This part is devoted to the study of the interplanetary magnetic field due to the sun. It starts with the basic concept of an expanding solar corona which results in what is called 'solar wind' with a magnetic field 'frozen in'. A brief discussion of the configuration and strength of the interplanetary magnetic field as given by Parker is undertaken. It is followed by a short account of the model as envisaged by Axford, Dessler and the author. The importance of the charge exchange between galactic neutral hydrogen and the solar wind protons has been pointed out. It is shown that the solar wind velocity undergoes shock transition from supersonic to subsonic level due to interaction with galactic magnetic field and the galactic matter. Finally, the magnetic field configuration and its strength in interplanetary space due to non-uniformity of solar wind velocity is examined.
1. The solar wind and the magnetic field in interplanetary space

1.1. Solar wind

Solar corona has a temperature of the order of $10^6 \text{K}$. There is some controversy as to the manner in which the corona is heated. Chamberlain assumes the heating to be confined to the base of the corona while Parker assumes that it extends to several sun's radii. According to both the models the corona must continuously expand even against the solar gravitational attraction. The different boundary conditions put by Chamberlain and Parker however result in different velocities with which the coronal matter is being expelled outwards. Chamberlain gets a value of about 20 km/sec, while Parker gets a value of about 500 km/sec. During solar flares when the temperature of the region may rise to as much as $10 \times 10^6 \text{K}$ it is possible to get velocities in the range of 1000 - 2000 km/sec. (Parker 1961 a). The expanding solar corona is called 'solar wind'.

1.2. Parker's interplanetary magnetic field for uniformly expanding solar corona.

Chapman and Bartels pointed out that solar matter, moving radially out will cause the magnetic field to follow the form of an Archimedes spiral due to the
rotation of sun about its axis. As the plasma is highly conducting the magnetic field frozen into it must necessarily follow the solar matter provided the kinetic energy density frozen in it. Therefore the magnetic configuration should be of the form of an Archimedes spiral. The interplanetary magnetic field for uniform solar wind is derived by Parker\textsuperscript{208, 209} as:

\begin{align*}
B_t &= B_0 \left(\frac{a}{r}\right)^2 \left(1 + \frac{r^2}{v^2}\right)^{1/2} \quad \text{.. (42)} \\
B_{\parallel} &= B_0 \left(\frac{a}{r}\right)^2 \quad \text{.. (43)} \\
B_{\perp} &= B_0 \left(\frac{a^2}{r^2}\right)/(rv) \quad \text{.. (44)}
\end{align*}

where $B_t$ is the total magnetic field at a distance $r$ from the sun, $B_0$ is the field strength in the corona where the effective freezing takes place, $B_{\parallel}$ is the component of $B_t$ parallel to the radius vector and $B_{\perp}$ is the component perpendicular to it.

The details of the quiet day field are given in the paper by Axford, Dessler and the author (1962). The pre-print of the paper is attached in the Appendix. It is emphasised that magnetic lines of force directed in opposite directions can coexist without merging together because of the high conductivity of the plasma. Also, because of the local fields in the sun, the direction of the field should change with movement along or across the radius vector. The distance at which this change occurs may be
about 0.3 to 0.5 A.U.

1.3. Corotation of the interplanetary magnetic field

The interplanetary magnetic field on the average corotates with the sun even though the plasma moves radially outward. All the effects arising out of a moving magnetic field can be understood by the idea of corotation of the spiral magnetic field. The analogy with a needle moving radially outwards with a uniform velocity on a phonograph record is very informative to understand how the interplanetary magnetic field can corotate. As the record rotates the needle slips through the spiral groove. The needle does not cut across the grooves but only slips through, and in this process also moves outwards. In the case of interplanetary magnetic field the plasma also does not cut across the magnetic lines of force but slips through.

1.4. Charge exchange and the limits of the interplanetary magnetic field.

The solar wind cannot move outward indefinitely. The density of the plasma in the wind falls approximately as $1/r^2$. Thus at some great distance the kinetic energy density of the solar wind will be balanced by magnetic energy density of the galactic field (Davis'162). Another important force which retards the motion of the solar wind...
is the galactic neutral hydrogen. The neutral hydrogen being unaffected by the interplanetary magnetic field can move towards the sun till it suffers a charge exchange with the solar wind protons. The time constant (\( \tau \)) for this process is

\[
\tau = \frac{1}{R n_H} \quad \cdots (45)
\]

where \( R \) is the charge exchange rate in cm\(^3\)/sec and \( n_H \) the number of neutral hydrogen per cubic cm. The net result of such a charge exchange is that the solar proton velocity is almost brought down to that of the neutral hydrogen atom, while the neutral hydrogen atom moves outward with the velocity of the original proton (several hundred km/sec.). The effect of charge exchange is shown in equation (46).

\[
H_1 + P_h \rightarrow H_n + P_1 \quad \cdots (46)
\]

where \( H_1 \) is the neutral hydrogen atom moving with a velocity of a few km/sec. \( P_h \) is the solar proton moving radially outward with the velocity of a few hundred km/sec. \( H_n \) is the new neutral hydrogen atom which will eventually move in the general direction away from the sun with a velocity of several hundred km/sec while the low energy proton \( P_1 \) is left behind.
The net energy loss during each such charge exchange will be

$$\Delta E = E_p - E_H \quad \ldots \quad (47)$$

where $E_p$ and $E_H$ are the kinetic energies of proton and neutral hydrogen atom. The energy loss during each such interaction will be several hundred electron volts. This reaction rate will become increasingly important outward. The net result is that neutral hydrogen is expelled out with much higher velocity than with what it enters from the galaxy. The retardation of the solar wind due to charge exchange may not be important unless the density of neutral hydrogen is high. Most of the charge exchange takes place in the region II (defined later). The retarding effect of this reaction together with the pressure of the magnetic field of the galaxy (which is more important) results in the transition of the solar wind velocity from the supersonic to subsonic condition. The details of this transition are given in the paper in the Appendix.

The interplanetary space can therefore be divided into three regions - Region I, Region II and Region III (see Appendix for the diagram). Region I may extend up to about 50 A.U. The field in this region on the average corotates with the sun, and the solar wind velocity remains supersonic.
between the particles resulting in randomising their motions. The most effective collision appears to be the charge exchange between neutral hydrogen atom and the proton. If the charge exchange collision period is taken to be $10^7$ seconds, the magnetic field to be about 1 gamma and the proton number density to be 0.1, then it is possible to calculate the merging time by Sweet's mechanism. The merging time $t_m$ according to Sweet's mechanism (Parker 1957) is

$$t_m = L^{3/2} \sigma_3^{-1/2}/(\nu_{hm})$$

where $V_{hm}$ is the hydromagnetic wave velocity, $\sigma_3$ is the electrical conductivity and $c$ is the velocity of light. $L$ is the width of the region over which merging takes place. $\sigma_3$ can be calculated. Taking the values quoted above $\sigma_3$ comes out to be $10^7$ stat mho/cm. With this value of $\sigma_3$ and $L$ equal to 0.1 A.U., $t_m$ is about $3 \times 10^7$ sec. For a value of 1 A.U. it is $10^9$ sec. Thus as a first approximation $t_m$ may be taken to be around $10^8$ sec. or about 3 years.

As the magnetic connection can be broken only after the merging of the lines takes place, the plasma will be free to diffuse into the galaxy only after about three years. Thus the shell i.e. the region II contains a 3 years supply of solar matter. It appears that the shell may not be thicker than 10 A.U.
Details of some of the topics discussed above are worked out in the paper given in the Appendix. Instabilities of the interface of the interplanetary and galactic magnetic field are also discussed in detail.

2. Magnetic field in the cavity

2.1. Introduction

The study of the green coronal emission from the sun suggests that there are regions in the solar corona which have temperatures appreciably differing from that of their surroundings. It is therefore quite reasonable to expect temperature gradients in the corona (both, positive as well as negative gradients). A temperature gradient should result in a gradient in the velocity of the solar wind. Such a situation has been pointed out by Sarabhai. Sarabhai has further discussed the effect of a positive velocity gradient which occurs on the right side of a hot region and a negative velocity gradient on the left of it. (The angular position of a surface element on the sun is measured positive in the anti-clockwise direction starting from the sun-earth line). In the region with negative velocity gradient the fast plasma
runs with the slower one ahead creating a region in interplanetary space where the magnetic field may be irregular and turbulent. With positive velocity gradient the slow plasma follows the faster one. The distance between them will go on increasing resulting in what is called a 'cavity' where there will be, in general, a reduced magnetic field and plasma density compared to the surroundings. A cold region will bring about a reversal in sign of the velocity gradient. These hot regions (or cold regions) if persist for more than 27 days, the synodic period of rotation of the sun, will cause the recurrence of the magnetic conditions and the plasma density in interplanetary space after 27 days. The associated phenomena like the modulation of galactic cosmic ray and $K_p$, the planetary index of geomagnetic disturbance, will also show a 27 day recurrence tendency.

Here we shall attempt to determine the configuration of the magnetic field and its strength in the cavity. For the derivation of the magnetic field it is assumed that the field frozen in solar corona is of uniform strength in the region where the velocity is changing sharply. This need not be true and it is likely that the field strength on the sun's surface may itself be a function of $dv/d\theta$. 
Fig. 35. (a) Step function change in solar wind from 500 km/sec. to 300 km/sec. (The point B is merged with point A). Cavity $\beta$ lies between lines (1) and (2) corresponding to solar wind velocity 500 km/sec. and 300 km/sec. respectively.

(b) Gradual change (linear) in solar wind from 500 km/sec. to 300 km/sec. The angular distance between point A and B is 20°. The cavity $\beta$ lies between lines (1) and (2).
2.2. Strength of the field

Fig. 35 Gł shows the configuration of the magnetic field in the region called 'cavity' when a step function change in the solar wind velocity is taken. Fig. 35 Gł shows the same thing when the change in solar wind velocity is gradual.

Let us take a region A B in the equatorial plane (fig. 35 Gł) of the sun such that the solar wind velocity falls steadily from A to B. Let the velocity gradient be dv/dθ. Taking the motion of the wind radially outwards we note that the plasma moving out from A and B will have moved out to distances in time t given by

\[ r_A = v_A \times t \]
\[ r_B = v_B \times t \]

\[ S_r = r_A - r_B = (v_A - v_B) t \] \hspace{1cm} \ldots (49)

\[ S_r \] is represented by A'C' in Fig. 34 which in the limit is equal to A'C. Let the angle between the small arc A'D and A'B' be \( \alpha \) and that between the normal to the field direction at A' and A A' be \( \kappa \). \( \beta \) is the angle between A'B' and the normal. Then from the Fig. 34,

\[ \beta = (\alpha + \kappa - 90) \] \hspace{1cm} \ldots (50)

\[ \tan \alpha = \frac{dv/d\theta \cdot \theta/\Omega}{r} \] \hspace{1cm} \ldots (51)
\[
\tan \gamma = \frac{v}{r \Omega} \quad \text{... (53)}
\]

where \( \Omega \) is the angular velocity of the sun.

Remembering that the change in strength of the magnetic field is brought about by velocity gradient in the equatorial plane, and that \( \text{div. } B_t = 0 \) (where \( B_t \) is the magnetic field at a distance \( r \) from the sun), we get,

\[
B_t = B_0 \frac{r^2}{r^2} \frac{\cos \alpha}{\cos \beta} \quad \text{... (53)}
\]

where \( r \) is the radius of the sun and \( B_0 \) the frozen magnetic field at the sun.

or \( B_t = B_0 \frac{r^2}{r^2} \frac{\cos \alpha}{\cos(\gamma + \alpha)} \quad \text{... (55)} \)

Expanding \( \sin (\gamma + \alpha) \), and putting the values of \( \cos \alpha \), \( \sin \alpha \), \( \cos \gamma \) and \( \sin \gamma \), we get,

\[
B_t = B_0 \frac{r^2}{r^2} \frac{(r^2 \Omega^2 + v^2)^{1/2}}{v (1 + \frac{r \Omega}{v^2} \frac{dv}{d\phi})}
\]

\[
= B_0 \frac{r^2}{r^2} \frac{(r^2 \Omega^2 + v^2)^{1/2}}{v (1 + \frac{r \Omega}{v^2} \frac{dv}{d\phi})} \quad \text{... (56)}
\]

where \( \Theta = \frac{r \Omega}{v} \).
If $\frac{dv}{d\theta} = 0$, one gets the formula derived by Parker for uniform solar wind.

When $\frac{dv}{d\theta} \gg 1$ (e.g. during the solar flare), one can simplify

$$B_t = B_0 \frac{r^2}{x^2} \left( \frac{r^2 - \Omega^2 + v^2}{v^2} \right)^{1/2} \frac{\Omega}{r \cdot \frac{dv}{d\theta}}$$

The radial and the perpendicular component of the magnetic field are given by

$$B_r = B_0 \frac{r^2}{x^2} \left( \frac{r^2 - \Omega^2 + v^2}{v^2} \right)^{1/2} \frac{1}{v (1 + \frac{r \cdot \Omega}{v^2} \cdot \frac{dv}{d\theta})} \cdot \sin \gamma$$

$$= B_0 \frac{r^2}{x^2} \frac{1}{(1 + \frac{r \cdot \Omega}{v^2} \cdot \frac{dv}{d\theta})} \quad (58)$$

$$B_\perp = B_0 \frac{r^2}{x^2} \left( \frac{r^2 - \Omega^2 + v^2}{v^2} \right)^{1/2} \frac{\Omega}{v (1 + \frac{r \cdot \Omega}{v^2} \cdot \frac{dv}{d\theta})} \cdot \cos \gamma$$

$$= B_0 \frac{r^2}{r} \frac{-\Omega}{(1 + \frac{r \cdot \Omega}{v^2} \cdot \frac{dv}{d\theta})} \quad (59)$$

2.3. Discussion

Equation (56) shows that if there is a positive velocity gradient at the sun then the field in the inter-
planetary space corresponding to the region decreases considerably. The factor by which it decreases to that for the uniform solar wind as given by Parker is

\[
\frac{1}{1 + \frac{\Omega r}{v^2} \cdot \frac{dv}{d\theta}} \quad \ldots \quad (60)
\]

Thus, greater the value of \(dv/d\theta\) weaker the field in the cavity. In the extreme case when \(dv/d\theta\) is infinite the cavity will be completely devoid of any plasma or magnetic field. In deriving the magnetic field in the cavity no consideration is made for the interaction of the fast plasma with the slow plasma ahead. If there were no interactions both the density of the plasma and the magnetic field would have decreased, compared to uniform wind velocity values, with the increasing distance from the sun i.e. the cavity would have grown indefinitely as one moves away from the sun. Actually due to interaction with the slow plasma ahead, the fast plasma slows down to the background velocity. The distance at which this occurs will depend upon the density of the fast plasma, its width and velocity. Thus \(dv/d\theta\) in space may be expected to decrease with the increasing distance from the sun and will become negligible after a few A.U. (Parker 1962). Thereafter the cavity will cease to grow and there will not be further weakening of the magnetic field (compared to the uniform solar wind field).
The magnetic field inside the cavity need not be uniform even if the gradient $dv/d\theta$ is constant. Equation (5b) indicates that the field will become smaller with increasing value of $v$. Thus, at a particular distance $r$ and with a fixed value of $dv/d\theta$ one finds decrease in the magnetic field, as one moves in the cavity from west to east. A change in $dv/d\theta$ will further complicate the evaluation of the magnetic field.

2.4. Conclusion

As suggested by Sarabhai the positive gradient in the solar wind velocity gives rise to a cavity in the interplanetary space. The cavity has the following properties:

1. The magnetic field and the plasma density in general will be smaller compared to the surroundings.

2. The effect of cavity will be stronger when the velocity gradient $dv/d\theta$ is high.

3. The cavity grows as the distance from the sun increases. After some distance, however, the cavity will cease to grow because of the slowing down of the fast plasma as it interacts with the slow plasma ahead.
(4) $K_p$, the planetary index of the geomagnetic disturbance, should show a low value because of the low density of the plasma and the absence of turbulence.