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Hydromagnetic Wave Resonances in the Magnetosphere*

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ABSTRACT

Theoretical and observational research on the hydromagnetic wave resonances in the magnetosphere is reviewed. The magnetosphere is divided into three regions: 1) the plasmasphere, 2) the outer magnetosphere and 3) the magnetospheric tail. Applicable theoretical models in each of these regions are discussed. Observations of the resonant periods in several satellite experiments are compared with the models and predominant resonance periods in these regions are suggested. Observed resonance periods and the size of the resonating regions are discussed for a possible use as diagnostics of the magnetosphere.

I. Introduction

The environment of the earth containing the geomagnetic field and low density plasma is called the magnetosphere. In recent years observations by satellite experiments have provided quantitative information regarding the shape of the magnetosphere which is formed by the constant flow of the plasma from the sun. Even though much information is known about the regions near the equatorial plane and far in the tail out to 80 earth radii, the complicated structure of the field at high latitudes and near the beginning of the neutral sheet in the tail remain to be explored experimentally. The magnetosphere has certain regions which are approximately regular and symmetric in some ways. These regions allow the calculation of the hydromagnetic wave resonances. The magnetic field in the magnetosphere is inhomogeneous and theoretical study of the hydromagnetic waves has been found to be a tough problem. On the contrary, the magnetosphere has provided a natural laboratory where the waves can experimentally be studied in the low density plasma and inhomogeneous magnetic field. Certain assumptions on the boundary conditions on these symmetric resonanting regions and other idealizations allow us to compute resonance frequencies. These waves, with definite frequency values, propagate to the surface of the earth and appear as "micropulsations" in magnetograms. Some of the observations of the periodic wave field fluctuation in the magnetosphere and on the surface of the earth can also be used to predict the size of the resonating regions of the magnetosphere.

It is the purpose of this paper to review the present theoretical and experimental knowledge on the HM wave propagation in the resonating regions of the magnetosphere. Historically, in 1954, it was J. W. Dungey who realized the importance of the application of hydromagnetic theory to the earth's environment. At that time, the term "magnetosphere" was not coined and our knowledge of that region was far from what we know at present through satellite experiments. Dungey (1954a, 1954b) obtained from the MHD and Maxwell's equations, coupled wave equations in a dipole magnetic field. These equations were decoupled by using an assumption of an axially symmetric field i.e. $H_\varphi = 0$ and variation of type $\frac{\partial}{\partial\varphi} = 0$. The two decoupled equations give pure wave modes which are known as toroidal and poloidal modes. The toroidal mode has wave field in spherical coordinates as

$$(E_r, E_\theta, 0); \quad (0, 0, b_\varphi); \quad (0,0,V_\varphi) \qquad (1)$$

where E, b and V are wave perturbations. Dungey assumed standing wave resonances along the dipole field lines and obtained the relationship between the period T and co-latitude θ

$$T \approx 0.6 \operatorname{cosec}^2 \theta \quad \text{where } \theta \leq 60^\circ. \qquad (2)$$

The poloidal mode has wave fields as

$$(0, 0, E_\varphi), \quad (b_r, b_\theta, 0); \quad (V_r, V_\theta, 0) \qquad (3)$$

Dungey presented an approximate treatment of the poloidal mode.

After the basic work of Dungey (1954a,b) several researchers made refinements in the theory by making modifications on the initial assumptions, especially in the density dependence, used in the Dungey model (Kato and Watanabe, 1956; Westphal and Jacobs, 1962; Seibert, 1964; Radoski and Carovillano, 1966).

II. Resonating Regions

The present knowledge of the magnetospheric shape is summarized in Fig. 1. The exact size of a particular region at any time is a variable depending on the solar wind plasma velocity, density and to some extent the direction of the interplanetary magnetic field. However, the regions which can be classified as workable, for the purpose of the calculation of hydromagnetic wave resonances, are designated in Fig. 1 as 1) plasmasphere, 2) outer magnetosphere, and 3) tail region. The wave propagation in these three regions will be discussed in detail.

We should point out that there are three more resonating regions which will be excluded in this paper. These regions are a) the ionosphere-earth cavity, b) the ionosphere and Alfven velocity maximum region at about 2500 km shown by dotted circles in Fig. 1 and c) the region near the beginning of the tail. The regions a) and b) are important for the propagation of Pcl (0.2 to 5 sec period) type hydromagnetic waves. Manchester (1966) has suggested that a duct centered at F_2 region of the ionosphere is more acceptable for Pcl propagation (4 sec period cutoff) at low latitude than the ionosphere-earth cavity. Jacobs and Watanabe (1962) have calculated resonance frequencies for the ionosphere and Alfven maximum region to 2000 km and showed that 8 sec is the fundamental period in this region. The propagation of the hydromagnetic waves of type Pcl is greatly influenced by the ionospheric parameters and the charge particle population in the exosphere. We will not go into the details of these phenomena. Some discussion can be found in a monogram by Jacobs (1970) and a review paper by Saito (1969). The cavity region near the tail may support hydromagnetic resonances as suggested by Raspapov (1968). These resonances are described as a possible source of the Pi2 pulsations.

III. Waves in the Plasmasphere

This region is labeled as 1 in Fig. 1. The plasmasphere contains high density plasma of usually above 100 protons per cm^3. The region outside of the plasmasphere has plasma density of 10 to 1 protons per cm^3. This change usually occurs within one earth radius (Carpenter, 1966). The radius of the plasmasphere is 3 to 4 earth radii for disturbed days ($k_p > 2$-4), but it may extend to 6 or 7 earth radii in quiet days.

Resonances in the plasmasphere have been studied by Radoski and Carovillano (1966). They used Dungey equations for the plasmasphere plasma density

$$n = 6.4 \times 10^5 \ (a/r)^6 \qquad (4)$$

where a = 6400 km and r is the distance in km. This form of the density is in agreement with observed whistler data (Helliwell, 1964). Axisymmetric toroidal mode waves were studied by WKB method and compared to the stretched string model. Resonant periods up to 140 sec were predicted. Cummings et al (1969) using a similar approach interpreted ATS-1 observations at 6.6 earth radii as second harmonics of a standing Alfven wave. They observed predominant periods of 102 and 190 seconds as the resonant periods in the plasmasphere. The data used were taken in the quiet period so that the plasmapause was most likely beyond

6.6 earth radii. They also showed that the resonating periods of 102 and 190 give reasonable values of the equatorial plasma density in their model. Heppner et al (1969) have reported from OGO 3 and OGO 5 data that pulsations in the 45-120 sec period range are observed within L = 5 and 8 earth radii. This author has found, while analyzing Explorer 26 data at the University of Minnesota, that periods 120-180 sec are usual within 3 to 6 earth radii. (The results are obtained in collaboration with L. J. Cahill and further study is in progress). Recently, Dwarkin et al (1971) have observed toroidal and poloidal resonant modes in the plasmasphere at 6.25 earth radii. They have used DODGE satellite data and concluded that periods between 3 to 240 seconds with 1 to 20 gammas amplitudes are observed. They report that the waves with eigen periods of about 40 sec are dominant in the quiet-time. The location of these observations at 6.25 earth radii is certainly within the plasmasphere. From these observations it is apparent that the resonant periods in the plasmasphere are 40, 110-120 and 180-190 second. If we exclude occasional observations of the Pc1 type, the resonant periods are in the categories of Pc2, Pc3 and Pc4. Future observations on the magnetospheric satellites (e.g. s^3) will certainly be useful to confirm the above statements.

IV. Waves in the Outer Magnetosphere

Axially symmetric models can be used in this region labled as 2 in Fig. 2. All the discussion given in previous sections is valid if a larger radius of the cavity is considered. The models will work for closed field lines. Dungey and Southwood (1970) have discussed the resonant modes in this region for large $m \to \infty$ where m is exponent in $e^{im\varphi}$. They argue that this approach allows them to include a large longitudinal extent of the wave propagation. Waves have been found to be confined to the oscillations of L shells within 10 degrees longitudinal extent (Patel, 1966). Localized resonant modes in the outer magnetosphere can be interpreted as resonant modes of large m values. The additional feature of the waves in this region is that the magnetopause boundary can provide a source for the generation of the waves. The Kelvin-Helmholtz instability is a possible cause of the waves. This fact has been demonstrated by Dungey and Southwood (1970) by using Explorer 33 magnetic field data near the magnetopause.

This region supports the resonating hydromagnetic waves with periods of Pc4 and Pc5 classes. Waves with 150-600 periods are most likely to occur on the dayside of the magnetosphere. The mechanisms which generate such waves are discussed in reviews by Saito (1969), Dungey and Southwood (1970) and Jacobs (1970). We will not discuss observations in the ground data. This aspect of the study is covered in these reviews.

Direct observations of the waves in this region were reported by Patel and Cahill (1964) and Patel (1965) in the 0650-1200 local time sector. The periods in the range of 100-200 sec and amplitudes of 10γ were obtained. It was also shown that these waves propagated to the surface of the earth. Explorer 6 observations by Judge and Coleman (1962) were at 1900 local time and it is not certain they can be considered in this region. Some of the observations by OGO satellites in the magnetosphere beyond plasmapause are in this region (Heppner et al, 1969). Storm-related pulsations with 250-900 sec periods at ATS-1 orbit (Barfield and Coleman, 1970) and some of Explorer 14 observations (Patel, 1966a) are possibly in this region. These observations are taken sporadically and continuous observations are required at various latitudes and L values to compare the resonance periods with any particular model. From these few observations listed above, the predominant resonant periods are from 40 to 600 sec.

We should remark that the region near the magnetopause is the main source of pc5 (150-600 sec) periods. Surface waves on the magnetopause and the resonances of the field lines near the boundary in the sunward side of the magnetosphere are sources of the pc5. From the surface observations it appears that the pc5 are most likely to occur in the dayside. In conclusion, the outer region of the magnetosphere has resonant periods of the hydromagnetic waves which are in the categories of pc4 and pc5. It should be pointed out that the longer periods of 10 to 20 min range in this region in the nightside probably have origin in the tail region.

V. Waves in the Magnetospheric Tail

The solar wind plasma flows past the earth and stretches the magnetic field of the earth behind it (region 3 in Fig.1). A tail-like configuration of the magnetic field is formed in the nightside magnetosphere (Ness, 1969; Behannon, 1968). The tail region has approximate cylindrical shape confined to about 40-44 earth radii. The tail has been detected up to 80 earth radii and it is possible that the regular magnetic field might exist up to 100-200 earth radii. The upper part of the tail has magnetic field lines directed toward the earth, while the lower part has the field lines directed away from the earth. The central part of the tail of approximate dimension of 4 - 6 earth radii has very weak or almost zero magnetic field. This region is called neutral sheet. The upper and lower parts can be idealized to the cylinders with radii of about 7 to 10 earth radii. Both of these regions have steady and regular magnetic field which remains undisturbed for a period of one or two hours (Behannon, 1968). Using above observational results, Patel (1967) suggested that the geomagnetic tail can be considered as a hydromagnetic wave guide. McClay and Radoski (1967) independently considered the theta-model of the tail for the hydromagnetic wave propagation. Patel (1968) calculated resonant period of 218, 1888 and 1445 sec from the double cylinder model. McClay and Radoski (1967) obtained resonant periods of 1734 and 1675 sec for TE modes. Later, Patel (1968a) suggested a hydromagnetic resonator model which can explain extremely long periods of greater than 30 min. This model can explain the long periods observed in the geomagnetic field (Herron, 1967; Pai and Sarabhai, 1964).

The models discussed are able to explain the origin of the long period micropulsations with 20 and 30 min and longer periods as resonances in the tail. However, these models neglect the effect of the neutral sheet which is thin compared to the wavelengths of the long period resonances. Two recent models (Siscoe, 1969; McKenzie, 1970) have included the possible effect of the neutral sheet. The most recent model of McKenzie considers the tail as a long cylindrical current-vortex sheet. The neutral sheet is considered as a slab of hot plasma surrounded by a cold plasma. The cylindric tail has resonant periods of 13 min, while the plasma sheet has oscillations of 6 min (sausage - symmetric) and 3 min (kink - asymmetric) periods. Siscoe (1969) obtained periods of 11 and 2 min for resonant compressional waves. Experimental evidence of these resonances in the tail is found in some isolated events of the pulsation associated with the sc (Ness, 1969). Most of the long periods have been detected on the surface of the earth. Some of the Explorer 14 observations (Patel, 1966a) at 12 earth radii in the magnetosphere has possible effect of the resonances in the tail. The difficulty in the direct detection of the hydromagnetic resonances is that the long periods of 10 - 30 min require undisturbed, continuous and very long stretch of data for power spectrum analysis.

VI. Micropulsation Periods, Size of the Resonating Regions and the Solar Wind.

Periods of the micropulsations observed in the surface geomagnetic data indicate the dependence on the solar activity cycle. During minimum solar activity longer period (pc4) are more likely to occur. In maximum solar activity pc2, pc3 and pc4 have equal probability to occur. (Troitskaya, Bolshakova and Shchepetnov, 1967). Bolshakova (1965) has shown that when magnetopause is at 10 earth radii, pc4 periods occur. As the magnetopause distance decreases, pc2 and pc3 periods appear. A relationship between period T and the size of the outer magnetosphere region R_m (labeled 2 in Fig. 1) was given as follows:

$$T \approx R_m^{\ n} \quad \text{where } n = 4.8 \tag{5}$$

However, we should remark that this result is based on 8 points taken from Explorer 12 observations. Patel and Hastings (1970) extended this study by using Explorer 12 and IMP-1 data. The scatter of the data points was large and index $n \approx 10$ to 13 was obtained. Further extensive study using all available magnetopause data is under way. We should point out that until consistant and reproducible results are obtained for value of n, secondary conclusions using index n = 5 for calculating solar wind velocity and other parameters with K_p index should be taken as tentative.

Periods of the micropulsations have been shown to be correlated with the outer boundary of the radiation belt (Troitskaya and Gule'lmi, 1967). These results certainly indicate that the resonance periods are related to the size of the outer magnetosphere. However, the functional relationship which can be used to relate other indexes of geomagnetic activity is still to be determined. Another method of determining the size of the resonating region 2 is given by Hirasawa et al (1966). They used pc5 periods associated with the sudden impulse (si). The argument is based on the fact that the size of the resonating region will change when the si is registered on the earth. This change will cause a change in the period of the micro-pulsation. They obtained a formula

$$dT \approx n \; (T/R_m) \; dR_m \qquad (6)$$

where $dT = T'-T$ and $dR_m = R'_m - R_m$ and T' and T are periods before and after the si.

Caution is again urged in the use of formulas (5) and (6). One example of an erroneous result that is obtained from these formulas and velocity - K_p relation is the dependence of period T on the solar wind velocity, v. This relationship between T and v is in contradiction with the observation of T and v presented in a paper by Gringauz et al (1971). In fact, their results obtained from Venera 5 and

Venera 6 spacecraft showed no clear dependence of T on V. The important result of their study is that not the velocity of the solar wind plasma but the flux nv and more clearly plasma density n is related to the micropulsation period T.

The size of the resonating region of the plasmasphere (region 1 in Fig. 1) has been varified with the observation obtained by ATS-1 (Cummings et al, 1969). With the model they used, it was shown that the predominant resonances of 102 and 190 are consistent with the size of the plasma-sphere larger than 6.6 earth radii. Thus with a reasonable plasma density model, observed resonant periods in the region allow to estimate the size of the plasmasphere. Resonant periods calculated for the tail region have not been directly varified with the observation in that region (labeled 3 in Fig. 1). The models in this region still remain theo-retical guess work as far as the relationship between the size of the region and the resonant periods are concerned.

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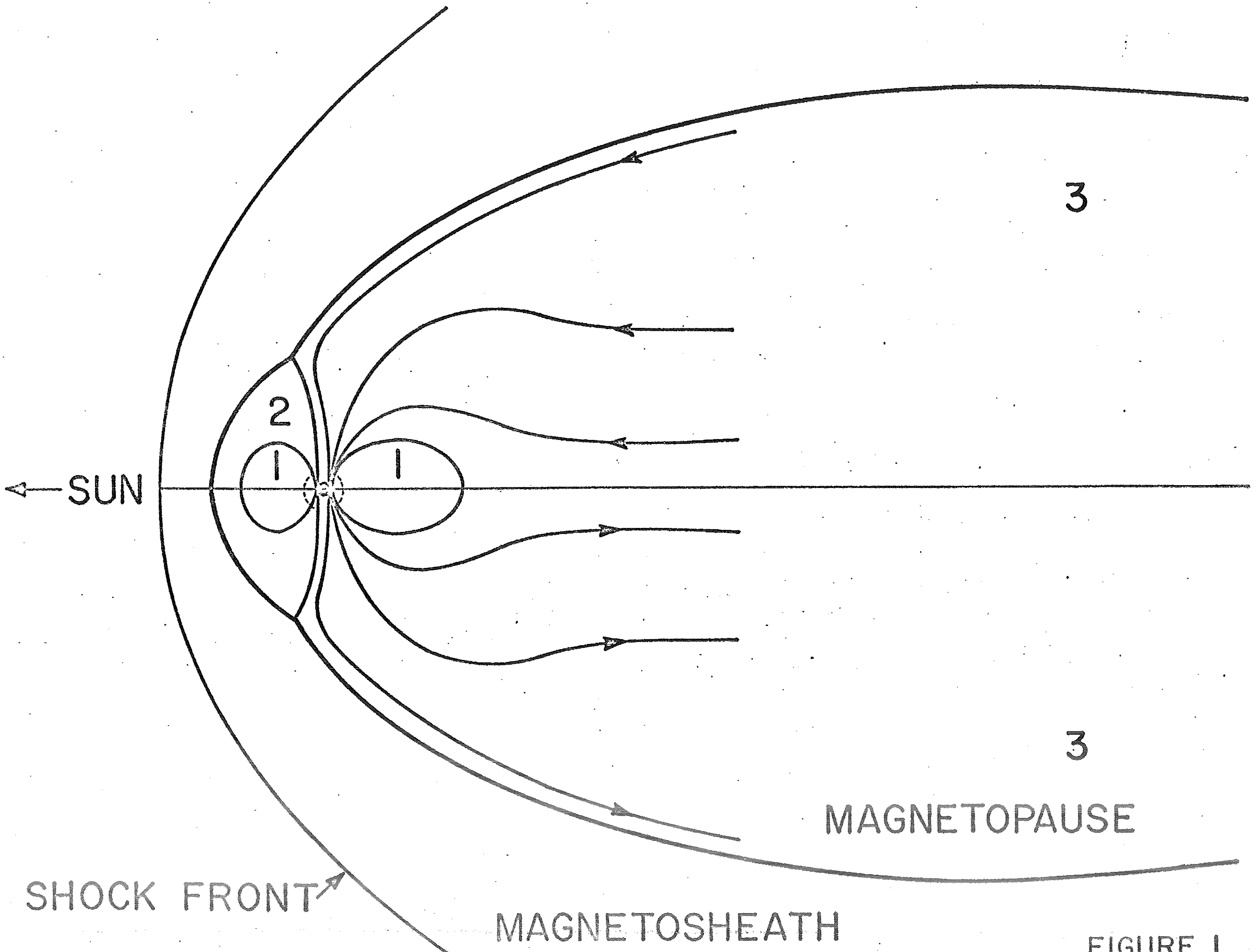

FIGURE 1