SPACECRAFT WITH INTERSTELLAR MEDIUM MOMENTUM EXCHANGE REACTIONS: THE POTENTIAL AND LIMITATIONS OF PROPELLANTLESS INTERSTELLAR TRAVEL

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Abstract

Various methods have been proposed for transporting large probes or colony ships through interstellar space to nearby stellar neighborhoods. All methods proposed thus far encounter monumental technological or engineering roadblocks, or even rely on speculative unknown science. In particular light of the recent public excitement and ensuing disappointment regarding the exotic “EM drive” we feel it worthwhile to point out that propellantless space travel through a stationary interstellar medium is eminently possible based on well established physical principles. We propose a new mode of transport which relies on electric-field moderated momentum exchange with the ionized particles in the interstellar medium. While the application of this mechanism faces significant challenges requiring industrial-scale exploitation of space, the technological roadblocks are perhaps more easily addressed than the issues presented by light sails or particle beam powered crafts. This mode of space travel is particularly well suited to energy efficient space travel at velocities \( \lesssim 0.05c \), and compares exceptionally well to light sails on an energy expenditure basis. It therefore represents an extremely attractive mode of transport for slow (\( \sim \) multi-century long) voyages carrying heavy payloads to nearby stellar neighbors. This could be very useful in missions that would otherwise be too energy intensive to carry out, such as transporting bulk materials for a future colony around \( \alpha \) Cen A, or perhaps a generation ship.

Keywords: ISM, propellantless space travel, plasmas, electric sail, Magsail, light sail, SWIMMER

1. INTRODUCTION

The tyranny of the rocket equation has long been recognized as a crucial impediment to becoming a truly spacefaring species. Due to the exorbitant reaction mass that would be required for traditional rockets in interstellar travel, there has been considerable attention toward methods of space travel that circumvent the rocket equation. Laser-driven light sails are a prominent and long-standing idea (Forward 1984). While light sails are well established and also the engine of the widely publicized “Breakthrough Starshot” program (Lubin 2016), their thrust is fundamentally limited to 6.67 N GW\(^{-1}\). For comparison, the Three Gorges Dam, the largest capacity power plant currently in operation, has a capacity of about 22.5 GW. If this was transmitted with 100% efficiency to a light sail it would provide thrust equivalent to the force required to lift a 15 kg mass on Earth. Scaling light sails up to larger-than-gram-scale spacecraft therefore necessarily depends on humanity’s ability to harness incredible power. Alternatively, direct sunlight could be used as the source of photons rather than laser beams, neatly avoiding the problem of requiring construction of immense power stations and laser arrays. Unfortunately, the material properties suggested to be necessary for a practical interstellar solar sail require extremely low areal density materials with \( \sigma \lesssim 10^{-2} \) g m\(^{-2}\) (Heller & Hippke 2017). Current state-of-the-art reflective films developed for light sails reach areal densities of \( \sim 10 \) g m\(^{-2}\) - four orders of magnitude too massive even without including any support structure, so it is uncertain when if ever we will develop suitable materials for a solar sail (Spieth & Zubrin 1999).

Another idea oriented around external reaction mass is the particle-beam powered spacecraft. This idea hinges on a sail formed by an extended electric or magnetic field which is able to deflect a remotely-beamed stream of charged particles. Since charged particles carry much more momentum per unit energy this could be much lower in power requirements than light sails. This concept has its origins in the Magsail, a large loop of current carrying wire which deflects passing charged particles in the interstellar medium (ISM), eliciting a drag force which could be used as a brake to slow spacecraft down to rest with respect to the ISM after a high speed journey (Andrews & Zubrin 1990). To provide acceleration, one could simply replace the ISM with a beamed source of high velocity charged particles (Landis 2001). Providing a long distance beam of charged particles is, however, quite difficult because of beam divergence due to particle thermal motion and interaction with interplanetary or interstellar magnetic fields. Andrews (2003) suggests that construction of a highway of beam generators every couple AU or so along the route on which the craft accelerates would be necessary. The related concept of the electric sail instead uses an electric field generated by a positively charged grid of wires or wire spokes extending from a central hub to push against the outward streaming solar wind (Janhunen 2004). This is a very promising concept which has the near term potential to allow travel within our own stellar neighborhood with very low energy costs. The electric sail, like the Magsail however, ultimately relies on a drag force, decelerating the spacecraft to rest with respect to the surrounding medium (the outward moving solar wind in this case). It is therefore unable to accelerate beyond the heliosphere, nor can it accelerate directly inwards towards the sun while in the heliosphere (though tacking at an angle to
the wind along with gravitational attraction do allow it to more slowly reduce its radial distance.

To overcome these obstacles we consider the prospect of actively pushing against the charged particles of the ISM, rather than passively coming to rest with respect to the medium, as in the case of Magsails or electric sails. These spacecraft with interstellar medium momentum exchange reactions (SWIMMERs) can accelerate with respect to the ISM, are significantly more energy efficient than light sails, do not require pre-established infrastructure along the route, and are based on elementary physical principles. Recently Robert Zubrin published his independent work on a ‘dipole drive’ concept which bears a striking resemblance to the SWIMMER concept we describe. Although the two ideas are related and even share a similar geometry, they were arrived at independently, and we believe the dipole drive suffers from a fatal flaw which prevents its successful acceleration in the ISM. In section [2] we discuss the conceptual mechanism providing SWIMMER thrust and compare it to a dipole drive. In section [3] we review the mathematical properties of the idealized governing equations, in section [4] we discuss some possible SWIMMER missions, and in section [5] we consider sources of uncertainty and future work and provide concluding remarks. Throughout, we will ignore relativistic effects as these are negligible at the velocities of interest. We will also adopt the nomenclature that $\log(x) \equiv \log_{10}(x)$.

2. SWIMMER DRIVE

Both the Magsail and electric sail concepts are based on the fact that we can interact with significant mass in the ISM (or the heliosphere) using relatively low mass structures consisting of charged or current carrying wires. How then can we interact with the medium to accelerate rather than decelerate?

One method of doing so would be to incorporate one of these sails in a larger structure such that the sail itself moves about within the larger structure and is only turned on at certain intervals. We can imagine, for instance, a large paddy-wheel structure, shown schematically in Fig. 1. Two electric sails are mounted opposite each other at the ends of two long tethers which are electrically connected, and which we can apply a potential difference across. The tethers are mounted to a reaction wheel in the center, and the whole system is set spinning with the spin axis perpendicular to the direction of travel (which we define as the positive direction). As one of the electric sails (sail ‘A’) approaches the portion of the cycle when its velocity is negative with respect to the ISM (the orientation in the top left panel of Fig. 1) we apply a potential difference, charging sail A positively and sail B negatively. At this point in the cycle in the frame of sail A, ions in the ISM are streaming towards it and pushing it in the desired direction of travel. We note that simultaneously the negatively charged sail B will be reflecting electrons in the positive direction causing some drag. Fortunately, as ions out-mass electrons by at least a factor of $m_i/m_e=1836$, the electrons contribute negligible drag, and in general we will ignore them here and throughout the analysis. As the rotation cycle continues, sail A moves into the portion of the cycle where its velocity is no longer negative with respect to the ISM, and the electric sails are neutralized. Then as sail B approaches the negative velocity portion of the cycle, we turn on and reverse the potential difference, charging B positively. In this way, even while the overall system can have positive velocity, with a fast enough spin rate there can still be a portion of the cycle when the sails themselves have negative velocity. By turning the sails on only at these times, they can operate like standard electric sails, exchanging momentum with the ambient medium and slowing down, while giving the overall spacecraft a positive momentum boost. This will also slow down the spin rate of the overall vehicle, but this can simply be spun up again by use of the central reaction wheel. We have imagined this example with the use of electric sails, though it could be easily adapted to use Magsails similarly. Although this is perhaps the most straight-forward expression of a SWIMMER, it would likely pose extreme difficulties in implementation for fast ($v \sim 0.05 \, c$) space travel. Note that each sail can only ‘push’ when its velocity is negative with respect to the ISM. To accelerate the spacecraft up to 0.05 $c$ then, would require that the electric sails be moving at a speed of at least 0.05 $c$ with respect to the vehicle center of mass. Based on the requirement that the sails be of low mass as possible, likely constructed out of thin strands of superconducting wire, they are likely to be fragile, wispy structures. Although some reinforcement may be possible, it seems unlikely that we would be able to construct sails and tethers that would be robust against the strains involved while retaining their low mass which is essential to high speed space travel.

![Figure 1](image_url)
equally in one direction. One particularly simple implementation, schematically shown in Fig. 2, would feature a pusher plate made of a large grid or long tethers of wires moving face-on through the ISM (much like the proposed geometry of a standard electric sail). Unlike a standard electric sail, however, the grid of wires would actually be two identical layers of wire sandwiching a strong insulator between them to keep the two layers electrically isolated. These wire grids or tethers could be made from very fine superconducting wire, and spun to create tension and keep the grids extended without heavy support structure. In the ‘primer’ portion of the operation cycle, we raise both layers in our pusher plate to a relatively high potential, well above the stopping potential of the ions, \( \phi_{\text{stop}} \equiv \frac{m_{\text{ion}}}{e} v_{\text{ion}}^2 \) where \( v_{\text{ion}} \) represents the maximum of either the ion thermal velocity or the streaming velocity (the velocity of the spacecraft itself, assuming travel through a stationary medium). We note that, with a lack of easy grounding options in space, in order to raise both wire layers to a high positive potential, we will need to have a third component which we can lower to a negative potential. This third component could be located far away from the main plates (on a trailing tether or a leading strut) so we can ignore it in our analysis of the electrical field near the main plates, and as before the negative electrical charge will only repel electrons, so its effect on the overall thrust will be negligible. Ions in the vicinity of the pusher plate will see a large potential barrier and quickly be pushed away, forming a gap in the ion density near the plates, and overdensities on either side of the plates. In the following ‘pusher’ stage of the operation cycle, we set up a large potential difference between the two layers of the main plate, charging the leading plate negatively and the trailing plate positively. Due to edge effects of the finite plates and the self-shielding behavior of plasmas, this results in a decaying electric potential of opposite sign on either side of the plates. The ion clump that was formed in front of the plate will be attracted to the negative front layer, pulling the spacecraft forward, and the clump that was formed trailing the plate will be repelled by the positive back layer, pushing the spacecraft forward. As the front clump approaches the plates the potential difference is removed before they pass through the pusher plate. The clumps drift away backwards as they disperse, and the distribution of the ISM is allowed to settle back into a homogenous steady state before repeating the cycle. The primer stage of operation does cause some drag as it pushes those ions in front of it into a clump, but all of this momentum can be regained during the pusher stage with a large enough potential difference, leaving the clumps traveling backwards at a greater velocity than their initial streaming velocity. This process is conceptually straightforward and obeys all conservation laws. The spacecraft gains forward momentum (to the left in Fig. 2) by giving backward momentum to the ISM. The source of the potential difference does work in the primer stage when it sets up the positive potential raising the electrical potential energy of the ion clumps, and in the pusher stage when it raises the trailing clump to an even higher potential, and yet again just after the pusher stage when the leading clump is raised from a very negative potential to a potential of zero. In this idealized one-dimensional case, it is also very energy efficient. By tuning the cycle timing and the electrical potential levels we can avoid sending any ions initially in the vicinity of the plates forward to infinity (to the left). Electrons streaming from the left and encountering the deep negative potential in the pusher stage will be reflected to the left, but as discussed above this causes only a negligible momentum drag, and for those electrons that started far away (\( \phi = 0 \)) and are reflected far away (\( \phi = 0 \)) the total energy loss will be 0. Electrons that are initially in the vicinity of the plates could get caught in the initial positive potential of the primer stage, and then if they happen to be just on the leading edge of the plates during the transition to the pusher stage they will be given a large potential energy and sent off to infinity on the left. Those electrons will present an energy loss, but this can be mitigated by transitioning from the primer to pusher potentials through a neutral state, on a timescale that is very fast for ions (IE too short to allow the ion clumps to dissipate) but quite long for the electrons, allowing those that are initially caught in the positive primer potential to dissipate. In a real three dimensional case, there will also be some loss of efficiency due to particles which do not interact perfectly in one dimension, but instead are pushed off to the side as they pass by the charged wires. The magnitude of this efficiency drop will need to be investigated carefully with particle-in-cell (PIC) simulations.

We acknowledge that in this qualitative conceptual analysis we have not accounted for the self influencing behavior of plasma. This will undoubtedly strongly influence the ion (and electron) distributions and the extended electric potential. Detailed PIC simulations will be necessary to investigate the optimal tuning of cycle timings and electrical potentials, and these will be affected by ISM density, pusher plate size, plasma (spacecraft) bulk velocity, plasma temperature, and the available power. These simulations are beyond the scope of this paper but these collective plasma effects are unlikely to affect the qualitative features of having leading and trailing ion clumps with an underdensity in the middle.
created in the primer stage. These inhomogeneities are the crucial feature that allow SWIMMERS to push on the ISM in a single direction.

The configuration described here, a large pair of wire grids with opposite charges to push on the ambient ISM, is very similar to that recently described by Robert Zubrin as the dipole drive (Zubrin 2018). In the case of the dipole drive, however, the electric field is apparently static rather than pulsed, the wire grids are separated by some distance, and they push on the charged particles as they pass between the plates. At first look, this seems like a reasonable and simpler approach. Introductory E&M tells us that two oppositely charged infinite plates produce a strong electric field between them and no electric field outside, so if we can simply push the heavy ions between the plates in the correct direction this static electric field should give us thrust. Unfortunately, the approximation of infinite plates leads us astray here. In fact, a finite system of parallel plates will produce an electric field outside the plates pushing in the opposite direction. Although these fields will be weaker than the field between the plates, they will also extend over a larger region, cancelling out the thrust gained from particles between the plates. Indeed, any system of static charges over a finite area must leave the electric potential zero at infinity. Without any change in the electric field, any particles coming from far away and leaving far away begin and end with zero electric potential energy and no change to their kinetic energy. At most their velocity vector may change and lead to a change in momentum, but this change in momentum could only be used to decelerate (with respect to the ambient medium) or change the direction of the charged system.

3. MATHEMATICAL EXPRESSION OF AN IDEALIZED CASE

We now turn to an idealized case to examine the limits of SWIMMERS. Consider a spacecraft of mass, m, moving with some velocity, v, in the frame of the surrounding medium (this would be the stationary ISM frame in interstellar space, or a frame that is traveling along with the solar wind within a heliosphere). We will further define that the spacecraft is traveling in the positive direction. Ignoring the details of operation, at a given moment the spacecraft is traveling in the positive direction. Although these fields will be weaker than the field between the plates, they will also extend over a larger region, cancelling out the thrust gained from particles between the plates. Indeed, any system of static charges over a finite area must leave the electric potential zero at infinity. Without any change in the electric field, any particles coming from far away and leaving far away begin and end with zero electric potential energy and no change to their kinetic energy. At most their velocity vector may change and lead to a change in momentum, but this change in momentum could only be used to decelerate (with respect to the ambient medium) or change the direction of the charged system.

By conservation of energy and momentum we find the final ship velocity, v’, and the ion velocity v_{ion}:

\[ v' = \frac{m^2v}{m_{ion}m + m^2} + \frac{(2\Delta E m_{ion}^2 m + 2\Delta E m_{ion}m^2 + m_{ion}^2 m^2v^2)^{1/2}}{m_{ion}m + m^2} \]

(1)

The arguments of the square roots are real and positive, and both roots represent physically meaningful interactions. Choosing the negative root corresponds to the situation in which the spacecraft gives up some momentum and sends the ions in the positive direction while slowing itself down, a braking force. Choosing the positive root corresponds to the spacecraft sending the ions in the negative direction and accelerating itself forward.

Now we assume the energy donated to the ions is given by some power, P, applied over a small amount of time, \( \Delta t \): \( \Delta E = P \Delta t \), and the mass of the ions it is applied to is given by the mass of ions swept out in time \( \Delta t \) by some cross sectional interaction area of the pusher plate, \( A \): \( m_{ion} = A v n m_p \) where \( n \) is the ion density and we have made the simplifying assumption that all the ions are protons with mass \( m_p \). To find the acceleration of the spacecraft we make these substitutions in Eq. (1) subtract the initial velocity v from v’, divide by \( \Delta t \), and then take the limit as \( \Delta t \to 0 \). The force on the ship, \( F_{SWIMMER} \), is simply acceleration times the ship mass, and is given by:

\[ F_{SWIMMER} = \pm(A m_p n v (2P + A m_p n v^3))^{1/2} - A m_p n v^2 \]

(2)

Again, the argument of the square root is real and positive, and choosing the negative root corresponds to a braking force, and the positive root to an acceleration force. We can imagine a braking force being generated by reversing the polarity of the pusher plates during the pusher stage (see Fig. 2).

The power we refer to throughout is the delivered electrical power. Thus far we have not discussed the source of power a SWIMMER might use. There is no reason a SWIMMER could not use an onboard power source, making it totally independent of external infrastructure. This, of course, would require an exceptionally energy dense fuel source as well as a very efficient generator to achieve useful velocities for interstellar travel (note that if the spent fuel mass rate is high and used fuel is continuously ejected, this would alter eqs. (1) and (2) as the ship’s mass decreases throughout the interaction, but if spent fuel is held on board these equations would not change). We will instead generally consider the case where power is beamed remotely to the SWIMMER, which invites a direct comparison to light sails. In this case we include an additional \( P/c \) term to eq. (2) corresponding to the photon pressure of the beamed energy being absorbed by the spacecraft (although as we will see, this photon force makes little difference in most of the situations we will be interested in). The force we will be investigating is then:

\[ F = \pm(A m_p n v (2P + A m_p n v^3))^{1/2} - A m_p n v^2 \pm \frac{P}{c} \]

(3)

The photon pressure term is added or subtracted depending on whether the beamed energy is directed in the same direction as the SWIMMER velocity, or op-
posed to it respectively. Explicitly then, there are four different modes of operation for a SWIMMER depending on the orientation of the velocity, the photon force, and the interaction force from pushing on the ions in the surrounding medium (\( F_{\text{SWIMMER}} \)). These are illustrated in Fig. 3 along with their corresponding implementations of eq. 3 with explicit positive and negative sign choices of the photon force and the root of the SWIMMER force. We refer to these four modes respectively as ‘normal’ mode when the velocity, \( F_{\text{MER}} \) and photon force are all aligned in the same direction; ‘tractor beam’ mode when the velocity and \( F_{\text{SWIMMER}} \) are aligned with each other but opposed to the photon force; ‘destination braking’ when the photon force and velocity are aligned but opposed to \( F_{\text{SWIMMER}} \); and ‘home braking’ when the photon force and \( F_{\text{SWIMMER}} \) are aligned but opposed to velocity. The ability to operate in these multiple modes is one of the advantages of SWIMMERS. Unlike light sails they are able to decelerate at their destinations, or even be accelerated back towards their origin without additional infrastructure such as a laser array or giant reflector previously prepared at the destination (or launched along with the spacecraft and allowed to travel ahead). Since \( F_{\text{SWIMMER}} \) is velocity dependent and drops to zero at zero velocity, we do note that a SWIMMER would never be able to completely come to a stop and reverse in the dead of the ISM. Additional means of propulsion such as a modest rocket engine could be carried along to provide this last \( \Delta v \) to reverse the direction after most of the braking was accomplished in destination braking mode, and then the SWIMMER could begin operating again in tractor beam mode. If the destination were not the dead of the ISM, but a star with an active heliosphere, however, this would be unnecessary. Upon entering the alien heliosphere a SWIMMER could begin destination braking and reduce its velocity to near zero. We remind the reader that the velocity of interest is the spacecraft’s velocity with respect to the interacting medium. Therefore, within the alien heliosphere destination braking would allow the SWIMMER to approach the velocity of the outward streaming solar wind. It could then coast along with the solar wind until exiting the heliosphere, at which point its velocity with respect to the interacting medium would change from nearly zero to whatever the solar wind velocity was (\( \sim 5 \times 10^5 \) m s\(^{-1} \) \( \approx 0.0017c \) around our sun and likely similar for other stars of similar type). At that point the SWIMMER could operate in tractor beam mode until approaching its origin and switching to home braking. A SWIMMER launched within our heliosphere but at low velocities below the solar wind would also operate in home braking mode. A SWIMMER sent to the edge of our heliosphere which needed to return swiftly could accelerate directly inward in tractor beam mode, unlike electric sails.

All four of these modes of operation could be useful for different missions, however, for any SWIMMER mission to another stellar system, the normal mode will be used for the bulk of the journey. We explore the behavior of this mathematical representation of SWIMMERS in further detail. For the rest of this section we will adopt the version of eq. 3 with the positive root and the positive photon force. It will also be useful to consider the ratio, \( R \), of the force on a SWIMMER to the force of an ideal light sail \( (2P/c) \), which we can write as:

\[
R = \frac{1}{2} \left( 1 - \frac{A}{P} cm_p n v^2 + c(2A/P m_p n v + (A/P)^2 m_p^2 n^2 v^4)^{1/2} \right). \tag{4}
\]

In Fig. 4 we show R as a function of velocity for a few values of A/P. There is some uncertainty surrounding the structure and properties of the local ISM, but there is general consensus that a journey to \( \alpha \) Cen A will involve passage through some combination of the Local Interstellar Cloud, the Circum-Heliospheric Interstellar Medium, and the G Cloud. Therefore, we conservatively assume \( n \approx 0.07 \) cm\(^{-3} \) a low ion density consistent with any these clouds (eg. Crawford 2011). Fig. 4 shows the force initially rising with velocity due to the increasing volume of ISM swept out. The force peaks at some velocity, \( v_{\text{peak}} \), and then decreases as the ratio of the change in momentum to change in energy shrinks with faster ion velocities. Due to this initial rise in force with velocity, it may be useful to give SWIMMERS an initial velocity boost through other means (such as conventional rockets, gravitational assists, particle beam assists, or through home braking SWIMMER mode operations allowing electric sail-style passive interaction with the solar wind) to take advantage of the forces at higher velocities. Taking the derivative of eq. 3 with respect to \( v \) and setting it equal to zero we find the velocity of this peak force:

\[
v_{\text{peak}}^3 = \frac{P}{4m_p n A}. \tag{5}
\]

Larger A/P values give significantly better performance at lower velocities, but trend together as velocity increases, with the force approaching \( \frac{P}{c^2} \), shown by the red line in Fig. 4. As a somewhat arbitrary metric, we note that this implies...
an order of magnitude larger force relative to light sails up to \( v = c/19 \) or about 5% c. This also illustrates that it is not always advantageous to increase the pusher plate area arbitrarily. If, for instance, we started our SWIMMER operation with an initial velocity of \( 10^6 \) m s\(^{-1} \) with \( \log(A/P)\) =3, increasing A by a factor of 100 will not give dramatically better performance since at our initial velocity the force is already close the limit of \( F \propto v^2 \) and it would presumably require an increase in the spacecraft mass and thus a net decrease to the acceleration. It might even be useful to adjust pusher plate area en route by discarding bits of the pusher plate as the SWIMMER reaches higher velocities. If, after accelerating to velocities \( v >> v_{peak} \), we can significantly reduce the total SWIMMER mass by discarding pusher plate area then we can achieve higher accelerations. We also note that increasing \( A/P \) by simply reducing the power will increase R as seen in Fig. 4, but it decreases the overall force.

Finally, we note that SWIMMERs should probably not be completely dominated by the mass of either the pusher plate or the power conversion system which converts beamed light into electrical energy. If the SWIMMER mass were dominated by the pusher plate, which we assume is made up of a wire mesh or tethers, as suggested in Section 2, then the mass will grow roughly as \( \sigma A \), where \( \sigma \) is the areal density of the wire mesh. The acceleration will then be given by the force in eq. 3 divided by \( \sigma A \), which can be shown to always have a negative first derivative with respect to \( A \), indicating that adding mass to increase the cross sectional area will only result in slower acceleration. If instead the mass is dominated by the power conversion system, the mass grows with \( P \). This is fairly reasonable if we consider the power system as a thermodynamic heat engine, absorbing the remotely beamed energy, and converting it to electrical power through a temperature differential with a heat sink radiating to empty space. To convert more power at the same efficiency, the surface area of the heat sink, \( S \), must increase proportional to \( P \). Exactly how the mass of the heat sink varies with surface area depends on its geometry, but it is safe to assume \( m \propto S^\gamma \propto P^\gamma \) where \( 1 \leq \gamma \leq 3/2 \). In the most optimal case we use \( m \propto P \), and we find the acceleration by dividing the force by \( \kappa P \) (where \( \kappa \) represents the specific power, W kg\(^{-1} \) of the power conversion system). Again, we find the first derivative is always negative indicating that higher acceleration could be achieved by decreasing the power and the mass associated with the power system.

Figure 4. The total force on a SWIMMER in normal operation \( (F_{SWIMMER}+F_{photon}) \) divided by force on an ideal light sail \( (F_{SWIMMER}) \), as a function of velocity. We show trends for \( \log(A/P) = 6, \ 4, \) and 2 in solid, dash dotted, and dashed lines respectively. In general, high values of \( A/P \) give superior performance relative to light sails. The straight red line indicates \( F_{SWIMMER} \), the ratio approached at high velocities.

4. POTENTIAL SWIMMER MISSIONS

To illustrate the potential utility of SWIMMERs in interstellar travel, we now consider some possible future missions. We will focus on the SWIMMER itself, and ignore the infrastructure associated with the stationary beamed power station, as this has already been explored in some detail in regards to light sails. In general, the specific power of the onboard SWIMMER power converter will be an important parameter for our consideration as it determines the mass devoted to the onboard power systems. Photovoltaic cells have fairly poor specific power, \( \sim 80 \) W kg\(^{-1} \) in space based applications (Dankanich et al. 2015). Although technological advances such as inflatable solar arrays might improve their specific power, even these foreseen developments may not increase photovoltaic specific power sufficiently for use in a SWIMMER. Rectennas may be more promising, with near-term estimates of specific power as high as 4 kW kg\(^{-1} \) (Dankanich et al. 2015). Although there is ongoing work to extend rectennas to the optical regime (e.g. Modeld 2013), current rectennas are only able to convert light at \( \sim cm \) wavelengths to electrical power. At such long wavelengths however, the diffraction of the light beam would be too large to provide useful power at interstellar distances without an interstellar highway of booster beams or lenses along the route of travel. Perhaps the ideal power converter would be a simple reflector consisting of thin aluminized plastic stretched across an aperture and electrostatically curved to a focus by a grid of charged wires behind it. Beamed optical or UV light would then hit the reflector, and converge toward a heat engine. The heat engine would need to be very low mass, but not necessarily efficient if we can muster a little more power output from our remote beam station. In fact, an inefficient heat engine with a relatively hot ‘cold’ side would radiate to space more efficiently and require a lower mass radiative heat sink. The practical limits of such a system are not well known and we will not attempt to estimate them here. Instead, we will assume a specific power of 4 kW kg\(^{-1} \), while acknowledging that if heat engines are unable to achieve this, and neither rectennas nor photovoltaics are able to be sufficiently developed, we will not be able to achieve the relatively short travel times presented here. For these examples we will adopt a simplified model of the ISM and the heliospheres. We assume the ISM has a density of 0.07 cm\(^{-3} \), a temperature of 7000 K, and therefore an electron Debye length \( \lambda_D = 21.8 \) m. We assume the heliospheres of both the sun and \( \alpha \) Cen A have a density...
of 7.3 cm$^{-3}$, a temperature of 140000 K, and therefore an electron Debye length $\lambda_D = 9.5$ m. Furthermore, we assume the solar wind in both heliospheres is uniformly streaming away at a velocity of $5 \times 10^6$ m s$^{-1}$ out to a distance of 100 AU at which point the surrounding medium abruptly transitions to a stationary ISM.

### 4.1. Space probe rendezvous at $\alpha$ Cen A

A relatively early stage SWIMMER mission might have the goal of transporting a modest space probe, $m_{\text{pay}} = 1000$ kg to $\alpha$ Cen A and then decelerating to allow gravitational capture for a permanent orbital space telescope. We will assume a modest electrical power delivered to the SWIMMER of 10 MW. The pusher plate will be made up of several long tethers. In practice these tethers will consist of very fine braided filaments to prevent failure due to micrometeoroid and interstellar dust collision, as described for the electric sail (Janhunen 2004), but we will consider them to be single wires with an effective diameter of 30 $\mu$m. This is equivalent in material to eight filaments with diameters of about 10 $\mu$m. We will also include strategically weak breakpoints in our tethers which can be activated by simply increasing the spin rate such that the centripetal force exceeds the break point capacity. As we reach higher velocities then, we may leave behind mass from the pusher plate. Given the pulsed nature of the SWIMMER electric field, the wire tethers should be made out of superconducting materials. A full analysis of the material requirements is beyond the scope of this paper, but will depend on the necessary current density based on the geometry of the pusher plate as well as the timescale of the primer and pusher stages. For our example we will use MgB$_2$, a well known super conductor with a density of $\rho = 2570$ kg m$^{-3}$ and a high critical temperature ($T_c = 39$ K) which should passively reach super conductivity beyond approximately 5-50 AU depending on its surface emissivity. A single charged wire will interact with charged particles passing within $\sim \lambda_D$ on either side of it. The total cross sectional interaction area is given by $A = L \times 2 \lambda_D$ where $L$ is the summed length of all the tethers. The mass devoted to this pusher plate will be $m_{\text{pusher}} = \rho \times L \times \pi r_{\text{wire}}^2$.

The total mass of the SWIMMER ship is comprised of $m_{\text{pay}} = 1000$ kg, $m_{\text{power}} = 2500$ kg (given by our 10 MW electric power supply and its assumed specific power), and $m_{\text{pusher}}$. At the moment it is unclear how much mass to devote to $m_{\text{pusher}}$, however we will show that a mass of 7400 kg is useful. The mass for the tethers could be mined in situ from asteroids. This mass provides for a total summed tether length of $4.1 \times 10^9$ m. While this is seemingly a very long tether, it does not in any way represent the spatial scale of the SWIMMER as the pusher plate will be made up of several thousand tethers, possibly splitting off from each other at greater radial distances. The summed length is merely a useful value for determining the total cross sectional area in plasmas of different temperatures and densities.

We will assume the SWIMMER begins at rest with respect to the sun near its creation site by the asteroid belt at 3 AU. Within our heliosphere the SWIMMER will be able to operate in home braking mode by producing a drag force with respect to the solar wind. Our pusher plate tethers will not be super conducting in the inner solar system, but even while operating totally passively with $P=0$, essentially operating as a normal electric sail, a static charge on the plates will produce a significant drag force accelerating the SWIMMER towards the velocity of the solar wind. Based on the total tether length, our SWIMMER will have a total cross sectional interaction area of $7.7 \times 10^{10}$ m$^2$ within the heliosphere. Using simple code written in Interactive Data Language (IDL) (available in appendix) we iteratively track the SWIMMER path according to eq. (3) while also introducing a gravitational attraction inwards toward the sun. After 1.5 years the SWIMMER enters the ISM at 100 AU with a velocity of $4.0 \times 10^6$ m s$^{-1}$.

Upon entering interstellar space, the SWIMMER begins normal mode operations. Simultaneously the ion density drops and the cross sectional area of our tethers increases by a factor of $\lambda_D(\text{ISM})/\lambda_D(\text{helio}) = 2.3$. At this distance from the sun our tethers will be superconducting, and we can begin applying our 10 MW of power. We will also begin discarding mass from the pusher plate as it accelerates. The optimal rate to discard mass will change based on the specific details of any given mass distribution, power, and journey length. To investigate this situation we parameterized the problem by assuming that at any given moment, if the pusher plate mass is a significant fraction of the total mass, $m_{\text{pusher}}/m_{\text{tot}} > \chi$, we will discard mass from our pusher plate until $A = \psi A_{\text{peak}}$ where $A_{\text{peak}}$ is the pusher plate area that corresponds to the $A/P$ value which lets the current SWIMMER velocity match $v_{\text{peak}}$. We experimentally vary the parameters $\psi$ and $\chi$ to find the minimum travel time. Running our simple code with a range of $\psi$ and $\chi$ values we find a minimum 1 pc travel time of 263 years for our SWIMMER with $\chi = 0.13$, and $\psi = 0.53$. The ship arrives with a velocity of $6.0 \times 10^6$ m s$^{-1}$ ($0.02$ c). Without allowing the pusher plate mass to be discarded en route, the journey would take slightly longer at 340 years. For comparison, an ideal light sail dominated by $m_{\text{pay}} = 1000$ kg (IE ignoring the light sail mass and assuming perfect reflectivity) pushed with the same delivered power, would take 793 years to complete the same journey, and it would not be able to stop at the destination without very complicated optics such as a detachable mirror that sails out ahead (Forward 1984).

As the SWIMMER approaches $\alpha$ Cen A it begins destination braking. This would begin in nearby interstellar space at a distance of $\sim 2500$ AU from $\alpha$ Cen A. By this distance $\alpha$ Cen A it begins des-
orbit, or stop braking and enter a highly elliptical orbit that will allow it to pass through the inner and outer regions of the α Cen A system. The full journey takes just under 290 years. This is a significant amount of time for a scientific endeavor, but there is good precedent for multi-century science projects for worthwhile investigations (cf. Kivilaan & Bandurski 1981; Johnston 2013; Cockell 2014).

4.2. Ark ship

Due to their extremely favorable performance at lower power and velocities, SWIMMERs would make excellent transporters for large masses that can take long timescales. This could be used as the basis of a generation ship, or perhaps a transporter for bulk colony materials sent out ahead of time before a fast moving low mass people transporter arrived. For this example we will assume a payload mass, \( m_{\text{payload}} = 8 \times 10^9 \) kg, equivalent to the Super Orion ship discussed by Dyson (2002). Since such a mission would likely only be attempted after significant technological advances, we will slightly improve our material properties by assuming a specific power in our power conversion systems of 10 kW kg\(^{-1}\), and superconducting materials which are able to passively operate beyond 3 AU. We will take our delivered SWIMMER power to be 10000 GW, thus \( m_{\text{power}} = 1 \times 10^9 \) kg. We will use a pusher plate of mass \( m_{\text{pusher}} = 3.7 \times 10^{10} \) kg, with a summed tether length of 2.0 \times 10^{16} m. As before, this pusher plate mass is based on our optimization of the travel time during the normal SWIMMER operation as a function of velocity, \( \psi \), and \( \chi \).

In the initial stage the ark SWIMMER accelerates in home braking mode from rest at 3 AU, with the full benefit of the beamed power. In the heliosphere the pusher plate has a cross sectional interaction area of 3.0 \times 10^{17} m\(^2\). Although it requires relatively little mass, this is, admittedly, very large (\textasciitilde 20\% of the sun’s cross sectional area). Care would need to be taken during construction to ensure tidal forces with any nearby asteroids do not disrupt the pusher plate. This results in an eight year journey to the edge of the heliosphere at 100 AU, where it enters the ISM at a velocity of 1.3 \times 10^5 m s\(^{-1}\). Due to the larger Debye length, the cross sectional interaction area in the ISM is 6.8 \times 10^{17} m\(^2\). Operating in normal mode with \( \psi = 0.070 \) and \( \chi = 0.17 \) it takes 375 years to travel 1 pc, at which point it has a velocity of 4.3 \times 10^6 m s\(^{-1}\) and a remaining total mass of 1.09 \times 10^{10} kg. For comparison, this 1 pc long journey through interstellar space would require 2300 years for an ideal light sail pushed by 10000 GW and with the same payload and negligible sail mass.

The very large pusher plate of the ark ship allows it to decelerate even faster than the previously considered space probe. If it begins destination braking at a distance of 6500 AU from α Cen A, then after 12 years it will reach the edge of the heliosphere with a velocity of 1.6 \times 10^6 m s\(^{-1}\). Entering the heliosphere the cross sectional area changes as before, and we continue destination braking with power. After another year the SWIMMER arrives at a a distance of 3.7 AU from the star, and has braked to escape velocity at 2.3 \times 10^4 m s\(^{-1}\) (with respect to α Cen A). Slight variations in the onset of braking and the applied electrical power will allow it to reach any orbit within the heliosphere in comparable times. The full journey takes just under 400 years.

5. Summary

SWIMMERs represent a new mode of interstellar transport. By disposing of onboard reaction mass they circumvent the rocket equation, and by exchanging momentum with ions in the ISM they improve by orders of magnitude over the energy efficiency of traditional light sails. The key to this momentum exchange is the changing electric field which allows us to create inhomogeneities in the surrounding plasma, and then push on these inhomogeneities to create thrust. SWIMMERs perform exceptionally well at lower velocities, with their advantage over light sails diminishing quickly at \( v > 0.05 \) c. Furthermore, by relying on the ambient ISM as a momentum exchange medium, they are quite versatile, able to accelerate either away or towards a beamed energy source, opening up myriad opportunities to serve as oneway transport, roundtrips, or even statites in stationary positions.

The examples discussed here only scratch the surface of the possible roles for SWIMMERs in our spacefaring future. Their characteristics make them ideal for any mission with large masses in which relatively low velocities (\( v < 0.05 \) c) are acceptable. They are unlikely to be the sole mode of space transport due to their diminishing advantages at high velocities and their structural complexity which requires onboard power conversion systems with significant mass. Nonetheless, SWIMMERs will play an important role in future space exploration and augment other modes of transport. They might, for instance, also be well suited to aiding the construction of a fast interstellar highway by transporting massive particle beam stations along with their fuel supply out to stationary positions between us and our target destinations. These particle stations could be used to swiftly carry light weight Magsails along the path, and simultaneously augment the power of future SWIMMERs by replacing the stationary ISM with a corridor of fast moving beamed particles.

The missions we focused on regard one way interstellar trips. While they do push the limits of current technology by assuming relatively high specific power electrical systems, and very thin mass-produced super conducting wire, (as well as very large laser arrays which we have ignored) we see no obvious material or theoretical limits which would prevent these missions from realization. Future work in this vein will need to examine several issues we ignored here. Areas of further investigation, include the efficiency of the SWIMMER drive in three dimensions; the electrical potential, and cycle timings during the pulsed SWIMMER operation and how they effect the required current density of the tethers; the expected impact of interstellar dust collisions and redundant tether configurations to ameliorate damage; and realistic limits on power conversion systems capabilities.

As our understanding of interstellar travel develops, we must face the realization that, not only is it difficult, but there is no one-size-fits-all solution. Where SWIMMERs excel in one metric, other methods may excel in another. Ultimately our best strategy is to develop all possible methods in the hope that their synergy will provide a
means to accomplish our goals.

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The code used to calculate the SWIMMER journey, written in Interactive Data Language (IDL) is included below.

```idl
; The next three functions return the force in different SWIMMER operation modes

function forcenormal, A, P, v, n
; A is area (m)
; P is power (W)
; v is velocity with respect to medium (m/s)
; n is ion density (m^-3)
  c = 2.99792458d8
  mp=1.6726219d-27
  f=sqrt(A*mp*n*v*(2.*P+A*mp*n*v^3))+P/c-A*mp*n*v^2
  return, f
end

function forcehomebrake, A, P, v, n
  c = 2.99792458d8
  mp=1.6726219d-27
  f=-sqrt(A*mp*n*v*(2.*P+A*mp*n*v^3))-P/c-A*mp*n*v^2
  return, f
end

function forcedestinationbrake, A, P, v, n
  c = 2.99792458d8
  mp=1.6726219d-27
  f=-sqrt(A*mp*n*v*(2.*P+A*mp*n*v^3))+P/c-A*mp*n*v^2
  return, f
end

; This function finds the pusher plate area, A which would make $v_{peak} = v$ (see eq. 5)
function apake, P, v, n
  c = 2.99792458d8
  mp=1.6726219d-27
  apake=P/(4.0*mp*n*v^3)
  return, apake
end

; This procedure simulates a SWIMMER voyage in normal operations.
; The option to discard pusher plate mass may be turned on or off
pro testflight_normal, Area0, P, v0, m0, range, n, results, chi=chi, psi=psi
; P is power
; Area0, and v0 give the initial pusher plate area and velocity
; m0 gives the initial SWIMMER mass. It may either be a single value,
; giving the total mass (in kg), or it may be an array of three values which give:
; [m_pusher, m_power, m_pay]
; If one value is given, the mass is assumed to stay constant.
; If three values are given,
; the pusher plate mass will be decreased throughout the voyage.
; range gives the distance (in m) at which we stop the simulation
; n gives ion density (in m^-3)
; results returns an array giving the voyage time (in years), the final velocity (m/s),
; the final total mass (m_pusher + m_power + m_pay), and the final cross sectional
; interaction area of the pusher plate
; EXAMPLE:
; a modest probe travels through interstellar space for 1 pc
; testflight_normal, 1.7743395 d11,10 d6, 4d5, [7386.1387 ,2500. ,1000.], 3.086 d16, 7d4,
; results, chi =0.12554352 , psi =0.53182959
; chi = sailfrac
; psi = relativepeak
; sail = pusher
if n_elements(m0) eq 3 then sd=1 else sd=0
; ( turn on mass discarding if m0 is an array)
if keyword_set(chi) eq 0 then chi=0.1
if keyword_set(psi) eq 0 then psi=1.
if keyword_set(silent) eq 0 then silent=0.1
if keyword_set(silent) eq 0 then silent=0 else silent=1

; useful constants
autom = 1.496d11
rearth = 6.371000d6
pcm=3.086d16
yrstosec = 3.1536d7
bs=2.99792458d8
mp=1.6726219d-27

d / These effect our time steps (larger values mean fewer time steps)
selfrac=0.016
psfrac=0.005d

; set some records
area=[
vrec=[
trec=[
mrec=[
arec=[
areapusherrec=[
arec=[
]}
]}
]}
]}
arec=[]
t=0
iteration=0

; src=forcenormal(area,p,v)
if sd then begin
  sigma=m0[0]/area0
  areal density of pusher plate
```
SWIMMERS: POTENTIAL AND LIMITATIONS OF PROPELLANTLESS INTERSTELLAR TRAVEL

```
while x lt range do begin
  iteration=iteration+1
  ; want to chuck out some pusher plate mass ?
  if sd then begin
    ; based on our power and current velocity,
    ; we find the pusher plate area such that v_peak = v, and scale by psi
    newarea=psi*apeak(P,v,n)
    newmpusher=newarea*sigma
    ; only make this change if it has a big effect on overall mass (governed by chi)
    if newmpusher/total(m) gt chi then begin
      area=newarea
      m[0]=newmpusher
      endif
    area.pusherrec=[area.pusherrec,area]
    mrec=[mrec,total(m)]
  endif else begin
    areapusherrec=[areapusherrec,area]
    mrec=[mrec,m]
  endelse
  f=forcenormal(area,p,v,n)
  a=f/total(m)
  ; we want an adaptive time step that will allow us to reevaluate the forces
  ; as the velocity changes, and reevaluate the position as we get close to the end
  timestep1=velfrac*v/a
  timestep2=(range/v)*(posfrac)
  timestep3=(range-x)/v
  timestep=min([timestep1,timestep2,timestep3])
  t=t+timestep
  arec=[arec,a]
  xrec=[xrec,x]
  trec=[trec,t]
  vrec=[vrec,v]
endwhile

; confirm we didn't overshoot our range too much
overshoot=x-range

; for comparison, how long would it take a light sail pushed by the same power, and with
; ONLY the mass of the payload to complete the same journey?
fsail=2.*P/c
if sd then asail=fsail/(m[2]) else asail=fsail/(m)
tail=(sqrt(v0^2+2.0*asail*range)-v0)/asail
if silent eq 0 then begin
  print, "overshoot/AU: ", overshoot/autom
  print, "journey time (yrs): ", trec[-1]/yrstosec
  print, "final velocity (m/s): ", v
  print, "m0(pusher, power, payload): ", m0
  print, "mfinal(pusher, power, payload): ", m
  print, "A0 (pusher area): ", areapusherrec[0]
  print, "Aend: ", area
  print, "Light sail time for same journey: ", tail/yrstosec
plot, trec/yrstosec, vrec, xtitle='years', ytitle='m/s'
end
```

This procedure simulates a SWIMMER voyage in home braking operations:
Gravity may be turned on or off
pro testflight_homebrake, Area0, P, v0, m0, range, n, x0, results, silent=silent, grav=grav

Parameters are mostly as in the previous procedure:
If it is now a two element array giving the velocity with respect to the surrounding
medium, and velocity with respect to the sun.
The parameter n gives the initial starting distance (in m) from the sun.
By default gravity is ignored, but by turning on the grav keyword it will be included.
Results returns journey time, final velocity (w.r.t. solar wind), final velocity
(w.r.t. sun)

Example:
A modest probe accelerates from rest near the asteroid belt without power
/testflight_homebrake, 1.773202541d+0, 52.21, 02., 5d0, [500000. ,0 ], 10886.193 , 3d1
if keyword_set(silent) eq 0 then silent=0 else silent=1
if keyword_set(grav) eq 0 then grav=0 else grav=1

Useful constants
axion = 1.406d11
rearth = 6.371000d6
pcm=3.086d16
yrstosec = 3.1536d7
c = 2.99792458d8
msun=1.989d30
mp=1.6726219d-27

These affect our time steps (larger values mean fewer time steps)
svelfrac=0.01d
postfrac=0.005d

Set some records
src=[]
vheliorec=[]
vwindrec=[]
trec=[]
arec=[]
areapusherrec=[]
srec=[]
m=m0
vwind0=v0[0]
vhelio0=v0[1]
area=area0
x=x0
t=0
vwind=vwind0
vhelio=vhelio0
iteration=0

types=['t1','t2','t3']
ttyperec=[]
while x < range AND vwind gt 0 AND iteration lt 10000 do begin
  iteration=iteration+1
  if grav eq 0 then fgrav=0 else fgrav=6.67408d-11*m*msun/(x^2)
f=forcehomebrake(area,p,vwind,n)+fgrav
  a=f/m
  tstep1=velfrac*abs(vwind/a)
tstep2=(abs((range-x0)/vhelio))*posfrac
tstep3=(range-x)/abs(vhelio)
tstep=min([tstep1,tstep2,tstep3],tminloc)
srec=[srec,tstep]
ttyperec=[ttyperec,ttypes[tminloc]]
t=t+tstep
  ; the acceleration is negative, so our positive vwind will decrease
  ;(IE the SWIMMER will be dragged up to rest w.r.t. solar wind)
  newvwind=vwind+tstep*a
  ; vhelio (defined as positive going away from the sun) will increase
  newvhelio=vhelio-tstep*a
  x=x+tstep*(vhelio+newvhelio)/2.
vwind=newvwind
vhelio=newvhelio
arec=[arec,a]
xrec=[xrec,x]
trec=[trec,t]
vwindrec=[vwindrec,vwind]
vheliorec=[vheliorec,vhelio]
endwhile

overshoot=x-range
if silent eq 0 then begin
  print, "overshoot/AU: ", overshoot/autom
  print, "journey time (yrs): ", t/yrstosec
  print, "v(wind,helio) at end: ", vwind, vhelio
  plot, trec/yrstosec, vwindrec, xtitle='years', ytitle='m/s',
  title='(vwind␣solid,␣vhelio␣dashed)'
  oplot, trec/yrstosec, vheliorec, linestyle=2
endif
results=[t/yrstosec,vwind, vhelio]
end

This procedure simulates a SWIMMER voyage in destination braking operations
;gravity may be turned on or off
pro testflight_destinationbrake, Area0, P, v0, m0, range, n, results, silent=silent, $
g=grav, vcut=vcut, escape=escape
;parameters are mostly as in the previous procedure
; x0 could have two components, wind (wrt to wind) helio (wrt to helios)
; all is the distance from Alpha Centauri at which the SWIMMER starts
; range is the distance at which the simulation stops (we assume range < x0 since we're
; coming from the ISM and trying to stop)
; by setting the vcut keyword we have the option of stopping the simulation
; when the SWIMMER decelerates to vcut (w.r.t. Alpha Centauri)
; note that a negative velocity u.*-1. d Cen indicates the SWIMMER approaching the star
; alternatively you can set the escape keyword, and the simulation will calculate escape
; velocity of each step and use that for vcut

;example
; ;; a modest probe begins braking in interstellar space
; testflight_destinationbrake, 1.2451736 d10, 10 d6, 
; [6018922.8, -6018922.8], 4005.5601, 
; 100.*1.496 d11, 7d4, 100.*1.496 d11, results, / escape
; ;; the probe then enters heliosphere of Alpha Centauri (effective area changes,
; ;; density changes, vwind gets a boost, power cut to 0)
; testflight_destinationbrake, 1.2451736d10*9.53/21.82, 0d6,
; [results[1]+5 d5, results[2]], 4005.5601, 1.*1.496 d11, 7.3d6, 100.*1.496 d11, 
; results, / escape, / grav
if keyword_set(silent) eq 0 then silent=0 else silent=1
if keyword_set(grav) eq 0 then grav=0 else grav=1

; useful constants
autom = 1.496d11
rearth = 6.371000d6
pcm=3.086d16
yrstosec = 3.1536d7
c = 2.99792458d8
msun=1.989d30
mAC=msun*1.1
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mp=1.6726219d-27

; these effect our time steps (larger values mean fewer time steps)
velfrac=0.01d
posfrac=0.005d

; set some records
src=[]
vheliorec=[]
vwindrec=[]
trec=[]
arc=[]
xrec=[]

m=m0
vhelio0=v0[1]
vwind0=v0[0]
area0=area0
x=x0

while x gt range AND vhelio lt vcut AND iteration lt 10000 do begin
  iteration=iteration+1
  if grav eq 0 then fgrav=0 else fgrav=6.67408d-11*m*mAC/(x^2)
  f=forcedestinationbrake(area,p,vwind,n)+fgrav
  a=f/m
  tstep1=velfrac*abs(vwind/a)
  tstep2=((range-x0)/vhelio)*posfrac
  tstep3=(range-x)/vhelio
  tstep4=velfrac*abs(vhelio/a)
  tstep=min([tstep1,tstep2,tstep3,tstep4],tminloc)
  if we put in strange numbers we can end up with a positive vhelio
  for our purposes that means we’ve brake too much, so we wait for a
  negative time step to show up and then throw an error
  IF TSTEP LE 0 THEN BEGIN
    PRINT, "TSTEP ERROR!"
    STOP
  ENDIF
  srec=[srec,tstep]
ttyperec=[ttyperec,ttypes[tminloc]]
  t=t+tstep
  newvwind=vwind+tstep*a
  newvhelio=vhelio-tstep*a
  x=x+tstep*(vhelio+newvhelio)/2.
  vwind=newvwind
  vhelio=newvhelio
  arc=[arc,a]
  xrec=[xrec,x]
  arec=[arec,a]
  trec=[trec,t]
  vheliorec=[vheliorec,vhelio]
  if keyword_set(escape) then begin
    vcut=-1.0*sqrt((2.0*6.67d-11*2.1879d30)/x)
  endif
endwhile

; overshoot is not so useful here since we may be stopping at a specified velocity
; rather than at range
overshoot=x-range
if x le range then criteria="reached extent of range - did not meet vcut="+string(vcut)
if silent eq 0 then begin
  PRINT, "journey time (yrs): ", t/yrstosec
  PRINT, "v(wind,helio) at end: ", vwind, vhelio
  PRINT, "final distance from A.C. (in AU): ", x/autom
  PRINT, "simulation completed because SWIMMER “criteria
title="(vwind solid",_1,1,0,vhelio,dashed)"
  oplot, trec/yrstosec, [1,0,vhelio,dashed]
endif

results=[t/yrstosec,vwind, vhelio]