Stellar Engines: Design Considerations for Maximizing Acceleration

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Abstract

Stellar engines, megastructures used to control the motion of a star system, may be constructible by technologically advanced civilizations and used to avoid dangerous astrophysical events or transport a star system into proximity with another for colonization. This work considers two designs for stellar engines, for both human applications in the solar system and for advanced civilizations around arbitrary stars more generally, and presents analytic calculations of the maximum acceleration and deflection of a star in its galactic orbit. The first is a large 'passive' solar sail, similar to that proposed by Shkadov, which we find produces accelerations of order 10^{-12} m/s^2 for sun-like stars. The second 'active' engine uses a thermonuclear driven jet, as in a Bussard ramjet, which collects matter from the solar wind to drive He fusion. This engine requires additional mass to be lifted from the sun, beyond what is provided by the nascent solar wind, but may achieve accelerations up to 10^{-9} m/s^2 producing deflections of 10 pc in as little as 1 Myr for a sun-like star. While passive engines may be insufficient for catastrophe avoidance on short timescales, they can produce arbitrary deflections of a star in its galactic orbit over a stellar lifetime. Active engines are sufficient for retrograde galactic orbits or galactic escape trajectories, which we argue are useful to expansionist civilizations. These populations of stars may be candidates for observationally detecting megastructures.

Keywords: Stellar engines, Dyson sphere, Megastructure, Interstellar Travel, Shkadov thruster, Nuclear ramjet

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1. Introduction

Megastructures, hypothetical stellar scale machines, must generally be constructed by Type II Kardashev civilizations, which are civilizations that have complete control over the energy radiated by a star [1]. Such a technologically advanced civilization will have energy and mass needs greater than their home planet can provide and will have expanded to utilize their star, and entire planetary system by proxy.

1.1. Dyson Spheres

Criswell suggests that human energy needs and environmental mass processing grow exponentially, so humans will necessarily begin to engage in projects astronomical in scale (such as megastructure construction) within the next few centuries. Criswell also presents qualitative arguments that 'exponentiating construction systems' may be used to develop solar power collectors using mass from Mercury [2].

Analytic arguments by Armstrong and Sandberg suggest that the construction of a Dyson sphere in the solar system is a relatively straightforward endeavour from physics alone. Although a Dyson sphere (or any comparable energy collecting megastructure such as a Dyson swarm) requires of order the gravitational binding energy of a planet to construct, it is not impossible. Rather, energy generated by the partially completed Dyson sphere is used to construct the Dyson sphere further, and exponential growth makes it possible to disassemble a planet such as Mercury on timescales comparable to a human lifetime starting from only a 1 km^2 array of solar collectors (with appropriate assumptions regarding technology and manufacturing scaling) [3].

Even if the arguments and extrapolations of these authors are several orders of magnitude too optimistic, it is still possible that intelligent civilizations elsewhere in the galaxy have had sufficient time to produce megastructures even if humans have yet to. Sagan argues that such advanced civilizations may be abundant in the galaxy [4]. This would motivate astronomical observations to detect such structures. For example, Dyson's original work on his namesake Dyson sphere was observationally motivated: a megastructure which collects a star's flux would alter that star's spectra and enhance its infrared emission as it both obscures the star and as the civilization uses the collected energy [5]. The viability of observing a Dyson sphere has received further consideration by recent authors [6, 7, 8]. Megastructures have also been invoked as a possible explanation for anomalous observations of several candidates, such as KIC 8462852 ("Tabby's Star"), though these explanations are disfavored in the literature [9, 10, 11] With large catalogs of astrometric and photometric observations of galactic stars from modern surveys now available we may expect many such megastructure candidates in the near future.

In contrast, the absence of observed megastructures has been invoked to resolve the Fermi paradox, which is the lack of observed technological civilizations despite the large size of the universe and the many chances for them to emerge. If life is common, it may be that the technological leap to construct a megastructure is impossible to overcome, or that technological civilizations tend to destroy themselves quickly. Such a 'Great Filter' would suggest that technological intelligence, when it emerges, is often confined to one planet and perhaps even short lived, as a monoplanetary civilization should be more susceptible to catastrophic extinction events than an interplanetary or interstellar civilization. If the Great Filter were thus, it may motivate human action against this existential threat.

Taken together, these arguments motivate the study of hypothetical megastructures both observationally and for future human technological development.

1.2. Stellar Engines

If an advanced civilization were to construct a Dyson sphere, they would certainly have the means of constructing a 'stellar engine,' another megastructure used to control the peculiar motion of their star through the galaxy (which may or may not be powered by the Dyson sphere). A stellar engine produces a small net acceleration of the star, not large enough to disrupt the planetary system on short timescales, but sufficiently large to deflect the star and planetary system in its galactic orbit by many light-years given millions of years. Such a civilization may inhabit a number of suitable planets orbiting the star, while disassembling the others for materials to construct megastructures in orbit around the star [3, 12, 13].

We can only speculate on the motivations an advanced civilization might have for constructing a stellar engine of any kind, though they may be similar to our own. Avoiding supernova (or any similar cosmic catastrophe) and their negative effects on an inhabited planetary system could be one motivation. For example, ozone depletion in the earth's atmosphere due ultraviolet radiation from a supernova within 10-100 pc may result in a mass extinction event [14, 15, 16]. Amusingly, mounting evidence for one or several nearby supernova (~ 100 pc) approximately 2 million years ago now forms the basis for recent suggestions that nearby supernova caused climatic shifts which directly influenced human evolution [17]. The effect of a supernova on an exoplanetary biosphere inhabited by an advanced civilization will depend on that planet's atmospheric composition and biosphere, and may be very different from earth, possibly extending the danger zone of supernova by an order of magnitude relative to earth. A catastrophe such as a supernova could likely be predicted millions of years in advance, at minimum, for an advanced civilization with detailed understanding of star formation and the supernova mechanism.

Previously proposed stellar engines produce accelerations which can deflect a sun-like star by approximately 10 pc per galactic orbit (225-250 Myr). Such timescales may be too short for supernova avoidance maneuvers if the progenitor forms in a region obscured to observation. We suppose that an advanced civilization which was motivated to control the peculiar motion of its star may construct a stellar engine capable of delivering the maximum peculiar acceleration possible, motivating this work.

Furthermore, advanced civilizations that have outgrown their star system may seek to colonize others. Criswell's arguments that human growth may necessitate stellar scale construction may generalize to advanced civilizations that have completely developed their own star system. Such civilizations would need to expand to others for more energy and matter. If such a civilization disfavors generation ships, large spacecraft for interstellar colonization whose voyages take longer than a generation of the passengers, then they may favor relocating their entire star system to close proximity with the target system and populating it with short distance migrations.[1,2]

Such expansion would initially be slow. Nevertheless, if each newly colonized system is also developed into an independent Type II Kardashev civ-

[1]Generation ships may be disfavored for a number of reasons, such as (1) a high risk of accident in interstellar space which destroys the colonists, (2) prohibitive engineering and energy requirements for long-haul spacecraft, (3) long timescales for technological development in the colonized system using in situ resources, or even (4) in recognition of individual rights of the intermediate generations who did not consent to spending their entire lives in interstellar space.

[2]See Forward (1986) for a review of the feasibility of interstellar travel [18], and Antonelli and Klotz (2017) for the kinematics of travel to Alpha Centauri [19].

ilization complete with a Dyson sphere and stellar engine, the number of civilizations would grow exponentially. If the arguments of Armstrong and Sandberg hold then development of a star system is quick so the rate limiting step is interstellar travel, again motivating an expansionist civilization to construct an engine capable of maximum acceleration. In this case, retrograde motion relative to the galatic orbit is advantageous as it maximizes the rate of stellar fly-bys. This criteria may narrow human observational efforts to detect megastructures and advanced civilizations.

A number of proposed designs for stellar engines exist in the literature. Badescu and Cathcart consider three classes of stellar engines. Class A are non-Dyson sphere variants, class B are Dyson sphere thermal engines, and class C employ aspects of both class A and B. For example, class A engines have included variants such as the Shkadov thruster, which uses large statites in orbit around the sun to generate thrust from radiation pressure, while the type C engine proposed by Badescu and Cathcart generates a comparable thrust [12, 13, 20]. Earlier, Zwicky proposed using beams of colloidal particles accelerated to relativistic velocities to achieve fusion in the outer layers of the sun, driving a jet for propulsion, though no quantitative results for the acceleration exist in the literature [21].

In this work we adopt a slightly different naming convention for convenience, referring to class A variants as 'passive' thrusters as they may operate without intervention, such as a solar sail. We define other types as 'active' thrusters as they must maintain non-equilibrium states.

In the sections that follow we consider the design requirements and maximum acceleration achievable for two designs of stellar engine. In Sec. 2 we consider a passive stellar engine, a variation of the Shkadov thruster, which generates thrust purely from solar radiation pressure like a solar sail. We consider the geometry, material requirements, and some miscellaneous criteria for the mirror. Sec. 3 considers an active stellar engine, which uses a thermonuclear driven jet to accelerate the sun. Such a stellar engine acts as a tug, pushing the sun through the galaxy. We consider the nuclear fuel, fuel mass requirements, jet kinematics, and orbital properties of this engine. We summarize in Sec. 4, discussing the feasibility of these engines and making suggestions for observationally detecting megastructures.

2. Passive Thrusters: The Solar Sail

We first consider the acceleration produced by a large reflective solar sail, similar to the Shkadov thruster [12]. Shkadov considered a spherical mirror, subtending some angle, which reflects light back at the sun thus resulting in an assymmetric distribution of solar radiation. This assymmetry imparts a net force on the sun in the direction of the solar sail, as the photons carry momentum out of the solar system.

The solar sail does not orbit the sun. It is a 'statite,' with outward solar radiation pressure balancing the inward gravitational force. The ideal design may be a parabolic reflector truncated at the latus rectum with the sun at the focus so that it reflects half of all radiation from the sun in parallel, similar in form to a half-sphere. This solar sail reflects a significant fraction of the stellar radiation along the symmetry axis of the reflector, as shown in Fig. 1. This avoids a design concern of previously proposed Shkadov thrusters where reflected sunlight raises the temperature of the star.

In the figure, both the sun and mirror accelerate to the left with acceleration a. The sun accelerates toward the mirror of mass m due to F_G the force of gravity between them. The mirror is also attracted to the sun, but the radiation pressure force F_R is slightly greater. Due to the low mass of the mirror relative to the sun, the F_R needed to overcome F_G and produce a small acceleration equal to that of the sun is only slightly greater than F_G, so for order of magnitude estimates we can treat F_G and F_R as equal. [3] This argument demonstrates that the mirror geometry and the details of any asymmetry are irrelevant so long as it is stable, as the acceleration is entirely due to the momentum flux carried by solar radiation.

A single monolothic mirror may be susceptible to impacts or catastrophic failure, and may instead be a 'swarm' consisting of many mirrors. Design concerns for the production and launching of mirror swarms using the mass of Mercury are presented by Armstrong and Sandberg [3]. For the purposes of this work, we accept their arguments that megastructures are generally constructible.

Considerations for a paraboloid are more detailed than the spherical cap from Shkadov. The angle of incidence on the mirror changes with each ring-like element of the paraboloid. In the center of the mirror there is approximately normal incidence resulting in maximum momentum transfer. Near

[3] Specifically, $ma = F_R - F_G$ and $M_\odot a = F_G$ so $(F_R - F_G)/F_G = m/M_\odot$ which is small.

Figure 1: Artist's rendition of a passive thruster, where sunlight is reflected by a large parabolic mirror, not to scale. The sun and mirror accelerate to the left. Illustration by Michelle Buhrmann.

the edge incident photons are reflecting at approximately a 90 degree angle, resulting in a reduction of radial momentum transfer by 1/2 relative to normal incidence. This requires mirror thickness to vary across the paraboloid, having a factor of 2 lower mass per area at the edges. Future authors may calculate the detailed geometry and mass distribution, however this does not need to be known to calculate the acceleration.

The maximum net acceleration of the solar system is due to the momentum flux carried by solar radiation out of the solar system along the axis of the mirror, and can be approximated as

$$a \approx (1/2 + 1/6)\,\epsilon\, L_\odot/(cM_\odot) \sim 4 \times 10^{-13}\ \mathrm{m/s^2},$$

where ϵ is the mirror efficiency (considering reflectivity, absorptivity, and transmissivity and taken to be order unity here), the 1/2 is due to the reflected radiation from the mirror, and the 1/6 is due to the net momentum carried by the sunlight radiated away from the paraboloid mirror.[4]

The approximate orbital deviation over a galactic orbit (225 Myr) is of order 325 pc for perfect efficiency. Our theoretical upper-bound for the passive thruster is somewhat greater than the design described in Shkadov's work, which proposes a maximum deflection of 10-12 pc per galactic orbit, as Shkadov considers only a small semi-spherical cap [12]. If we suppose the timescale to safely avoid an imminent supernova is the star formation and evolution timescale of 10 million years, we see this thruster can only produce a deflection of 0.6 pc, insufficient to avoid the supernova 'kill radius.'

2.1. Orbital and Material Criteria

We first consider the orbital properties of the mirror. At a given distance solar radiation produces a pressure of $L_\odot/(4\pi r^2 c)$. This is several orders of magnitude greater than the ram pressure produced by the solar wind, which we neglect here. For a perfectly reflective mirror of some arbitrary area A, thickness x, and density ρ we can calculate the thickness required for the 'statite' solution, a hovering orbit, given that the force exerted by gravity equals the force from radiation. For $2L_\odot A\epsilon/(4\pi r^2 c) = GM_\odot \rho A x/r^2$,[5] we find that the maximum thickness is

$$x = \left(\frac{1.54 \text{ g/cc}}{\rho}\right) \epsilon \ \ \mu\text{m}. \tag{1}$$

The inverse-square dependencies cancel, so a statite of fixed thickness is equally stable at any distance from the sun, though the material density and optical properties are of concern.

In Tab. 1 we consider three elements, iron, aluminum, and silver, for these mirrors. Iron is included due to its abundance in Mercury, while aluminum

[4] The 1/2 and 1/6 terms can be understood from a simple geometric argument. Assuming the sun radiates isotropically then photons carry momentum equally in each of the six Cartesian directions $(\pm x, \pm y, \pm z)$. The origin of the 1/2 from the parabolic reflector (in the $+z$ direction) is trivial, while the 1/6 is due to the momentum in the $-z$ direction. Photon momenta orthogonal to the axis of the paraboloid cancel due to symmetry.

[5] The prefactor of 2 is for momentum transfer in the case of normal incidence and is an upper-limit.

Table 1: Optical properties for 2.5 eV photon energies ($\lambda = 500$ nm, approximately the peak of the solar black body curve) at room temperature and normal incidence (from Paquin [22]). 'Alloy X' is conjecture.

Element	Reflectivity	Density (g/cc)	Maximum Thickness for $L_\odot$ (μm)
Iron	0.57	7.8	0.19
Aluminum	0.92	2.7	0.55
Silver	0.91	10.5	0.14
Alloy X	0.90	1.0	1.54

and silver are included due to their near ideal optical properties.

For high efficiency, the mirror must have high reflectivity and low absorptivity and transmissivity. This is optimized when the mirror is sufficiently thick that it transmits negligible amounts of light. The skin depth δ, the distance for an electromagnetic wave to attenuate by $1/e$ in a material, is approximately 50 nm at optical frequencies in most metals. The minimum thickness need only be a few skin depths (e.g. $e^{-4x/\delta} \sim 0.02$), so mirrors of at least 0.2 μm are desirable. Metal foils of this thickness are commercially available.

Iron has a high density and low reflectivity, and so it will be difficult to construct mirrors greater than a few skin depths, resulting in some transmission of solar flux. If approximately half of the mass of a mirror is allocated for structural components (as in Sandberg and Armstrong, and in the following section), a foil of iron will likely not suffice for solar system purposes.

Despite their relatively low abundances on Mercury, other elements may be synthesized in large amounts if the energy of a Dyson sphere is used to drive nuclear reactions on iron. Even with low efficiency, it should be possible to process the mass quite quickly.[6] Silver's high reflectance makes it a frequent mirror coating on earth, but the reflectance drops quickly in the ultraviolet and the density is high so we consider its viability comparable to iron. The high reflectivity and low density of aluminum at optical wavelengths make it a promising candidate for pure mirrors or alloys. Aluminum is also

[6]For comparison, a 1 μm thick spherical shell at 1 au from the sun contains 10^{23} cc of material, of order 1% the volume of Mercury. To process order 10^{23} g of material with nuclear reactions of order 1 MeV/u, we require order 10^{34} J, which is of order one year of solar flux. Even at very low efficiency this is achievable with the energy from a Dyson sphere.

abundant in earth's crust, and if it exists in comparable abundances on Mercury there may be sufficient Al mass with minimal or zero nuclear processing. Some future alloy ('Alloy X'), perhaps of Al-Li, may achieve even lower densities and higher reflectivities desired for solar system purposes. Further considerations, such as temperature dependence of the electrical properties, may also have order of magnitude effects on the reflectivity depending on the mirror's distance from the sun and may motivate interest in superconducting alloys as possible mirror materials. As in the previous section, we consider mirror efficiencies of order unity (or perhaps more realistically near 0.9) to be reasonable.

A typical mass-luminosity relation suggests that main sequences stars slightly larger than our sun may be well suited for this kind of stellar engine. Taking $L \sim L_\odot (M/M_\odot)^{3.5}$ we find that a 2 $M_\odot$ star has a luminosity over an order of magnitude greater than the sun. This provides an order of magnitude greater radiation pressure which supports order of magnitude thicker mirrors, which thus achieves the multiple skin depths of thickness needed for any element with high reflectivity. Known materials would suffice for such a mirror. With the order of magnitude greater intrinsic luminosity, a passive thruster attached to a 2 $M_\odot$ star will produce thrusts five times that of a comparable thruster in the solar system. In contrast, the material concerns may become prohibitive for main sequence stars even slightly less massive than the sun as the radiation pressure will not be sufficient to support the mirrors.

2.2. Solar Radiation Returned to the Sun

A small amount of solar radiation is returned to the star by the mirror which will raise the effective surface temperature of the star. For the parabolic mirror considered here this is a much smaller effect than the hemispherical mirror of Shkadov. Approximating the center of the mirror as planar, the relevant area for returning radiation to the sun is of order $R_\odot^2$. For a mirror at 0.4 au the relevant solid angle is of order 10^{-4}, so any effect is small. To prevent any radiation return the central mirror geometry may be modified to include a cone which reflects radiation toward the wings of the paraboloid. A central circular hole of a solar radius may also be used to eliminate the returned radiation with negligible effect on the thrust.

2.3. Mirror Stabilization

Should humans, or any advanced civilization, construct mirrors like this they must also take care to be sure the megastructure remains parabolic. As the mirrors are not oriented spherically those whose normal incidence makes an angle with respect to the sun will experience a net torque from the solar radiation pressure gradient, causing them oscillate. Any damping force is likely to return them to a stable equilibrium where they are aligned radially, thus reflecting light back at the sun. Such a stabilization system along with any struts supporting the mirror foil will require thinner foil in order to budget mass for these systems, thus resulting in great transmittance of sunlight. Nevertheless, stabilizers are necessary if the mirrors are to remain parabolic on astronomical times.

This instability can be solved by incorporating gravity gradient stabilizers; tidal forces exerted on a long tail extending away from the mirror can stabilize a mirror at an almost arbitrary orientation [23]. For example, a 1 km^2 mirror at 0.4 au from the sun inclined from normal incidence by 45 degrees (in the case of the mirror edges) will have displacements at the edge of order 1 km. At $r = 0.4$ au radiation pressure is order 10^{-5} Pa, and for these edge displacements the pressure gradient is of order 10^{-13} Pa. This produces non-negliglble torques on astronomical timescales; the torquing force is of order 10^{-7} N. With micron thicknesses, the mass is order 10^3 kg, so a 1 km tether of the same mass extending radially away from the sun experiences tidal forces of order 10^{-6} N, sufficient for stabilization.

2.4. Mirror Orientation

The orientation of the mirror in the solar system is a major design concern due to its effects on the planets. If built over the poles of the sun at $a = 0.4$ au the mirror would not obscure sunlight to the earth or other planets and would still leave half of the sun's radiation available for collection. Such a structure would only produce acceleration orthogonal to the plane of the solar system, which may not be ideal. If constructed at an arbitrary inclination in the solar system at $a = 0.4$ au, it would obscure sunlight to the planets for part of their orbits while potentially increasing the received solar flux drastically during others. This may also not be ideal, but can be solved by using secondary reflectors to provide sunlight during times the sun is obscured and by using large shades to obscure the reflected sun while transiting the column of light reflected from the mirror. For a mirror at greater than 1 au, planets may need to be rearranged which should also be possible for a Type II Kardashev civilization.

2.5. Maximum Velocity

Though more massive stars may have greater luminosities which produce greater accelerations (recall $a \approx L/Mc$), they do not necessarily permit greater maximum Δv to the star's peculiar velocity in Milky Way. Consider the mass-luminosity and lifetime-luminosity relations for a main sequence star of mass m,

$$L = L_\odot (M/M_\odot)^{3.5} \tag{2}$$
$$\tau = \tau_\odot (M/M_\odot)^{-2.5}, \tag{3}$$

where $\tau_\odot \sim 10^{10}$ yrs, approximately the lifetime of the sun. We can find that $\Delta v_{max} \approx a\tau$ such that

$$\Delta v_{max} \approx \left(\frac{L_\odot}{Mc} \left(\frac{M}{M_\odot} \right)^{3.5} \right) \left(\tau_\odot \left(\frac{M}{M_\odot} \right)^{-2.5} \right) \tag{4}$$
$$\approx \frac{L_\odot \tau_\odot}{M_\odot c} \tag{5}$$
$$\approx 200 \text{ km/s}. \tag{6}$$

As Δv_{max} is independent of the mass of the star and is only approximately equal to the virial velocity of the Milky Way, we can conclude that passive thrusters are insufficient to bring an arbitrary star system into retrograde galactic orbits. Furthermore, this is an upper-limit on Δv_{max}. Factor of two losses due to the finite time for advanced civilizations to emerge around a star system (i.e. the current age of the sun is $\tau_\odot/2$) and lower efficiencies of the mirror due to geometry and material limitations can easily reduce Δv_{max} by nearly an order of magnitude.[7]

[7] The mass-luminosity and mass-lifetime relations used here are derived by assuming that the star burns a fixed fraction of its mass to energy (i.e. $L\tau \approx fMc^2$) such that the power output integrated over the lifetime of the star per unit mass is constant, and determined by the mass-energy conversion efficiency f.

2.6. Summary of Passive Thrusters

We find that passive thrusters at Mercury's orbit are viable in the solar system, provided low density high reflectivity elements or alloys are used. Accelerations of order $L_\odot/(cM_\odot)$ are possible, approximately 10^{-12} m/s^2, producing approximately 325 pc of deflection in a galactic orbit. Passive thrusters produce less than 1 pc of deflection in their first 10 Myr of operation, which may be insufficient for cosmic disaster avoidance, such as a supernova.

Stars with masses even slightly greater than $M_\odot$ may be well suited to stellar engines of this type, and may easily achieve accelerations and deflections per orbit which are several orders of magnitude greater, while material limitations may render passive thrusters inviable for stars only slightly less massive than the sun. We find that the maximum Δv a passive thruster can deliver to a star in its galactic orbit is less than the virial velocity (~ 200 km/s) and is independent of the mass of the star, so arbitrary peculiar motions and retrograde orbits in particular are generally impossible with passive thrusters alone.

Other design concerns which are beyond the scope of this work may be interesting to future authors. These may include (1) the robustness of passive thrusters on astronomical timescales against impacts from dust and other macroscopic objects, (2) mirror degradation by the solar wind, (3) disruption of the solar wind and its impact on the solar system, (4) orbital stability of the mirror against tidal disruption by planets, (5) orbital stability against resonances which may tend to circularize the mirror, and (6) stability against self gravity which may tend to cause the mirror to collapse on itself.

3. Active Thrusters: Thermonuclear Driven Engines

We consider the possibility of using a near-relativistic jet of exhaust to accelerate the solar system. The acceleration can be straightforwardly estimated analytically. A jet with mass loss rate $\dot{m}$ and average speed $\langle v \rangle$ gives the sun an acceleration of $\dot{m}\langle v \rangle/M_\odot$. To maximize a, one must simply maximize $\dot{m}$ and $\langle v \rangle$ without having $\dot{m}$ so great that the life and luminosity of the sun are significantly altered.

The proposed stellar engine is a modified form of the Bussard ramjet, a space propulsion system which collects the sparse interstellar matter from a wide area using electromagnetic fields and compresses them to achieve fusion. The resulting energy from fusion and high temperatures drive high velocity exhaust, producing thrust. Bussard argues that the maximum acceleration of a nuclear ramjet for interstellar propulsion is limited by the density of material in space in front of it, but that relativistic exhaust velocities are possible [24]. Andrews and Zubrin consider a design similar to Bussard, and suggest that thermonuclear driven exhaust velocities greater than $0.01c$ are possible [25].

The engine or thruster considered in this work collects the solar wind to power fusion, and schematic illustrations are shown in Fig. 2 and Fig. 3. Exhaust from the engine be may collimated with magnetic fields into two oppositely directed jets, one aimed toward the sun and one away from the sun. The jet aimed away from the sun imparts a net momentum to the solar system, while the jet aimed toward the sun prevents the engine from colliding with the sun. This engine is effectively a tugboat which pushes the sun.

3.1. Thermonuclear Reactions

We first consider the exact fusion reactions in the engine.[8] The most abundant nuclide in the sun and solar wind is ^{1}H which cannot be used directly for fusion, as the first step in the pp-chain is rate limited by the weak interaction:

$${}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{2}_{2}\mathrm{He} \longrightarrow {}^{2}_{1}\mathrm{H} + \mathrm{e}^{+} + \nu_e \,.$$

As the diproton is unbound its probability to decay by dissociation to two protons is much greater than the probability to beta decay to a deuteron at all energies. Likewise, the natural abundance of deuterium is $10^{-4}n_H$, which can be treated as negligible. This rules out direct proton fusion as a possible power source. This may seem peculiar as ^{1}H fusion occurs readily in stars, but this is a slow process resulting in astronomically long main sequence lifetimes. We require nuclear fuel capable of near complete burning on short timescales for this work.

We now consider helium as a fuel. He fusion via the triple alpha process proceeds explosively in a number of astrophysical environments due to its high temperature dependence ($\propto T^{41}$ near $T \approx 0.1$ GK [27]) .The triple alpha process proceeds via

$${}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{8}_{4}\mathrm{Be}$$
$${}^{8}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{12}_{6}\mathrm{C}$$

releasing approximately 7.3 MeV. During explosive burning, temperatures

[8] See Bussard (1960) and Whitmire (1975) for relevant discussions of nuclear reactions in interstellar ramjets [24, 26].

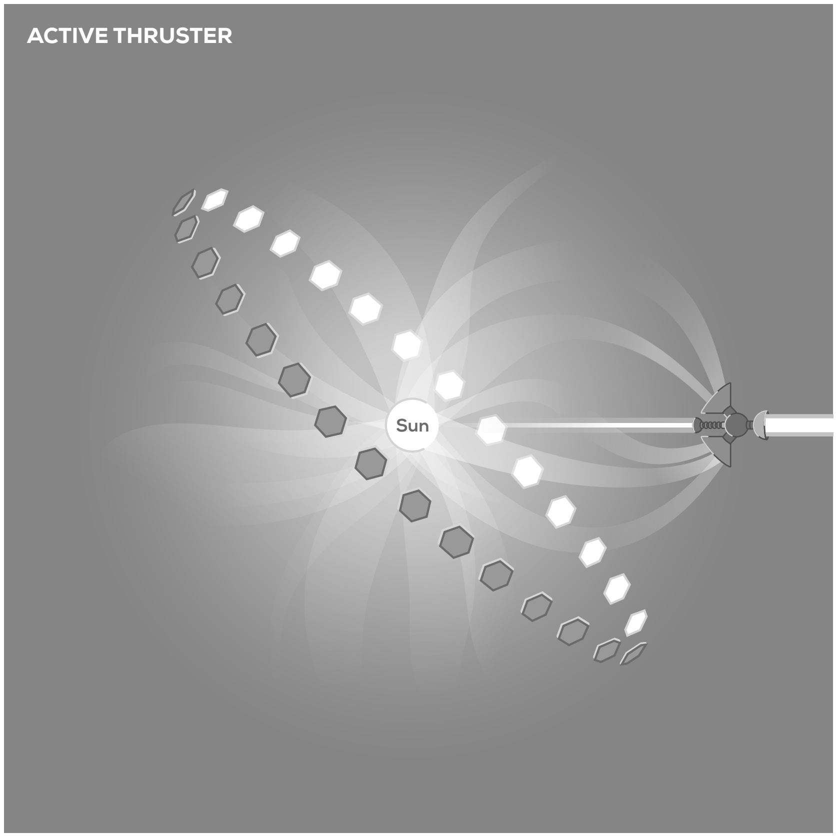

Figure 2: Artist's rendition of an operational active thruster around a star with a Dyson swarm, where the solar wind is collected by an engine which drives a jet of exhaust. The sun and ramjet accelerate to the left. Illustration by Michelle Buhrmann.

reach order 10^8 K where average thermal velocities of ^{12}C are $\langle v \rangle = \sqrt{8kT/(\pi m)} \approx 4 \times 10^5$ m/s, or $0.001c$.

The fuel mixture should be considered. For highest efficiency the H should be separated from the He. As ^{1}H and ^{4}He have different m/q, this can be easily accomplished with electromagnetic separators. Including a small amount of H in the fusion reactions enables the reactor to take advantage of the first steps of the hot CNO cycle, where H fuses onto ^{12}C,

$$^{12}_{6}\mathrm{C} + ^{1}_{1}\mathrm{H} \longrightarrow ^{13}_{7}\mathrm{N} + \gamma$$
$$^{13}_{7}\mathrm{N} + ^{1}_{1}\mathrm{H} \longrightarrow ^{14}_{8}\mathrm{O} + \gamma$$

which release 1.9 and 4.6 MeV respectively. The rate limiting step is again a weak reaction, the beta decay of $^{14}_{8}$O proceeds with a half-life of 70 seconds.

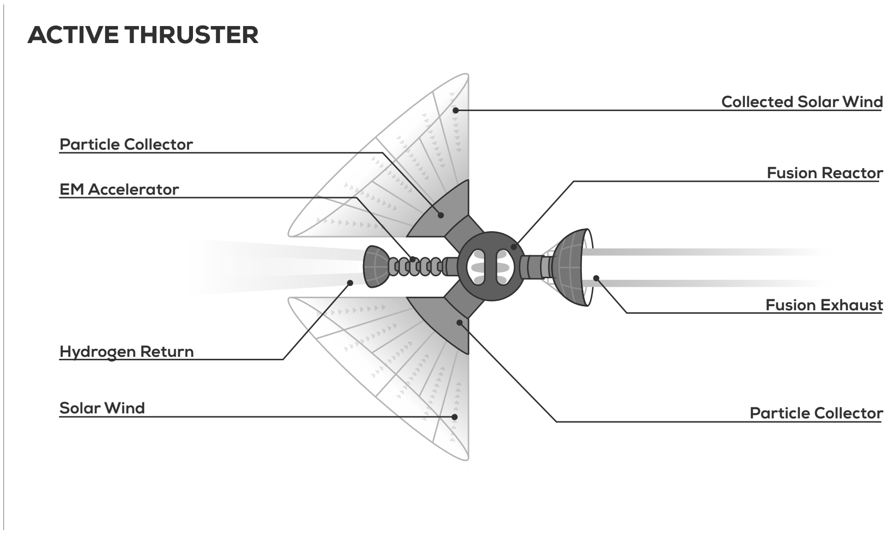

Figure 3: Schematic of an active thruster. Solar wind is collected by large scale electric or magnetic fields, which funnel matter into the engine. H and He are separated, with a He fuel mixture being used to drive a high velocity jet of exhaust away from the sun and out of the solar system, while H is returned to the sun using traditional electromagnetic accelerators, transferring exhaust momentum to the sun. The sun and engine accelerate to the left. Illustration by Michelle Buhrmann.

Any further captures of ^{1}H on $^{14}_{8}$O produces $^{15}_{9}$F which is unbound and decays by proton emission back to $^{14}_{8}$O. The inclusion of additional CNO nuclei to catalyze further H fusion seems possible and was discussed by Whitmire in the case of an interstellar nuclear ramjet, but we expect any such catalysts to be lost to the jet in this work so we do not consider this further [26].

If fusing conditions can be achieved through either magnetic or inertial confinement (or some as of yet uninvented ramjet technique), it may be possible to reach temperatures comparable to that of a type I X-ray burster, near 10^9 K. For complete burning to $^{14}_{8}$O at 1 GK, thermal velocities reach $0.004c$.

The inclusion of additional reaction mass in the exhaust reduces the effectiveness of the thruster. For thermal particle velocities of $v \propto (kT/m)^{1/2}$ we have particle energies $E \propto kT$ and momenta $p \propto (kTm)^{1/2}$. Maximizing exhaust momentum per unit energy requires high m, as $p/E \propto m^{1/2}$. Obtaining high m reaction mass is a challenge due to the Coulomb barrier to fusion, so we argue we are limited to $^{14}_{8}$O in the primary exhaust jet.

3.2. Maximum Acceleration and Mass Lifting

The mass abundance of helium in the solar wind is reported to be approximately 0.09, with some uncertainty in the literature [28]. The mass loss rate to the solar wind is a few times 10^{12} g/s, so for convenience we take an average He flux in the solar wind to be 10^{11} g/s [27].

Using the entirety of the solar wind He mass to fuel the primary jet we may expect accelerations of order 10^{-16} m/s^2 for ^{14}O at 1 GK, four orders of magnitude less than the maximum acceleration achievable for the passive thruster considered above.

In contrast to the passive thruster, whose upper limit to acceleration is set by $L_\odot$, the acceleration of the active thruster scales with fuel and reaction mass. By engaging in 'mass lifting,' the removal of mass from the sun (see Criswell [2]), an almost arbitrary amount of He can be acquired to power these jets. To match the passive thruster, we may desire upwards of 10^{15} g/s of solar material. As solar material also has a higher He concentration than the solar wind, the mass requirements may be reduced by a factor of a few.

Considerable energy is required to overcome gravitational binding to lift 10^{15} g/s of solar material, of order 10^{23} W ($10^{-3}L_\odot$).[9] This may be possible for a Dyson sphere at reasonably high efficiency. Alternatively, such mass lifting may be possible at very high efficiency using similar principles to concentrated solar power. Reflecting large amounts of sunlight directly to one spot or small region of the sun's surface (perhaps with statite mirrors like those described above) will locally increase the temperature and mass loss rate. Physically, the mirror reduces the area over which the sun radiates and drives up the surface temperature by the Stefan-Boltzmann law. Similar radiatively driven mass loss is believed to occur in Wolf-Rayet stars [29].

The maximum acceleration this engine can achieve is limited by the maximum mass lifting rate, which will be set by the solar luminosity. A Dyson sphere operating at perfect efficiency can lift $L_\odot/(GM_\odot/R_\odot) \sim 10^{18}$ g/s, producing accelerations of 10^{-9} m/s^2. This produces deflections of order 10 pc in 1 Myr. In 5 Myr the sun can achieve $\Delta v \approx 200$ km/s, the peculiar velocity of the sun in the galaxy, allowing for arbitrary redirection of the solar system on timescales much faster than previously proposed engines.

The mass loss rate of the sun at maximum acceleration is $10^{-8}M_\odot$/yr, so the engine may only be operated for order 100 MYr. Given the discus-

[9] From $\dot{E} = GM_\odot \dot{m}/R_\odot$

sion above, it suffices to operate the engine for 10 MYr to achieve arbitrary redirection of the solar system onto any chosen trajectory with bursts of corrections as needed. As acceleration scales linearly with $\dot{m}$, complete redirection of the sun can be achieved on any timescale at the expense of only $0.1M_\odot$. In the case of maximum acceleration, the effectively instantaneous loss of $0.1M_\odot$ at a time in the near future will extend the life of the sun by a few billion years, as main sequence lifetimes scale like $\tau \propto (M_\odot/M)^{2.5}$. The associated decrease in luminosity would require orbital repositioning of the planets to maintain their current stellar flux or redirection of solar flux with the Dyson sphere to compensate, similar to the design concerns for the passive thruster.

Maximum accelerations decrease as a significant fraction of a solar mass is removed from a main sequence star. Consider again $a \approx \dot{m}\langle v\rangle/M$. Though M decreases, the maximum mass lifting rate is dependent on M through mass-luminosity and mass-radius relations, which approximately scale like $(M/M_\odot)^{3.5}$ and $(M/M_\odot)^{0.8}$, so

$$a = 3.0 \times 10^{-7}\,\epsilon\,\left(\frac{\langle v\rangle}{c}\right)\left(\frac{M}{M_\odot}\right)^{2.3}\ \mathrm{m/s^2}, \tag{7}$$

where ϵ is the efficiency of the Dyson sphere. Badescu argues that $\epsilon_{\max} \lesssim 0.1$ for Dyson spheres of order 2 au which if true would limit a sun-like star to maximum accelerations of 10^{-10} m/s^2 [30].

It is natural at this point to wonder if greater accelerations are achievable by using traditional electromagnetic accelerators to further raise the exhaust velocity of the primary jet. Kinematic arguments again show us that this is an inefficient use of the Dyson sphere's power $\dot{E}$. The momentum flux we seek to maximize is proportional to $\dot{m}\langle v\rangle$. Mass lifting scales linearly as $\dot{m} \propto \dot{E}$, while electromagnetic acceleration of exhaust scales like $\langle v\rangle \propto \sqrt{\dot{E}}$ (from kinetic energy), thus mass lifting is generally more efficient than direct acceleration. For completeness, we consider a solar system Dyson sphere operating at perfect efficiency but used to accelerate the mass of the nascent solar wind ($\dot{m} \approx 10^{12}$ g/s) rather than lift mass for fusion. In this case, $L_\odot/\dot{m} \approx 4$ GeV/u. For protons, this implies relativistic gamma $\gamma \approx 5$ and velocity $v \approx 0.98c$. Momentum flux from the solar system is therefore $\gamma\dot{m}v$. Although this expression is relativistic it obeys Newton's second law, allowing us to calculate the acceleration of the sun via $a = \gamma\dot{m}v/M_\odot \approx 7\times10^{-13}$ m/s^2, which is comparable to the passive thruster. For comparison, the energy to lift a particle from the surface of the sun to 0.4 au is approximately equal to the kinetic energy to accelerate it to $0.001c$. As active thrusters are capable of producing jets greater than $0.001c$ through fusion we argue it is a more efficient use of the Dyson sphere to lift mass for fuel than to directly accelerate the primary jet. However, this all assumes perfect efficiency and future authors may be interested in estimating the efficiency of mass lifting relative to electromagnetic acceleration. If the efficiency of direct acceleration is found to be much greater than mass lifting then this argument may not hold.

3.3. Orbital Properties and Secondary Jets

We consider the orbital requirements of the engine. As with the passive thruster, a stationary orbit over the sun is preferable to generate thrust along a fixed vector. The force generated by an active thruster will accelerate it in the direction of the sun and will be greater than the force due to gravity using many of the assumptions taken here, so it must transfer the momentum of the exhaust jet to the sun to prevent collision. To prevent this, a secondary jet may be fired at the sun. This beam could be composed of separated H that is unused in the fusion process. This is approximately three-quarters of the lifted mass. This secondary jet, having greater $\dot{m}$ than the exhaust, can be at proportionally lower speeds. Conventional electromagnetic accelerators suffice to accelerate this jet to speeds of approximately $10^{-4}c$ requiring only $10^{-6}L_\odot$ for 10^{15} g/s, easily obtained from a Dyson sphere. As arbitrary trajectories can be achieved with the expenditure of $0.1M_\odot$ even without H-return, the depletion of solar He is negligible.

As in a ramjet, it may be possible for the engine to achieve continuous burning, in which case the momentum transfer can be balanced to achieve static equilibrium for a statite orbit. Pulsed bursts may also be possible at high efficiency depending on the exact method for achieving ignition. In this case, the time between pulsed bursts should be less than the free fall time for a thruster to fall into the sun as the burst is used to transfer momentum and keep the thruster afloat. We calculate the free-fall time from Kepler's third law. An orbit at 0.4 au with $e = 0$ has a semi-major axis of $a = 0.2$ au, so a half period is the free-fall time, $T = (1/2)(4\pi^2 a^3/(GM_\odot))^{1/2}$ about 16 days. This seems sufficiently long so that collisions between pulsed fusion engines and the sun are not a risk. Alternatively, given the high mass fluxes and large area the solar wind must be collected over, one can easily imagine that many active thrusters orbit in one or a few planes and gather fuel simultaneously (similar to a Dyson swarm), each firing only once per orbit.

The long term stability of the solar system should be considered. All accelerations considered here (for passive and active thrusters) are much less than the centripetal acceleration of the earth due to the sun's gravity (10^{-3} m/s^2) and should pose little risk to solar system stability on short timescales, though future authors may be interested to study solar system stability over the timescale of an engine's operation with n-body simulations. Designs for other megastructures which safely provide orbital perturbations to planetary systems may also be of interest to future authors.

3.4. Maximum Velocity and Intergalactic Expansion

Recognizing that the exhaust velocity for the jet is constant, it suffices to observe that this engine satisfies the classical rocket equation with known result for the change in velocity

$$\Delta v = \langle v \rangle \ln m_1/m_2 \tag{8}$$

where $\langle v \rangle$ is the exhaust velocity and m_o and m_f are the initial and final star masses, respectively. Assuming the engine is at 0.4 au, the effect of solar gravity decelerating the exhaust is negligible. If only a quarter of the mass star can be treated as reaction mass (the initial He fraction), $\Delta v_{max} \approx 0.001c$ (340 km/s) for any initial mass. This is of order the Δv required for galactic retrograde orbits or to reach galactic escape velocity. A main sequence star near the end of its life has a higher helium mass fraction, suggesting that older stars have greater maximum velocities. For example, one zone models suggest that at end of the main sequence prior to ascending the subgiant branch the solar core may be 90% He by mass [31, 32]. It seems possible that asymmetric heating due to mass lifting and H-return can excite a convective giant dipole mode, as seen in simulations by Herwig *et al.*[33], which will replenish helium in the outer layers through convective dredge-up. Detailed simulations of late main sequence evolution with mass loss to jets are required to understand the exact He budget available, but we find it reasonable to assume a significant fraction of a star's mass may be available for an active thruster attached to an appropriately evolved main sequence star.

An expansionist civilization may use such a star system on a galactic escape trajectory as a generation ship for intergalactic colonization. Ejecting half the initial mass a sun-like star in the jet can produce $\Delta v \approx 0.003c$ (900 km/s) in the galactic rest frame. In this case, galactic escape velocities of 550 km/s ($0.001c$) are easily reached and intergalactic travel becomes possible. With trajectories chosen many megayears in advance, an appropriate He rich star can be launched so that other galaxies in the Local Group may be reachable within the lifetime of the star. Fuel concerns for deceleration on arrival which plague many designs for interstellar propulsion may be solved by the same argument; approximately half the remaining mass of the star can be used to decelerate. The deceleration timescale will be an order of magnitude longer than the acceleration timescale, due to the $a \propto M^{2.3}$ dependence described above. An advanced civilization may only perform a few acceleration and deceleration maneuvers with a given star before exhausting its He. Furthermore, with its mass approximately halved by each maneuver, a sun-like star used for intergalactic travel may fall below the $\sim 0.5M_\odot$ limit for entering the asymptotic giant branch and not enter a helium burning stage. Even without an operational stellar engine due to helium exhaustion, such a star would remain viable for habitation for billions of years.

Intergalactic expansion may be both possible and exponential, providing a viable pathway for a 'self-replicating' Type II Kardashev civilization to become a Type III civilization spread across multiple galaxies, but may proceed sufficiently slowly within the current age of the universe that it does not contradict the Fermi paradox. For example, Andromeda is approximately 10^6 pc from the Milky Way, so a Type II Kardashev civilization departing the Milky Way at $0.003c$ would arrive in just under a billion years. This is well within the lifetime of a $\sim 1M_\odot$ star but an order of magnitude faster than the galaxy merger timescale.

We therefore argue that hypervelocity stars on escape trajectories from the galaxy may be observable candidates for detecting megastructures, even though the operation timescales of stellar engines are short relative to intergalactic flight times. Recent work suggests that known hypervelocity stars may be traveling above the upper limit for classical ejection methods [34]. Such stars may be candidates for detecting megastructures if additional powerful dynamical ejection methods are ruled out.

4. Summary

Analytic arguments suggest that passive thrusters, such as a large statite solar sail, may be constructible in the solar system. We find that the maximum accelerations of appropriately designed passive thrusters are sufficiently large to produce solar system accelerations of 10^{-13} m/s^2 with stellar deflections of order 100 pc in a galactic orbit. This may be insufficient to avoid predictable cosmic catastrophes such as supernova which could destroy human civilization. On timescales of the lifetime of the sun this acceleration is sufficient to obtain large orbital deflections within the galaxy.

When considering passive thrusters constructed by advanced civilizations around arbitrary stars, we find that main sequence stars of $2M_\odot$ or greater may face fewer engineering challenges in designing their passive thruster which will produce accelerations several orders of magnitude greater than possible in the solar system. Nevertheless, maximum velocity perturbations are of order the virial velocity of the Milky Way for all masses, so arbitrary reorientation of the peculiar velocity of a star and retrograde galactic orbits are not possible. Lastly, specific design concerns related to the mirror construction find that existing materials may suffice for such a mirror and should be straightforward to obtain for any Type II Kardashev civilization with Dyson sphere level technology.

Active stellar engines, which accelerate the sun using electromagnetic mass collectors and thermonuclear driven jets, produce accelerations three orders of magnitude less than a passive stellar engine when utilizing the mass flux from the nascent solar wind alone. When coupled with a Dyson sphere, mass lifting can provide an almost arbitrarily large amount of fuel to power these jets and may generate accelerations as large as 10^{-9} m/s^2 which are capable of producing deflections of 10 pc in the first Myr of operation, likely sufficient for cosmic disaster avoidance. Arbitrary control of the peculiar motion of a star and planetary system seem possible on timescales of 10 Myr with the expense of $0.1M_\odot$ for a sun-like star. Operating a stellar engine at large accelerations does not necessarily exhaust a star, but will extend its life. The maximum acceleration for a thermonuclear driven stellar engine is limited by the mass lifting rate from the star, and scales approximately as $a \propto M^{2.3}$. The maximum velocities achievable for solar composition main sequence stars are large enough for galactic retrograde orbits or hypervelocity escape trajectories, with appropriately chosen He rich stars having the greatest maximum velocities.

These megastructures may be interesting to search for observationally and in archival surveys. Several candidates for megastructures such as Dyson spheres exist, though we propose no specific candidate stars in this work. A passive thruster or large statite solar sail may effect the appearance of a star as seen from earth; if obscured, the stellar flux will be shifted toward the infrared, as in a Dyson sphere. If the earth falls within the reflected beam, the flux would be enhanced which should be discernible from photometry (and parallax) measurements. If such passive thrusters are stable on astronomical timescales without intervention, it is possible that extinct civilizations or previously inhabited but currently abandoned stars may host these megastructures. If an advanced civilization is operating an active thruster similar to the design proposed in this work observers may look for signatures such as (1) extended electromagnetic fields from collectors, (2) evidence of hotspots due to mass lifting, or (3) the interaction of a near-relativistic jet of CNO enhanced matter with the interstellar medium. Lastly, observational efforts may be focused on hypervelocity stars on escape trajectories or stars with retrograde galactic orbits as expansionist civilizations may want to maximize the rate of stars they can access via close flybys.

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