperature
u = mass per unit area of sail
v = velocity of sail
v_0 = velocity of sail at end of constant acceleration period
v_t = terminal velocity of sail
λ = wavelength of microwave radiation

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Introduction

CONSTRUCTING a spacecraft capable of traveling over interstellar distances in not trivial. Even the launching of a one-way, flyby probe to the nearest star is a major undertaking. There have been many concepts published for attaining interstellar transport.[1,2] The general conclusion is that because of the exponential increase in the mass fraction for velocities approaching that of flight, ordinary rockets will not suffice for rapid interstellar transport, unless, perhaps, the rockets are powered by antimatter.[3]

The interstellar ramjet[4] is one example of a "rocketless" solution to the interstellar transport problem, since it extracts its fuel from "empty" space, but there are major difficulties in building a sufficiently lightweight scoop for the ramjet. Another solution is to use energy "beamed" to the vehicle using some transmitter in the solar system. One example is the use of high power lasers to push lightsails over interstellar distances.[5] This paper will discuss a near-term system that is a variant of the laser-pushed sail: a maser-pushed sail called Starwisp.

Starwisp is a net of semi-intelligent wires that will be accelerated to near-relativistic speeds by modest amounts of beamed microwave power. During its flyby through the nearer stellar systems, it will send back pictures that will allow us to count and determine the size of the planets and even obtain pictures of some of the planetary surfaces if the probe can be made to pass within a few astronomical units (a.u.) of the planets.

A source of microwave power that might be available in the near future would be a solar-power satellite. One proposed solar-power satellite design uses large arrays of solar cells to convert sunlight into electricity, which is then used to generate about 10 GW of microwaves. In normal use, these microwaves would be beamed to antennas on the Earth's surface and converted into electrical power. During the testing phase of the solar-power satellite, this microwave power could be used to launch one or more modestly sized Starwisp probes to the nearer star systems. For more distant journeys with more massive probes moving at higher velocities, it would be necessary to construct a special purpose source of microwave energy with power levels of 1-100 TW (terawatts = 1000 GW).

Acceleration of Sail

The normal transmitting antenna for a solar-power satellite is not large enough to transmit a microwave beam over the distances that will be needed during the acceleration phase of the Starwisp mission. It will be necessary to construct a very large transmitter lens to relay the microwave power to the Starwisp sail. The transmitter lens will be a microwave Fresnel zone plate with rings of wire mesh alternating with empty rings. The wire mesh will have holes larger than the microwave wavelength but small enough to affect the phase of the microwaves passing through them so that the phase shift is exactly 180 deg. Thus, the microwaves passing through the mesh portions will be a half-wavelength out of phase with the microwaves passing through the empty portions, causing all the different pathlengths to be in phase at the focal point.

A Fresnel lens can focus radiation to a spot size given by the relation:

$$B = 2.44\lambda s/D \tag{1}$$

where the factor 2.44 indicates that the diameter of the focal spot is taken not at the half-power point of the main beam but at the diameter of the first null in the diffraction pattern of a circular lens. There is a maximum of 84% of the energy in this main lobe, which gives a beam efficiency of $e_b = 0.84$. There will be some loss at the transmitting antenna due to energy reflected and absorbed by the phase-shifting mesh and the fact that a Fresnel zone plate is not a perfect lens. Thus, of the transmitted power from the source, the maximum amount of incident microwave power at the focal spot is:

$$P_i = e_b e_f P_t \tag{2}$$

This incident microwave power will give the sail an acceleration

$$a = \frac{2e_m P_i}{Mc} \tag{3}$$

The efficiency of transfer of photon momentum to the sail consists of two components. First, when the microwaves strike the sail, the sail receives an impulse from all the microwave flux except that which passes through the sail $(1 - e_t)$, including the portion of the microwaves absorbed by the resistive losses in the sail. Second, the sail receives another impulse from the portion of the microwaves reflected from the sail. Thus, the momentum transfer efficiency is given by:

$$e_m = [(1-e_t) + e_r]/2 = (2e_r + e_a)/2 \sim e_r \tag{4}$$

There will be two phases of acceleration. First there will be a constant acceleration while the sail is still close to the transmitting lens and the lens can focus on a spot smaller in size than the sail. If we include all the efficiencies in the power transmission system, then the initial acceleration is:

$$a_0 = \frac{2e_p P_t}{Mc} \tag{5}$$

where the "propulsion" efficiency is the product of the Fresnel lens efficiency, the beam efficiency, and the momentum transfer efficiency

$$e_p = e_f e_b e_m \sim e_f e_b e_r \tag{6}$$

The distance over which the acceleration stays constant is:

$$s_0 = \frac{Dd}{2.44\lambda} \tag{7}$$

When the sail reaches this distance, it will have reached a velocity of

$$v_0 = (2a_0 s_0)^{1/2} \tag{8}$$

in the time

$$t_0 = (2s_0/a_0)^{1/2} \tag{9}$$

The sail is now at the point where the beam diameter is greater than the sail diameter; the power on the sail drops off with distance. The power incident on the sail is then

$$P_i = (d^2/B^2) e_b e_f P_t \tag{10}$$

Using Eqs. (1) and (7), it can be shown that the acceleration from that power is:

$$\dot{v} = \frac{2e_m P_i}{Mc} = \frac{a_0 s_0^2}{s^2} \tag{11}$$

This acceleration can be integrated from the point $s = s_0$ out to infinity to obtain the solution for the terminal velocity of the sail:

$$v_t^2 = 2v_0^2 = 4a_0 s_0 \tag{12}$$

Substituting in Eq. (5) for a_0 and Eq. (7) for s_0 and rearranging, an equation for the transmitted power needed to accelerate a sail to a given terminal velocity can be obtained

$$P_t = \frac{2.44 Mc v_t^2 \lambda}{8 e_p d D} \tag{13}$$

Sail Parameters

The mass of a mesh sail depends predominantly upon the diameter of the sail, the diameter and density of the wire used in the mesh, and the maximum diameter of the holes in the mesh. There is also a slight variation depending upon the geometry of the mesh. For a square sail with an $n \times n$ square mesh, the length of the wire is easily determined to be

$$L = 2n(n+1)r \sim 2n^2 r \tag{14}$$

The mass of a square sail is then

$$m = (\pi/4) q b^2 L \tag{15}$$

The diameter of the sail (along the diagonal dimension) is

$$d = nh = 2^{1/2} nr \tag{16}$$

and the area of the square sail is

$$A = n^2 r^2 = d^2/2 \tag{17}$$

Thus, the mass per unit area of the square sail is

$$u = \frac{m}{A} = \frac{\pi q b^2}{2r} \tag{18}$$

For a square mesh, the maximum hole size is along the diagonal of the square hole, or

$$h = 2^{1/2} r \tag{19}$$

If it is assumed that the actual sail is circular in shape with a diameter equal to the longest dimension of the square sail, but rounded out with square mesh elements with the same mass per unit area, then the mass of the circularized sail is found to be:

$$M=\frac{\pi}{4}ud^2=e_q\frac{\pi^2}{4}\frac{qb^2d^2}{h} \tag{20}$$

where $e_g=0.707$ for a square sail. Similar analyses with hexagonal and triangular meshes give the same equation, provided the maximum hole diameter is kept the same. As is shown in Table 1 and Fig. 1, the geometry factor varies slightly with the choice of mesh structure, with the heavier mesh structures being those having more wires meeting at each intersection.

If it is assumed that the maximum hole diameter in the mesh is some fraction of the wavelength of the microwave radiation:

$$h=e_h\lambda \tag{21}$$

and Eq. (21) is substituted into Eq. (20), it is found that the mass of the sail is inversely dependent on the microwave wavelength

$$M=\frac{\pi^2 e_g qb^2 d^2}{4e_h\lambda} \tag{22}$$

Substituting this equation for the mass into Eq. (5), it is seen that the initial acceleration increases with increasing wavelength.

$$a_0=\frac{8e_p e_h P_t \lambda}{\pi^2 e_g cqb^2 d^2} \tag{23}$$

If is it assumed that the transmitted power is fixed and the terminal velocity desired is fixed, then there is a fixed relationship between the ratio of the diameter of the sail and the diameter of the transmitting lens. Substituting Eq. (22) for the mass in Eq. (13) and solving for the ratio D/d, it is found that the ratio of the lens diameter to the sail diameter is independent of the wavelength of microwave radiation and depends only on the parameters of the mesh wires, the transmitted power, and the terminal velocity desired

$$\frac{D}{d}=\frac{2.44\pi^2 e_g cqb^2 v_t^2}{32e_p e_h P_t} \tag{24}$$

In actuality, the propulsion efficiency does vary slightly with the wavelength, but parametric studies with various choices of wavelength, wire size, and wire spacing were carried out, and it was found that the combination of the two efficiency factors, $e_p e_h$, is roughly a constant with the value 0.04 for all reasonable values of those parameters.

Reflectance of a Wire Mesh

The reflectance of a wire mesh for microwaves has received some study because a wire mesh makes a good ground plane for an antenna. The complete theory for arbitrary relative orientation and polarization is complicated, but does seem to agree with experiment.[6] The reflectance efficiency of a perfectly conducting, square, bonded wire mesh at normal incidence is a function of a mesh parameter that depends not only upon the ratio of the mesh spacing to the microwave wavelength h/λ, but also logarithmically on the ratio of the mesh spacing to the wire diameter h/b

$$K=(2h/\lambda)\ell n h/\pi b \tag{25}$$

The reflectance as a function of the mesh parameter is shown in Fig. 2, which was derived from Fig. [4(a)1] of Ref. 6. (It

Table 1 Parameters of various mesh patterns

Mesh type	No. of intersecting wires	Geometry factor, e_g
Hexagonal	3	$3^{-1/2}$ (0.577)
Square	4	$2^{-1/2}$ (0.707)
Triangular	6	3/4 (0.750)

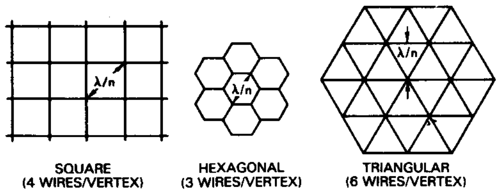

Fig. 1 Basic types of mesh structures.

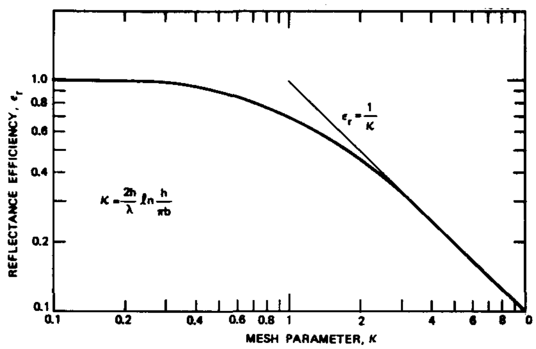

Fig. 2 Mesh reflectance vs wire size and spacing.

should be noted that Figs. 2 and 3 of Ref. 6 seem to be for mesh spacing of $\lambda/4$ and not $\lambda/2$ as stated in the text.)

The reflectance of the mesh also depends upon the electrical conductivity of the wires.[6] Aluminum has a room temperature resistivity of 28 nΩ – m. An aluminum wire 1 μm in diameter and 1 cm long will have a resistance of 360 Ω. This is almost perfectly matched to the free space impedance of 377 Ω, which would make the wire an absorber rather than a reflector. Fortunately, Starwisp will be bathed in the 2.7 K temperature of deep space and hence will be quite cold. The resistivity of pure aluminum, like most metals, drops rapidly with temperature.[7] At 40 K, for example, the resistivity is down to 1% of room temperature value and is decreasing as the fifth power of the absolute temperature.

There is a good possibility that the mesh in Starwisp could be made superconducting, which would increase the reflectivity and eliminate the problem of heating. Bulk aluminum becomes superconducting at 1.2 K, while thin films of aluminum have shown superconductivity up to 3.7 K, which is higher than the sky temperature.[8] Other possibilities are beryllium, which has a transition temperature of 8.4 K in thin films, and various aluminum alloys.

Because high conductivity and possibly superconductivity at the low temperatures found in deep space can be expected, it will be assumed for the rest of this paper that the effect of wire resistance on the microwave reflectance can be neglected, even for submicrometer wires. This assumption must be thoroughly reexamined in any detailed engineering study, since simple conductivity analyses are not adequate for wires with submicrometer dimensions. Only experiments on freestanding mesh structures will give believable numbers.

Information Return from the Starwisp Probe

At each intersection of the fine wires in the Starwisp mesh is a tiny microcircuit that controls the currents and voltages across the intersection. The microcircuits can assist in adjusting the microwave impedance at each intersection to maximize the reflected power during the acceleration period and keep the sail centered about the main microwave beam. Later, on arrival at the target star system, the microcircuits can be rearranged to select certain pairs of wires to act as a retroresponder antenna to an interrogating microwave signal beamed from the solar system. The microcircuits would be bigger than a wavelength of light in at least one dimension so they could be used to provide directional sensitivity to photo, i.r. and uv detectors built into them, but would be small in the other dimension to reduce weight. The mass of a chip 5 μm square by 0.5 μm thick with the density of silicon carbide (3200 kg/m^3) would be about 4×10^{-14} kg.

As the Starwisp probe approaches a nearby stellar system, the microwave beam will be turned on to flood the stellar system with microwave energy. At the star, the microwave beam from the transmitter lens will have spread out until the beam has the diameter

$$B_* = 2.44 \lambda s_* / D \tag{26}$$

The power collected by the sail at the star is then

$$P_* = (d^2 / B_*^2) e_b e_f P_t \tag{27}$$

The microcircuits at each intersection of the Starwisp mesh will collect this energy using the wires in the mesh as microwave antennas. In the process, each circuit will phase-lock its internal clock to the microwave phase it is receiving. In this manner, the circuits can determine their relative position on the phase front of the microwave beam and compensate for any variation in the position of their portion of the sail. Working in coordination, the circuits will analyze the light, i.r., and uv signals each is receiving through its detectors. The detectors will be designed so that each has a limited field of view, with different microcircuits having detectors that look in different directions. By using the known background stars as reference point sources in a form of speckle interferometry, the microcircuits can unscramble the responses from the individual detectors to produce an image.[9] That image will be inserted as modulation on a return microwave beam that is sent back to Earth in the same direction as the incident beam by the microcircuits using the wires in the mesh as a phased array antenna.

Acting as a phased array antenna, the Starwisp probe will produce a beam back at Earth with a diameter of

$$B_e = 2.44 \lambda s_* / d \tag{28}$$

The amount of power received back at Earth through the large transmitter lens is

$$P_e = (D^2 / B_e^2) e_c P_* \tag{29}$$

Shannon[10] has shown that the amount of energy needed to transmit a bit of information when limited by thermal noise is

$$E = kT \ln 2 = 0.69 kT \tag{30}$$

For a sky temperature of 2.7 K, this minimum required energy is only 2.6×10^{-23} J/bit. If it is assumed that to provide adequate signal-to-noise ratio a signal energy that is a factor of $1/e_i$(100-1000) times this minimum energy is required, then the received power at Earth will be able to carry a bit rate of

$$\dot{N} = e_i P_e / E \tag{31}$$

A high-resolution picture (1000 by 1000 pixels) with a good gray scale (256 shades of gray or 8 bits per pixel) requires $N_p = 8 \times 10^6$ bits per picture. Thus, the time to transmit one picture is

$$t_p = N_p / \dot{N} \tag{32}$$

Interstellar Missions

Now that we have the basic equations for a Starwisp probe mission, let us look at a couple of examples. In the first example it will be assumed that the amount of microwave power available will be limited to that from a typical solar power satellite. In this case, the weight of the sail and the terminal velocity must be kept low, which results in a long mission and minimal data return. Also, the diameter of the transmitter lens needed becomes undesirably large (although the mass in not that large for the size of the object). In the second example, it is assumed that sufficient microwave power is available to carry out fast missions with good data return to more star systems than just the nearest one. In this case, the size and mass of the sail and lens are more reasonable and the mission times are more reasonable. However, the amount of microwave power needed becomes undesirably large.

Power-Limited Mission to Alpha Centauri

We will want to transport a Starwisp probe over the 4.3 lightyears to the nearest star system, Alpha Centauri, and get the information back well within the lifetime of the human generation sending it. To accomplish this, it will be assumed that the Starwisp probe will be accelerated to one-fifth the speed of light ($v_t = 6 \times 10^7$ m/s). At this speed, Starwisp will reach the nearest stars in 21.5 years, and the information will return to Earth 25.8 years after launch.

The plans for the first solar-power satellite may seem extensive to their planners, but they are marginal for an interstellar probe. Starwisp would perform better with more power at a longer wavelength, but a solar-power satellite design that produces a transmitted power of $P_t = 10$ GW at a wavelength of $\lambda = 3$ cm (X-band) will suffice. The Starwisp sail will be a square mesh with a geometry factor of $e_g = 0.707$ made of aluminum wire with a density $g = 2700$ kg/m^3, diameter $b = 0.1$ μm, and mesh spacing $h = 0.3$ cm ($e_h = 0.1$). This gives a mesh parameter

$$K = (2h/\lambda) \ln h / \pi b = 1.83 \tag{33}$$

Determining this value in Fig. 2, it is found that the reflectance of the sail is $e_r = 0.50$. If the Fresnel lens efficiency is estimated to be $e_f = 0.80$ and the beam efficiency to be $e_b = 0.84$, then the "propulsion" efficiency of the microwaves on the sail is

$$e_p = e_f e_b e_r = 0.34 \tag{34}$$

The ratio of the transmitter lens diameter to the sail diameter is then calculated to be

$$\frac{D}{d} = \frac{2.44 \pi^2 e_g c q b^2 v_t^2}{32 e_p e_h P_t} = 50{,}000 \tag{35}$$

If the sail diameter is $d = 1$ km, then the transmitter lens diameter must be 50,000 km or four times the diameter of the Earth. Since half the lens is empty and half a sparse mesh with spacing larger than a microwave wavelength, the mass of the lens is estimated to be only 50,000 tons.

The mass of the Starwisp sail is easily calculated from Eq. (22) and is only 16 g of wire. For a sail with diameter $d = 1$ km and a mesh spacing of 3 mm, the number of mesh intersections is about 10^{11}. The mass of the 10^{11} chips would be 4 g, bringing the total weight of Starwisp up to 20 g.

The acceleration of a sail of 20 g driven by a microwave beam of 10 GW is quite high

$$a_0=\frac{2e_pP_t}{Mc}=1130\ \mathrm{m/s^2}(\sim 115\ g) \quad (36)$$

although the microwave flux level is reasonable

$$F=P_t/A=8.6\ \mathrm{kW/m^2}(\sim 6\ \mathrm{suns}) \quad (37)$$

The constant acceleration period lasts until Starwisp exceeds the reach of the transmitter lens at the distance

$$s_0=\frac{Dd}{2.44\lambda}=6.8\times 10^{11}\ \mathrm{m}(\sim 4.5\ \mathrm{a.u.}) \quad (38)$$

in the time

$$t_0=(2s_0/a_0)^{1/2}=35{,}000\ \mathrm{s}\ (\sim 10\ \mathrm{h}) \quad (39)$$

After a week of further acceleration at a slowly decreasing rate, Starwisp will have reached its maximum velocity of $c/5$ and left the solar system on its 270,000-a.u. journey to the nearest stars.

As Starwisp approaches Alpha Centauri at one-fifth the speed of light, it will travel from -30 to $+30$ a.u. on the other side (about the distance across the Pluto/Neptune orbits) in about 40 h. During that time (as well as periodically during the mission for calibration and update) the transmitter system on Earth will send a beam of microwave power to interrogate the microcircuit transponders built into the Starwisp mesh. The microwave beam will also supply the power needed to operate the transponders.

The distance to Alpha Centauri is 4.3 lightyears or 4.1×10^{16} m. At this distance, the beam from the transmitter lens has spread out until the beam diameter at Alpha Centauri is

$$B_*=2.44\lambda s_*/D=6\times 10^7\ \mathrm{m} \quad (40)$$

The power P_* collected by the sail is then:

$$P_*=(d^2/B_*^2)e_je_bP_t=2\mathrm{W} \quad (41)$$

The Starwisp probe, acting as a phased array antenna, will produce a beam back at Earth with a diameter of

$$B_e=2.44\lambda s_*/\mathrm{d}=3\times 10^{12}\mathrm{m}\ (\sim 20\ \mathrm{a.u.}) \quad (42)$$

If a collection-computation-retrodirection power efficiency of the sail of 1% is assumed, then the amount of power received back at Earth through the large transmitter lens is

$$P_e=(D^2/B_e^2)\,e_cP_*=5\mathrm{pW} \quad (43)$$

If a signal-to-noise ratio of 1000 is assumed, then this power level will allow the transmission of

$$\dot{N}=(e_iP_e/E)=2\times 10^8\ \mathrm{bits/s} \quad (44)$$

or a high resolution picture every

$$t_p=N_p/\dot{N}=40\ \mathrm{ms} \quad (45)$$

or close to television frame rates.

High-Power, High-Speed Mission to Epsilon Eridani

Let us now consider a mission that is not limited by the amount of microwave power available. If all the parameters are the same as in the power-limited mission, but the microwave power level is increased to 10 TW and the terminal velocity to half the speed of light, then the ratio of the lens diameter to the sail diameter becomes

$$D/d=300 \quad (46)$$

A sail diameter of 30 km now can be chosen. This gives a more realistic sail mass of 14 kg, including a number of kilograms of payload more sophisticated than small detectors. The diameter of the transmitter lens is now a more reasonable 9000 km, only three-quarters the diameter of the Earth. The microwave flux on the sail and the sail acceleration will stay about the same, but with the new sail and lens dimensions, the constant acceleration period will last 18 h and reach out to 23 a.u.

With the higher terminal velocity of half the speed of light, missions to more distant stellar systems, such as Epsilon Eridani, at 10.8 lightyears, can be considered. The high-speed macro-Starwisp will reach Epsilon Eridani in 21 years, and the data will return after 32 years. At Epsilon Eridani, the higher transmitted power and the larger size of the sail will give the sensors and processors on the larger Starwisp 9 kW of power. This higher power level and the larger diameter of the sail acting as a phased transmitting array will allow the larger Starwisp to send back to Earth a continuous series of high resolution color pictures during the flythrough of the Epsilon Eridani system.

Conclusion

Unmanned star travel is difficult, but not impossible. In this paper, a concept for an interstellar flyby probe that is capable of traveling to the nearby stars at near-relativistic velocities and returning significant amounts of data during its flythrough of the target stellar system has been presented. The concept uses reasonable extrapolations of our present capabilities in microelectronics, thin films, and the generation of microwave power. If it were desired, the first Starwisp probe could be sent to Alpha Centauri before the millennium is out.

There are still a number of unanswered questions about the feasibility of this concept. They are:

1) What are the performance and structural parameters of a large, wire-mesh, Fresnel-zone plate microwave lens?

2) Can the wires in the Starwisp mesh be made superconducting? Will they remain superconducting at these high microwave flux levels?

3) What is the real reflectivity of mesh structures made of submicrometer wire?

4) Can the wire mesh withstand the high accelerations while carrying its load of microcircuits?

5) How shall the multitude of microcircuits be organized to perform as a coherent whole?

6) What is the algorithm for extracting images from the outputs of a multitude of sensors? What is the quality of those images?

Further work must be done to determine the answers to these questions. For questions 1-3, it will be necessary to carry out experiments on scale models, since thin films and strands of both conductors and superconductors have significantly different properties than the bulk material.

Acknowledgments

This paper is the result of a serendipitous conversation with Freeman Dyson on the subject of interstellar transport. While discussing the idea of a perforated lightsail[11] with holes smaller than the wavelength of light to decrease the mass without decreasing the reflectivity, Dyson produced some notes[12] from his files on an interstellar perforated sail pushed by microwaves. The Dyson maser-driven sail is an extreme version of the perforated lightsail, with the area of the holes very much larger than the area of the wires. Dyson found that for a given amount of microwave power, the acceleration of the sail increased in direct proportion to the wavelength of the

microwaves. By combining the Dyson maser-driven sail concept with some previous ideas on communicating over interstellar distances with thin wire mesh spacecraft carrying microcircuits,[13,14] the author produced the Starwisp concept for a lightweight, high-speed interstellar probe capable of returning useful information from the nearest stars.

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