Magnetic and electric sails 13

We saw in the previous chapter that the Sun emits a wind of charged particles. If the momentum of these charged particles can be coupled to a spacecraft, it could be used as a means of propulsion, either to accelerate an outgoing spacecraft or to decelerate an incoming one. In a similar way, the charged particles of the ISM could be used to decelerate a spacecraft that is moving relative to them. In this chapter we look at two distinct methods of using charged particles in this way, namely magnetic sails and electric sails.

13.1 Magnetic sails

13.1.1 Concept

The idea of magnetic sail propulsion is to use a magnetic field to generate a magnetosphere around the spacecraft. This is conceptually the same as the magnetosphere around the Earth generated by its magnetic field. When such a spacecraft is within the solar system, the solar wind will in effect reflect off the surface of the magnetosphere, imparting its momentum onto the magnetosphere, and therefore onto the spacecraft from which the field is generated. The size of the acceleration depends on the velocity of the wind particles relative to the spacecraft. The same principle applies when the spacecraft is moving through the ISM, as this also contains charged particles.

To create a magnetosphere, a spacecraft deploys a large conducting loop. The loop is orientated so that its axis is perpendicular to the direction towards the Sun. Running a current through the loop generates a dipole magnetic field. In a vacuum, such a field would be symmetric about the loop's axis. But when impacted by a moving plasma, the shape of this field is distorted by the interaction of the charged particles with the field, as shown in figure 13.1. The field is compressed in the upwind direction and extended in the downwind direction. The boundary of the magnetosphere is the magnetopause, defined as the surface where the magnetic pressure from the field, $B^2/2\mu_0$, equals the ram pressure of the plasma, $(1/2)\rho_p v^2$, where ρ_p is its density and v is its velocity normal to the magnetopause. B is the magnetic field strength at the boundary and μ_0 is the vacuum magnetic permeability (approximately $1.26 \times 10^{-6}\,\mathrm{N\,A^{-2}}$). As the magnetic field strength and the velocity and density of the plasma vary spatially due to the interaction, the shape of the magnetopause needs to be found via an iterative numerical method. Few plasma particles penetrate deeply into the magnetosphere, so this is a region where the plasma density is low but the magnetic field strength is high. Outside the magnetosphere the plasma density is higher, but the magnetic field strength from the loop is low.

Charged particles that encounter the magnetopause with a velocity $\mathbf{v}$ are deflected by the magnetic field $\mathbf{B}$ according to the Lorentz force, $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$. Charges of different sign are

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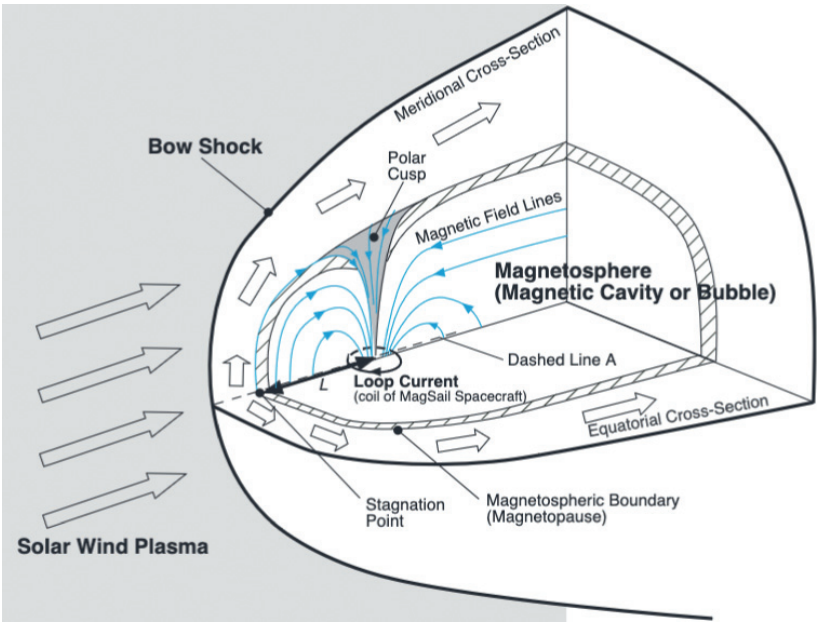


Fig. 13.1 The magnetic sail concept. A current through the loop creates a magnetosphere that then deflects a moving plasma, shown by the large arrows. Credit: Funaki and Nakayama (2012), licensed under CC-BY-3.0, obtained from IntechOpen.

deflected in different directions (and by different amounts when their velocities differ). This generates a current in the magnetopause, and this current interacts with the magnetic field to create a Lorentz force on this field, and therefore on the spacecraft. The net force acts in the initial direction of the solar wind, which is radially away from Sun. The magnetopause can be considered as a magnetic sail against which plasma particles are deflected and thereby exert a force on it and, by extension, on the loop (spacecraft) that created the magnetic field.

We can compute the size of this magnetic force analytically to within numerical factors. From the Biot–Savart law, a loop of radius a carrying a current I produces a magnetic field at a large distance r ($r \gg a$) of magnitude[1]:

$$B \sim \frac{\mu_0 I a^2}{r^3}. \tag{13.1}$$

This is only valid in the absence of the plasma, of course, because that distorts the field. At the magnetopause, the magnetic pressure $B^2/2\mu_0$ equals the plasma ram pressure $(1/2)\rho_p v^2$. Equating these and inserting for B from the above equation gives us the approximate distance of the magnetopause from the loop,

$$r_m \sim \left(\frac{\mu_0 I^2 a^4}{\rho_p v^2}\right)^{1/6}, \tag{13.2}$$

to within numerical factors. To within an order of magnitude, the upwind cross-sectional profile of the magnetopause that exchanges momentum with the plasma is a circle of area

[1] There is a numerical factor missing here that depends on the position with respect to the loop axis, and which component of the vector field we are considering.

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πr_m^2, and so the force from the plasma is $(1/2)\pi r_m^2 \rho_p v^2$. This is analogous to the drag force in fluid mechanics. The force on the magnetopause and thus on the spacecraft is therefore

$$F = k\,(\mu_0 I^2 a^4 \rho_p^2 v^4)^{1/3} \tag{13.3}$$

for some dimensionless constant k. This force acts in the direction that the plasma moves relative to the spacecraft. Evaluation of the constant k requires a proper integration of the magnetic pressure over the magnetopause, and depends on the approximations used in the field calculation to make the integrals tractable. Freeland (2015) gives a value of $0.354\pi = 1.11$, which I adopt here. Other authors also arrive at equation 13.3, but with different values of k. The values of the exponents in equation 13.3 are not intuitive, but the proportional dependence (as opposed to an inverse) of the force on all four physical terms on the right side of equation 13.3 makes sense. Note that ρ_p is the density of the charged particles in the plasma, so excluding any neutral particles. The solar wind can be taken as completely ionized, but the ISM is not (section 12.3).

Considering the plasma to be the solar wind, the force on the sail points radially away from the Sun when the spacecraft is moving radially. As long as the spacecraft is moving outward slower than the wind, this force will accelerate the spacecraft outward. Once the spacecraft reaches the velocity of the wind, their relative velocity is zero, so the force is zero, and the spacecraft is no longer accelerated. When the spacecraft is instead moving towards the Sun, or indeed another star, the oncoming solar wind will act to decelerate the spacecraft. In that case, the faster the spacecraft, the larger its velocity relative to the wind, and so the larger the deceleration. For this reason a magnetic sail is often considered as a means for braking at a target star instead of accelerating out of the solar system.

In a similar way, a high-velocity spacecraft moving through the ISM will also be decelerated. This can be used to decelerate the spacecraft over much larger distances than with the solar wind and so potentially achieve a larger change in velocity.

13.1.2 Application

We first use the above theory to calculate the acceleration of a magnetic sail by the solar wind. For this purpose I adopt a plasma density of $\rho_p = 8.35 \times 10^{-21}\,\mathrm{kg\,m^{-3}}$ (five protons per cubic centimetre), and a wind velocity of $v = 400\,\mathrm{km\,s^{-1}}$, values that are appropriate for the solar wind 1 au from the Sun. For the sail I adopt $I = 50\,\mathrm{kA}$ and $a = 31.6\,\mathrm{km}$. Such a large loop (compared to a solar sail, for example) is required because of the low ram pressure of the solar wind, and because the magnetic field of a loop falls rapidly with distance (equation 13.1). From equation 13.2, we find that the magnetopause is 115 km from the loop's centre, so the condition $r_m \gg a$ for equation 13.1 to be valid is only just satisfied (a larger current may be required in practice). Equation 13.3 tells us that the resulting force on the sail is 20 N.

The acceleration this force produces depends on the mass of the spacecraft, which is likely to be dominated by the mass of the loop. To be able to maintain such a large current for a long period of time without a heavy power supply, the loop needs to be superconducting. Superconductors are materials that conduct without resistance, so once the current has been set up, no power source is required to maintain it (although impacts from charged particles may complicate this). Only certain materials are superconducting, and then only if they are below a certain critical temperature. For niobium–titanium, for example, the critical temperature is

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about 10 K. High-temperature superconductors have a critical temperature above 77 K (but still well below room temperature), one class of which is based on copper oxides. Materials are only superconducting if the magnetic field strength remains below some critical value, which corresponds to a maximum current per unit cross-sectional area of the conductor, J_s. This depends on the material, but is of order $10^{10}\,\mathrm{A\,m^{-2}}$. Adopting this value as the upper limit, and assuming the superconductor material has density $\rho_s = 5000\,\mathrm{kg\,m^{-3}}$ (approximately that of copper oxide), we can compute the minimum cross-sectional area – and hence minimum mass – of the loop required to carry a given current. The mass of a loop of radius a made from wire of constant cross-sectional area A is $m = 2\pi aA\rho_s$. The maximum current is $I = J_sA$, in which case the minimum mass loop is $2\pi aI\rho_s/J_s$.

Using these two expressions for the mass of the loop and equation 13.3 for the force on the loop, the magnitude of the acceleration is

$$\frac{dv}{dt} = \frac{F}{m} = 3bv^{4/3} \quad \text{where} \quad b = \begin{cases} \dfrac{k}{6\pi}\dfrac{1}{A\rho_s}(\mu_0 I^2 a\rho_p^2)^{1/3} & \text{(in general)} \\ \dfrac{k}{6\pi}\dfrac{J_s}{\rho_s}\left(\dfrac{\mu_0 a\rho_p^2}{I}\right)^{1/3} & \text{(minimum mass loop).} \end{cases} \tag{13.4}$$

Note the inverse dependence of the acceleration on the (maximum) current for the minimum mass loop. This suggests that for a given superconductor we should make the current as small as possible, because this will minimize the thickness and therefore the mass of the loop. There is a lower limit to the current we need, however, because a minimum magnetic field strength is required to set up the magnetosphere in the first place. With the above choices for the current and loop size and materials, the magnetic field strength at the centre of the loop is $B = \mu_0 I/2a = 10^{-6}\,\mathrm{T}$ and the minimum radius of the wire is $\sqrt{I/\pi J_s} = 1.3\,\mathrm{mm}$. This gives a mass of five tonnes for the loop. Equation 13.4 gives the acceleration of this minimum mass loop to be $0.004\,\mathrm{m\,s^{-2}}$.

To put this value into context, the acceleration of a solar sail of lightness number $\lambda = 1$ at 1 au from the Sun is $GM_\odot/r^2 = 0.006\,\mathrm{m\,s^{-2}}$ (section 10.2). This is quite an extreme solar sail by current standards, but so is a superconducting wire 200 km long with a cross-sectional radius of 1.3 mm. This wire must also have enough tensile strength to support the current, and to transfer the acceleration to the rest of the spacecraft.

The magnetic sail could be used to accelerate a spacecraft away from the Sun. By tilting the sail, the spacecraft receives a non-radial force, and thus can be made to move on a non-Keplerian orbit, just as can be done with solar sails (see section 10.3.2). This could be used to manoeuvre to the planets in the solar system, although the variability of the solar wind would make this a challenge in practice.

By integrating equation 13.4 we can compute the velocity of the loop as a function of time. This is the velocity of the loop relative to the solar wind. To find the velocity of the loop relative to the Sun (or other star) we need to know how the velocity of the solar wind varies with distance from the star. Zubrin and Andrews (1991) investigate using a magnetic sail for both an interplanetary mission and for escaping the solar system. For the latter they find that a sail could reach a terminal velocity of $95\,\mathrm{km\,s^{-1}}$, reaching 1000 au in 50 years.

As a second application, we can use the magnetic sail to decelerate a fast moving spacecraft, one which has previously been accelerated by a nuclear rocket or laser sail, for example. In this case we can consider the charged particles in the wind or ISM as approximately

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stationary relative to the star. We neglect gravity. The acceleration is $-3bv^{4/3}$ from equation 13.4. Integrating this from an initial velocity v_0 at time $t = 0$ gives the velocity at some later time t to be

$$v = v_0(1 + bv_0^{1/3}t)^{-3} . \tag{13.5}$$

Integrating again we get the distance travelled after time t,

$$s = \frac{v_0^{2/3}}{2b}\left[1 - (1 + bv_0^{1/3}t)^{-2}\right] . \tag{13.6}$$

To get a sense of the magnitude of the plasma-induced deceleration, let us first compute the deceleration due to the solar wind at 1 au from the Sun for the previously discussed minimum mass loop (parameter values given above). When the initial velocity is 0.1 c, the deceleration is 1.3 m s^{-2}. If the plasma density remains constant over 10 au, the velocity decreases by just 0.2%.[2] Assuming we cannot target a star with a much denser stellar wind, this result implies that to achieve a significant deceleration, the spacecraft needs to decelerate over a much larger distance. This in turn means it must brake using not the stellar wind, but the charged particles in the ISM.

Figure 13.2 shows a scenario of braking with the charged particles in the ISM, computed using equations 13.5 and 13.6. The spacecraft is initially moving at a velocity of 0.1 c. It then unfurls the same loop as used above: $I = 50$ kA, $a = 31.6$ km, $J_s = 10^{10}$ A m^{-2}, $\rho_s = 5000$ kg m^{-3}, which has a loop mass of five tonnes. The payload is assumed – somewhat unrealistically – to have negligible additional mass. The middle line in figure 13.2 shows how the spacecraft is braked by the ISM when the ion mass density is 150×10^{-24} kg m^{-3}. This corresponds to the density of the local interstellar cloud with an ionization fraction of 0.25 (see Table 12.1). The figure shows that it takes many years for a significant deceleration to be achieved. When the loop is deployed 1 ly from the destination star, the spacecraft's velocity is reduced by a factor of four, to 0.024 c, by the time it arrives at the star. This deceleration takes 20 years, so adds 10 years to the travel time compared to the non-braked spacecraft continuing at 0.1 c.

The lower line in figure 13.2 shows the deceleration with four times the local interstellar cloud density. This gives a reduction in the velocity by a factor of 16 after 20 years. As the size of the magnetosphere is inversely proportional to the density of the plasma (equation 13.2), this scenario has the smallest magnetosphere of the examples shown, with 42 km radius. The upper line in the figure is for a density one-sixth that of the local interstellar cloud, characteristic of the local bubble. It gives much less reduction in velocity, a factor of only 1.7 after 20 years.

The density of the ISM varies and cannot be accurately measured at high spatial resolution from the Earth, so future mission planners are unlikely to be able to accurately predict what braking can be achieved with a magnetic sail. Note also that the masses involved here are large: five tonnes of loop in order to achieve the braking shown in figure 13.2. To accelerate such a mass to 0.1 c in the first place requires a lot of energy. In practice, the superconducting coil needs to be shielded against erosion from collisions with the ISM (section 12.4), and this would add mass, more than the wire itself. This would decrease the deceleration and thus

[2] For this configuration, equation 13.2 gives a characteristic radius of the magnetosphere of $r_m = 27$ km. Although this is not an exact value, it is smaller than the loop radius, so the expressions used may no longer be a good approximation.

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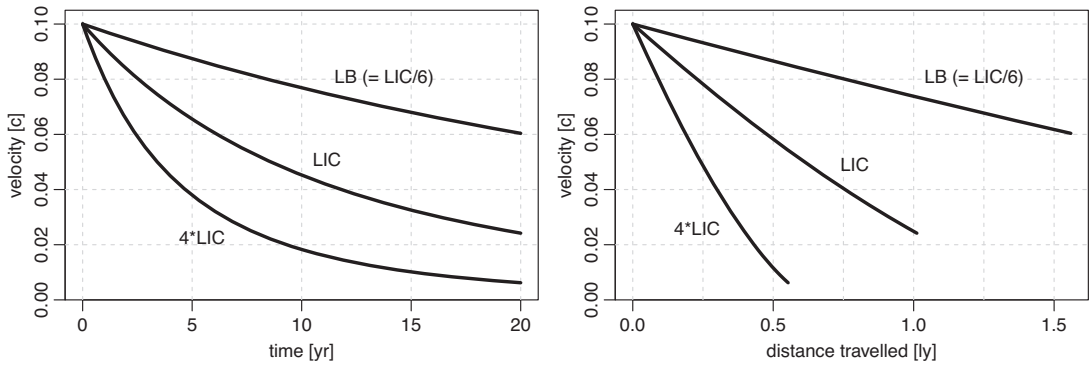


Fig. 13.2 Braking with a magnetic sail using the drag of charged particles in the ISM. The panels show how the velocity of the spacecraft changes as a function of time (left) and distance travelled (right) over a period of 20 years. The middle line is for an ISM density typical of the local interstellar cloud (LIC) assuming an ionization fraction of 0.25. The lower line is for four times that density, and the upper line is for the typical density of the local bubble (LB), which is a sixth the LIC.

extend the total mission time significantly. Clearly, such a system cannot be used to brake a small lightweight spacecraft like a laser sail and so can only be considered for spacecraft with masses of many tonnes, which more plausibly would have been accelerated by nuclear rockets.

13.1.3 Other magnetic sail concepts

The big drawback of the magnetic sail described above is the large mass of the superconducting loop (plus shielding) required to produce the magnetosphere, resulting in a modest acceleration. This could be addressed using a much smaller coil – diameter of centimetres to metres – to produce a plasma that is injected into the space around the spacecraft, which then generates the magnetosphere. For this reason, the type of sail discussed in the previous section is sometimes called plasma-free magnetospheric propulsion. Whereas the magnetic field of a dipole decreases with distance r from the dipole as r^{-3} (equation 13.1), the field from the plasma decreases as r^{-1}, meaning a comparatively small coil could be used to generate the plasma. Essentially, the plasma inflates the coil-generated magnetic field.

This concept was originally introduced under the name mini-magnetic plasma propulsion (M2P2) by Winglee et al. (2000). They outline a scenario using a loop of 10 cm radius with over 1000 turns (total length 700 m) producing a magnetic field strength at the centre of the loop of 0.1 T. This ionizes a gas that is injected into the loop to produce a plasma with a temperature of around 5 eV. This plasma expands out of the loop to make a magnetosphere. When interacting with the solar wind, this produces a force on the artificial magnetosphere of a few newtons. They adopt a total mass of the spacecraft of 100 kg, of which 30 kg is the gas used to produce the plasma. Starting at the Earth's orbit and accelerating away from the Sun, they find that within a year the spacecraft achieves $\Delta v = 75\,\mathrm{km\,s^{-1}}$ and reaches 14 au, having used 20 kg of its gas to maintain the plasma, as this slowly leaks from the magnetosphere. This velocity is considerably larger than what has been achieved to date with chemical rockets, but is still far too slow for a desirable interstellar mission, requiring 17 thousand years to reach Alpha Cen.

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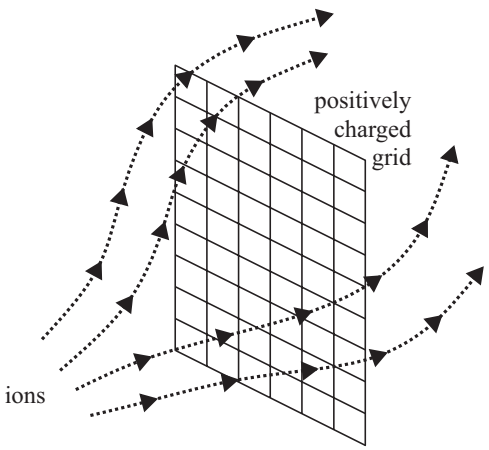
There have been several criticisms of the original M2P2 concept, however. Khazanov et al. (2005), for example, argue that magnetohydrodynamics (MHD) is not an appropriate description and that the M2P2 design would deliver a much smaller thrust than claimed. Others have pointed out that much of the momentum of the solar wind imparted onto the plasma would not be transferred to the spacecraft, thus resulting in a much smaller acceleration. A variation of M2P2 goes by the name magnetoplasma sail (MPS), as reported by Funaki and Nakayama (2012). Numerical simulations show that a plasma produced by a coil can create a large magnetosphere and that it could achieve an acceleration comparable to the dipole-based design, but using a much smaller and less massive loop/coil.

13.2 Electric sails

An electric sail, like a magnetic sail, also uses the momentum of charged particles to accelerate, but is conceptually simpler. The electric sail is a large, positively charged body, for example a flat mesh of metal wires (see figure 13.3). When positively charged ions (from the solar wind or ISM) approach this, they are repelled and deflected by the Coulomb force. This force does work, decelerating the protons and passing their kinetic energy and momentum on to the sail.

The solar wind and ISM are neutral overall, so the solar sail also experiences a Coulomb attraction from the electrons. However, as the electrons have much smaller masses, this produces a much smaller acceleration. These electrons will tend to recombine with the positive charges in the sail, though, which over time would make it neutral. The sail therefore needs to be fitted with a gun to remove the electrons and keep the sail positively charged.

Just as with the magnetic sail, the electric sail could be used for accelerating away from a star on the solar wind or for decelerating against the ISM.



A schematic of an electric sail. Fig. 13.3

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To determine the force that charged particles exert on an electric sail, we consider first the electrostatic potential due to an infinitely long line of charges with charge per unit length λ. This corresponds to a long charged wire. The electric potential at distance r from the centre of the wire in a vacuum is found from Gauss's law to be

$$\phi(r) = \frac{\lambda}{2\pi\epsilon_0} \ln(r_0/r), \tag{13.7}$$

where r_0 is the distance at which the potential is zero. For a wire with a circular cross-section of radius r_w, the potential at the surface of the wire is

$$\phi_0 = \frac{\lambda}{2\pi\epsilon_0} \ln(r_0/r_w)\,, \tag{13.8}$$

so we can write equation 13.7 as

$$\phi(r) = \phi_0 \frac{\ln(r_0/r)}{\ln(r_0/r_w)}\,. \tag{13.9}$$

When the wire is embedded in a proton/electron plasma, where each particle has number density n, the electrons in the plasma shield the potential and make it drop faster. From comparison with plasma simulations, Janhunen and Sandroos (2007) find that a good approximation for the potential in this case is

$$\phi(r) = \frac{\phi_0}{2} \frac{\ln[1 + (r_0/r)^2]}{\ln(r_0/r_w)} \tag{13.10}$$

for $r_w \ll r_0$. The distance r_0 is now determined by the plasma electron temperature T_e and charge e as

$$r_0 = 2\sqrt{\frac{\epsilon_0 k T_e}{ne^2}}, \tag{13.11}$$

where ϵ_0 is the vacuum permittivity. The length r_0 is twice the Debye length, which is the characteristic distance over which electric fields are screened by a plasma due to its charge separation. At the Earth's distance from the Sun, the solar wind has $T_e = 10^5$ K (about 9 eV) and a density of $n = 5 \times 10^6\,\mathrm{m}^{-3}$, giving $r_0 = 20$ m.

The wire presents an electrostatic barrier of some effective width r_b perpendicular to its length against which the plasma pushes. The force per unit length acting on the wire is this width times the plasma ram pressure $m_p n v^2$, where m_p is the mass of the proton and v is the asymptotic velocity of the plasma relative to the wire. Thus the force per unit length is

$$\frac{F}{L} = m_p n v^2 r_b. \tag{13.12}$$

We now assume that the barrier width r_b is proportional to the proton stopping distance r_s in the potential. Even though these two distances are perpendicular to one another, the cylindrical symmetry of the wire's potential suggests that these two lengths scale in the same way, so we can write $r_b = b r_s$, where b is a dimensionless constant. Using numerical simulations, Janhunen and Sandroos (2007) find $b = 3.09$ gives a good fit.

The stopping distance r_s is the distance protons travel as their kinetic energy is converted into electrostatic potential energy by the field. Solving the energy balance equation $e\phi(r_s) = (1/2)m_p v^2$, with $\phi(r = r_s)$ given by equation 13.10, we find

$$r_s = \frac{r_0}{\sqrt{\exp\left(\frac{m_p v^2}{e\phi_0} \ln\left[\frac{r_0}{r_w}\right]\right) - 1}}\,. \tag{13.13}$$

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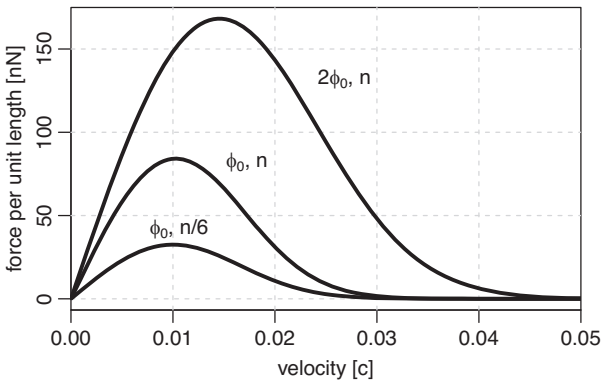
This stopping distance decreases monotonically and rapidly with increasing velocity. Inserting this into equation 13.12 gives the force acting on the wire,

$$F = \frac{bm_p n v^2 L r_0}{\sqrt{\exp\left(\frac{m_p v^2}{e\phi_0} \ln\left[\frac{r_0}{r_w}\right]\right) - 1}} . \tag{13.14}$$

We can use the above equation to calculate the acceleration of a sail away from the Sun under the action of the solar wind. As the solar wind ram pressure drops with distance from the Sun as $d^{-7/6}$, rather than d^{-2} for solar radiation pressure, electric sails appear favourable for exploring the outer solar. Studies have suggested that velocities of $40\,\mathrm{km\,s^{-1}}$ could be achieved in this way, which is an improvement over chemical rockets, but is insufficient for interstellar travel.

An alternative use of the electric sail is as a brake, because a sail moving at high velocity through the ISM experiences a drag force. Equation 13.14 shows that the force increases with increasing electric potential. It also increases with increasing wire radius, although the dependence is weak. Because the wire mass increases with the radius squared, we probably want very thin wires in practice.

The dependence of the force on velocity is more complex. It is shown in figure 13.4 for a wire of radius $r_w = 5\,\mu\mathrm{m}$ with potential $\phi_0 = 10^6\,\mathrm{V}$ and electron temperature $T_e = 8000\,\mathrm{K}$, which is characteristic of the local ISM. The middle line assumes an electron number density of $n = 0.075 \times 10^6\,\mathrm{m^{-3}}$, which is appropriate for the local interstellar cloud with an ionization fraction of 0.25 (table 12.1). The force has its maximum value at around $0.01\,c$. This force is a product of the plasma ram pressure and the effective area of the barrier presented by the sail. At low velocities the force initially increases because the solar protons then have more momentum (pressure $\sim v^2$). But the stopping distance r_s decreases monotonically and rapidly with increasing velocity, meaning the effective barrier gets smaller. Above some velocity this effect dominates, and then the force decreases with increasing velocity, despite the increasing ram pressure.



The variation of the force per unit length on an electric sail as a function of its velocity relative to the ISM (equation 13.14). The middle line assumes the sail is held at a potential $\phi_0 = 10^6$ V and that the electron number density in the ISM is characteristic of the local interstellar cloud with an ionization fraction of 0.25. The lower line is for a smaller plasma density (appropriate for the local bubble), and the upper line for twice the potential.

Fig. 13.4

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The lower line in figure 13.4 shows the smaller force from a less dense ISM, and the upper line shows the larger force from a larger potential. For velocities greater than $0.05\,c$, the force becomes tiny in all cases shown. In order to shift the peak of the curve towards $0.1\,c$, and so to be able to decelerate the sail from this speed, we would need to increase the potential by two orders of magnitude, a tall order.

To determine how the velocity of a spacecraft of mass M varies with time due to the drag force, we use Newton's second law:

$$M\frac{dv}{dt} = -F(v)\,. \tag{13.15}$$

Integrating this from an initial spacecraft velocity v_0 at time $t = 0$, the time taken for the velocity to decrease to v is

$$t = -\frac{M}{bLr_0 m_p n}\int_{v_0}^{v}\frac{1}{v^2}\sqrt{\exp\left(\frac{m_p v^2}{e\phi_0}\ln\left[\frac{r_0}{r_w}\right]\right)-1}\,dv\,. \tag{13.16}$$

This integral has no closed-form solution, but it can be solved numerically.

By way of illustration, we adopt the following parameters: $T_e = 8000\,\mathrm{K}$, $n = 0.075 \times 10^6\,\mathrm{m}^{-3}$, $r_w = 5\,\mu\mathrm{m}$, and $\phi_0 = 2 \times 10^6\,\mathrm{V}$, which corresponds to the upper line in figure 13.4. For the spacecraft we adopt $L = 50 \times 10^6\,\mathrm{km}$ and $M = 10^4\,\mathrm{kg}$. This is a huge length of wire. With a density of $1500\,\mathrm{kg\,m}^{-3}$ its mass is 5890 kg. The remaining 4110 kg is for wire shielding, current generation, and payload.

With initial velocity $v_0 = 0.05\,c$, I carry out a series of integrations at equally spaced velocity steps down to a final velocity of $30\,\mathrm{km\,s}^{-1}$. The results are shown as an interpolated curve in figure 13.5. The initial deceleration is small. This is because at the large initial velocity, the drag force is small, as can be seen from figure 13.4. But after about 18 years, the velocity drops to a value where the drag is larger and the velocity drops much more rapidly. In total it takes 19.6 years to decelerate the spacecraft to $30\,\mathrm{km\,s}^{-1}$, but it takes the first 17.6 years to decelerate to $0.04\,c$. Had the spacecraft started at $0.04\,c$, it would only have taken 2.0 years to decelerate to $30\,\mathrm{km\,s}^{-1}$.

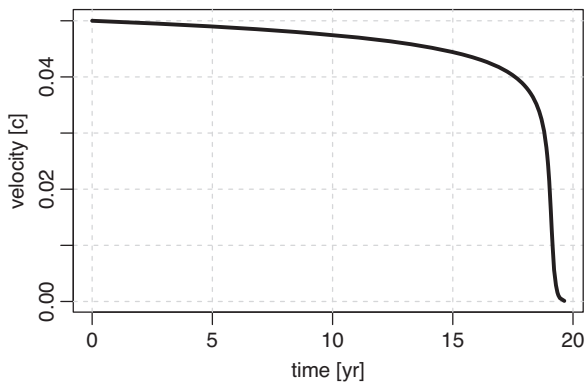


Fig. 13.5 The variation of the velocity of an electric sail with time due to the drag of the ionized ISM (equation 13.16) for $T_e = 8000\,\mathrm{K}$, $n = 0.075 \times 10^6\,\mathrm{m}^{-3}$, $r_w = 5\,\mu\mathrm{m}$, $\phi_0 = 2 \times 10^6\,\mathrm{V}$, $L = 50 \times 10^6\,\mathrm{km}$, and $M = 10^4\,\mathrm{kg}$.

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The deceleration also depends strongly on the potential. When the potential is half as large, 1 MV, the deceleration from $0.05\,c$ takes 101 thousand years. On the other hand, when the potential is 3 MV, it takes just 1.9 years.

The deceleration time is linearly proportional to M/L. When the density of the wires is ρ_s, their mass is $\pi r_w^2 L \rho_s$. If the wires dominate the total mass of the spacecraft, the M/L term in equation 13.16 can be replaced with $\pi r_w^2 \rho_s$, in which case the deceleration time no longer depends on the wire length. But in reality a lot of extra mass is required for wire shielding, for the power supply for the electron gun to maintain the potential, and for the payload. So in practice there is a minimum wire length.

The sail would not be made of a single straight wire, as this may be broken by a dust impact, plus it would be rather unwieldy. We may instead arrange it as a set of many wires fanning out from the spacecraft in a plane at all angles, or in a flat grid as sketched in figure 13.3. When the wires are separated by the barrier width or less, the plasma essentially encounters a continuous potential barrier which it cannot pass through. We don't want the wires to be much closer than the barrier width, however, otherwise their barriers overlap and they will 'overly stop' the plasma, leading to a decrease in the amount of wire that acts as an effective barrier and so unnecessary wire mass.

As the width of the barrier increases rapidly with decreasing velocity, we need very large structures in order for all of the wire to be used effectively when decelerating at lower velocities. For the above configuration at $v = 0.01\,c$, the barrier width is $r_b = 130\,\mathrm{m}$. If we arrange the wires on a square mesh with a separation equal to this, it would have a side length of $\sqrt{L r_b/2} = 1800\,\mathrm{km}$. Electric sails are big.

In conclusion, an electric sail can be used to decelerate a spacecraft from large velocities ($0.05\,c$) on a reasonable timescale (years). But to do so, we need an enormous length of wire (millions of kilometres) weighing many tonnes, together with large electric potentials (millions of volts).

13.2.1 Combining magnetic and electric sails

Perakis and Hein (2016) investigate braking a spacecraft using a combination of a magnetic sail and an electric sail. The magnetic sail is more efficient at decelerating from large velocities, so this is used initially, then ejected once the velocity is small. The remaining deceleration at lower velocities is done with a lighter electric sail. The study authors adopt a similar approach as in section 13.1 to compute the deceleration from the magnetic sail, but adopt a larger value of the maximum current density, $J_s = 2 \times 10^{10}\,\mathrm{A\,m^{-2}}$, a larger loop radius, $a = 50\,\mathrm{km}$, and a slightly lower ISM plasma density, $n = 0.05 \times 10^6\,\mathrm{m^{-3}}$. They find that a spacecraft of mass 8250 kg can be decelerated from $0.05\,c$ to $35\,\mathrm{km\,s^{-1}}$ in 29 years. Of this mass, 7500 kg is taken up by the deceleration system (10 times the payload), with just over two-thirds of this taken by the magnetic sail part. The magnetic sail is ejected at a velocity of $0.03\,c$ after about 14 years. Just using the magnetic or electric sail alone of the same mass (7500 kg) would have required 40 years and 35 years respectively to brake by the same amount. If, however, a final speed above a few hundred kilometres per second is acceptable, then they find that the magnetic sail alone is optimal.

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13.3 Summary

Charged particles in the solar wind or ISM can be used to accelerate a spacecraft. A magnetic sail works by using an electric current in a superconducting loop to establish an artificial magnetosphere around a spacecraft. Moving ions are deflected by this magnetic field via the Lorentz force and exchange momentum with the sail. An electric sail works by positively charging long wires. These repel ions via the Coulomb force, thereby accelerating the sail.

Both magnetic and electric sails could be used to accelerate a spacecraft away from the Sun using the solar wind. Spacecraft velocities of 50–100 km s^{-1} could probably be achieved in practice, but these sails are ultimately limited by the speed of the solar wind, because there is no force when the spacecraft is stationary relative to the wind.

An alternative and more promising use of these sails is to decelerate a high-velocity spacecraft using the drag on the ions in the ISM. A deceleration from 0.04–0.1 c almost to rest is theoretically possible over timescales of a few to a few tens of years using an electric sail. This requires a total wire mass of many tonnes, plus significantly more mass for the power supply and for shielding the wires against particle impacts. Magnetic and electric sails are therefore only feasible for massive spacecraft. But they are one of the few mechanisms available for significant deceleration at a target star.

Not knowing accurately the actual ISM ion density is a challenge for using such sails in practice. If the density is lower than expected, the deceleration will be lower. In the case of a magnetic sail, provision could be made to increase the current in the loop to compensate for this. But this implies that the nominal current is below the maximum possible, and so the loop is larger than necessary for the nominal mission. Such a margin comes at a high cost in performance if it is not required.

13.4 Exercises

1. Derive equations 13.5 and 13.6.
2. Investigate how the force per unit length on an electric sail varies with the plasma number density and the electron temperature in equation 13.14. Note that both variables appear in the expression for r_0. Do this for the nominal values listed in the text, for velocities of 0.01 c and 0.05 c. Explain the results physically.

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