INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONE: 2240-1
CABLE: CENTRATOM - TELEX 460392 - I

H4.SMR.203 - 32

" SPRING COLLEGE ON GEOMAGNETISM AND AERONOMY "

(2 - 27 March 1987)

" Magnetic fields in solar systems "

presented by :

F. MARIANI
Dipartiemtno di Fisica
II Università di Roma
Via Orazio Raimondo
00173 Roma
Italy

MAGNETIC FIELDS IN SOLAR SYSTEM

1. INTRODUCTION

The interaction and relationships between solar radiation (electromagnetic and corpuscular) and the terrestrial environment have been already extensively treated in other lectures. A very complicate overall picture of the physical characteristics has been observed; many questions have been answered but there is a number of unsolved problems, yet.

In our lectures we shall consider in some detail the physical properties of the interplanetary medium and of the celestial bodies pertaining to the solar system, also taking advantage from the progress made in recent years on the knowledge of the terrestrial environment.

In summary, the plasma properties close to Earth, as derived by in-situ observations of the interplanetary magnetic field started in the early sixties, are given below:

(i) the field intensity at 1 A.U. from the Sun is of the order of a few nanoteslas (or gammas);

(ii) the geometrical structure of the field vector is on average well described by a heliocentric spiral configuration where the field tends to be at an angle of 45 or 225 degees from the outward direction from the Sun.

(iii) the solar wind, mainly composed by protons and electrons, propagates at a radial velocity of several hundreds km/sec.

(iv) the particle density at the Earth's orbit is of the order of a few particles/cm3; the flux is of the order of

10^8 particles/cm**2/sec.

(v) the particle energy flux is of the order of 10^8 keV/cm**2/sec, while the magnetic energy flux is of the order of a few percentof that.

2. THE INTERPLANETARY MAGNETIC FIELD AND ITS SOURCE REGION.

2.1 THE PHOTOSPHERIC MAGNETIC FIELD.

It is known since a long time that the Sun is surrounded by a large scale magnetic field, other than that of up to several thousands Gauss present in the sunspot regions. But it was not until 1953 that it became clear that a sort of "regular" field existed in the polar caps at latitules above 55 degrees, with a strength of a few Gauss.

The detailed structure of the field topology is very complex to describe in the photosphere, where the field lines originate. However, such a complexity is not apparent in the interplanetary field: the reason is that in the terminology of polynomial expansion the higher harmonics of the photospheric field are not present at the heights in the corona, where the field pattern is frozen in the solar wind.

The simple patterns of the interplanetary field suggest, as we shall see, that large unipolar (on the average) areas of the photosphere extend in longitude one fourth to one half of the solar circumference close to ecliptic. Existence of extensive unipolar regions was postulated much earlier to explain the features of some magnetic storms.

The present status of knowledge of the large scale magnetic field in the photosphere derived by low angular resolution can be be summarized as follows:

(i) during quiet years the field often has a north-south dipole structure, although there are periods when the same polarity is observed in both polar caps.

(ii) The field in the two caps can reverse its magnetic orientation, not necessarily at the same time.

(iii) During active periods also persistent east-west (as opposed to north-south) dipole structures have been observed.

(iv) The complexity of the field configuration increases when higher resolution observations are made.

In principle, the mathematical description of the photospheric field is possible by techniques similar to those used for the geomagnetic field, but big complications arise because of the fact that:

(i) only the line-of-sight field component is observed from Earth,

(ii) some kind of temporal averaging must be made due to the long period of observations required to collect a reasonable map of the global photospheric field configuration around the Sun,

(iii) data gaps are almost always present in the central meridian region (where the field observations are more reliable) so that the less reliable data collected away from the central meridian are to be used. As a result of all above

It is evident that appropriate corrections are to be applied on the data to guarentee that the necessary boundary conditions are fulfilled (in particular, that the global magnetic flux emerging from the Sun is zero).

Reminding the geometrical and physical meaning of the spherical harmonics (fig. 1) it is interesting to see the results of a long term study of the contribution of the different harmonics to the large scale photospheric field in the years 1959-1972. As a whole the field has often a predominant dipole structure in a east-west direction. more often two (dipole) than four (quadrupole) or more sectors. However, zonal structures are not unfrequent, expecially in proximity of big events on the Sun. The rapid changes in the global harmonics suggest either that the source of the global field is not very deep or that very strong fluid flows couple photosphere and lower layers.

2.2 THE MAGNETIC FIELD IN THE SOLAR CORONA.

The familiar expression of the magnetic field potential derived by an internal source and no currents outside of a sphere of radius R is given by

$$(1) \qquad \psi(r,\theta,\phi) = R \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left[\left(\frac{R}{r}\right)^{n+1} (g_n^m \cos m\phi + h_n^m \sin m\phi) P_n^m(\theta) \right]$$

This satisfies the conditions $\underline{\nabla} \times \underline{B} = 0$ and $\underline{\nabla} \cdot \underline{B} = 0$.

A current density vector $\underline{J}$ satisfying similar conditions ($\underline{\nabla} \cdot \underline{J} = 0$, i.e. no electric charge build up and $\underline{\nabla} \times \underline{B} = 0$, which is a simple consequence of $\Delta\psi = 0$) may be written in a similar

way as

$$(2) \quad \begin{cases} \dfrac{4\pi}{c} J_r = -\dfrac{1}{R} \displaystyle\sum_{n=1}^{\infty} \sum_{m=0}^{n} n(n+1) \left(\frac{R}{r}\right)^{n+2} (c_n^m \cos m\phi + d_n^m \sin m\phi) P_n^m(\theta) \\ \dfrac{4\pi}{c} J_\theta = \dfrac{1}{R} \displaystyle\sum_{n=1}^{\infty} \sum_{m=0}^{n} n \left(\frac{R}{r}\right)^{n+2} (c_n^m \cos m\phi + d_n^m \sin m\phi) \frac{dP_n^m(\theta)}{d\theta} \\ \dfrac{4\pi}{c} J_\phi = -\dfrac{1}{R} \displaystyle\sum_{n=1}^{\infty} \sum_{m=0}^{n} n \left(\frac{R}{r}\right)^{n+2} (c_n^m \sin m\phi - d_n^m \cos m\phi) \frac{m}{\sin\theta} P_n^m(\theta). \end{cases}$$

Spherical harmonics expressions of the field components can be computed as a consequence. Another interesting case solvable by means of spherical harmonics is that of a force-free current system, defined by the condition $\underline{\nabla} \times \underline{B} = \alpha \underline{B}$ (to which J x B=0, i.e. no force density, is associated).

Some examples of computed field line topology are shown in fig. 2 and 3 , respectively for a curl-free or a force free current system. Expressions of field components are given in fig. 4.

The conclusion of these studies is that, unless coronal currents are relatively large, the effect produced by these currents do not significantly affect the actual magnetic field configuration as compared to that obtained in the case of potential field configuration. In other words, any agreement between coronal observations and coronal potential magnetic field configurations should not be interpreted to mean that coronal electric currents are necessarily absent or insignificant.

Taking into account the fact that the solar wind is flowing outward from the Sun and that it tends to stretch radially the local magnetic field lines, the simple assumption can be made that at a certain distance R* from the Sun (which in many studies has been taken $R^*=1.6$ solar radii above the photosphere the field is radial. In the potential field (PF) model this means that the surface $r=R^*$ is an equipotential. It is easy to show that the magnetic potential is expressed by

$$(3)\quad \Psi(r,\theta,\phi)=R\sum_{n=1}^{N}\sum_{m=0}^{n} f_n(r)P_n^m(\theta)(g_n^m\cos m\phi+h_n^m\sin m\phi),$$

where

$$f_n(r)=\frac{1}{a_n-1}\left[a_n\left(\frac{R}{r}\right)^{n+1}-\left(\frac{r}{R}\right)^n\right],\qquad a_n=(R_w/R)^{2n+1}>1,$$

R_w = radius in the corona at which $\Psi=0$, or equivalently, the radius at which the magnetic field is radial;
R = the solar radius at which the line-of-sight magnetic fields are measured, that is, the photospheric radius (696 Mm);
$N=\max(n)$ = truncation limit of the harmonic series.

and the field components by

$$(4)\quad \begin{cases} B_r(r,\theta,\phi)=\sum_{n=1}^{N}\sum_{m=0}^{n} U_n(r)P_n^m(\theta)(g_n^m\cos m\phi+h_n^m\sin m\phi),\\ B_\theta(r,\theta,\phi)=-\sum_{n=1}^{N}\sum_{m=0}^{n} V_n(r)\frac{dP_n^m(\theta)}{d\theta}(g_n^m\cos m\phi+h_n^m\sin m\phi),\\ B_\phi(r,\theta,\phi)=\frac{1}{\sin\theta}\sum_{n=1}^{N}\sum_{m=0}^{n} mV_n(r)P_n^m(\theta)(g_n^m\sin m\phi-h_n^m\cos m\phi),\\ U_n(r)=-R\,df_n(r)/dr,\quad V_n(r)=Rf_n(r)/r. \end{cases}$$

Using an equal area grid of up to 180x360 elements the detailed structure has been evidenced with different geometrical resolutions (fig. 5).

One power spectrum is also shown in fig. 6. The attenuation of higher order spatial frequencies is expected because the line-of-sight field on each grid element is the average of many measurements over several days during which fine details are lost. The change at about $n=42$ is consistent with a distribution of proper motion velocities up to roughly 100 m/sec, in agreement with direct observations of such velocities. The flattening of the spectrum at $n=80$ is

attributed to the instrumental noise.

The method of determination of the harmonics expansion coefficients implies inversion of big matrices, which becomes prohibitively time consuming when the order n increases beyond 10 (or so). A big simplification was introduced by Altschuler (1) by taking advantage of some symmetry properties associated with spherical harmonics. In this way it was possible to increase the degree of harmonics expansion to $n=90$.

More recently, Neubauer and Riesebeiter (2) pointed out that the orthogonality relations of the spherical harmonics allow further reduction of the computational efforts: in particular, the harmonic coefficients can be determined very simply once those of the highest order are computed by a set of recursion formulae allowing determination of the remaining coefficients down to the lowest order.

It is worth mentioning that some more complicate geometries, in particular non spherical, have also been studied by some authors: their results are useful to interpret some observational details but the overall descriptive picture is not changed so much. More effective in determining some features of the interplanetary field configuration is the magnetic field in the solar polar regions, whose relevance was first realized by Pneuman et al.

2.3 THE EXPANSION OF THE SOLAR MAGNETIC FIELD INTO THE INTERPLANETARY MEDIUM.

2.3.1 General considerations. The basic model of the field expansion toward the interplanetary medium is described by the equations

$$(5) \quad \nabla \cdot \underline{B} = 0 \quad \text{(the field is solenoidal)}$$

$$(6) \quad \nabla \times (\underline{v} \times \underline{B}) = 0$$

Equation (6) is a straightforward consequence of Maxwell equations assuming a steady expansion of a highly electric conductive solar wind toward interplanetary medium. The physical meaning of (6) can be better understood showing (Cowling's or Alfven's theorem) that it is equivalent to state the time invariance of the total magnetic flux through any closed line each point of which drifts at the velocity v of the local solar wind.

Assuming spherical symmetry the equation (5) can be reduced, in a polar reference system, to

$$(7) \quad \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 f v_r\right) + \frac{1}{r \sin\vartheta}\frac{\partial}{\partial\varphi}\left(f v_\varphi\right) = 0$$

where $f(r,\theta)$ is an arbitrary function of the heliocentric distance r and heliographic colatitude θ ,and v_r, v_φ are the radial and the azymuthal components of the solar wind velocity.

As a consequence of above equations

$$r^2 f(r,\theta)\, v_r = g(\theta)$$

$f(r,\theta) = g(\theta)/(v_r r^2)$ with $g(\theta)$ arbitrary function of θ and the field components can be written as

$$(8) \quad B_r = \frac{g(\theta)}{r^2} \qquad B_\varphi = \frac{g(\theta)\,\Omega \sin\theta}{v_r\, r}$$

where Ω is the solar angular velocity.

We can also write [redacted], in a different way,

$$\tan\alpha = \frac{B_\varphi}{B_r} = \frac{\Omega r}{v_r}$$

Taking v_r=400 km/sec, r=1.5 x 10**8 km, $\Omega = 2\pi/(27\cdot 86400)$ one gets α=45° (or 225°) for the angle of the field with respect to the outward radius vector r from the Sun.

2.3.2 THE OBSERVATIONAL RESULTS.

Direct exploration of the interplanetary medium has been performed by a large number of space vehicles. Dynamical characteristics of the possible orbits limit the region where the observations are made to the heliographic latitude interval ± 7.3 degrees, with some extension to higher latitudes only in very special cases (see 2.4). Some informations at latitudes beyond above limits to get a better "tridimensional" picture of the solar wind have been collected by some indirect method [redacted]. The minimum distance from the Sun reached by a space vehicle has been 0.29 A.U. by Helios 2. We shall consider in the following paragraphs the field characteristics between Sun and Earth.

2.3.2.1 THE RADIAL COMPONENT B_r.

Before the Helios measurements inside 1 A U, the only available informations were from individual radial escursions of Pioneer 6, Mariner 5 and Mariner 10 (see the review by Behannon) (3). Data were in the first case solar rotations averages, in the second and third case smoothed 3 day running averages or respectively daily averages.

Linear best fits of log $\langle/B_r/\rangle$ versus log r indicated a slope s close to the theoretically expected s=-2, although with not negligible statistical uncertainties, with the exception of Mariner 5 which gave $s=-1.78 \pm 0.02$.

Helios 1 and 2 had the unique possibility to explore repeatedly and quickly the inner heliospheric range of distances range from 1 to 0.3 A.U. so that long term variations do not generally affect too much the results and thus a "good" time resolution is possible.

As concerns the specific variation law of the field components, the absolute values of daily averages $/\langle B_r\rangle/$ have been shown (4) to scale with r as Ar^s with $s=-2.00$, during the first radial excursion of Helios 1 (Dec. 10, 1974 - March 15, 1975): fig. 7 a shows the large scatter of individual averages which is at least partially an effect of the variations of the heliographic longitude and to a lesser extent of the latitude and time. The observed B_r variation appears to be in good agrement with the model predictions. Actually, data by other s/c show some difference which is probably due to the use of different time intervals of different solar cycle conditions, as well as, last not least, to the use of different definitions of the displayed "radial" component.

Data with higher time (and hence also spatial) resolution

(3 to 12 hours) were used by Mariani et al. (5), who also considered two regions of low and high solar wind velocity. They also found a substantial agreement with the expected power law with s=-2, for the B_r component (Table 1).

2.3.2.2 THE AZIMUTHAL COMPONENT B_ϕ. It was evident since the early studies that in general observational data using $\langle/B_\phi/\rangle$ do not exactly fit the asymptotic power law r^{-1} expressed by (8). Values s=-1.29 or s=-1.85 were derived in the inner heliosphere by Mariner 10 (0.46 to 1 A.U) and Mariner 5 (0.66 to 1 A,U) data, respectively.

The best fit of Helios 1 daily averages has given an exponent s=-1.0. Actually, a number of following studies which all use $\langle/B_\phi/\rangle$ lead consistently to somewhat larger values of /s/, either inside or outside the terrestrial orbit. Higher resolution Helios data lead (fig. 8 a) to an exponent s=-1.27 for solar wind velocity v <500 km/s and s=-1.08 for v >600 km/s. Table 1 shows an homogeneous set of results on B_ϕ computed on both Helios, essentially in the same time interval, corresponding to the primary mission of Helios 2. A consistent value of $s \cong 1.10$ is found independently upon the solar wind velocity regime down to time scales as low as few hours. These results, combined with those at distances r>1 A.U. allow the conclusion that s=-1.10 is to be taken as the normal value of s, at least in the inner heliosphere if one fits $\langle/B_\phi/\rangle$ and s=-1.0 if one fits $/\langle B_\phi\rangle/$. The discrepancy between the predicted variation and the observations may be attributed to several different mechanisms. One possibility is that the rectification of B_ϕ in $\langle /B_\phi/ \rangle$ used by most authors enhances the influence of fluctuations on the results. $/\langle B_\phi \rangle/$ is less dependent on fluctuations and may be more representative of magnetic flux elements being compared. Note also that the quantity $\langle /B_\phi/ \rangle$ is difficult to treat theoretically.

As early suggested by Jokipii (6) an additional contribution to the radial variation may be due to correlated fluctuations of B_ϕ and the solar wind velocity. Under the conditions that $B_\theta = 0$ and v is independent upon the distance, the radial variation of B_ϕ is given by

$$(9) \quad \langle B_\phi \rangle = \frac{c}{r} - \frac{\langle \delta v \, \delta B_\phi \rangle}{v}$$

where any correlation between B_ϕ and v fluctuations implies a non zero $\langle \delta v \, \delta B_\phi \rangle$ and hence a decrease steeper than r^{-1} if $\frac{\partial}{\partial r}(r \langle \delta v \, \delta B_\phi \rangle) > 0$. Further theoretical considerations and model calculations for an idealized situation of stream-associated fluctuations inside the propagating solar wind indicate that particular choices of the boundary conditions in the source region of the solar wind may lead to an exponent /s/ slightly larger than 1, so to result in a decrease up to 10% between 1 and 6 A.U.; but at lower distances the effect might by significantly smaller, although still observable, due to the non linearity on the effect

itself.

Other mechanisms have been suggested, (7,8) to justify discrepancies from expectation. One of these (8) is based on the fact that, as a consequence of a meridional magnetic pressure gradient, a meridional flow is established which tends to decrease the azimuthal Maxwell stress in the equatorial plane where azimuthal magnetic flux is accumulated compared with the polar region. The B_ϕ decrease, close to r^{-1} up to 10 solar radii, beyond that becomes steeper so to be in the order of several percents higher than 1 at 1 A U, and in the order of 25% between 1 and 5 A U. The mechanism also predicts similar deviations for the radial field component B_r, which implies that the angular azimuthal orientation is not affected. One obvious difficulty of this sketch is that experimental data do not support a faster than r^{-2} variation of B_r, so that its revelance is questionable. On the other hand, some evidence that the overall structure of the field topology is consistent with meridional transport of magnetic flux to higher latitudes has been given.

The second mechanism (9) is based on the consideration of the kinematic effects which are expected because of the presence of streams, which tend to modify both B_r and B_ϕ. Two parameters are potentially important: the azimuthal angle at the source region which may be different from the exact radial orientation ($\phi_0 = 90^\circ$ or 270°); and the solar wind velocity azimuthal profile (in particular due to the presence of streams) which although it may be stationary in a corotating frame appears as temporally variable to a fixed observer. A model computation with four identical streams, simulating in some way the typical four sectors around the Sun, shows that while the averaged B_r over the time profile of an individual stream still has a r^{-2} variation law, the average B_φ exhibits a strong dependence upon the deviation of the field orientation from the ideal Parker's model and on a shorter time scale its actual values depend very much upon the averaging time interval. This may justify the usually large scatter of individual points by Helios (fig. 8), as well as a significant discrepancy from the r^{-1} law, in particular when averages of B_ϕ are computed over time intervals during which streams are present.

On a much longer time scales there are somewhat contradictory results: using averages from Pioneer 10 and 11 data computed over distance intervals of 0.5 A.U. (corresponding to temporal intervals of several months), Smith et al. have found that the product rB_ϕ is very much indipendent upon r; however, using annual averages of the same data a best fit value $s=-1.12 \pm 0,04$ has been found (8) in the distance range 1 to 12 A.U.

In conclusion, a variety of effects can affect the B_ϕ radial variation at any distance from the Sun (the rectification effect, latitudinal and temporal effects, solar wind velocity fluctuations, presence of streams, kinematic

effects, etc.). The Helios data in the inner heliosphere summarized in Table 1 suggest that a value $s \approx 1.1$ can be taken as a good representation of the actual radial variation of $\langle |B_\phi| \rangle$ inside the terrestrial orbit. But a substantially similar value of s can also be adopted at much larger heliocentric distances.

2.3.2.3 THE NORMAL COMPONENT B_θ .

Despite the fact that $B_\theta = 0$ is predicted by Parker's model, a significant component B_θ is experimentally observed on relatively short time scales. Best fits on Helios 1 and 2 12-hours averages $\langle |B_\theta| \rangle$ suggest a radial power law with an average value $B_{\theta o}$ at 1 A U in the range 1.4 to 1.9 nT for $B_{\theta o}$ and a slope $s=-1.24$ to -1.35, with no appreciable difference at different velocity regimes. The values of s are consistent with those from Mariner 4 and 10 beyond or inside the terrestrial orbit; the values of $B_{\theta o}$ from different s/c are remarkably different from each other, probably also because of the rather large systematic uncertainties occurring on the spin component of the observed fields. On longer time scales, in the order of solar rotations or more, the average $\langle B_\theta \rangle$ are essentially equal to zero, once the above systematic effects on the spin component are properly taken care of. In conclusion, although occasionally even large B_θ components do exist, they have the characteristics of "short" temporal fluctuations.

2.3.2.4 THE FIELD MAGNITUDE B.

According to the Parker's model the field magnitude cannot be properly fitted by a simple power law; even so, several authors used this approach, obtaining values of s less than 2. Actual values range from -1.56 for Helios 1 to -1.86 for Helios 2, which compare with values s=-1.65 for Mariner 10 and -1.37 for Pioneer 10 (in this case at distances up to 3 A.U.). A study(9) of combined data from Helios 1 using heliocentric distance bins of 0.1 A.U. and from Pioneer 10 up to 3 A.U. has shown that the radial variation of B is consistent with the expression

$$(9) \qquad B = a\left(1+r^2\right)^{1/2}/r^2$$

with a=5 nT (if r is in A U).

A similar result has been found by Mariner 10, in the range 0.46 <r<1 A U; in this case, however, the factor a was equal to 4 nT.

2.3.2.5 THE FIELD ORIENTATION.

The magnetic field vector orientation, as given by the observed elevation θ on the equator and the azimuth ϕ, exhibits significant deviations from the heliocentric expected variation of the theoretical model, expecially at lower time scales. A simple way to represent these fluctuations is to look at the differences between the observed angles and the theoretically predicted values expressed by definition as

$\theta' = 0°$ and $\phi' = 0°$ (or 180°) for a nominal solar wind speed of 430 km/sec.

A study of this type(10) on Helios 1 and 2 data extended over 21 solar rotations centered on the perihelions (the maximum distance from the Sun, although variable, never exceeded 0.38 A.U., the time duration of each SR was close to 39 days), has shown that in the inner solar system the peaks of the azimuthal frequency distribution are well centered on the angles $\phi' = 0°$ and $\phi' = 180°$ with a trough in between of about 4% of the peak values. By comparison a similar study in the distance range 1 to 8.5 A.U. led to a trough about 17% of the peaks.

As concerns the elevation angle θ the Helios data show a substantial simmetry about 0 (with more than 2/3 of the available data having $|\theta| < 20°$), which confirms what we have seen before.

The narrower angular distributions observed closer to the Sun might be the simple consequence of the still small effects of stream interactions. Also, the included angle between sunward and antisunward peaks is 180° not only on the average during the seven years total interval, but also for individual years, some small differences in the last case are only latitudinal effects, i.e. a consequence of the different percentages of inward and outward field lines observed at different latitudes.

2.4 THE SECTOR STRUCTURE AND THE HELIOMAGNETIC CURRENT SHEET.

The existence of an internal organization of the interplanetary magnetic field with a well defined gross structure on the scale of hourly averages, was the result of the early observations of Explorer 18.[11] The so-called magnetic sector structure was found, i.e., a spiral field line configuration, as implied by the solar wind Parker's model, with alternatively outward (positive) or sunward (negative) magnetic polarities. At the time of discovery four sectors per solar rotation were present. Beyond a few degrees above or below the ecliptic plane, due to the limited latitudinal heliographic excursion of the presently possible orbital planes, no direct information was since then available on the three dimensional structure. There was an early feeling that the separation line of positive and negative sectors might be more or less meridional. It was on the other hand found in subsequent studies that a characteristic magnetic polarity signature existed, the so-called dominant polarity effect,[12] i.e. that there was a preferential polarity of the field when the observing spacecraft was north of the ecliptic plane, and an opposite preferential polarity with the s/c in the southern hemisphere. Also, the sign of preferred polarity changed as the sector polarity changed its sign.

Some years later it was suggested[13][14] that the surface separating positive and negative sectors around the Sun might

be a warped (non planar) surface at some variable inclination to the ecliptic plane anyway much closer to the ecliptic than to a meridian.

A clear-cut indication came by the Pioneer 11 magnetometer: during the encounter phase with Jupiter the s/c took a gravitational kick off the ecliptic plane which moved it to a modified orbit to a maximum heliographic latitude of about 18 degrees. During a 27 days interval corresponding to a full solar rotation the field polarity was always positive. This result showed that above a certain latitude the field has the same outward (or inward) orientation: the interplanetary field then appears as the expansion into the interplanetary medium of a field rooted on the Sun with field lines pointing in opposite orientations in the opposite higher latitude regions of the Sun. The separation between the two regions is a tridimensional, non planar, surface now known as heliomagnetic sheet. If the source field was that of a perfect Sun centered dipole, we should observe a sinusoidal separation line; in contrast, any other shape is indicative of higher order contributions (quadrupole, octupole, and so on).

A systematic study on data by Helios 1 and 2 for the year 1976 showed for the first time the shape of the heliomagnetic sheet as observed beyond 0.3 A.U.

These Helios observations represent a very significant improvement in the knowledge of the latitudinal dependence of the IMF polarity, also because of the availability of simultaneous plasma data: precise knowledge of the solar wind radial velocity allows the projection of the field polarities from the observing spacecraft onto the actual coronal source point of each field line through the s/c. So, the azimuthal width at Helios location was used(15) as input to determine the corresponding width on the corona. Data for early 1976 relative to 4 solar rotations show that the azimuthal widths of the unipolar region were actually independent of the heliocentric distance; the positive and negative polarity distributions and the projected sector boundary locations were consistent with an average quasi planar configuration at an inclination $\alpha_s \approx 10^\circ$ with respect to the heliographic equator. In addition, a distortion of the boundary surface above the equator was noticed such that a four sector structure could be observed within a certain latitudinal interval, but only a two sector structure in another latitudinal interval south of the equator (fig. 10). Local triangulation of a sector boundary using Helios 1 data(16) also showed significant deviations from the picture of a rigidly rotating, flat current sheet.

A study(17) extended over the solar minimum, based on data from the two Helios, has shown that the angle defining the least square fit of the inclination of the boundary surface to the equatorial plane in 1975 and early 1976 was close to 19°, with the dominant two sector configuration which was also observed in the nearly equatorial region on the Heos data since 1972. The change of α_s between 1975 and 1976 can be

considered as a direct indication of a temporal, i.e. solar cycle, variation of the inclination of the boundary surface. Both values of α_s are compatible with the results obtained at larger distances by Pioneer 11.

The overall picture for the years 1972-75 is then that of an approximately flat current sheet inclined to the Sun's equatorial plane, from which, due to the solar rotation, a spiral wave(18) is produced propaganting outward (fig. 11). Smaller scale variations are superimposed to it.

Approaching the solar maximum in 1978 and beyond it, the dominant polarity effect was no longer observable,(19) a feature which is to be related to the change of configuration of coronal holes, and solar wind streams,(20) with opposite polarities extending beyond the equator in the opposite hemispheres and a highly erratic behaviour, as expected for a highly irregular and rapidly evolving IMF organization.

The appearence of a four sector configuration implies a heliospheric current sheet already not planar in the solar corona. Working in this frame, the quadrupole contribution to the magnetic field potential was estimated(21) to be in the order of 17% of the dipole for the one year time interval May 1976 to May 1977. All above results consistently confirmed the picture of an heliospheric current sheet, not planar, at a variable "average" inclination with respect to the solar equatorial plane, with an overall geometry depending upon the solar cycle phase in that it modifies the geometry of large solar scale features in particular of the coronal holes.

The very existence of an heliospheric current sheet immediately raises the problem of connecting the interplanery observed field of solar origin to its source on the Sun. We have already considered this problem assuming that the field is an expansion of the photospheric field. Here we like to look at a complementary observational approach taken by Hansen et al. (22) They locate the projection of the sector boundary on the source surface on the bright features observed in the white light corona.

In a study of the coronal and interplanetary current sheet, the sector pattern from the Helios 1 and 2 data in early 1976 was compared (23) with the maximum brightness curve (MBC) obtained from plots of the K-coronameter brightness contours as the line, encircling the Sun, connecting the latitudes of maximum brightness (fig. 12).

The projected polarities have been compared with the neutral line as computed by the PF model, during four consecutive solar rotations. Interestingly enough, although the neutral lines derived from the two methods are somewhat different from each other, they also show considerable qualitative similarities. Apparently, the excursion of the neutral line about the equator was a little larger for the PF model than for the MBC model. The observed sector boundaries extrapolated back to the Sun match the crossings of this line with the warped neutral sheet inferred by the two techniques

to within the expected accuracy of the sector boundary extrapolation and the neutral sheet (in the order of ± 10°). In the case shown in fig. a the separation of the Helios 1 and 2 orbital paths by about 10 in latitudes made possible a precise latitudinal determination of the neutral line which looks better represented by the MBC curve than the PF determined contour. The time resolution of the two neutral line determinations was good in the hypotesis of little structure changes during 27 days (for the MBC) or 6 months (for the PF model), so that short term transients are not properly taken care of. Apparently, in the case of fig. 12 b the PF neutral line should be displaced southward by about 20° to agree with the pattern observed by Helios (see also fig. 13). This raises several questions: in particular on the distortion due to the poorly known strength of the polar magnetic field, on the shape of the source region, which might well be far from spherical, and on the field orientation at the source not necessarily radial as generally assumed.

Introducing a solar polar field, although largely unknown and then arbitrary, in the PF model, (24) has the important effect of reducing the latitudinal excursion of the computed sheet (fig. 14). Such study extended over the 18 months following the last sunspot minimum has also shown a slow but steady increase of the latitudinal excursion from about 15 near the start of the interval to about 45° near the end. An overall survey (25) of the structure of the heliospheric current sheet in the years

1978-82 gives further support to the picture of an evolving structure during the solar cycle up to and beyond the reversal of the solar polar field orientation. A remarkable feature is the continuos evolution from a four sector boundary topology to a complex situation, approaching the solar maximum, when the heliographic latitude of the sheet approaches the poles and also disconnected current sheets are predicted not necessarily intersecting the terrestrial orbit (fig.15).

The improved neutral lines derived from the PF and the MBC models have been shown (26) to be closer to each other. Comparison over six solar rotations (fig.16) shows that only during a 6 days period the PF and MBC curves failed to be close to each other and this occurred in coincidence with the appearence of an unusually large photospheric region of unbalanced "toward" polarity which was not present neither in the previous nor in the following solar rotations. An overall conclusion is that the MBC method works better when large bipolar magnetic regions suddenly appear on the photosphere, the PF method works better when fast evolving deformations appear. This means that, when approaching solar maximum the coronal structure becomes much more complex and the PF method seems to be preferable, while when a more stable situation occurs the MBC method is somewhat more reliable.

It is not very satisfactory in these studies of the connection between the solar magnetic and the interplanetary field at r > 0.3 A.U. that no direct measurement of the

magnetic field are generally available between the photosphere and 0.3 A.U. However, for a limited number of cases, Faraday rotation measurements have been obtained when the spacecraft-Earth line passed through the corona. A combination between a three-dimensional MHD model of the solar wind away from the Sun and the potential magnetic field close to it (30) was used to compute a simulated Faraday rotation profile during the outbound pass of Helios 1 after first perihelion in 1975. The results were composed with the observed Faraday rotation profile. It was found to closely agree in a broad longitude band but to strongly disagree in another well defined longitude band. This represents direct evidence for major shortcomings in the potential field models.

3. THE INTERACTION OF THE SOLAR WIND WITH THE BODIES OF THE SOLAR SYSTEM: general considerations.

The study of the solar wind characteristics in proximity of a solar system body is a complementary tool to obtain informations on the magnetic field topology about the body itself. Actually, in the region where the magnetic energy density and the kinetic energy density of the particles are comparable both the field topology and the particle parameters are mutually and strongly affected due to the induced electric field and electric currents, which in turn modify the field. If the body possesses a sufficiently strong magnetic field the solar wind cannot penetrate deep into the planetary environment: the particle flux will be deflected around a limiting surface which, in analogy with terrestrial case, is still called magnetopause (or more generally magnetoionopause), which includes the planetary ionized atmosphere (if any). Although the precise shape of such a surface is extremely difficult to compute some qualitative considerations are of interest here: two basic situations may occur when the planet has an atmosphere and, respectively, has or has not an intrinsic internal magnetic field (fig.17). The first case is that of the Earth and the giant planets (Jupiter, Saturn and Uranus); the second case occurs when only a ionosphere exists, produced by the ionizing UV solar radiation on the planetary ionosphere.

In both cases a magnetoionopause is generated, although very different in size. The magnetic field lines configuration inside the magnetoionopause is completely separated by that outside: as a consequence a discontinuity of the field occurs, which also means that the separation surface becomes a current layer (because of $\nabla \times H = J$). When no intrinsic field exists around the planet, still a magnetic field is produced around the planet due to the induced currents; a perturbed solar wind plasma is observed outside the magnetoionopause and a relatively stationary plasma is observed inside.

A different situation (fig.17) occurs when the body has no atmosphere; in this case the solar wind can freely impinge on its surface (as in the case of the Moon). No case is known at present of a strongly magnetized body with no atmosphere.

The perturbation of the solar wind beyond the magnetoionopause extends externally up to another limiting surface which separates the interplanetary undisturbed solar wind from that inside. This surface is a shock-wave, i.e. a surface where the parameters describing the characteristics of the solar wind (in particular the pressure and the temperature) and the magnetic field undergo a pronounced discontinuity, which again can be described as a complex current layer. The shock is generated because of the fact that the velocity of the impinging solar wind is much higher than that of the wave propagation in the magnetoionic gas, in analogy with what happens in similar hydrodynamical problems.

It is somewhat surprising that a good hydrodynamical analogy can be established, although the plasma is rarefied to the point to be considered collisionless. As matter of fact, the ambient and/or the induced magnetic field acts as a powerful mechanism strongly affecting the plasma flow, so to produce effects similar to those of collisions in the case of ordinary elastic fluids. A sketch of the field configuration in a meridian plane, for the Earth's case is shown in fig. 18, where levels of theoretical description are also indicated in order of increasing difficulty.

Since the exact mathematical treatment of the problem becomes immediately almost impossible, some approximations are generally made:

(i) due to the generally high Alfven Mach number M_A a hydrodynamic approach is taken and the magnetic field is added as a second step, once the flow has been computed;

(ii) the pressure of the solar wind on the magnetopause is approximated by $p = k n_{p\infty} m v_\infty^2 \cos^2\psi$ where k is a constant of the order of 1; $n_{p\infty}$, v_∞ are the asymptotic number density and velocity; ψ is the angle of the flow to the normal to the magnetopause;

(iii) the actual magnetic field is the dipole field plus an estimated field produced by the currents flowing on the magnetopause current layer.

A summary of results is shown in fig. 19, where old and new more accurate computed shapes of the magnetopause are shown,

for a meridian and an equatorial cross section.

Remarkably, the distance D of the so called stagnation point, i.e. of the nose of the magnetoionopause, is proportional to the 1/3 power of the dipole moment M of the planetary field, and then [redacted] slightly sensitive to variations of the solar wind parameters. As a consequence, the observational value of the distance D, as well as the observed shape of the magnetopause, may be taken as a good indicator of the planetary dipole moment. For the Earth's case, with M =8.10**25 gauss.cm3, $m = 1.6 \cdot 10^{-24}$ g , $n_p = 5$ cm^{-3} $v_\infty = 4 \cdot 10^7$ cm/sec one gets D=9 Earth's radii. As fig. 20 shows the distance of magnetopause increases monotonically as the angle ψ inceases. Along the flanks of the magnetopause, where ψ becomes close to 90°, the approximation on which the theory is based becomes bad. Fortunately, in some special case, one can compute exactly the shock boundaries and the magnetopause (for example when the flow velocity is aligned with the frozen-in magnetic field). A remarkable finding is that the gasdynamic shock description becomes coincident with the magnetohydrodynamic description when the Alfven Mach number is greater than 10. In general the nose gets closer to the planet when M_A becomes smaller; on the flanks of the magnetopause just the opposite occurs, since they move outward.

A somewhat simplier physical situation occurs in the absence of an intrinsic magnetic field, as is the case of the solar wind interaction with the venusian ionosphere. It is worth mentioning that a compression of the frozen-in magnetic field occurs outside the magnetoionopause; in terms of electric currents this means that a current circulation is required outside the ionopause. A summary of results is shown in fig. 17 where a variety of situations and planets is taken into account.

The picture given so far completely neglects dissipative effects, so that the boundary surfaces are considered as geometrical surfaces. Actually, when dissipative effects (due to fluid viscosity, thermal and electric conductivity) are taken into account a finite thickness of the surfaces is obtained, generally variable from point to point.

A very important feature of the magnetic field topology, in the antisolar direction is the so called magnetic tail, which is a magnetic flux tube extending in a direction opposite to the Sun, where a northern and a southern lobes can be identified with respectively antiparallel field lines: in the case of Earth, field lines are away from Earth in the southern region, below the so called neutral sheet, and earthward north of this plane. The magnetic tail represents a channel of access for solar wind particles along the field lines to the innermost part of a planetary magnetosphere. Because of the instability associated with the closeness of antiparallel field lines on the two sides of the neutral sheet, one can expect transient phenomena, like particle

acceleration and dumping toward the planet, with associated magnetic field variations. Phenomena of this type are well observed in the Earth's polar caps, also in association with auroral activity.

4. PLANETARY MAGNETISM: some general considerations.

It is generally accepted that the field of strongly magnetized planets is produced by an internal dynamo. Assuming a primordial small field, a regenerative action of organized fluid motions is supposed to lead, by a progressive autoexcitation process, to a stable field configuration. The mathematical problem is exceedingly difficult, also because of the non linearity of the basic equations. An obvious requirement for fluid motions is the existence of a conductive liquid core. This emphasizes that the study of planetary magnetic fields can lead to unique informations on the body inner structure.

The first question to be answered is whether or not generation and amplification of the field connected with electrical fluids symmetric motions is possible. An early general statement , that stable symmetric fields cannot be generated that way, puts strong constraints on any theory. In a qualitative way, we can say that a symmetric motion around a symmetry axis has the effect of transporting the axisymmetric field lines without creation of any new field line. So, the simultaneous field diffusion due to the finite conductivity necessarily leads to the progressive decay of the field itself, which is thus not stable.

The first successfull attempt of a non-symmetric circulation model leading to a "stable" field is due to Parker, who showed the possibility of convective fluid motions

capable to distort the field lines in such a way to support the regeneration mechanism.

It has also been convincingly shown that, in addition to stable magnetic field configurations, time variable oscillatory solutions exist which might be appropriate to describe the periodic reversals (like the 22 year reversals of the solar polar field). However, the more or less random temporal distribution of the geomagnetic field reversals implies that solutions of the basic equations not simply oscillatory are to be expected when dynamical (rather than simply kinematical) treatment is used, in particular when a variability of the fluid velocity is introduced in the theory. Consideration of the dynamical approach is completely out of the purpose of our lectures. We only show as an example, in fig. 21 , a sketch of a model by Busse where Coriolis and pressure forces have an essential role to produce the necessary non-symmetric motion. Although energy considerations show that the growing field tends to an equilibrium amplitude of the field, the details of the equilibrating mechanism are not known. The driving force of the fluid motion is also unknown: possible candidates are thermal buoyancy, chemical separation of lighter constituents, relative motions by differential precession rates of internally to the planet.

The magnetic moment predicted by the Busse model is given by

$$M = B_c R_c^3 = k(\mu_0 \rho_c)\,\Omega\, R_c^4 \tag{10}$$

where B_c is the field strength in the core, ρ_c, R_c are its density and radius.

Other ways have been suggested by other authors to estimate magnetic moments on the basis of scaling laws, i.e. more or less empirical relationships between some typical planetary parameters: one classic example, dating back to Schuster, is the assumption of a proportionality between magnetic and angular momenta. This relationship is often called magnetic Bode's law (fig. 22). Although one can bring some physical support to such scaling laws, yet significant discrepancies do exist between the observed values and those "predicted" by them. It is quite clear that the radius of the liquid core is a critical parameter upon which the magnetic moments strongly depend. The Earth represents the only case where the core size is well known by seismic information. In all other cases only estimates are available. Recently some new ideas have been suggested: Elphic and Russell [28] used as core size the depth at which dipole and higher harmonics give the same contribution to the RMS magnetic field (which happens to be the case of the Earth). Temporal variations of the field as a function of depth have been used to look for the depth at which the vertical component of the field becomes constant, which means that the field is frozen-in. In the case of the Earth, such tehnique leads to a core within 2% of that actually known.

5. DIRECT OBSERVATION OF PLANETARY MAGNETIC FIELDS

In this section we summarize the results of recent in-situ measyrements of the magnetic field around the planets (and some of their implications). Physical interpretations are based on spherical harmonics analysis of the field, on scaling of properties from the Earth's magnetosphere and particle properties or on other indirect observations (radioemission, optical observations, etc.).

5.1 MERCURY.

Data collected by Mariner 10 revealed [29] a small but still surprisingly high field in the order of several hundreds gammas. Bow shock and magnetopause qualitatively similar to those surrounding Earth have been clearly observed. However, due to the lower field intensity the two surfaces are much closer (in units of planetary radii) to the planet and the possibility exists for solar wind particles to hit the Mercury's surface. The external field configuration strongly suggests existence of a tail-like structure in the antisolar direction. The main field is described by a centered dipole, inclined about 11° to the orbital normal, oriented southward, just as for Earth. No radiation belts have been observed.

Table 2 gives best fit estimates of the lower multipole coefficients as computed by simple use of low order approximations of (1) with the addition, in some cases, of simple external current configurations.

As regards the origin of the field, [30] two possible mechanisms have been suggested: a dynamo action as inside Earth and/or a remnant magnetization. A third possibility, induction by the magnetized solar wind magnetic field, does not seem reasonable because of the too high observed planetary field, compared with the frozen-in solar wind field. The fact that the matter density of Mercury is comparable with that of the Earth strongly supports the idea of an internal core essentially made by iron and nickel. If this is the case, the magnetic Reynolds number must be big enough to allow the internal fluid motions necessary to produce and amplify the field at a rate faster than it can be diffused. Some difficulties, i.e. that the core is very probably not molten, can actually be overcome because of the fact that Busse's theory only requires that part of the core, in particular an outer shell be molten. As regards the hypothesis of a remnant magnetization, only a spherical layer several hundreds km thick of uniformly magnetized matter at a level comparable to that of the samples returned from the Moon might be sufficient to produce the observed field. In this case an open question would be the source of the inducing external field. One may think in terms of a strong polarizing solar field, as big as 10 Oersted at the Mercury orbit; however, since the cooling time is long and the solar field is known to change its polarity periodically, one should not expect a significant effect from the mechanism. Also some arguments have been raised against the remnant magnetization mechanism, at present

it cannot be completely disregarded. An active dynamo mechanism is more likely. A crucial test would be to look for a possible secular change, similar to that on Earth. Actually the few available observations, although some differences were found between the results from the 1974 and the 1975 flybys, cannot be of much help due to the fact that they are not out of the experimental uncertainties.

In conclusion, looking at magnetic data and related theoret:cal studies, it is possible to think of Mercury interior in terms of a core whose outer portion is molten so to make possible the required dynamo active circulation. The excitation is to be attributed to thermal effects, rather than precession induced turbolence which seems to be weak.

5.2 VENUS

Early finding by Mariner 2 (31) and 5 (32) that no significant field existed down to 0.7 venusian radii from the surface puts an upper limit of 8.10**22 G.cm3 for the magnetic moment. Interpretation of simultaneous data by Venera 4 allowed a reduction of the upper limit to less than 10**22 G.cm3. The existence of a bow shock is convincingly seen (fig.23) on the data by Venera 9 and 10, as well as on early data from Mariner 10. The shock is very close to the planetary surface, as a consequence of a very low (or even null) internal magnetic field. Existence of a tail-like field is also evident. The critical question, whether or not an intrinsic small field exists, requires cleaning the observational data from the effects of a complex external current system.

At present, the best available data come from the Pioneer-Venus Orbiter. Existence of very low fields is systematiocally confirmed: field strengths up to a few tens gammas are observed down to the periVenus regions . A very peculiar observational feature is the existence of localized ionospheric regions where high fields are observed (fig. 24). This feature has been interpreted as an indication of twisted bundles of magnetic flux or "flux ropes" . In principle, the root of the observed magnetic flux might be either below the ionosphere or in the magnetosheath; the authors believe that actually the tubes originate in the magnetosheath, which means that the field is not an intrinsic field from the planetary body. An estimated upper limit of the planetary dipole moment would be much lower than 10**22 G.cm3. All above implies that motions in the venusian core, if at all existing, are extremely slow, because of a less efficient energy source and/or of a much lower electric conductivity.

5.3 MARS.

In principle, the most interesting data are those by Mars 2, 3 and 5, since the early flyby by Mariner 4 occurred so far that only a grazing encounter with the planetary bow shock was apparently possible.[33,34] The interpretation of the few available magnetic data is very controversial, since no general consensus has been reached. However, it is evident that the

intrinsic martian field, if any, is very low. On one side Dolginov claims that a planetary field exists, corresponding to a magnetic dipole moment of the order of 2.10**22 G.cm3; on the other side, after a data reinterpretation Russell concluded that the observed field might be produced by a mechenism similar to that operating about Venus.

Actually, the geometry of the bow shock, although only observed on the dusk side of the planet (fig.23) indicates that a small internal field may exist. Considerable confusion exists about the orientation of the dipole. After the initial estimate by Dolginov,[35] who indicated a tilt of 72° from the normal to the orbit, the same author more recently quoted[36] a much different value, i.e. 15°.

The present knowledge of Mars interior is very poor: no doubt that the lower matter density implies a significantly different constitution of the inner core, as compared with that of Earth or Mercury. The size of the core is estimated to be 1500 to 2000 km and the seismic activity appears to be smaller than on Earth. So, although several authors assume the existence of a fluid core, the possibility it is frozen-in cannot be disregarded. In the first case, if an intrinsic field is proved to exist, a dynamo mechanism is a real candidate. In conclusion, new reliable in situ measurements are required to prove (or disprove) the very existence of an intrinsic martian field.

5.4 JUPITER.

This giant planet is a very special body in the solar system, surrounded by a cloud of 15 (?) satellites, one of which, IO, exhibits very unique features. That Jupiter was highly magnetized is known since several decades, on the basis of observations of polarized decametric and decimetric radioemissions, interpreted as synchrotron radiation by relativistic electrons in an ambient magnetic field. The early estimates of the field gave strenghts from some tenths to more than 10 Gauss in the radiation region, which after extrapolation to the planetary surface implied an equatorial field of 3 to 15 Gauss. The large margin of uncertainty was due to the uncertainties of the theoretical parameters used in the computation. It was not until 1974 that direct measurements were obtained (fig. 25) onboard Pioneer 10, whose data suggested a moment of about 1.5.10AA30 G.cm3. (37) Results from a second flyby, by Pioneer 11 one year later, after some controversy because of differences between the measurements by the two onboard magnetometers (a vector helium magnetometer and a high field fluxgate magnetometer) indicated a substantial agreement (38,39) on a dipole moment of 1.55.10AA30 G.cm3 and a ratio of dipole to quadrupole and to octupole moments of 1:0.25:0.20.

By comparison with the Earth's case, the non-dipole terms are significantly higher in the Jupiter's case. In addition, an inclination of the dipole with respect to the jovian rotation axis of about 10° in a direction opposite to the

Earth's dipole, i.e. toward the North pole, was determined in substantial agreement with the findings of radioemission observations, which were very consistent with each other although made at different wavelengths.

Table 3 summarizes the best fit parameters (moment and dipole tilt, higher order moments, offset) derived by the Pioneers' flybys. The large contribution from from higher order moments implies significant axial non asymmetry of the internal source which extends out of the center more than in the Earth's case. The dipole moment derived by Pioneer 11 appears to be a few percent higher than that from Pioneer 10 one year earlier: if the difference is real it might be indicative of a secular variation.

More recently, Jupiter was revisited by Voyager 1 and 2. The flyby of Voyager 1 was selected to make possible a close encounter with IO, which, although implying a higher perijovian distance, had the advantage of allowing the exploration of the dusk side also including the region where a tail structure was expected, by analogy with the Earth's case. Fig. 26 snows in the upper panel location and model shapes of the bow shock and of the magnetopause, as derived by the combined magnetic and plasma data. Some details of the field strength are shown in the lower panel , where also individual identifications of the magnetopause (MP) and bow shock (BS) crossings are indicated. The magnetopause nose is located about 60 R_J and the bow shock close to 80 R_J, in the Sunward direction. But these distances become several times larger along the dusk side of the huge jovian magnetosphere. An important feature of this cavity is its remarkable compressibility, as compared with that of the Earth.

The rapid rotation of the planet and the several days long residence of the Voyagers close to Jupiter allowed a better geographycal sampling distribution, i.e. better informations on the field distribution around the planet. An interesting result is that the reversals of field polarity at the location expected because of the inclination of the magnetic dipole to the orbital plane, are only observed (40) up to a maximum distance of about 80 R_J. This is interpretable as the warping effect of a diamagnetic plasma sheet with a thin embedded current sheet on which a field directional discontinuity occurs. During the planetary rotation at distances exceeding a certain value the s/c no longer reaches the plasma sheet and then no polarity change is observed.

Several explanations have been suggested to justify the warping. One is the centrifugal force distortion in the outer region, which would however lead to a symmetry between the two types of crossings. Also a spiral shaped distortion has been suggested. In both cases North to South reversals, and viceversa, should be expected at constant longitudes, and this is only roughly true looking at the observed crossings longitudes. Also, a significant asymmetry between N→S and S→N reversal longitudes is observed. A more plausible

suggestion is that of the bending of a plane current sheet depending upon the angle between the solar wind direction and the dipole direction, in a way very much the same as for the Earth's neutral sheet. This idea is corroborated by the fact that the field intensity corresponding to the crossing tends to be smaller and vanishing as the antisolar distance from the planet increases. The general structure of the jovian magnetosphere, as outlined above by using magnetic observations, is confirmed by the results of solar wind observations: locations and shapes of bow shock and magnetopause, compatible with the measured solar wind pressure are found as well as a remarkable compressibility of the jovian magnetosphere. As regards trapped particles, they corotate in the inner region of the magnetosphere, i.e. rotate rigidly with the planet, with two flux maxima per rotation. However, above a jovian distance of about 85 R_J only one peak remains and this concurs with the magnetic data to show the distortion of the plasma sheet from a planar to a bended configuration.

5.5 JUPITER'S SATELLITES.

Unexpected results of the in-situ plasma and field observations are the perturbations correlated with the position of some jovian satellites, in particular IO and Ganymede. Voyager 1 was targeted to cross the jovian field tube connecting IO and the jovian surface , with closest approach at 20500 km,i.e. 11 IO radii.

Significant field directional changes, with no intensity changes, were observed in the few minutes when the flux tube was crossed by the s/c. The field perturbation, superimposed to the ambient Jovian field (fig. 27) has been very consistently interpreted as an effect of a twin current system, one flowing toward Jupiter and the other outward, both being aligned along the local field lines, distributed on a cylindrical tube flux thick just one IO's radius. The existence of no radial variation of the field strength rules out the possibility of an Io intrinsic field. The observations support the idea of IO's role as a unipolar dynamo where the electromotive force is generated by the IO's motion in the corotating jovian magnetosphere plasma. A power of the order of 10**12 watts is dissipated in the current loop. This power, close to that dissipated by tidal forces, may play an important role inside IO and/or its plasma torus.

With regard to Ganymede, a distinct perturbation was observed at distances approximately between -60 and + 60 R_J. No definite statement can be made on the origin of this perturbation. The hypothesis that long wavelength Alfven waves may be responsible was suggested; but also some kind of instability might be the source.

5.6 SATURN.

Similarity with Jupiter and the tentative observation of radio bursts from Saturn at decametric wavelength suggested a magnetic field of the order of that of Jupiter. But there

only was little observational evidence whether or not a field actually existed until the first in situ observations during the Pioneer 11 flyby (61). Bow shock and magnetopause crossings were clearly identified (fig. 28). The character of the field inside 10 planetary radii is of the r^{-3} type, i.e. closely dipolar and symmetric around the rotation axis of Saturn. Significant diascrepancies from the dipole are found only above 10 R_S. The spherical harmonics analysis shows that the only internal coefficients (of degree n=1 and 2) different from zero are g_1^0 =0.203 and g_2^0 =0.015. No significant external contribution has been derived inside a few R_S from the analysis. The ratio of quadrupole to dipole moments is about 0.07, remarkably smaller than the corresponding values for Earth and Jupiter. A small, but significant offset of the dipole along the rotation axis (Δ z=0.04 R_S) is sufficient to remove the quadrupole effects. The most striking result of these observations is the near-axial character of the field (i.e. no tilt of the dipole with respect to the rotational axis). This requires an explanation to be conciled with planetary dynamo theory. A consequence is that the high symmetry of the field precludes the of possibility of determining the rotation period by using magnetic field data. The smallness of the quadrupole moment is interpretable as a consequence of a small size of the internal conductive core where the dynamo action takes place. In comparison, the Jupiter's core is larger than the Saturn's core. As matter of fact current models of Saturn and Jupiter internal structure assume metallic H_2 cores having a radius between 0.2 and 0.5 Saturn radii or between 0.2 and 0.75 Jupiter's radii.

About one year after the encounter of Pioneer 11 the Saturn's magnetosphere was visited by Voyager 1 on a trajectory which covered a larger latitudinal interval than Pioneer 11. In addition, another flyby was also made by Voyager 2.

(fig. 29)

Generally speaking, Voyager 1 confirmed the basical findings by Pioneer 11.(42) However, the much larger transversal excursion allowed better exploration out of the equatorail plane. The offset of the dipole was reduced to about 0.02 R_J. Appreaciable contribution by external sources beyond several planetary radii made necessary the introduction of external currents effects in the models. A dipole moment of about 0.2 R_S^3 Gauss.cm3 was found again; addition of an equatorial ring current to interpret the external source, makes no change in the RMS residuals, which is interpreted as an effect of non-potential sources (for example field aligned currents associated with the interaction of the corotating magnetosphere with a saturnian satellite or Birkeland currents driven by some asymmetry). The best fit tilt of the dipole is slightly less than 1°. The orientation of the moment is northward, similarly to the jovian dipole.

The field at larger distances in the antisunward direction shows a structure interpretable in terms of a

magnetotail; on the sunside a compressed dipole is seen.

Some inference about the field at high latitudes can be made looking at the radioemission which is definitely proved to be generated by Saturn. This emission shows some asymmetry as a consequence of the axial asymmetry of the field at high latitudes.

5.6.1 TITAN.

A possible intraction of this satellite with the saturnian magnetosphere has been suggested: the interaction might be explained as that between a corotating magnetized plasma and a conducting or magnetized object at a distance of about 145 Titan radii.

5.7 URANUS.

The first observations of this planet, at 19 A.U. from the Sun, have been made(43) by Voyager 2 during its closest approach at 107000 km from the planet on Jan. 24,1986. The orbit was chosen in such a way to make possible also a close approach to Miranda, one of its 15 moons :5 already known, Miranda, Ariel, Umbriel, Titania, Oberon (which is the outermost) and 10 newly identified.

The planet points its rotation axis approximately sunward; it has a dense atmosphere with methan ice clouds at a level where the pressure is 1300 mbar and the temperature is 81 °K. At 2000 and 3500 km a two layer ionosphere has also been found, with electron density peak of several 10^^3 el/cm3. Fig.30 shows the observed field strength: several boundaries corresponding to the bow shock and the magnetopause have been identified. Upon entry into the magnetosphere the field magnitude was about 7 nT; it reached a maximum of 413 nT slightly before closest approach; then it decreased steadily to a few nT. In the time spent by the s/c inside 12 R_U, the subspacecraft longitude varied by a full 360° cycle, while latitude varied from +52 to -78 degrees. An offset, tilted dipole representation of the field had to be assumed from the very beginning: best fit computation of the parameters led to a moment of 0.23 GR_U^3 and a positive pole tilt of 60° from the rotation axis. The magnetic field intensity on the planet's surface ranges from a minimum 0.1 G on the sunlit hemisphere to a maximum of 1.1 G on the opposite hemisphere. This large 10:1 difference in surface field magnitude is far greater than that of either Jupiter or Saturn and strongly affects trapped and precipitating charged particles. The magnetosphere of Uranus also has a fully developed magnetic tail: the observed magnetic field direction is consistent with a progressive sweeping back of the planetary magnetic field by the solar wind to form a two-lobed, bipolar magnetic tail. Fig.31 indicates three complete crossings of the neutral uranian sheet separating the two lobes. It appears that the tail rotates with the dipole motion with a slight ($\approx$ 5.5°) helical twisting. A 10 R_U thickness has been estimated for the neutral sheet; the tail radius is about 42

R_U. The nose of the magnetopause in the sunward direction is about 18 R_U, i.e. slightly less than the Oberon distance from Uranus. This implies that a large fraction of the Uranus' satellites orbits are internal to the magnetosphere; this also means that the moons can be very effective in sweeping up the trapped energetic particles.

No atmosphere has been observed around any of the moons, although there are possible mechanisms to produce some tenuous gaseous environment. Thus, similarly to the case of the terrestrial moon, we can expect small field perturbations and dimensions of a shadow region not much more than a moon diameter perpendicular to the magnetic field direction.

The Uranus magnetic field is supposed to be produced by a dynamc mechanismn rather than by a permanent magnetization: the real question is the radial range inside which the dynamo is operating. The planetary interior is believed assumed to be made by a three layer spherical structure: an upper molecular layer, an intermediate "oceanic" layer and an internal "rocky" core. The oceanic layer might be the region where the fluid motions take place; however, at present status of knowledge, the possibility also exists of an iron liquid inner core inside the "rocky" core, similarly to Earth's case. The high dipole inclination might also mean that the planet is the phase of polarity reversals, well known in the Earth's history. It is also possible that the dynamo is not in statiorary status.

The peculiar field configuration has been particularly suitable to make good determination of the planetary rotational period (17.3 hours), which is then ~~less~~ more than previously estimated.

5.8 MOON.

Following the first measurements by Lunik 2 which led to an upper limit of 6.10**21 Gauss.cm3 for the dipole moment based on observations taken as close as 50 km above the surface, the first extensive measurements are those by Explorer 35 which showed evidence of no bow shock, i.e. of the fact that solar wind particles are just impinging on the lunar surface. Occasional increases of field in the lunar wake were however observed. This revealed the existence of local fields as strong as tens up to more than 100 gammas, with typical sizes of the order of hundreds of kms. Continued magnetic measurements on the Moon surface have been essential to establish the lunar soil conductivity, because of the correlations between field perturbations in the solar wind and induced perturbations of the field at the surface.

The systematic magnetic survey onboard the Apollo subsatellites has been used to compute the lower order coefficients of the spherical harmonics expansion. The dipole term is as low as 0.04 gammas, which means an upper limit of 1.3.10**18 Gauss.cm3 for the magnetic moment.

The obvious question of the origin of the lunar magnetic fields is yet largely unanswered. Runcorn suggested that the

magnetization of the returned samples could be the product of an internal dynamo active in the past. The very low dipole field is too small to be reconciled with a uniformly magnetized crust of reasonable thickness. The problem was solved when it was shown that a uniform spherical shell magnetized by an internally generated field much later disappears and produces no external magnetic field at all. Thus the null value of the present lunar dipole field would argue in favour of an early dipole field. This idea has been tested by studying the magnetic anomaly maps of the Apollo 15 and 16 subsatellites: important informations on the direction of magnetization of areas of the lunar crust (a few hundreds km across) were collected. As for other solar system bodies the dominance of the Coriolis force on the core hydrodynamics would have resulted in the mean dipole lying along the rotation axis. Consequently, the palaeomagnetic poles calculated from the directions of crustal magnetization are ancient poles of rotation. These are found to fall into three groups, in each of which poles are antipodally arranged along an axis, the mean poles being at 180 apart. These "reversals" may be reversals of the polarity of the lunar dynamo or they may arise because of anomalies produced by demagnetization of already magnetized crust or by excess magnetization.

As concerns comets please refer: (i) to the preprints and/or reprints left at the end of lecture; (ii) ~~and~~ to the Nature issue describing Halley's encounters _ (iii) to the copies of viewgraphs which are added as an appendix to these notes