

Solar Terrestrial Environment - Space Weather

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THE SOLAR WIND AND INTERPLANETARY DISTURBANCES

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THE SOLAR WIND

The solar wind is a flow of ionized solar plasma and a remnant of the solar magnetic field that pervades interplanetary space and results from the huge difference in pressure between the solar corner and the interstellar medium (ISM.). This pressure difference drives the plasma out despite the restoring influence of solar gravity. The first indication of the existence of the solar wind came from observations of comet tails, which always pointed away from the Sun suggesting an outward flow of matter from the Sun. Since the early 1960's however, measurements taken by spacecraft-borne instruments have yielded detailed descriptions of the solar wind from just outside the photosphere, or visible surface of the Sun, to distances well beyond Saturn.

The reason why the solar wind needs to be understood is because it is significantly influenced by events occurring on the Sun and can in fact transmit this influence to the planets, comets and other celestial bodies immersed in the solar wind. This branch of study is referred to as "*solar-terrestrial relationships*". Another reason is that the enormous expansion of the solar wind into the interplanetary medium (IPM) takes the magnetized plasma through very huge variations in its properties. For example the densities change by a factor of 10^7 between the base of the corona and 1 AU. Thus the physics of this plasma system can be studied under a wide variety of conditions.

The solar wind consists largely of ionized hydrogen (or protons and electrons in nearly equal numbers), with about 5% of ionized Helium and traces of heavier elements. Embedded in this plasma is a weak magnetic field.

Table 1 – Observed Properties of the Solar Wind at 1 A.U.

Proton density	6.6 cm^{-3}
Electron density	7.1 cm^{-3}
He^{2+} density	0.25 cm^{-3}
Flow speed	450 km s^{-1}
Proton temperature	$1.2 \times 10^5 \text{ K}$
Electron temperature	$1.4 \times 10^5 \text{ K}$

It is often useful to describe the solar wind in terms of fluxes or flux densities of quantities that are conserved in a plasma flow.

Table 2 – Solar Wind Flux Densities and Fluxes at 1 AU

	Flux Density	Flux through a sphere at 1 AU
Protons	$3.0 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1}$	$8.4 \times 10^{35} \text{ s}^{-1}$
Mass	$5.8 \times 10^{-16} \text{ g cm}^{-2} \text{ s}^{-1}$	$1.6 \times 10^{12} \text{ g s}^{-1}$
Radial Momentum (dynamic pressure)	$2.6 \times 10^{-9} \text{ pascal (Pa)}$	$7.3 \times 10^{14} \text{ newton}$
Kinetic Energy	$0.6 \text{ erg.cm}^{-2}.\text{s}^{-1}$	$1.7 \times 10^{27} \text{ ergs.s}^{-1}$
Magnetic Energy	$0.01 \text{ erg.cm}^{-2}.\text{s}^{-1}$	$0.025 \times 10^{27} \text{ ergs.s}^{-1}$

4×10^8 g mass of the Sun over its surface (4×10^8 g) is negligible. The solar wind energy flux is less than 10^{-6} of the 4×10^{33} ergs.s⁻¹ radiated from the Sun *i.e.* the present day solar wind is negligible in its overall mass and energy balance of the Sun.

The pressure in an ionized gas with equal proton and electron density is $P_{\text{gas}} = nK(T_p + T_e)$ where T_p and T_e are the proton and electron temperatures respectively. Thus $P_{\text{gas}} = 3 \times 10^{-10}$ dyne cm⁻² = 30 pico pascals (pPa). Some derived properties are given in table 3.

Table 3 – Some Derived Properties at 1 AU

Gas Pressure	30 pPa
Magnetic Pressure	19 pPa
Sound speed	60 km.s ⁻¹
Alfvén speed	40 km s ⁻¹
Proton gyro radius	80 km
Proton-Proton collision time	4×10^6 s
Electron-Electron Collision time	3×10^5 s
Time for solar wind to flow a distance of 1 AU	~ 4 days = 3.5×10^5 s

Sound waves in an ionized gas with pressure P_{gas} and mass density $\rho = n(m_e + m_p)$ travel at

$$c_s = \left(\frac{\gamma p}{\rho} \right)^{\frac{1}{2}} = \left\{ \frac{\gamma k}{m_p + m_e} (T_p + T_e) \right\}^{\frac{1}{2}}$$

where γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume. Using $\gamma = 5/3$ and temperatures quote in the Table –I $c_s \sim 60$ km.s⁻¹. Thus the typical speed of the solar wind at 1 AU of 400 km s⁻¹ is highly supersonic. If we look at the magnetic pressure (using $\mu_0 = 4 \pi \times 10^{-7}$ N A⁻² and a typical B of 7×10^{-9} tesla)

$$P_{\text{mag}} = \frac{B^2}{2\mu_0}$$

at 1 AU is $\sim 1.5 \times 10^{-10}$ dyne cm⁻² or ~ 15 pPa

This value is comparable to the gas pressure indicating that magnetic effects will be as important as pressure effects in the solar wind. In particular small amplitude Alfvén waves driven by magnetic fluctuations will move at a speed comparable to the sound speed.

Models that extend the observed solar magnetic field into the corona indicate average field strengths of a few thousand Tesla at the base of the corona. Such a field would be sufficiently strong so that the magnetic pressure in this region ($P_{\text{mag}} \sim 10$ mPa) would be several times greater than the gas pressure. Thus magnetic effects would dominate the region where the solar wind originates. For example, Alfvén waves would travel several times faster than ordinary sound waves in the corona.

Lastly it should be remembered that the values quoted for various quantities are long-term average values. Even at a given distance say 1 AU; solar wind properties can vary widely on many different time scales. For example the flow speed of the solar wind can be as low as 150 km s⁻¹ or as high as 1500 km s⁻¹.

Our basic understanding of the solar wind formation comes from a theoretical model of the solar wind, as an equilibrium state of the hot coronal plasma in the gravitational field of the Sun.

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$

Conservation of momentum :

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mathbf{J} \times \mathbf{B} + \rho \mathbf{F}_g$$

For a plasma flow that is assumed to be steady and independent of time – all time derivatives can be set to zero. Thus

$$\nabla \cdot \rho \mathbf{u} = 0$$

$$\rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mathbf{J} \times \mathbf{B} + \rho \mathbf{F}_g$$

If we further assume that the system is spherically symmetric and all physical properties are functions of radial distance only; then it is natural to write the conservation equations in spherical polar coordinates. We know that in spherical polar coordinates

$$\nabla \cdot \mathbf{A} = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 A_r) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (A_\theta \sin \theta) + \frac{1}{r \sin \theta} \frac{\partial A_\phi}{\partial \phi}$$

$$(\nabla f)_r = \frac{\partial f}{\partial r}; \quad (\nabla f)_\theta = \frac{1}{r} \frac{\partial f}{\partial \theta}; \quad (\nabla f)_\phi = \frac{1}{r \sin \theta} \frac{\partial f}{\partial \phi}$$

Thus, if $\hat{\mathbf{e}}_r$ represents a unit vector that points radially out from the Sun.

$$\mathbf{F}_g = -\frac{GM_s}{r^2} \hat{\mathbf{e}}_r$$

$$\bar{\mathbf{u}} = u(r) \hat{\mathbf{e}}_r$$

$$\nabla_p = \frac{dp}{dr} \hat{\mathbf{e}}_r \quad \text{and}$$

$$\rho \mathbf{u} \cdot \nabla \mathbf{u} = \rho u \frac{du}{dr} \hat{\mathbf{e}}_r$$

If we neglect the magnetic fields, the conservation equations in spherical polar coordinates will be

$$\frac{1}{r^2} \frac{d}{dr} \rho u r^2 = 0 \tag{1}$$

$$\rho u \frac{du}{dr} = -\frac{dp}{dr} - \rho \frac{GM_s}{r^2} \tag{2}$$

This system of equations has a simple solution and until the late 1950's was considered as a valid description for the equilibrium state of the corona. The solution stems from the assumption that the corona is in static equilibrium or that $u(r) = 0$ everywhere. Equation (1) is then automatically satisfied.

Equation (2) becomes

$$-\frac{dp}{dr} - \rho \frac{GM_s}{r^2} = 0 \quad (3)$$

This is simply a statement of the balance of pressure gradient and gravity. If we take coronal protons and electrons to have the same temperature, from the ideal gas laws

$$p = nk(T_e + T_i) = 2nkT$$

Mass density $\rho = n(m_e + m_p)$; $\rho = nm$ where m is the mass of the protons (m_p) and electrons (m_e)

$$\rho = m \frac{p}{2kT}$$

Substitute ρ in (3) and assuming that the temperature is constant, the equation for pressure in a static isothermal atmosphere is written as

$$\frac{1}{p} \frac{dp}{dr} = -\frac{GM_s m}{2kT} \frac{1}{r^2} \quad (4)$$

The solution to this differential equation is

$$\ln p = \frac{GM_s m}{2kT} \frac{1}{r} + K \quad (5)$$

Where K is an arbitrary constant. Setting $p(r) = p_0$ at the base of the corona where $r = R$ gives the value of K .

$$K = \ln p_0 - \frac{GM_s m}{2kT} \frac{1}{R}$$

Substituting back in equation (5) gives

$$\ln \frac{p}{p_0} = \frac{GM_s m}{2kT} \left(\frac{1}{r} - \frac{1}{R} \right)$$

Or

$$p(r) = p_0 \exp \left\{ \frac{GM_s m}{2kT} \left(\frac{1}{r} - \frac{1}{R} \right) \right\} \quad (6)$$

For $r > R$

$$\left(\frac{1}{r} - \frac{1}{R}\right) < 0 \text{ thus } p < p_o$$

Equation (6) is therefore a generalization of the familiar exponential decay of pressure in a static, isothermal atmosphere. This formula is generally valid for an atmosphere that is so shallow that the variation in gravitational field can be neglected, over the range of 'r' that is of interest.

If we measure r from the base of the corona in terms of height h such that $h = (r-R)$ and consider only $h \ll R$

$$\frac{1}{r} = \frac{1}{R+h} = \frac{1}{R(1+h/R)} \approx \frac{1}{R} \left(1 - \frac{h}{R}\right)$$

$$p = p_o \exp \left\{ -\frac{GM_s m h}{2kTR^2} \right\} = P_o e^{\frac{-h}{\lambda}} \dots \quad (7)$$

Thus (6) becomes

Where
$$\lambda = \frac{2kTR}{GM_s m} = \frac{2kT}{mg}$$

is the scale height given in terms of the acceleration due to gravity at the base of the atmosphere. The problem with equation (6) is that as

$$r \rightarrow \infty; \quad p(r) \rightarrow p_o \exp \left\{ \frac{GM_s m}{2kTR} \right\}$$

For a coronal temperature of 10^6 K this is only about e^{-8} or 3×10^{-4} of the high pressure at the base of the corona. This is many orders of magnitude higher than the pressure thought to exist in the ISM ($\sim 10^{-14}$ Pa)

Thus equation (6) cannot represent the equilibrium state of the solar corona. Eugene Parker (1958) re-examined the equilibrium states implied by (1) and (2) by considering solutions with non zero flow speeds.

Equation (1) is satisfied if $\rho u r^2 = C$ (a constant); multiplying by 4π ; $4\pi r^2 \rho u = I$ (a constant). Now ρu is the rate at which mass is carried outwards through unit area on a Sun centered sphere of area $4\pi r^2$. Thus I is just the mass flux/sec through the entire sphere. For a time independent radial flow conservation of matter implies that the total flux through all Sun centered spheres must be the same.

In the momentum equation (2), written again below for convenience

$$\rho u \frac{du}{dr} = -\frac{dp}{dr} - \rho \frac{GM_s}{r^2}$$

$p = 2n kT$ can be differentiated and substitute above.

$$\rho u \frac{du}{dr} = -2kT \frac{dn}{dr} - \rho \frac{GM_s}{r^2}$$

substituting in the above equation $\rho = nm$, we can write

$$\rho u \frac{du}{dr} = -2kT \frac{dn}{dr} - \frac{GM_s m}{r^2} n$$

$$u \frac{du}{dr} = -\frac{2kT}{m} \frac{1}{n} \frac{dn}{dr} - \frac{GM_s}{r^2} \quad (8)$$

now $4\pi r^2 \rho u = I$; or $4\pi r^2 m n u = I$, hence

$$\begin{aligned} n &= \frac{I}{4\pi m u r^2} \\ \frac{dn}{dr} &= \frac{I}{4\pi m} \left\{ -\frac{1}{u} \frac{2}{r^3} - \frac{1}{r^2} \frac{1}{u^2} \frac{du}{dr} \right\} \\ \frac{1}{n} \frac{dn}{dr} &= \frac{4\pi m}{I} \cdot u r^2 \cdot \frac{I}{4\pi m} \left\{ -\frac{2}{u r^3} - \frac{1}{r^2 u^2} \frac{du}{dr} \right\} = -\frac{2}{r} - \frac{1}{u} \frac{du}{dr} \end{aligned}$$

Thus equation (8) becomes

$$u \frac{du}{dr} = \frac{4kT}{mr} + \frac{2kT}{m} \frac{1}{u} \frac{du}{dr} - \frac{GM_s}{r^2}$$

This is differential equation for $u(r)$ and its derivative du/dr in an expanding isothermal atmosphere and was recognized by Parker as recording the existence of the solar wind.

$$\begin{aligned} u \frac{du}{dr} - \frac{2kT}{m} \frac{1}{u} \frac{du}{dr} &= \frac{4kT}{mr} - \frac{GM_s}{r^2} \\ \left(u^2 - \frac{2kT}{m} \right) \frac{1}{u} \frac{du}{dr} &= \frac{4kT}{mr} - \frac{GM_s}{r^2} \end{aligned} \quad (9)$$

For any realistic temperature T at the base of the corona

$$\frac{GM_s}{r^2} > \frac{4kT}{mr}$$

Thus the RHS is negative near the base of the corona. However, GM_s/r^2 falls off more rapidly with r than $4kT/mr$. Thus the RHS grows and passes through zero at the radius

$$r_c = \frac{GM_s m}{4kT}$$

and becomes positive at still larger radii. This behavior of RHS has a profound influence on the nature of the solutions. The fact that $GM_s/r^2 > 4kT/mr$ at the base of the corona for any temperature T is simply a statement of the fact that the corona is gravitationally bound in spite of its high temperature.

If the RHS is zero at $r = r_0$ then the LHS must also be zero at $r = r_c$. This can happen if

$$\left. \frac{du}{dr} \right|_{r_c} = 0$$

i.e. these solutions have a maxima at $r = r_c$. If we restrict attention to start with small values of $u(r)$ near the base of the corona.

$$u^2 - \frac{2}{kT} < 0 \quad \text{for } r \text{ near } R$$

Since the RHS is negative; du/dr must be positive. i.e. $u(r)$ increases with r for these solutions until $r = r_c$, attains a maximum there, and then decreases (with $u^2 - 2kT/m$ still negative) for $r > r_c$ because the RHS is positive. For these solutions $u^2 < 2kT/m$ for all values of r .

However, there are special solutions for the equation below (9) with the LHS being zero at $r=r_c$. Thus we can start with a small value of $u(r)$, near the base of the corona with

$$u^2 - \frac{2kT}{m} < 0 \text{ and } \frac{du}{dr} > 0 \quad \text{for } R < r < r_c$$

But which passes through $r = r_c$ with $u^2 = \frac{2kT}{m}$ and $\frac{du}{dr}$

still positive because $u^2 - \frac{2kT}{m}$

must become positive for $r > r_c$. The change in sign on the RHS can still be accommodated with du/dr still positive and $u(r)$ can continue to increase for all values of r .
The sound speed is

$$c_s^2 = \gamma \frac{p}{\rho} = \gamma \frac{2nkT}{nm} = \gamma \frac{2kT}{m}$$

All solutions with

$$u(r) < \left(\frac{2kT}{m} \right)^{1/2}$$

at $r = r_c$ share the problem of having a very large pressure as $r \rightarrow \infty$. The special solution however, has $u(r)$ increasing with r ; exceeding $(2\gamma kT/m)^{1/2}$ i.e. becoming supersonic. From

$$n(r) = \frac{I}{4\pi m} \cdot \frac{1}{r^2} u(r)$$

$n(r) \rightarrow 0$ as $r \rightarrow \infty$; and $p = 2nkT$ also approaches zero. This therefore represents an equilibrium state connecting the high pressure corona to the low pressure ISM. This equilibrium is not static but one with flow or expansion of coronal plasma away from the Sun.

This change as $r \rightarrow \infty$ is a result of the flow breaking down the dependence of $n(r)$ on the scale height in the gravitational field and producing the $1/r^2$ geometric dependence through the continuity equation

On integrating equation (9), one obtains

$$\frac{1}{2} u^2 - \frac{2kT}{m} \ln u = \frac{4kT}{m} \ln r + \frac{GM_s}{r} + K'$$

where K' is an arbitrary constant. Imposing the condition that

$$u^2 = \frac{2kT}{m} \quad \text{at} \quad r = r_c = \frac{GM_s m}{4kT}$$

determines K' ,
which is obtained as

$$\frac{kT}{m} - \frac{kT}{m} \ln\left(\frac{2kT}{m}\right) - \frac{4kT}{m} \ln r_c - \frac{GM_s}{r_c} = K'$$

Substituting the above value of K'

$$\frac{1}{2}u^2 - \frac{2kT}{m} \ln u = \frac{4kT}{m} \ln r + \frac{GM_s}{r} + \left[\frac{kT}{m} - \frac{kT}{m} \ln\left(\frac{2kT}{m}\right) - \frac{4kT}{m} \ln r_c - \frac{GM_s}{r_c} \right]$$

or

$$\frac{1}{2}u^2 - \frac{kT}{m} \ln u^2 + \frac{kT}{m} \ln\left(\frac{2kT}{m}\right) - \frac{kT}{m} = \frac{4kT}{m} \ln \frac{r}{r_c} + GM_s \left(\frac{1}{r} - \frac{1}{r_c} \right)$$

or

$$u^2 - \frac{2kT}{m} \ln \frac{u^2 m}{2kT} - \frac{2kT}{m} = \frac{8kT}{m} \ln \frac{r}{r_c} + 2GM_s \left(\frac{1}{r} - \frac{1}{r_c} \right) \dots \dots \dots (10)$$

Figure I, shows this solution for $u(r)$ for a range of temperatures (Parker 1958).

FLUX FREEZING

In MHD; the electric field can always be computed from other variables because we do not have to consider E as an independent variable. This is called the "magnetohydrodynamic approximation" wherein the time derivatives of the electric field can be neglected.

Therefore the Maxwell equation

$$\nabla \times B = \frac{4\pi}{c} J + \frac{1}{c} \frac{\partial E}{\partial t}$$

can be written as

$$\nabla \times B = \frac{4\pi}{c} J \quad \text{and Ohms law} \quad J = \sigma \left(E + \frac{v}{c} \times B \right)$$

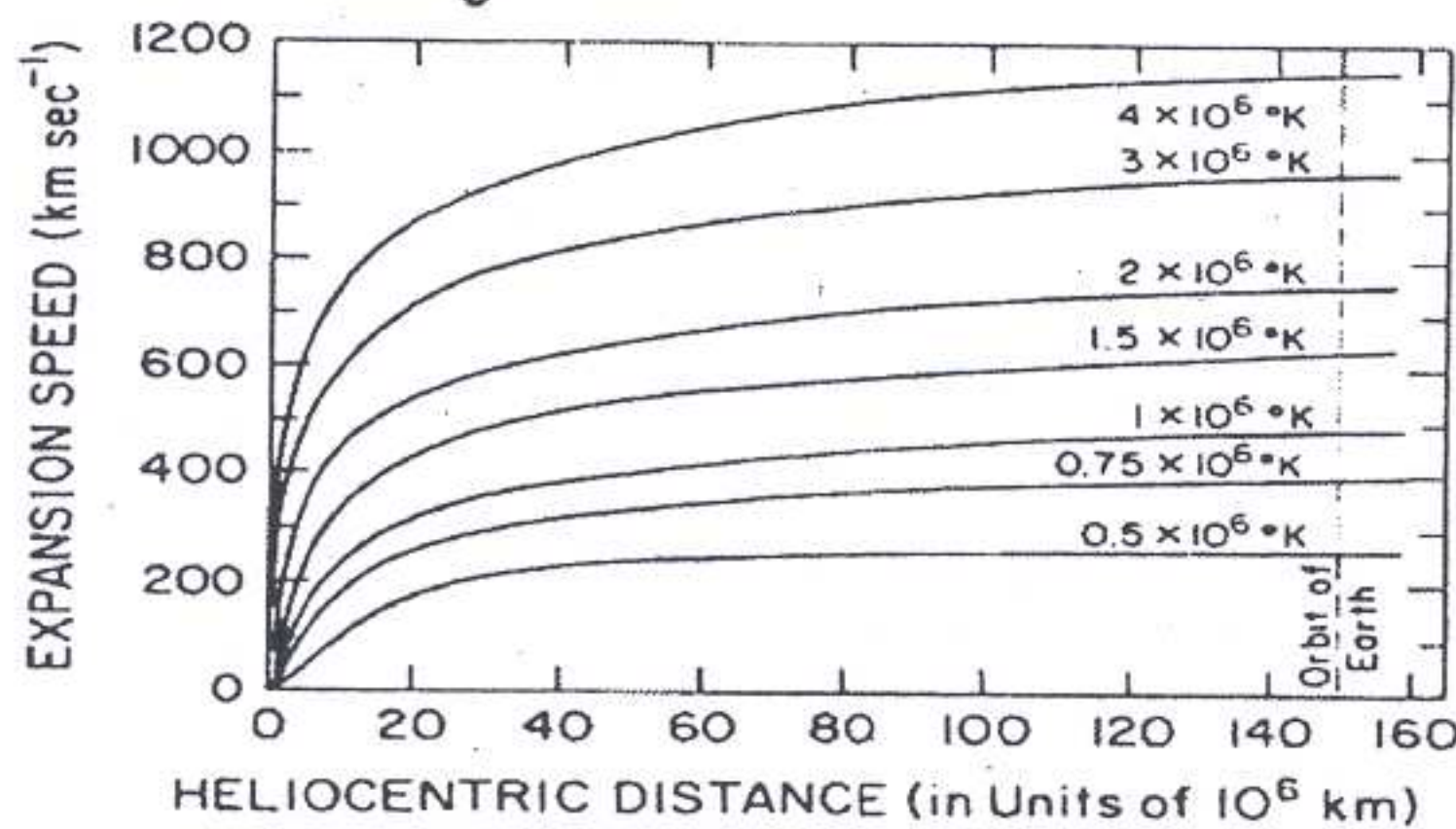


Fig. 1. Plots the solutions of equation (9), a differential equation for $u(r)$ and its derivative du/dr in an expanding isothermal atmosphere which was recognized by Parker as recording the existence of the solar wind.

combining the above

$$\mathbf{E} = \frac{c}{4\pi\sigma} \nabla \times \mathbf{B} - \frac{\mathbf{v}}{c} \times \mathbf{B}$$

Substituting in the Maxwell equation

$$\frac{\partial \mathbf{B}}{\partial t} = -c \nabla \times \mathbf{E}$$

we obtain

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \lambda \nabla^2 \mathbf{B} \quad (11)$$

where

$$\lambda = \frac{c^2}{4\pi\sigma}$$

is called the magnetic diffusivity and σ is the electrical conductivity. It may be noted that σ is assumed to be spatially constant and hence can be taken outside the spatial derivative. Equation (11) is called the induction equation.

CONSEQUENCES OF THE INDUCTION EQUATION

If B , V and L are the typical magnetic fields, velocity and length scale then the first term on the RHS of the induction equation is of the order of VB/L ; the second term is of the

$$\Re_m = \frac{VB}{L} / \frac{\lambda B}{L^2} = \frac{LV}{\lambda}$$

order $\lambda B/L^2$. If we take the ratio of these two terms we get which is the magnetic Reynolds number. Since R_m is directly proportional to L it is much larger for astrophysical plasmas than for laboratory plasmas.

For a fully ionized hydrogen plasma

$$\lambda = \frac{c^2 \eta}{4\pi}$$

where η is the resistivity

$$\eta = 7.3 \times 10^{-9} \frac{\ln \Lambda}{T^{3/2}} \text{ esu}$$

$$\Lambda = \frac{3}{2Ze^2} \left(\frac{k^3 T^3}{\pi n} \right)^{1/2}$$

Taking $\ln \Lambda \approx 10$; $\lambda \sim 10^7 \text{ cm}^2 \text{ s}^{-1}$

Laboratory system:

if we take $L = 10^2 \text{ cm}$ and $V = 10 \text{ cm s}^{-1}$

$R_m \sim 10^{-4}$

Astrophysical system : e.g. solar granulation scale sizes

If we take $L = 10^8 \text{ cm}$ and $V \sim 10^5 \text{ cm s}^{-1}$

$R_m \sim 10^6$. Thus the magnetic Reynolds number is generally very small ($\ll 1$) for laboratory

systems and generally very large for astrophysical systems. Therefore for a laboratory system

$$\frac{\partial B}{\partial t} \approx \lambda \nabla^2 B \quad (12)$$

and for an astrophysical system

$$\frac{\partial B}{\partial t} \approx \nabla \times (V \times B) \quad (13)$$

It may be noted that (12) and (13) are simple-minded approximations. The term $\nabla \times (V \times B)$ cannot be neglected in many laboratory systems and the term $\lambda \nabla^2 B$ can be important in many astrophysical settings. The main point however, is that magnetic fields behave very differently in laboratory and astrophysical settings, due to the dominance of two different terms in the induction equation. Alfvén who was a pioneer in the study of astrophysical magnetic fields coined the term "Cosmic Electrodynamics" for the study of electromagnetic phenomena in astronomical systems.

While mechanical properties of laboratory size and astronomical objects are not that different eg. the motion of stars in many ways is similar to the motion of balls. However, the vast magnetic fields generated in the interior of stars by interior plasma motions can never have any analogue in laboratory situations.

In the induction equation, in the limit $\sigma \rightarrow \infty$ {ideal MHD limit}.

$$\frac{\partial B}{\partial t} \approx \nabla \times (V \times B)$$

We know that for any arbitrary vector field Q satisfying

$$\begin{aligned} \frac{\partial Q}{\partial t} &= \nabla \times (V \times Q) \\ \Rightarrow \frac{d}{dt} \int_s Q \cdot ds &= 0 \end{aligned}$$

Thus

$$\frac{d}{dt} \int_s B \cdot ds = 0 \quad (14)$$

where the surface integral can be thought to be over a surface containing definite fluid elements and the Lagrangian time derivative implies that we are considering variation in time while following the fluid element. Physically (14) implies that magnetic fields move with the fluid. This result was pointed out by Alfvén and is called Alfvén's theorem on flux freezing. In astrophysical systems with high R_M the magnetic field is frozen into the plasma. If we have string at magnetic field lines through a column of plasma and if the plasma column is bent or twisted then the field lines will be similarly bent or twisted. Thus, in astrophysical systems the magnetic field can be considered to be some sort of plastic material that can be distorted by plasma motions. This is completely different from laboratory systems wherein the magnetic field is rather passive and can be turned on and off by sending or stopping current through a coil of wire.

We know that there is a one-to-one correspondence between magnetic field B and current density J i.e.

$$\nabla \times B = \frac{4\pi}{c} J$$

In astrophysical systems it is convenient to take B as our basic dynamical variable because if

we know the initial configuration of B and the nature of the plasma flows we can, from Alfvén theorem guess the final configuration of B . The advantage of taking B as a basic variable in high R_M situations is that we can visualize the evolution of B as opposed to considering J as a basic variable. In lab systems however we use J as a more basic element as we can control J and hence B .

If a magnetic field of order B is passing through an object whose equatorial cross-sectional radius is ' r '. Then the magnetic flux linked with the equatorial plane is Br^2 . If B is perfectly frozen then this flux should remain an invariant during contraction. Neutron stars have a field strength of $\sim 10^{12}G$. If we consider our Sun with a magnetic field near the pole of $\sim 10G$ and a radius 10^{11} cm, and shrink it to neutron star dimensions of $\sim 10^6$ cm, then the equatorial area would decrease by a factor of 10^{10} . If the magnetic flux remained frozen and had an initial value of $10G$, then after contraction it would be $10^{11}G$!!

SPATIAL CONFIGURATION OF THE SOLAR WIND MAGNETIC FIELD

If we take a spherically symmetric and radially expanding solar wind we would expect the IP magnetic field to have a very simple configuration. If a flow tube had an area dA_0 at the base of the corona then at any distance $r > R_\odot$ the flow tube would have an area

$$\left(\frac{r}{R}\right)^2 dA_0$$

i.e. magnetic field lines passing through area dA_0 would spread out to a larger cross sectional area. Conservation of magnetic flux (as implied by $\nabla \cdot B = 0$) would require

$$B(r) \left(\frac{r}{R}\right)^2 dA_0 = B_0 dA_0$$

or $B(r) = B_0 (R/r)^2$; where B_0 is the radial field at the base of the flux tube. *i.e.* the intensity of the purely radial magnetic field would fall off as $1/r^2$. However, this simple picture is not applicable to the solar wind because the solar atmosphere rotates about an axis nearly perpendicular to the ecliptic plane at the angular rate

$$\omega = 2\pi/25.4 \text{ days} = 2.7 \times 10^{-6} \text{ rad. s}^{-1}.$$

If we transfer ourselves to a frame of reference co-rotating with the Sun then the plasma still moves out radially with velocity $u(r)$. But it now has an apparent component in the direction of solar longitude ϕ .

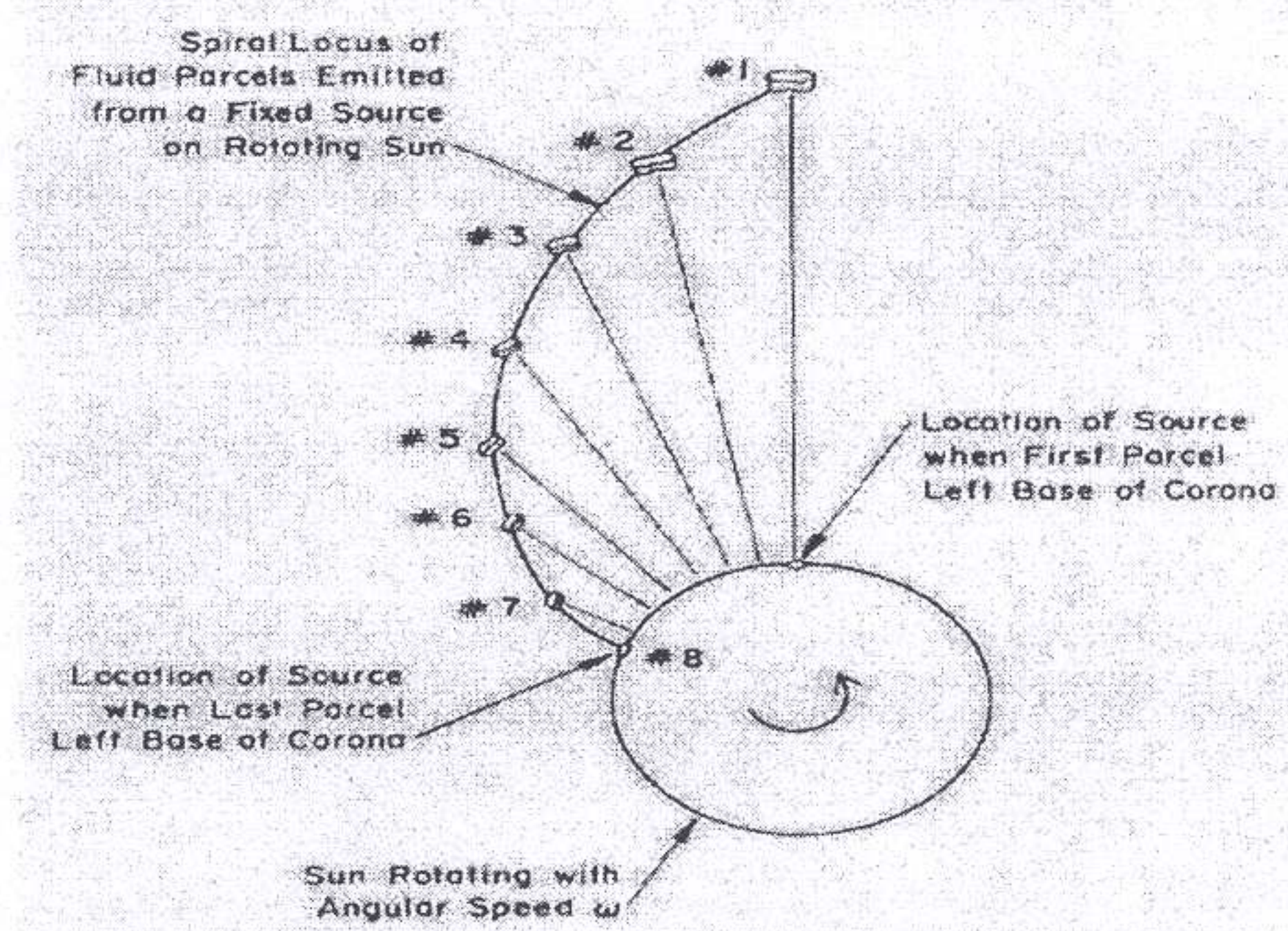


Fig. 2. Formation of spiral magnetic field.

The longitudinal component is given by

$$B_{\phi}(r) = -\frac{\omega r}{u} B(r)$$

Magnetic field lines frozen into the plasma will thus be drawn out into this same form i.e. a spiral as shown in figure 2.

TERMINATION OF THE SOLAR WIND

We know that the ISM has a pressure of $\sim 10^{-13}$ Pa. If we expect the solar wind to merge with the ISM then we would expect that at some large distance 'r' the momentum flux density would fall below the interstellar pressure. One would then expect the solar wind to slow down as it reacts to this external pressure from the ISM.

However, we have seen earlier from equation (10), that if $r \gg r_c$ and $u \gg (2kT/m)^{1/2}$

$$u(r) = 2 \left(\frac{2kT}{m} \right) \left(\ln \frac{r}{r_c} \right)^{1/2}$$

or

$$u^2 \approx \frac{8kT}{m} \ln \frac{r}{r_c}$$

because T is constant the ratio of flow speed to sound speed goes as $(\ln r)^{1/2}$ and the solar wind becomes more and more supersonic as it flows through the outer solar system. Even in models when T(r) is decreasing the ratio of flow speed to sound speed will increase. Thus no internal pressure or magnetic force can have any significant effect on slowing the solar wind. Thus the supersonic solar wind, even at very large heliocentric distances must drive a strong shock ahead of it. The radial momentum flux is $\rho u \cdot u = P_{int}$. For $P_{int} = 10^{-12}$ dyne. cm^{-2} and a radial momentum flux of 2.6×10^{-8} dyne. cm^{-2}

$$\left(\frac{r_{earth}}{r_{shock}} \right)^2 = \frac{10^{-12}}{2.6 \times 10^{-8}}$$

$$\text{or } \frac{r_{shock}}{r_{earth}} = (2.6 \times 10^4)^{1/2} \approx 160$$

or $r_{shock} \simeq 160 \text{ AU}$

What has been set forth in the above discussion is basically an idealized model of the solar wind formation, involving a supersonic expansion of the solar corona with the magnetic fields frozen into this expansion and the ultimate termination of the solar wind well into the outer solar system. It may be noted that in spite of the simplifying assumptions used here, the outward expansion of the corona due to the pressure difference between the corona and the ISM is still the basis of all current models of the solar wind. The spiral nature of the interplanetary magnetic field, the nearly constant flow speed, and the inverse square fall off in densities are all so fundamental that observations by spacecraft in the outer reaches of the solar system are used to look for deviations from these basic patterns.

EXTENSION OF THE CORONAL MAGNETIC FIELD INTO THE IPM

If we use the simplest of all realistic magnetic fields, a dipole, imposed as a boundary condition at the base of the corona and if the strength of this field were very small then we would expect this field to be dragged out into the IPM. If the field strength were very strong, then we would expect the magnetic configuration to be that of a pure dipole. For the real

corona, where the magnetic field is sufficiently strong that the magnetic pressure is a few times the gas pressure we would expect a mixture of these two extreme behaviors. Most of the field lines passing through the base of the corona should remain closed while a minority of the field lines should remain open, in the sense that they will be drawn out into the IPM so as not to return to the base of the corona at some other location. The first determination of the IP magnetic field lines using an isothermal MHD coronal expansion model was done by Pneuman and Kopp (1971) and Figure III shows the field lines in a plane of constant longitude. The dashed lines in the figure show the purely dipole magnetic field. The open field lines spread out to fill all space beyond about 2 solar radii and the plasma on them expand outward to form the solar wind. Attention should be paid to the field lines that are drawn out nearly parallel to the equator. Since the field lines come from opposite ends of the dipole, they must represent different polarities. Thus the sense of polarity of the distant IP magnetic field must change abruptly at the equator. This would imply a thin region of strong current density at the equator. This current circulates around the dipole in the equatorial plane. We would thus have an interplanetary current sheet and closed magnetic configurations should exist where the vertical component of the magnetic field at the base of the corona changes sign, or above what are called neutral lines.

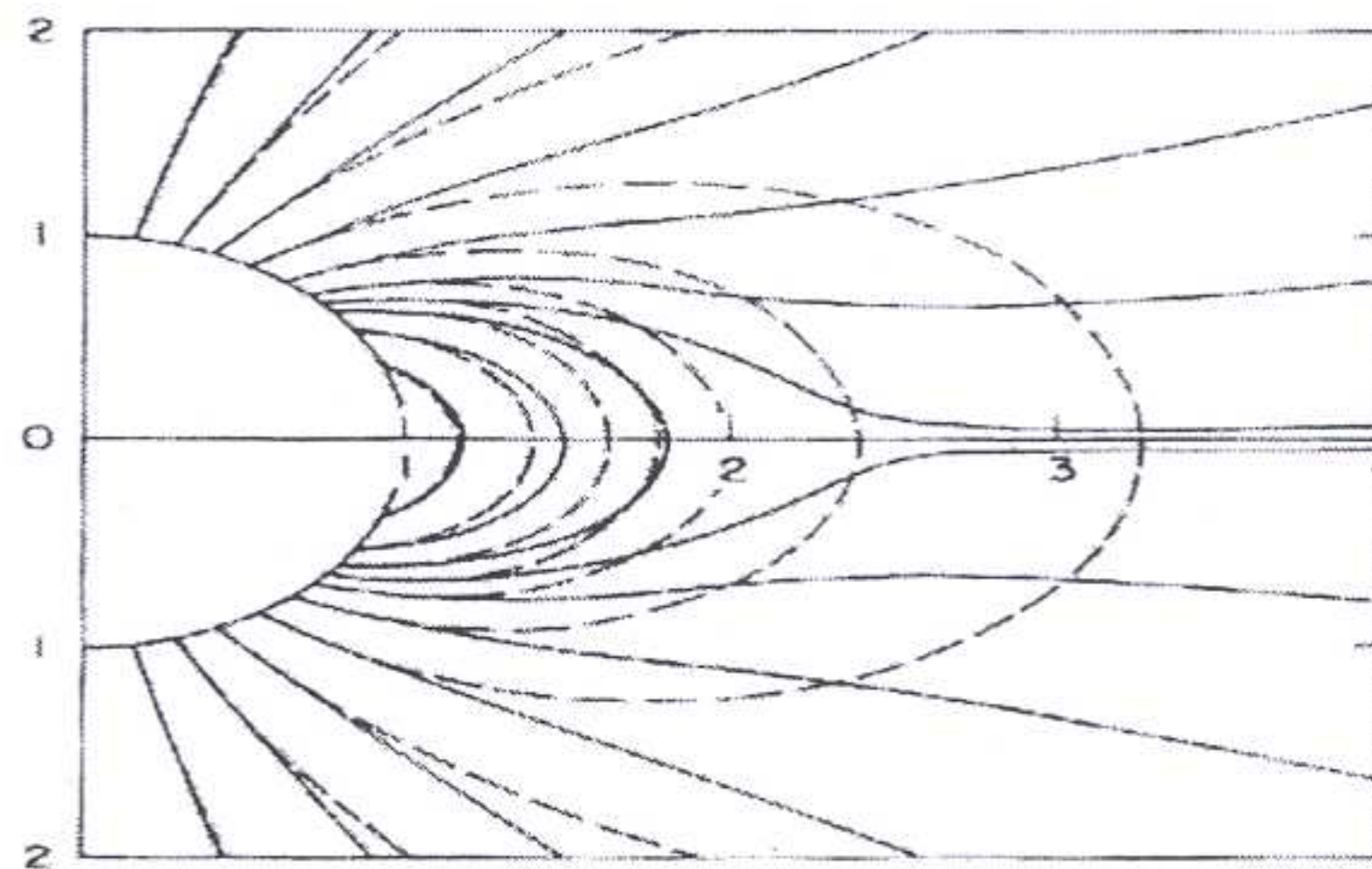


Fig. 3. Shows the magnetic field configuration derived from the model of Pneuman and Kopf (1971). The dashed lines indicate a purely dipole field configuration.

Open magnetic configurations should form over regions where the vertical component of the magnetic field at the base of the corona is of the same sense over large regions. These regions are called unipolar regions. The closed structures would extend to about 2 solar radii (in a dipole field). Open field structures with opposite magnetic polarities should come into close proximity above the closed magnetic regions and form current sheets extending into the solar wind.

From the above discussion it is clear that we would expect a current sheet to extend out into the IP medium. If the solar magnetic field were a simple dipole aligned with the solar rotation axis then the current sheet would simply extend out into the solar equatorial plane, separating the northern and southern hemispheres of opposite magnetic polarity. If on the other hand, the magnetic dipole axis were tilted to the rotation axis then the planar current sheet would be tilted out of the equatorial plane. A stationary observer on the Earth would thus be placed alternately above or below the current sheet as the sun rotates. Such an observer would see the interplanetary magnetic field change polarity once every two weeks on average, with the entire pattern being repeated every ~ 27 days (the synodic solar rotation period). In reality however, observations have shown that the magnetic field changes, on average, once a week. This would imply that the solar magnetic field is not a simple dipole and therefore has a polarity pattern that leads to more frequent crossings of the neutral line and thus shorter intervals of unchanging polarity. Actual observations have shown two-sector, four-sector and more complicated patterns at different epochs. The two-sector pattern is consistent with a dipolar magnetic field, while the four-sector pattern would imply a more

MODULATION OF SOLAR WIND SPEED AND SOLAR WIND DISTURBANCES

Systematic observations of the solar wind over several decades have shown that the Solar wind speed in the ecliptic is not constant. It shows systematic changes that occur in connection with the passage of magnetic sectors or polarity features. The solar wind speed is usually low at the sector boundaries, being approximately 300 to 400 km s^{-1} and then rises up to about 700 km s^{-1} part way through a sector and then drops again. The densities during the rising phase are usually high. The Ulysses spacecraft has very clearly shown that the solar wind is largely bi-modal with a constant belt of high speeds existing beyond latitudes or approximately 45° and a varying solar wind speed existing between the equator and $\sim 45^\circ$ in both hemispheres. Now, the shapes of the rotation induced spiral structures in the IPM depend on the solar wind speeds. The faster the solar wind, the less tightly wound are the spiral structures and vice versa. Thus, a non-uniform speed would lead to spirals that intersect one another. Such regions or compression caused by recurring co-rotation structures can drive shock fronts ahead of them and give rise to solar wind disturbances which can propagate to the Earth and beyond. Other agencies that can create propagating shock fronts and solar wind disturbances are solar flares and coronal mass ejection's (CME's). Traditionally, the genesis of shock waves and IP disturbances have been tied to solar flares. However, it has proved to be very difficult to establish this. The other major contributor to IP disturbances are CME's which are easily detected from space based platforms. Intensive studies are underway in recent times to look for connections between the flare and CME processes and to pinpoint the solar source of IP disturbances.

A NOTE TO THE READER

These notes are not exhaustive, in the sense that they do not cover all of the material that will be touched upon in the four lectures. I have tried to stress upon some important aspects, which in my opinion are crucial in the understanding of the nature of the solar wind. Additional material that will be covered in the lectures, and not a part of these notes, will be a brief introduction to "Space Weather", the various techniques used to study interplanetary disturbances and some recent results. The units are loosely used in the notes and are at times in SI units and at other times in CGS units. So to avoid confusion, I have given a small table below of some of the quantities used in both SI and CGS units. Figure I has been taken from the book "Introduction to Space Physics", Cambridge Univ. Press, Eds., M.G. Kivelson and C.T. Russell and is an adaptation of the plot originally published by Parker (1958a). Figure II is also taken from this book which is an excellent introductory book to Space Physics with contributions from well-known scientists in the field.

Quantity	SI Unit	Conversion to c.g.s Units
Energy	joule (J)	10^7 ergs
Power	Watt (W) (=joule sec^{-1}).	10^7 ergs s^{-1}
Magnetic Flux Density	tesla (T)	10^4 Gauss (G)
Force	newton (N) (= kg m s^{-2})	10^5 dyn
Pressure	Pascal (Pa) (= N m^{-2}) (= $\text{kg m}^{-1} \text{s}^{-2}$)	10 dyn cm^{-2}

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