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The Solar-Electric Sail: Application to Interstellar Migration and Consequences for SETI

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Abstract: The Solar-Electric Sail accelerates by reflecting positively charged solar wind ions. If it is used to propel an interstellar migration mission, its interstellar cruise velocity relative to the home star cannot exceed the solar wind velocity. In an effort to analytically determine interstellar cruise velocity for a 10^7 kg generation ship, a constant solar wind velocity within the heliosphere of a Sun-like star of 600 km/s is assumed. The solar wind proton density at 1 AU is also considered constant at 10 protons per cubic centimeter. Solar wind density is assumed to decrease with the inverse square of solar distance. It is shown that, to maintain sufficient acceleration to achieve an interstellar cruise velocity about 70% of the solar wind velocity, the radius of the sail's electric field is enormous—greater than 10^5 km. Because the solar wind velocity and density are not constant, field strength must be varied rapidly to compensate for solar wind variation. Although not competitive with the ultimate theoretical performance of solar-photon sail propelled migrations departing from Sun-like stars, the solar-electric sail might be superior in this application for migration from dim K and M main sequence stars. Such migrations conducted during close stellar encounters might have durations < 1000 terrestrial years. If only a tiny fraction of M dwarf stars host star-faring civilizations, a significant fraction of Milky Way galaxy planetary systems may have been inhabited, even if no major advances over currently postulated interstellar transportation systems are postulated. SETI theoreticians should consider this when estimating the effects of interstellar colonization.

Keywords: electric sail; interstellar migration; red dwarf stars; SETI

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1. Introduction: Sailing in an Erratic Wind

The Solar-Electric Sail functions by reflecting solar wind protons using an electric field [1]. If applied to the acceleration of an interstellar spacecraft, its maximum terminal velocity will be limited by the V_w, the velocity of the solar wind (300–800 km/s at 1 Astronomical Unit (AU) from the Sun) [1].

A 100 kg spacecraft equipped with 100 appropriately charged 10 km electrodynamic tethers can be accelerated by solar wind reflection at about 10^{-3} m/s^2 (~10^{-4} g) when it is situated at 1 AU from the Sun. A solar-powered electron gun would be used to maintain the tethers' positive potential, which might be as high as 20 KV [1].

The electric sail may also see application for the deceleration of star-bound spacecraft. As the spacecraft approaches the destination star, the electric sail would be used to decelerate the spacecraft to a planetary velocity by reflecting that star's stellar wind [2].

This paper concentrates on the possibilities and limitations of utilizing this technique to accelerate a much larger spacecraft to interstellar velocities by solar-wind reflection. It is assumed for simplicity that the solar wind is constant. This is of course a gross simplification.

The WIND spacecraft was utilized in January–May 1995 to measure solar wind velocities and densities at 1 AU from the Sun. The daily average solar wind velocity varied between 382 and 583 km/s. Peak daily solar wind velocities were 398–740 km/s. In the same time period, average solar wind density varied between 4.7 and 16.3 cm^{-3} [3]. Average solar wind ion density at 1 AU is often taken as 10 cm^{-3} [4].

Solar wind density is a function of solar distance. In the idealized case of a constant solar wind, solar wind density varies with the inverse square of solar distance [5].

The Sun resides within the Local Interstellar Cloud (LIC). An ion density of about 0.05 cm^{-3} seems reasonable from ground-based observations [6]. A somewhat higher ion density of 0.08 cm^{-3} has been measured by the Voyager 1 probe beyond the boundary of the heliopause. Voyager also determined that the ion density just inside the boundary of the heliopause is about 0.002 cm^{-3} [7].

There is a variable flow pressure associated with the solar wind that partially shields the inner solar system from galactic cosmic rays. Typical values for this pressure at a 1 AU solar distance are $\geq$2.5 nPa [8]. Variations in solar wind pressure during the solar cycle are considerable.

It has been demonstrated that mass loss to the stellar wind varies with a star's luminosity for giant and supergiant stars [9]. During the Sun's red giant phase (about 5 billion years in the future), the solar wind should be greatly enhanced [10].

It is evident from the above discussion that the solar wind is variable in many respects. This fact complicates a rigorous prediction of the possible interstellar cruise velocity for an electric-sail-equipped starship departing the solar system. However, application of certain approximations allows for some understanding of the craft's kinematics.

2. Approximate Analysis of Electric Sail Kinematics

This section presents an analysis of the kinematics of an electric sail propelling a starship migrating from the present-day solar system or the vicinity of a Sunlike star. The ship mass M_s is assumed to be 10^7 kg. Certain approximations are included. These include a constant solar wind with the following properties:

Wind velocity V_w = 600 km/s;
Wind ion density at 1 AU (ρ) = 10/cm^3 = 10^7/m^3;
Wind flow pressure at 1 AU $\geq$ 2.5 nPa.

Figure 1 presents a schematic representation of the spacecraft accelerating in the solar wind. In the figure, R_f is the effective radius of the sail electric field in the interplanetary medium. Assuming that protons are the dominant positive solar wind ions, the solar wind mass affected by the sail's electric field per unit time can be written as:

$$dM_w/dt = m_p\ \pi\ \rho\ R_f^2\ (V_w - V_s)\ \mathrm{kg/s}, \tag{1}$$

where $m_p = 1.67 \times 10^{-27}$ kg, the proton mass and V_s is the spacecraft velocity relative to the Sun.

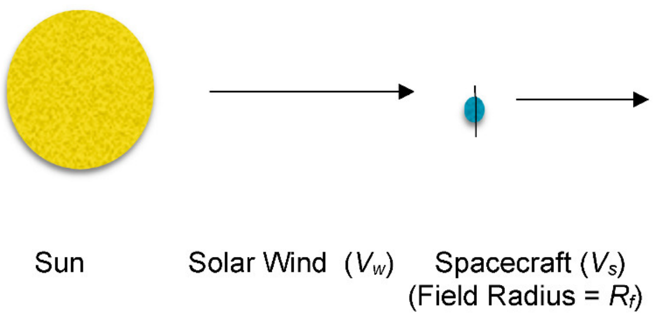

Figure 1. Starship acceleration by electric sail.

If all solar wind protons encountered by the sail's electric field are reflected back towards the Sun, the change in linear momentum of these particles can be written:

$$dP_w/dt = -2\ (V_w - V_s)\ dM_w/dt = -2\ m_p\ \pi\ \rho\ R_f^2\ (V_w - V_s)^2 \tag{2}$$

From conservation of linear momentum, $dP_w/dt = -M_s\, dV_s/dt$, where M_s = ship mass. Therefore,

$$dV_s/dt = 2\, m_p\, \pi\, \rho\, R_f^2\, (V_w - V_s)^2/M_s \tag{3}$$

Equation (3) can be rearranged and integrated:

$$\int_{V_0}^{\eta V_w} (V_w - V_s)^{-2} dV_s = 2 m_p \pi \rho {R_f}^2 (M_s)^{-1} \Delta t. \tag{4}$$

In Equation (4), $\eta < 1$, V_0 is initial spacecraft velocity relative to the solar wind and Δt is the total acceleration time. It is assumed that $\rho\, R_f^2$ is constant during the acceleration process. Since the integrand in Equation (4) is a standard form, an equation for Δt can be readily derived:

$$\Delta t = M_s \left(2 m_p \pi \rho {R_f}^2\right)^{-1} \left[(\eta V_w - V_0)(V_w - \eta V_w)^{-1}(V_w - V_0)^{-1}\right]. \tag{5}$$

It is next assumed that the 10^7 kg spacecraft is initially in a circular solar orbit 1 AU from the present-day Sun. Therefore, $V_0 = 0$. Reflection of solar wind protons is applied to accelerate the spacecraft to a velocity of 500 km/s relative to the Sun over a distance of 30 AU. Elementary kinematics reveals that the acceleration, which is assumed to be constant, is equal to 2.8×10^{-2} m/s^2 $\approx 3 \times 10^{-3}$ g. Acceleration time is about 1.8×10^7 s or 0.6 years.

If values of acceleration, ship mass, solar wind density and solar wind speed are known, Equation (3) can be rearranged to allow calculation of the effective radius of the sail's electric field:

$$R_f = \left[(M_s dV_s/dt)/(2 m_p \pi \rho)\right]^{1/2} (V_w - V_s)^{-1} \tag{6}$$

In all cases, $dV_s/dt = 2.8 \times 10^{-2}$ m/s^2, V_w = 600 km/s and $M_s = 10^7$ kg. At 1 AU, $V_s.$ = 0 and $\rho = 10^7$/m^3. Therefore, $R_f \approx 2800$ km.

At 30 AU, ρ has decreased to 1.1×10^4/m^3 and $V_s.$ = 500 km/s. Therefore, $R_f \approx$ 500,000 km at 30 AU.

The next scenario to be investigated is the case where $\rho\, R_f^2$ is constant during the acceleration process and is defined by initial conditions at 1 AU. For $\rho = 10^7$/m^3, and R_f = 2800 km, $R_f^2\, \rho = 7.84 \times 10^{19}$ kg/m. Substituting in Equation (5) with $\eta = 0.83$ (final spacecraft velocity = 500 km/s), constant solar wind velocity = 600 km/s and spacecraft velocity relative to the solar wind = 0 at 1 AU, the acceleration time for a 10^7 kg spacecraft is about 10^8 s or 3 years.

Acceleration time is longer in this case because acceleration decreases as the spacecraft moves out from 1 AU. At 30 AU, in a constant solar wind, solar wind density has decreased by a factor of 900. Sail effective electric field radius at 30 AU has therefore increased to about 84,000 km.

Table 1 presents approximate kinematics for this spacecraft. Please note that a 500 km/s terminal velocity is most unlikely for this configuration because the required acceleration distance is well outside the heliosphere.

Table 1. Kinematics of 10^7 kg electric sail starship. Acceleration begins at 1 AU from circular solar orbit; $R_f{}^2\rho = 7.84 \times 10^{19}$ kg/m.

Acceleration Time Seconds	Acceleration m/s^2	Velocity km/s	Distance AU
0	3×10^{-2}	0	
2.4×10^7	2×10^{-2}	100	8
3.0×10^7	1.3×10^{-2}	200	14
4.1×10^7	0.74×10^{-2}	300	32
6.1×10^7	0.33×10^{-2}	400	72
12.2×10^7	0.08×10^{-2}	500	255

This section concludes with a brief discussion of solar wind flow pressure (Force/Area) on the electric sail. The pressure of the impacting wind on the sail field can be written as:

$$P_i = dM_w/dt\ (V_w - V_s)/(\pi\ R_f{}^2) = \rho\ m_p\ (V_w - V_s)^2 \tag{7}$$

Substitution of the 1 AU values for solar wind density and velocity reveal that $P_i \approx 6 \times 10^{-9}$ nPa.

However, if one multiplies ship mass by the ship acceleration at 1 AU and divides by the value assumed above for sail field area at 1 AU, one obtains a pressure about twice the value calculated from Equation (7). The likely cause for this is the (likely unrealistic) assumption of elastic reflection of solar wind protons by the sail field.

3. Discussion of Kinematics Analysis

It is apparent that, in a constant solar wind, an ideal solar-electric sail can propel a starship to an interstellar velocity. Probably, the maximum interstellar velocity possible is 60–70% of the constant solar wind velocity.

Interstellar cruise velocities possible for ships departing Sunlike stars will be less than those possible for ships propelled by graphene solar-photon sails [11], because the maximum solar-electric sail interstellar cruise velocity is limited by the maximum solar wind velocity.

However, it is hard to steer graphene sails during the acceleration process, since these will likely be absorptive rather than reflective. Steering an electric sail might be easier if the symmetry of the sail electric field can be controlled.

The required radius for the electric field is enormous, considerably larger than the physical radius of a graphene sail. Because the solar wind is not constant, a starship accelerating using an electric sail must be able to rapidly and accurately alter the sail field radius to maintain constant acceleration.

It seems reasonable to conclude that a civilization hosted by a solar-type star that engages in interstellar migration might choose to propel their generation ships using photon sails rather than electric sails. However, the choice might be different if the civilization's host star is a red dwarf.

4. A Comparison of Interstellar Solar Photon Sailing and Solar Electric Sailing for Generation Ships Departing from M Dwarf Stars

In a recent publication, Lingam and Loeb claimed that electric sails are more effective than photon sails when applied to migrations from dim red dwarf stars [12]. Their comparison is not entirely fair. In that reference, both sails are assumed to depart from the same distance (1 AU) from the central star. As many references have revealed, a solar photon sail would likely be deployed from the perihelion of a parabolic pre-perihelion solar orbit [13]. If the payload is a generation ship, the sail would likely be huge.

However, the same is true for the electric sail. To accelerate a large payload to interstellar velocities, the network of electrodynamic tethers comprising such a sail would be very extensive, as demonstrated in the discussion above.

The acceleration of a solar photon sail decreases with the inverse square of solar distance. If an interstellar solar sail is deployed at 0.1 AU from our Sun, its acceleration will have decreased by a factor of 2500× when it crosses the orbit of Jupiter. One distinct advantage of the electric sail is that its acceleration decreases as the inverse 7/6 power of solar distance if the sail field strength is constant [1].

However, for cool stars such as the Sun, electromagnetic radiation pressure is essentially constant for periods of a billion years or more. The Sun's solar wind, on the other hand, is quite variable both in time and space [14,15].

The maximum velocity of an electric sail is limited by the solar wind velocity. If the electric sail's electric field remains in operation after the solar wind velocity is exceeded, the sail operates as a drag device because it will interact with solar wind particles in front of it rather than behind.

It has been demonstrated that an absorptive graphene photon sail carrying a human-occupied generation ship deployed from a 0.1 AU perihelion could depart our solar system at about 1000 km/s [11]. A robotic craft not limited by human acceleration tolerance could do better.

The solar wind has two components. Then average solar wind speed is about 500 km/s. However, the velocity of the high-speed component can exceed 750 km/s. So it seems that optimized solar photon sails will exit our solar system somewhat faster than ideal electric sails.

If solar system exit velocity were the only issue, solar photon sails are clearly superior to electric sails for departure from a Sun-like star. However, it should be remembered that both propulsion systems can be used for acceleration and deceleration and that the photon sail at least can be wound around the habitat during the cruise phase to provide extra cosmic ray shielding. It is also possible that electrodynamic tethers can serve as structural elements in a solar photon sail, thereby combining advantages of both approaches.

However, when we consider a generation ship departing from an M dwarf star, the clear winner is the electric sail. The electromagnetic flux from such a star will be greatly reduced when compared to the Sun's output. However, the stellar wind from such a star may not be affected as much. An extensive model study reveals that the stellar wind from low-mass M-class stars may have a higher mass density rate per unit area than the Sun. Average stellar wind velocities for such stars may approximate or exceed 500 km/s. Proton density at 1 AU may decrease with increasing stellar age and M stars are quite ancient [16]. Therefore, an interstellar cruise velocity of 500 km/s for a properly configured electric sail departing an M dwarf star is not unreasonable.

Some idea of the average acceleration of such an electric sail may be obtained by assuming that the boundary between the stellar wind and the interstellar medium (the heliopause) for such a star is about 120 AU, as is the case for the Sun [17].

Assume that the electric sail accelerates under the influence of the solar wind until its velocity (V) relative to its star is 500 km/s and acceleration distance is 110 AU (1.65×10^{13} m). At an average velocity of 250 km/s, the approximate time (t) required to reach 110 AU is 6.6×10^7 s (about 2 years). Substituting in the elementary equation

$$V = at, \tag{8}$$

and assuming constant acceleration (a), the acceleration is calculated as 7.6×10^{-3} m/s^2, or about 7.6×10^{-4} g. Such an acceleration is not unreasonable, at least for a low-mass spacecraft about 1 AU from our Sun [1]. No attempt is made in this paper to design electric field generators that can be rapidly adjusted to maintain constant acceleration as the spacecraft moves outward from its home star in a variable stellar wind.

5. M Stars, Electric Sails and SETI: Rethinking Habitability Assumptions

The assumption that intelligent extraterrestrial technological life would most likely originate on planets circling main sequence stars of spectral classes F, G, and K has long been a mainstay of organized SETI searches and likely originated as far back as 1964 [18]. Hot main sequence O, B, and A stars most likely are too short-lived to support Darwinian evolution of species capable of developing radio technology or interstellar space travel. Although cooler M stars have main sequence lifespans approximating one trillion years and are by far the most prevalent members of the stellar population, potentially habitable planets in such systems orbit close to the star and may be tidally locked so that rotation and revolution rates are equal. Evolution of advanced life on such worlds might be hindered by flares and coronal mass ejections from the nearby primary star.

Even if a stable technologically advanced civilization overcomes the odds and thrives on a planet in the habitable zone of an M star, it might be difficult for the population of such a world to engage in interstellar exploration and expansion. The low electromagnetic radiation pressure from the dim red dwarf star severely limits application of photon solar sailing, unless very long voyage durations are acceptable.

Perhaps it is the discovery of so many planets orbiting in the habitable zones of M dwarf stars that has encouraged a reappraisal of life possibilities on these worlds. As discussed in one recent paper [19], M star planetary systems are characterized by a paucity of Jupiter-mass giants and a preponderance of multiple smaller rocky worlds. About a third of these rocky worlds orbit in the habitable zones of their primary stars and may therefore contain ample reserves of liquid water.

A very substantial astrobiology study reconsidering the habitability of planets orbiting in the habitable zones of M stars has been published [20]. Many commonly held assumptions regarding these worlds are questioned in this paper.

For instance, it is widely believed that if a planet is tidally locked, the thermal gradients across the terminator and the resulting high winds might inhibit forest habitability. However, atmospheric heat transport likely mitigates this effect by reducing the amplitude and increasing the horizontal scale of such gradients.

Atmospheric photo-chemical reactions on a habitable planet circling an M star may differ from those in Earth's atmosphere because of the low ultraviolet (UV) flux from the star. Atmospheric lifetimes of biogenic compounds such as methane, nitrous oxide and methyl chloride will be larger than in Earth's atmosphere, greatly increasing the abundance of these compounds. Because methane is a greenhouse gas, this effect might increase the limits of the habitable zone. Geological activity on these worlds might increase the atmospheric levels of CO_2, which is also a greenhouse gas.

On small planets such as Mars, which circle G dwarf stars similar to our Sun, solar UV can ionize atmospheric molecules and contribute to the process of atmospheric escape. The much lower UV flux in the habitable zone of an M star might slow this process.

Our G dwarf Sun is gradually increasing its luminosity as it ages. If far-future terrestrial residents do not apply techniques such as orbiting sunshades, Earth's oceans may start to boil in about one billion years. The stabile lifetime of an M star's habitable zone should be much longer than that of a G star, since M dwarfs remain on the main sequence for a trillion years or longer.

A great deal of observational evidence and modeling is required before we can conclude that habitable-zone planets circling M stars are good candidates for the evolution and long-term stability of advanced life. However, the work summarized in [19,20] offer hope that previous thoughts on this matter might be unduly pessimistic.

Recent advances in the art of extrasolar planet detection indicate that some of the planetology assumptions may require revision. Potentially habitable planets circling M stars are apparently not uncommon. Model results reveal that previous estimates of M star planet habitability may be too pessimistic.

It is no longer possible to exclude M stars as possible sources of planets with advanced extraterrestrial life. Given the long lives of such stars, the long-term stability of their habitable zone, and the estimated frequencies of close stellar encounters, even one starfaring civilization may have long since expanded to occupy a significant fraction of the planetary systems circling suitable stars in the Milky Way galaxy.

6. Close Stellar Approaches and Interstellar Migration

If a spacecraft exits our solar system at 500 km/s, more than 2000 years will elapse before it approaches our nearest stellar neighbor: the Proxima/Alpha Centauri system at 4.3 light years from the Sun. Such a low interstellar cruise velocity is clearly unacceptable for lifeforms with a human-like lifespan.

However, on occasion, stars pass within a light year of our Sun. Any observational estimate of close stellar approaches to the Sun is likely an underestimate. For instance, Vityazev et al. investigated the kinematics of 1,260,071 main sequence stars out to a distance of 1.5 kilo parsecs included in the first Gaia data release [21]. Even though the majority of stars in our galaxy are M dwarfs, only 625 such stars are included in this data set. That is because most distant red dwarfs will not be detected by Gaia's instrument suite due to instrument limitations and the very low luminosity of these stars. The average age of the M dwarfs in this sample is 7 billion years [21].

About 70,000 years ago, a low-mass (M9 with brown dwarf companion) binary star (Scholz's Star) passed within the Sun's Oort Comet Cloud. The perihelion for this approach is estimated as about 52,000 AU or 0.25 parsecs [22]. Further work with the first Gaia data release indicates that approximately 1.35 million years in our future, another low-mass star (Gliese 710) will pass our solar system even closer, with a perihelion distance of only 13,365 AU [23].

Bailer-Jones et al. have used a sample of 7.2 million stars in the second Gaia data release to further investigate the frequency of close stellar encounters [24]. The results of this analysis indicate that seven stars in this sample are expected to approach within 0.5 parsecs of the Sun during the next 15 million years. Accounting for sample incompleteness, these authors estimate that about 20 stars per million years approach our solar system to within 1 parsec. It is, therefore, inferred that about 2.5 encounters within 0.5 parsecs will occur every million years. On average, 400,000 years will elapse between close stellar encounters, assuming the same star density as in the solar neighborhood.

At 500 km/s, a spacecraft covers about 0.9 light years in 500 years, so let's see how long it takes a space-faring civilization to occupy a significant fraction of the galaxy if it originates near an M-type star and transfers between stars only during close stellar encounters. The number of planetary systems (P) they occupy doubles every 500,000 years, based upon the discussion above.

Defining n as the multiple of 500,000 years, and assuming that each occupied planetary system sends out generation ships at the same rate,

$$P = 2^n. \tag{9}$$

At the start, $n = 0$ and $P = 1$. When 500,000 years have elapsed, the hypothetical space-faring civilization makes the first transfer, $n = 1$ and $P = 2$. After one million years ($n = 2$), both the original and occupied stellar systems experience a close stellar encounter, migration occurs and $P = 4$. After a total elapsed time of 1.5 million years, $n = 3$ and they occupy eight planetary systems. When $n = 5$, 10 and 20 the hypothetical civilization has respectively occupied 32, 1024 and 1,048,576 planetary systems.

Of course, not all encountered stars will have systems suitable for habitation and some stellar encounters will be repeats. On the other hand, it is also reasonable to assume that faster modes of interstellar transport will be developed by a space-faring civilization that exists for geologic eons.

7. Conclusions

In a constant solar wind, an ideal solar-electric sail can propel a starship to a significant interstellar velocity. The maximum interstellar velocity possible is ~70% of an assumed constant solar wind velocity.

Interstellar cruise velocities possible for ships departing Sunlike stars with solar-electric sails will be less than those possible for ships propelled by graphene solar-photon sails, because the maximum solar-electric sail interstellar cruise velocity is limited by the maximum solar wind velocity.

It is hard to steer graphene sails during the acceleration process, because these will likely be absorptive rather than reflective. Steering an electric sail might be easier if the symmetry of the sail electric field can be controlled and varied as required.

The radius for the solar-electric sail's electric field is enormous, considerably larger than the physical radius of a graphene sail. In a variable solar wind, a starship accelerating using an electric sail must be able to rapidly and accurately alter the sail electric-field radius to maintain constant acceleration.

Red Dwarf stars seem to be equipped with planetary systems. Many of the planets circling these dim stars are in or near the habitable zone. It is no longer possible to automatically reject the possibility that a technologically advanced civilization could develop on a suitable planet circling such a dim, long-lived star. Most stars in the galaxy are M dwarfs. It can no longer be assumed that advanced civilizations only develop on planets circling F, G and K main sequence stars.

Although stellar photon sailing may not be effective for generation ships departing from such a star system, an electric sail departing an M dwarf might be capable of reaching an interstellar cruise velocity of 500 km/s. At such a velocity, a terrestrial generation ship would require more than two millennia to reach our nearest stellar neighbor.

However, stars shift their relative positions as they circle the center of the Milky Way galaxy. According to data obtained using the Gaia space observatory and other instruments, stars approach our solar system within a light year or so at intervals of about 500,000 years. Migration from M dwarf stars at velocities approximating 500 km/s seems less daunting during a close stellar approach.

The typical estimated age of M dwarf stars observed using Gaia is 4.85 billion years, considerably older than the age of our solar system. Even a few star-faring civilizations originating on planets circling M dwarf stars may long since have occupied a significant fraction of our galaxy's planetary systems.

As we explore our solar system and dispatch probes to explore the vicinity of near stars, humans should keep an open mind. We may find that not only are we not alone, but we one of the most primitive civilizations in the galaxy. Let's hope that the Elders accept our intrusion.

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