6 The interplanetary magnetic field (IMF)

We have seen that - ignoring electromagnetic effects - the upper solar atmosphere (corona) is too hot to be in hydrostatic equilibrium. Instead, equilibrium could be reached if it streamed radially into space. Because of the high temperatures in the corona nearly all constituents (mostly hydrogen and helium) are fully ionized, making the plasma highly conductive. In highly conductive plasmas the magnetic field is frozen into the plasma. So if the coronal plasma is streaming into space, it would need to take the solar magnetic field with it. But it could also be that the thermal pressure of the hot corona is balanced by the magnetic pressure which we neglected in our earlier considerations. So what is it?

6.1 Solar wind, revisited

The relative dominance of the thermal and magnetic pressure is captured in the plasma beta. In the equatorial corona we find $T \sim 10^6$ K, $n \sim 10^{15}$ m^{-3} and hence $p_T \sim 10^{-2}$ Pa. The magnetic field strength is of the order of $B \sim 10^{-2}$ nT such that $p_B \sim 10^{-1}$ Pa and $\beta \sim 0.01$ - this is a low β regime such that in the equatorial solar corona the magnetic pressure dominates and there should be no outflow. But consider the magnetic topology assuming that the solar magnetic field is a dipole - which is certainly true during solar minimum.

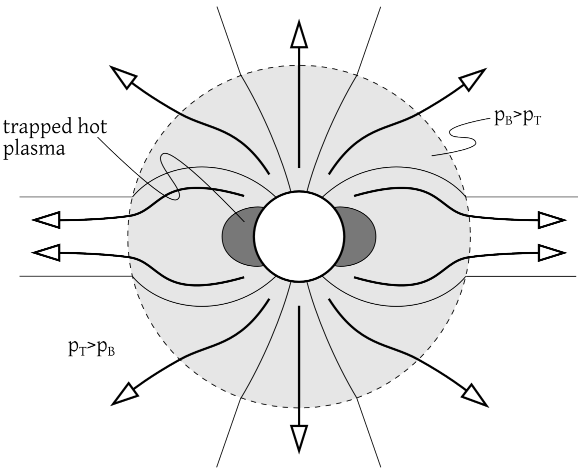

Figure 1: Solar corona plasma escape, looking from Earth at the Sun.

Plasma can move along magnetic field lines easily such that toward the polar regions, where the dipole magnetic field becomes more and more vertical, the solar wind can escape. Furthermore, the magnetic field energy density decreases as r^{-6} whereas the plasma temperature is roughly constant and the plasma density decreases as r^{-2}, such that at a distance of several solar radii the magnetic pressure drops below the thermal pressure, allowing the solar wind to stream into space. In fact, only in a relatively small area around the equator is the magnetic field strong enough to inhbit the coronal plasma to escape.

6.2 Jetlines

As the Sun rotates, the solar wind is continuously blowing into space. The jetline connects all plasma parcels that originated from the same spot on the Sun. Note that at any point along the jetline the flow is still radial and not along the jetlines.

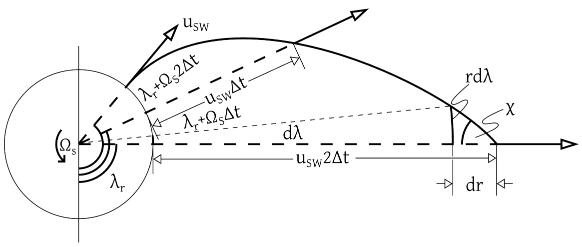

Figure 2: Schematic showing the evolution of a jetline.

The distance a parcel of plasma has traveled from the Sun's surface as a function of the time t and the solar wind speed u_{SW} is given by

$$r(t) = r_S + u_{SW} t \qquad (6.1)$$

but we can also express that in terms of solar rotation angle (solar longitude) λ if we first parametrize λ using the Sun's rotation frequency Ω_S

$$\lambda(t) = \lambda_r + \Omega_S t \qquad (6.2)$$

and then substitute:

$$r(\lambda) = r_S + \frac{u_{SW}}{\Omega_S}\left(\lambda(t) - \lambda_r\right). \tag{6.3}$$

Therefore, the distance traveled of plasma parcels originating at different solar longitudes is proportional to the longitude, $r(\lambda) \propto \lambda$, which is the expression for an Archimedean spiral - assuming that u_{SW} is purely radial and constant. We can estimate the angle between the radial direction and the spiral at a distance r as

$$\tan\chi \approx \frac{-r d\lambda}{dr} = -\frac{\Omega_S}{u_{SW}} r. \tag{6.4}$$

To investigate the exact orientation of the IMF, consider again that the magnetic field is frozen into the plasma - see Figure 3. At time t a point 1 on the solar surface ejects a parcel of solar wind plasma. At a later time, $t+\Delta t$, that parcel will have travelled with the solar wind speed u_{SW} by a distance of $u_{SW}\Delta t$ to point 2; meanwhile, the point on the surface from whence it originated has rotated to point 1′, by an angle of $\Omega_S \Delta t$. The frozen-in theorem theorem tells us that those two locations, 1′ and 2, are connected by a magnetic field line. Of course, while at point 1′ the Sun ejects a further parcel of plasma. At a later time $t + 2\Delta t$ the plasma parcel from point 2 has moved to point 3, while the parcel ejected at 1′ has now moved to 2′, while the surface point has rotated by $2\Omega_S \Delta t$ to 1″. This pattern continues as the Sun rotates, creating the Parker spiral.

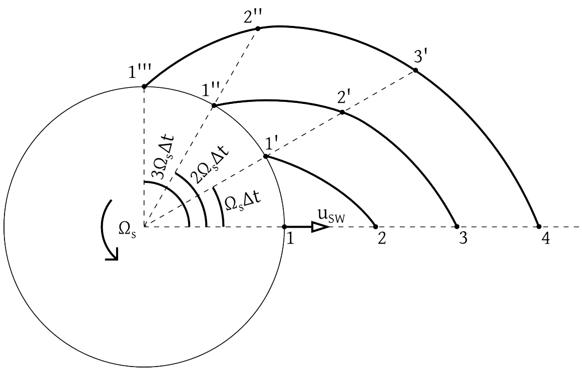

Figure 3: Schematic showing why the IMF is oriented along jetlines, looking down onto the Sun.

6.3 Radial component of the IMF

Because the solar magnetic field is frozen into the solar wind flow, the magnetic flux, i.e., the magnetic field integrated over an area A, is conserved as the corona expands into space. Close to the Sun, at a radial distance of r_0, the magnetic field is essentially radial such that $B(r_0) = B_r(r_0)$. Therefore (see Fig. 4)

$$\int_A \vec{B}\cdot d\vec{a} = B_r(r_0)A(r_0) = B(r_0)A(r_0) = B_r(r)A(r) \tag{6.5}$$

and since $A(r) = \pi\rho(r)^2 = \pi(r\tan\lambda)^2$ we get

$$B_r(r) = B(r_0)\left(\frac{r_0}{r}\right)^2 \propto \frac{1}{r^2} \tag{6.6}$$

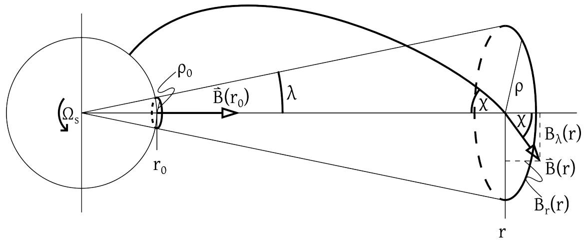

Figure 4: Schematic showing how the radial component of the IMF changes with radial distance, looking down onto the Sun.

6.4 Azimuthal component of the IMF

Once the radial component of the IMF is known we can easily estimate the azimuthal component by remembering eq. (6.4) and

$$\tan\chi = \frac{B_\lambda(r)}{B_r(r)} \approx -\frac{r\Omega_S}{u_{SW}} \tag{6.7}$$

and hence

$$B_\lambda(r) = -B(r_0)\frac{r_0\Omega_S}{u_{SW}}\left(\frac{r_0}{r}\right) \propto \frac{1}{r}. \tag{6.8}$$

At $r_0 \approx 1$ AU we then find (with $\Omega_S = 2.9 \times 10^{-6}$ Hz) that $B_\lambda \approx B_r$ and hence $\chi \approx 45°$.

6.5 General orientation of the IMF

As the solar wind streams from the Sun, it takes the solar magnetic field with it. Previously dipolar field lines are stretched such that they become more and more radial at larger distances.

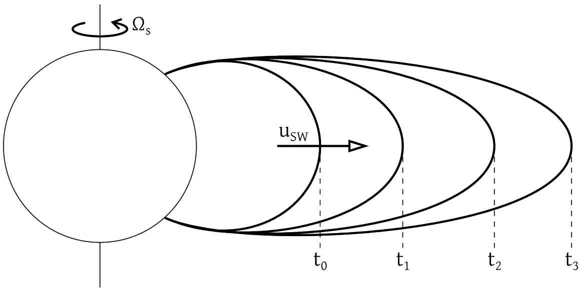

Figure 5: Stretching of the solar dipole field lines under the action of the solar wind, looking from Earth at the Sun.

The only way such a streched magnetic field configuration can be sustained is by a current which is flowing between the sheared magnetic field (Ampère's Law). This current is called the heliospheric current sheet.

6.6 Heliospheric current sheet

Consider a sheared magnetic field configuration as shown in Fig. 6. To calculated the magnetitude of the current, employ Ampère's Law in the integral form:

$$\oint_C \vec{B} \cdot \vec{l} = \mu_0 \int_S \vec{j} \cdot \vec{n} \, da. \tag{6.9}$$

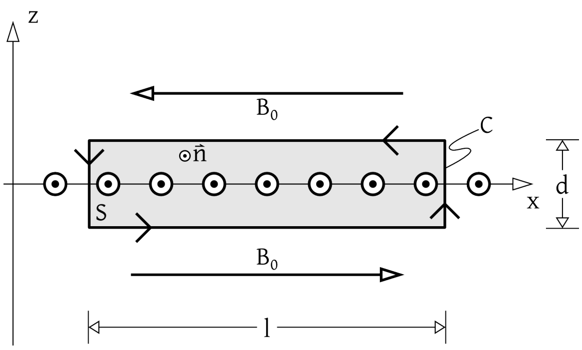

Figure 6: Schematic showing a sheared magnetic field and the associated current sheet.

The RHS integral gives the total current flowing through the surface S, $\vec{I}$ and the LHS integration gives

$$+B_0 l + 0d - B_0(-l) + 0d = 2B_0 l = \mu_0 I. \tag{6.10}$$

In terms of the line current $I^\star$ we get

$$I^\star = I/l = \frac{2B_0}{\mu_0}, \tag{6.11}$$

or more generally, where $\vec{n}$ now is perpendicular to the current sheet

$$\vec{I}^\star = \frac{2}{\mu_0} \vec{B}_0 \times \vec{n}. \tag{6.12}$$

We can evaluate this expression for the IMF components we determined earlier (in spherical coordinates):

$$\vec{I}^\star = \frac{2}{\mu_0} \begin{pmatrix} B_r \\ B_\lambda \\ B_\phi \end{pmatrix} \times \begin{pmatrix} n_r \\ n_\lambda \\ n_\phi \end{pmatrix} = \frac{2}{\mu_0} \begin{pmatrix} B_\lambda \\ -B_r \\ 0 \end{pmatrix}. \tag{6.13}$$

This shows that there exists a radial component of the heliospheric current, such that, depending on the polarity of the solar dipole, there also exists a net current toward or away from the Sun. This current is believed to flow inside the corona close to the Sun and then away or toward from the polar regions of the star.