Heliocentric Distance Dependence of the Interplanetary Magnetic Field

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Recent and ongoing planetary missions have provided and are continuing to provide extensive observations of the variations of the interplanetary magnetic field (IMF) both in time and with heliocentric distance from the sun. Large time variations in both the IMF and its fluctuations are observed. These are produced predominantly by dynamical processes in the interplanetary medium associated with stream interactions. Magnetic field variations near the sun are propagated to greater heliocentric distances, a process also contributing to the observed variability of the IMF. Temporal variations on a time scale comparable to or less than the corotation period complicate attempts to deduce radial gradients of the field and its fluctuations from the various observations. However, recent measurements inward to 0.46 AU and outward to 5 AU suggest that the radial component of the field on average decreases approximately as r^{-2}, as was predicted by Parker, while the azimuthal component decreases more rapidly than the r^{-1} dependence predicted by simple theory. Three sets of observations are consistent with an $r^{-1.3}$ dependence for $|B_\phi|$. The temporal variability of solar wind speed is most likely the predominant contributor to this latter observational result. The long-term average azimuthal component radial gradient is probably consistent with the Parker r^{-1} dependence when solar wind speed variations are taken into account. The observations of the normal component magnitude $|B_\theta|$ are roughly consistent with a heliocentric distance dependence of $r^{-1.4}$. The observed radial distance dependence of the total magnitude of the IMF is well described by the Parker formulation. There is observational evidence that amplitudes of fluctuations of the vector field with periods less than 1 day vary with heliocentric distance as approximately $r^{-3/2}$, in agreement with theoretical models by Whang and Hollweg. In relation to total field intensity, the amplitude of directional fluctuations is on average nearly constant with radial distance, at most decreasing weakly with increasing distance, although temporal variations are large. There is evidence that fluctuations in field intensity grow in relation to those in field direction with increasing distance. More observations are needed to confirm these conclusions. The number of directional discontinuities per unit time is observed to decrease with increasing distance from the sun. The apparent decrease may possibly be caused by geometric or selection effects. The relationship between fluctuations of the field and the corotating stream structure is still not understood in detail, and therefore the origins of the various mesoscale and microscale features are at present uncertain.

CONTENTS

INTRODUCTION

The study of the variations of various large-scale and microscale properties of the interplanetary magnetic field (IMF) with distance from the sun is at present in a rapidly expanding stage in its history. The ongoing missions of Pioneer 10 and 11 to the outer solar system, which began in 1971, and the Mariner 10 mission to the inner solar system to a heliocentric distance of 0.46 AU during 1973–1975 have provided many new data bearing directly on this study. The Helios 1 and 2 missions and the associated data analysis are also in progress. In the future the Voyager mission and hopefully other outer-planet missions will add to our knowledge of the radial gradients of the various properties of the IMF out to the limits of the solar system.

The large-scale structure of the IMF is determined in part by the distribution of open magnetic fields on the sun and in part by interplanetary dynamical processes. Knowledge of the large-scale structure of the coronal magnetic field is based primarily on magnetograph observations of the line-of-sight component of the field in the photosphere by using the Zeeman effect (see the review of *Howard* [1967]). The coronal fields are then modeled by calculating the potential field from the measured photospheric field (*Newkirk et al.* [1968], *Schatten* [1968], *Schatten et al.* [1969], and *Altschuler and Newkirk* [1969]; see also the review by *Schatten* [1975]). The results can be compared with measured interplanetary fields extrapolated toward the sun or by extrapolation of the coronal field outward [*Schatten*, 1968; *Stenflo*, 1971] using the assumption of transport of the field by a radially flowing plasma. The radial gradients of the field components used are those predicted by the spherically symmetric model of *Parker* [1958]. Thus a comparison of experimentally determined IMF gradients with the Parker model predictions is of interest to such coronal field studies as well as to the construction of solar wind models.

The radial gradients in the IMF are important for plasma physics problems associated with the radial distribution of energy in the solar wind. Investigations of the physical processes important in the expanding solar wind, such as the interactions between fast and slow streams and the growth and damping of waves, can also benefit from measurements of the radial gradients in the components of the field and in the fluctuations of both the field magnitude and the components.

The fluctuations are also important because of their influence on energetic particle propagation in interplanetary space. Most models of this propagation up to the quasi-linear approximation assume that to zeroth order such particles follow a helical orbit along the mean spiral field while undergoing

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some spatial diffusion due to the effects of field fluctuations [*Jokipii*, 1971; *Völk*, 1975*a*, *b*]. Recent nonlinear approaches [*Völk*, 1975*b*; *Goldstein*, 1976; *Jones et al.*, 1977] and the local approximation quasi-linear approach of *Klimas et al.* [1976*a*, *b*, 1977] seek to remedy the inability of previous theories to describe accurately the more complex motions of cosmic ray particles with large (near 90°) pitch angles and/or moderate to strong magnetic turbulence. There have been several attempts to determine the radial distance dependence of the cosmic ray diffusion tensor [*Jokipii*, 1973; *Völk et al.*, 1974], but these have relied heavily on theoretical models for the spatial dependence of the magnetic spectrum which may not correspond to the real situation [*Völk*, 1975*b*].

Accepting then that the variation of the IMF with heliocentric distance is of significance for several areas of solar and interplanetary research, we review the present state of knowledge in this area, attempting to sort out the confusion which exists about the interpretation of the observations. Recent reviews of this subject either have been concerned with a broad coverage of topics related to the magnetic field alone [e.g., *Schatten*, 1971; *Davis*, 1972; *Burlaga and Ness*, 1976] or have treated the more general subject of large-scale solar wind variations [*Neugebauer*, 1975]. *Smith* [1974] considered radial gradients of the magnetic field but concentrated on Pioneer 10 observations between 1.0 and 4.3 AU. Here we discuss in detail all radial gradients of importance in the IMF, including recent results which have greatly expanded the radial distance range available for interpretation.

In general, two methods of deriving radial gradients can be used: (1) use observations from a single spacecraft which moves over an extended range of radial distance during a correspondingly long time, or (2) use nearly simultaneous observations from two or more spacecraft performed at different heliocentric distances. There are problems associated with both of these approaches. The first method has been most used in IMF studies, but radial and temporal variations are mixed and must be carefully separated. It is customary to attempt to average through such variations in the data or to use only data subsets which correspond to periods of measurement within similar regions of the corotating stream structure. Least squares fits to the data can provide additional smoothing. Solar rotation averages are often used, since large variations are usually seen in the solar wind and IMF parameters during a single solar rotation [*Davis*, 1972; *Burlaga*, 1975]. Using such averages still does not eliminate time variations completely, however, since there can be significant variability from one solar rotation to the next either in the form of fluctuations or as a trend extending over a number of rotations. This problem will be considered in more detail in the discussion of the measurements of the azimuthal component gradient.

The second method, to combine data taken by two or more spacecraft at different radial distances after adjustment of time for corotation and radial propagation, has been used to look for a solar wind radial velocity gradient [*Collard and Wolfe*, 1974] and a latitude gradient [*Rhodes and Smith*, 1975; 1976*a*, *b*]. It is considered particularly important for studies in which the gradients are relatively weak and are easily masked by time variations. One must be concerned, however, about the 'correlation length' of the quantity being studied. Over large separation distances it may not suffice merely to adjust for corotation and propagation delays, since there may be additional effects due to continuous evolution both at the sources of the streams and in the interplanetary medium through stream collision processes. In that case, data taken at widely separated points in space are not strictly comparable under any circumstances. This is the same problem that arises in the single-spacecraft method: a steady state solar wind cannot be assumed in general, particularly when observations are taken in different streams. For some studies it may be important to correlate observations taken by different spacecraft of the same 'parcel' of plasma. Such opportunities depend on an interalignment of spacecraft that is seldom realized. Thus we must conclude that while multispacecraft studies can be extremely valuable, investigations of gradients in the IMF can be properly carried out only for a limited subset of relative geometries and under conditions that are approximately stationary in time, and such appropriate circumstances may be rare.

LARGE-SCALE STRUCTURE

The large-scale 'undisturbed' interplanetary magnetic field is the photospheric field of the sun carried outward into the solar system by the expanding coronal gas and twisted into a spiral by solar rotation. A zeroth-order model of this field was given by *Parker* [1958, 1963]. Its geometry has been calculated in three dimensions by *Hirose et al.* [1970] and is shown in Figure 1. Near-earth measurements of the IMF to date have been limited to the region within $\pm 7\frac{1}{4}°$ of the solar equatorial plane, the range of the earth's annual motion. Only Pioneer 11, en route from Jupiter to Saturn, has deviated significantly from this range, reaching 16° latitude in February 1976 [*Smith et al.*, 1976, 1977*b*].

That the photosphere was the source of the IMF was established in the mid-1960s by Ness and Wilcox, using measurements made by the Imp 1 spacecraft. They demonstrated that the IMF corotated with the sun, and they also discovered that the field was structured into sectors [*Ness and Wilcox*, 1964; *Wilcox and Ness*, 1965]. At that time there was shown to be, on average, a quasi-stationary pattern of alternating regions of field directed either toward (negative) or away from (positive) the sun along the spiral direction. The recent observations by Pioneer 11 [*Smith et al.*, 1977*b*] support the view that the boundary between magnetic sectors in the interplanetary medium is a warped current sheet that is nearly parallel to the solar equatorial plane except very near the sun.

It has been seen subsequently that some recurrent structural features of the IMF are associated with the interaction be-

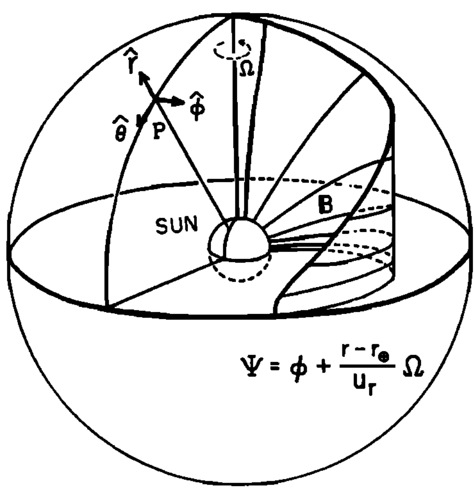

Fig. 1. The zeroth-order Archimedean spiral interplanetary magnetic field depicted schematically in three-dimensional space [*Hirose et al.*, 1970].

tween fast and slow solar wind streams (see *Hundhausen* [1972] for a review of this topic), and one or more high speed streams are observed in each magnetic sector in the IMF. The sector pattern evolves with time, the number of sectors and the dominant polarity in a given hemisphere apparently being related to the solar activity and magnetic cycles, respectively [*Ness and Wilcox*, 1967; *Coleman et al.*, 1966, 1967; *Rosenberg and Coleman*, 1969; *Hirshberg*, 1969; *Wilcox and Colburn*, 1969, 1970, 1972; *Wilcox and Scherrer*, 1972; *Svalgaard*, 1972; *Russell and McPherron*, 1973; *Fairfield and Ness*, 1974; *Svalgaard and Wilcox*, 1975; *Hedgecock*, 1975; *King*, 1976]. Thus although the long-term average large-scale state of the IMF structure may be the basic Archimedean spiral geometry, locally on short time scales there is considerable variation caused by variations at the source which are convected outward and to the colliding solar wind streams. These effects will be discussed in more detail in later sections.

The initial formulation for the IMF in terms of a reference field $B(\theta, \phi_0)$ at a heliocentric radial distance $r = b$, latitude θ, and azimuth ϕ_0 was given [*Parker*, 1958] in the form

$$B_r(r, \theta, \phi) = B(\theta, \phi_0)(b/r)^2 \qquad (1a)$$

$$B_\theta(r, \theta, \phi) = 0 \qquad (1b)$$

$$B_\phi(r, \theta, \phi) = B(\theta, \phi_0)(\Omega/V_s)(r - b)(b/r)^2 \sin\theta \qquad (1c)$$

where ϕ and r are related by the streamline formula

$$\frac{r}{b} - 1 - \ln\left(\frac{r}{b}\right) = \frac{V_s}{b\Omega}(\phi - \phi_0) \qquad (2)$$

V_s is the solar wind speed (assumed constant), and Ω is the angular speed of solar rotation. By using this model, power law radial distance dependences for the radial and azimuthal field components with exponents of -2 and -1 are predicted; in addition to the r^{-1} dependence, B_ϕ is proportional to V_s^{-1} as well, and the latitudinal component of the field is zero. The angle between the magnetic field and the radial solar wind flow direction, the 'spiral angle,' is about 45° (or 225°) at 1 AU and decreases for $r < 1$ AU. The reference field $B(\theta, \phi_0)$ could be a simple dipolar solar field, where $B(\theta, \phi_0) = B_0 \cos\theta$, or a more general and complex solar field structure [*Parker*, 1958].

During the decade between 1964 and 1974, measurements of the IMF by five deep-space probes have been analyzed in an effort to determine experimentally the heliocentric distance dependence of the field. The magnetic field experiments which have contributed to these studies are listed in Table 1 along with a description of the type of data used in each case in the least squares analysis. The results from these experiments will be reviewed and compared with theoretical expectations in the following sections.

Radial Field Component Radial Gradient

Observations by the various spacecraft listed in Table 1, with the exception of Mariner 4, have individually shown at least gross consistency with the inverse square radial distance dependence predicted for B_r by the Parker spiral model [*Burlaga and Ness*, 1968; *Coleman and Rosenberg*, 1968, 1971; *Coleman et al.*, 1969; *Rosenberg*, 1970; *Rosenberg and Coleman*, 1973; *Smith*, 1974; *Villante and Mariani*, 1975; *Rosenberg et al.*, 1975; *Behannon*, 1976*a*]. The various least squares analysis results are given in Table 2.

The large difference between the gradient observed by Mariner 4, and to a lesser extent by Mariner 5, and the expected inverse square dependence may be a result of the highly variable state of the IMF during the period of those measurements, which was a rising portion of the solar cycle. Mariner 4, for example, observed considerable evolution of the sector pattern from one solar rotation to the next [*Coleman et al.*, 1967] just after solar minimum, and variable to quasi-stationary conditions continued through 1967 [*Ness and Wilcox*, 1967; *Wilcox and Colburn*, 1969].

The Mariner 4 and 5 results were combined by *Neugebauer* [1975] with those from Pioneer 10 [*Smith*, 1974] to show that the total data set was consistent with an inverse square law variation. Neugebauer pointed out that the data sets from the various spacecraft were not strictly comparable, however, with differences both in methods of analysis (see Table 1) and in coordinate systems employed. The coordinate systems which have been used in radial gradient studies are heliocentric solar ecliptic (SE), solar equatorial (SEQ), and spherical coordinates. For an angle between the spacecraft-sun line and the solar equatorial plane of 7¼°, the maximum angular excursion of earth from the SEQ plane, the differences between components observed in two different systems at 1 AU in most cases would be less than 1 γ. The differences can be greater

TABLE 1. Summary of Experiments Measuring the Heliocentric Distance Dependence of the IMF

Spacecraft	Period of Observations	Radial Distance Range, AU	Investigators	Type of Analysis
Mariner 4	Nov. 28, 1964–July 14, 1965	1.0–1.5	P. J. Coleman, Jr., E. J. Smith, L. Davis, Jr., D. E. Jones	Least squares fits to field component and magnitude data which were smoothed by taking 27-day running averages at 3-day intervals [*Coleman et al.*, 1969]
Pioneer 6	Dec. 16, 1965–June 16, 1966	0.81–1.0	F. Mariani, U. Villante, N. F. Ness, L. F. Burlaga	Least squares fits to solar rotation averages of B_r and B_ϕ only [*Villante and Mariani*, 1975]
Mariner 5	June 14, 1967–Nov. 27, 1967	0.66–1.0	P. J. Coleman, Jr., R. L. Rosenberg	Same as Mariner 4 [*Rosenberg and Coleman*, 1973]
Pioneer 10	March 10, 1972–Nov. 20, 1973	1.0–5.0	E. J. Smith, R. L. Rosenberg, M. G. Kivelson, S. C. Chang	Least squares fits to solar rotation averages of field components and magnitude; polarity-weighting technique used in averaging [*Rosenberg et al.*, 1975]
Mariner 10	Nov. 3, 1973–April 14, 1974	0.46–1.0	N. F. Ness, K. W. Behannon, R. P. Lepping, Y. C. Whang	Least squares fits to daily averages of component and magnitude data [*Behannon*, 1976*a*]

TABLE 2. Radial Component Distance Dependence $B_r = A_r r^{C_r}$

Spacecraft	Radial Distance Range, AU	A_r	C_r	Remarks
Pioneer 6	0.81–1.0		-2.0 ± 0.2	
Mariner 5	0.66–1.0	3.50 ± 0.31	-1.78 ± 0.02	Smoothed data used for both Mariner 5 and Mariner 4 analysis
Mariner 10	0.46–1.0	3.12 ± 0.62	-1.96 ± 0.31	
Mariner 4	1.0–1.5	2.39 ± 0.17	-1.46 ± 0.02	Dependence for all data
		2.16 ± 0.12	-1.23 ± 0.02	Dependence for quiet data only
Pioneer 10	1.0–5.0	2.11 ± 0.55	-2.10 ± 0.30	Note that the best agreement is given by Mariner 10 and Pioneer 10, which have large radial ranges

than that, however, for strong field conditions (field magnitude of >10 γ in the plane of rotation between coordinate systems and for deep space probes at absolute heliocentric latitudes of >7½°). No attempt has been made to correct for coordinate system differences, although in principle this should be possible. In addition to coordinate system-related differences, the differences between the various results given in Table 2 for the best fit power law coefficients A_r may also include contributions from systematic measurement errors.

Figure 2 is a composite plot [*Behannon,* 1976*b*] of the Mariner 4, Mariner 5, and Pioneer 6 solar rotation averages as presented by *Neugebauer* [1975] plus Pioneer 10 solar rotation averages [*Rosenberg et al.,* 1975] and solar rotation averages of the Mariner 10 data. The dashed line drawn through the data points indicates the heliocentric distance dependence $B_r = 3.0r^{-2}$. Also shown (solid line) is the best fit of the nonlinear model $\langle f \rangle = Ar^C$ to the data. This gave the result

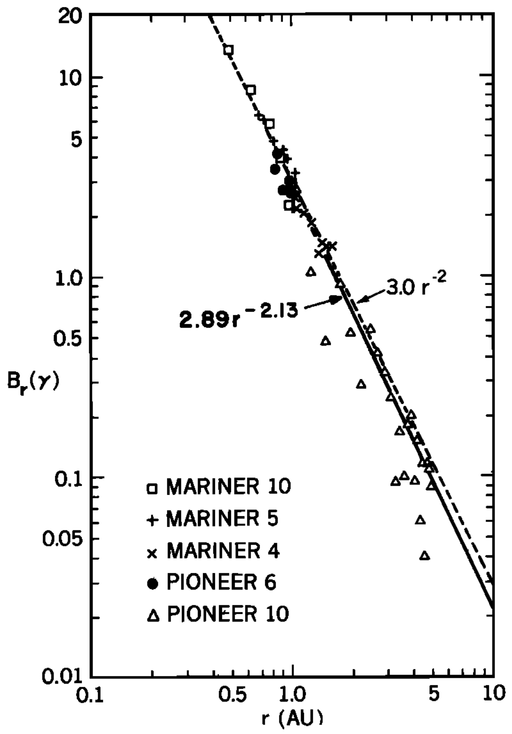

Fig. 2. Solar rotation averages of the magnitude of the IMF radial component B_r measured by Mariner 4, 5, and 10 and Pioneer 6 and 10. Curves showing an r^{-2} radial distance dependence (dashed curve) and the 'best' least squares fit to the combined data (solid curve) are included.

$$B_r = (2.89 \pm 0.16)r^{-2.13\pm0.11} \quad (3)$$

Fitting a linear model to logarithms of the data gave the even steeper dependence $r^{-2.27}$ as a result of low values of B_r having a stronger influence in the log linear case than in the nonlinear case.

Azimuthal Component Radial Gradient

In the review by *Neugebauer* [1975] the variation of the azimuthal component B_ϕ with heliocentric distance for a composite data set was also shown. Direct comparison was made difficult by the fact that the Mariner 4 and 5 data were averages of the magnitude of the heliographic azimuthal component B_ϕ, the Pioneer 6 data were averages of $(B_Y^2 + B_Z^2)^{1/2}$, and the Pioneer 10 data were the most probable values of $|B_\phi|$ reported by *Smith* [1974]. The various sets of data were consistent, however, in suggesting the exponent of the azimuthal component radial dependence to be >1.

Table 3 lists the individual results which have been obtained for the azimuthal component dependence. The Pioneer 10 result is derived from a least squares fit to polarity-weighted solar rotation averages [*Rosenberg et al.,* 1975] rather than to most probable values. It can be seen that the gradient obtained from this more recent Pioneer 10 analysis is in agreement with the Mariner 10 result as well as with that found for Mariner 4 when all of the data were used in the fit [*Coleman et al.,* 1969].

The most inconsistent results in this case were those from the Mariner 5 and Pioneer 6 measurements. In addition to the Pioneer 6 results shown in Table 3, *Villante and Mariani* [1975] obtained $\tan \alpha_B / \tan \alpha_P \propto r^{-1}$, where $\tan \alpha_B = B_\phi / B_r$ (α_B is the observed spiral angle) and $\tan \alpha_P = \Omega r \sin \theta / V_s$. Since $B_r \propto r^{-2}$, the above radial dependence implies that $B_\phi \propto r^{-2}$ also if V_s is taken to be independent of r, a valid assumption from observational evidence to date. An inverse square dependence is still significantly steeper, however, than the gradients found by Pioneer 10, Mariner 10, and Mariner 4. The discrepancy may be due to the small range of radial distance covered by the Pioneer 6 spacecraft, as well as to the small number of solar rotation averages used in the least squares analysis.

Figure 3 shows solar rotation average B_ϕ data from all five spacecraft from which we now have gradient measurements [*Behannon,* 1976*b*]. This includes Mariner 10 data and the Pioneer 10 data of *Rosenberg et al.* [1975]. The dashed line shows the Parker model r^{-1} dependence on radial distance, and the other broken line illustrates the $r^{-1.3}$ dependence with which three of the sets of data are individually consistent. A less steep distance dependence

$$B_\phi = (3.17 \pm 0.19)r^{1.12 \pm 0.14} \quad (4)$$

was obtained for the best fit to the composite set. This dependence is given by the solid line in Figure 3 and is in closer agreement with the theoretical r^{-1} dependence than that found for any of the individual sets of measurements, although such better agreement may simply be fortuitous.

Some physical mechanisms have been advanced to explain the fact that in each individual case the observed B_ϕ gradient is steeper than r^{-1}. *Nerney and Suess* [1975] have attempted to accommodate the observed falloff of B_ϕ with increasing heliocentric distance within the framework of steady flow three-dimensional solar wind theory by considering the effects of meridional flow. However, this theory also predicts a more rapid falloff in B_r than that predicted by the Parker model. In the Nerney-Suess model the corrections to B_r and B_ϕ relative to the Parker model are essentially the same, flux tubes opening in response to meridional flow, transporting both B_r and B_ϕ to higher latitudes and maintaining the same spiral angle as that in the classical model. Although the 'best fit' to the composite data for B_r in Figure 2 suggests a slightly steeper falloff than r^{-2}, the uncertainty associated with the fit is large enough so that its significance is questionable.

Jokipii [1975] suggested that the steeper than r^{-1} dependence for the azimuthal component could perhaps be accounted for at least in part by considering the influence of solar wind fluctuations, which do not influence B_r. Careful observations of $\langle \delta B_\phi \delta V \rangle$ as a function of r are required to test the importance of this suggestion. The first test, which used Pioneer 10 data, has suggested that the effect is not important [*Parker and Jokipii*, 1976]. However, from calculations using a numerical MHD model, *Goldstein and Jokipii* [1977] have concluded that nonlinear fluctuations due to solar wind stream interactions can cause $\langle B_\phi \rangle$ to decrease significantly faster than the Archimedean spiral calculated for $\langle V_s \rangle$ if certain conditions are satisfied, such as a correlation between B_r and V_r at the inner boundary.

Using a kinematic approach, *Burlaga and Barouch* [1976] have shown that although B_ϕ may vary as r^{-1}, it is also directly proportional to $\Phi_0 - 90°$, where Φ_0 is the initial azimuthal angle of the field near the sun. Since the initial value Φ_0 and its statistical properties may depend on both time and position, measurements of $\langle B_\phi \rangle$ performed during an extended period may well deviate significantly from an r^{-1} dependence. They have found by averaging over a typical stream that while the B_r variation is well described by the inverse square dependence, B_ϕ does not vary in a simple way. In the case illustrated in Figure 4, when Φ_0 takes values between 93° and 99°, measured B_ϕ at 1 AU can lie somewhere in the shaded area, i.e., 2.5 $\gamma \lesssim B_\phi \lesssim 7\ \gamma$. *Barouch* [1977] has used the kinetic model to extrapolate 1 year of plasma and field observations from 1 to

TABLE 3. Azimuth Component Distance Dependence $B_\phi = A_\phi r^{C_\phi}$

Spacecraft	Radial Distance Range, AU	A_ϕ	C_ϕ
Pioneer 6	0.81–1.0		-2.5 ± 0.2
Mariner 5*	0.66–1.0	3.23 ± 0.26	-1.85 ± 0.02
Mariner 10	0.46–1.0	2.49 ± 0.51	-1.29 ± 0.36
Mariner 4*	1.0–1.5	2.57 ± 0.21	-1.29 ± 0.02
		2.42 ± 0.14	-1.22 ± 0.02
Pioneer 10	1.0–5.0	3.93 ± 0.22	-1.29 ± 0.06

*See Table 2 remarks.

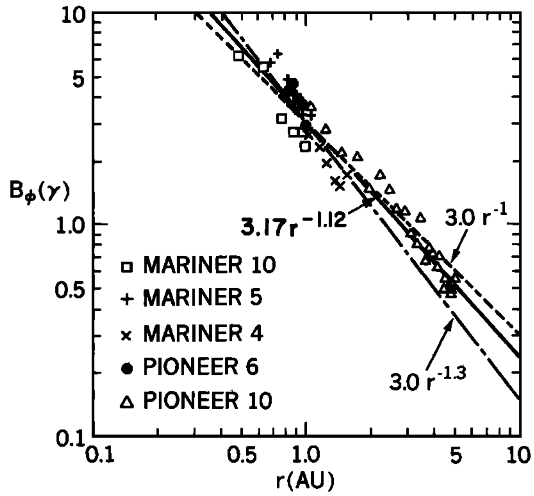

Fig. 3. Average azimuthal component magnitude B_ϕ data corresponding to B_r data shown in Figure 2. Curves superimposed on the data show (1) an r^{-1} radial distance dependence (short dashes), (2) the $r^{-1.3}$ dependence observed by three experiments independently (long dashes), and (3) the best least squares fit to the combined data (solid curve) which gives an $r^{-1.12}$ dependence.

0.3 AU and has concluded that directional fluctuations of the IMF on a 6-hour time scale are primarily due to interplanetary processes.

Even though these various effects may contribute to the observed radial gradient in B_ϕ, it has become obvious that the major influence on the calculation of a B_ϕ gradient from measured fields comes from variations in the solar wind speed. It was noted earlier that (1*a*)–(1*c*) were developed for the case of a steady solar wind. The plasma speed appears explicitly in the expression for B_ϕ (equation (1*c*)). With solar wind source regions at the base of the corona which differ in size and shape and are continuously evolving, so that both the reference field $B_0 (= B(\theta, \phi_0))$ and V_s are functions of time, it perhaps should not be surprising that measured $\langle B_\phi \rangle$ does not appear to obey the ideal Parker spiral model inverse power law exactly and

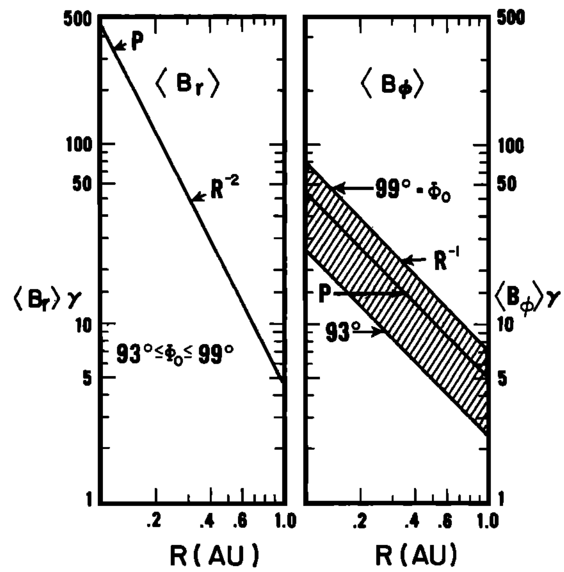

Fig. 4. Field components B_r and B_ϕ averaged over the time profile of a 'representative' stream as functions of radial distance from the sun, according to the kinematic model of *Burlaga and Barouch* [1976]. Here $\langle B_r \rangle \sim R^{-2}$, but $\langle B_\phi \rangle$ depends on Φ_0. P curves give $B_r(r)$ and $B_\phi(r)$ for Φ_0 in the Parker spiral direction.

that there are differences between different data sets taken at different times, especially since in every case only one spacecraft was available.

Using data from Mariner 2, 4, and 5, *Rosenberg* [1970] showed that the tangent of the observed spiral angle, tan α_B, has a dependence on solar wind stream flow speed. When the 'slow' streams dominate the flow, tan $\alpha_B <$ tan α_P from the Parker model, and when 'fast' streams dominate, tan $\alpha_B >$ tan α_P. Also, *Neugebauer* [1976] has found from a study of data from nine spacecraft taken during 14 'quiet' intervals that the average direction of the IMF varies with the solar wind speed in a way consistent with the Parker model.

Significant changes in average solar wind speed between successive solar rotations have been noted by various observers throughout the last solar cycle [*Neugebauer and Snyder*, 1966; *Lazarus and Goldstein*, 1971; *Rosenberg et al.*, 1975]. A survey of a composite set of 1-AU solar rotation average solar wind speeds over the last solar cycle, using only those averages which included at least one third of the hours in a complete solar rotation, yielded changes ΔV_s in average speed between successive rotations ranging from 3 to 94 km/s, with an average change $\langle \Delta V_s \rangle$ of 31 km/s for 103 rotations (J. H. King, private communication, 1976). The average value of ΔV_s during the Pioneer 10 transit to 5 AU was 38 km/s.

Figure 5 shows the most probable Pioneer 10 field angles for each solar rotation plotted as a function of heliocentric distance, together with least squares fits to the Mariner 4 and 5 data [*Smith*, 1974; *Neugebauer*, 1975], for the two sector directions. Also shown are the theoretical spiral angles for a constant solar wind velocity of 360 km/s. The Pioneer 10 solar rotation data clearly illustrate the considerable variability with time. *Parker and Jokipii* [1976] have computed the radial gradient in $\langle B_\phi \rangle \langle V_r \rangle$ using the Pioneer 10 solar rotation average magnetic field and solar wind speed data and have found a radial dependence of $r^{-1.10\pm0.08}$ compared with the best fit power law dependence $r^{-1.29\pm0.06}$ resulting from B_ϕ data without regard for speed variations [*Rosenberg et al.*, 1975]. To be completely rigorous, $\langle B_\phi V_r \rangle$ should be tested, however.

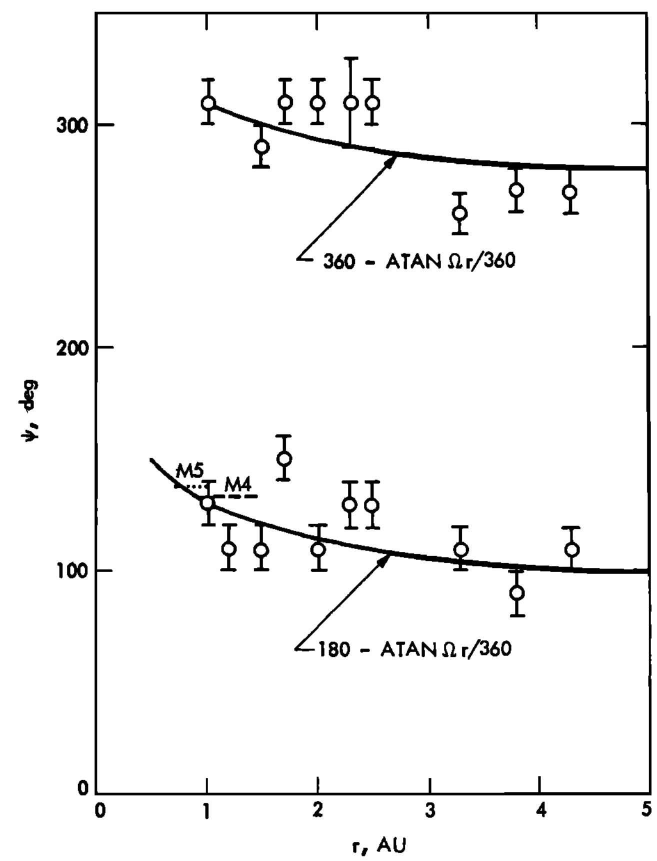

Fig. 5. Radial variation of the most probable values of the direction angle of the IMF observed by Pioneer 10 during a solar rotation. The short curves are the best fits to this angle computed from Mariner 4 and 5 data. The solid curves are the angles corresponding to the spiral model for a solar wind velocity of 360 km/s.

The good agreement with the Parker model of the best fit to the data in Figure 3 may reflect that a least squares fit to such a composite data set may tend to minimize the effects of time variations within and between the individual data sets from the different spacecraft. We conclude that although the individual sets of measurements suggest that the B_ϕ gradient is steeper than r^{-1}, there is also evidence that r^{-1} may still be the best large-scale long-term average radial gradient when proper consideration is given to the relevant temporal variations.

Normal Component Radial Gradient

As was indicated previously, in the Parker model there is no field component perpendicular to the solar equatorial plane in that plane because of symmetry. Although all measurements published to date have been taken in the region near the SEQ plane, the normal component is usually observed to be nonzero, and the various investigations of the radial distance variations of the IMF have included the determination of the radial gradient in that component as well. For Mariner 10 the measurements used were of $|B_n|$, the normal to the SEQ plane. The other investigators have all used measurements of $|B_\theta|$, the component of the field in the direction of the spherical coordinate unit vector $\hat{\theta}$. The component B_n is equivalent to B_θ in the SEQ plane, and for the majority of the measurements published to date, B_n and B_θ would not be expected to differ by more than a few tenths of a gamma at 1 AU.

The least squares fit results are given in Table 4. Note that there is considerable variation in the values of A_θ, the coefficient of the power law fit, which estimates the value of $\langle |B_\theta| \rangle$ at 1 AU. The results for those cases where B_θ values were used imply a large value for that component on average at 1 AU. Such large values are significant, considering that the expectation from simple theory is exactly zero. *Coleman* [1976] has demonstrated that time variations in the solar magnetic field may produce IMF B_θ components which are nonzero for significant periods and even at times comparable in magnitude to the B_ϕ component. However, systematic errors may also be important for the B_θ component results in all cases; for example, the uncertainty in the spacecraft field component in the B_θ direction could result in significant errors in measurements of B_θ for any of the spacecraft.

Some consistency is seen in the gradient results in Table 4. The $r^{-1.40\pm0.63}$ distance dependence obtained in the Mariner 10 analysis compares well with the Pioneer 10 dependence [*Rosenberg et al.*, 1975] as well as with that determined from the Mariner 4 quiet data set.

Field Magnitude Radial Gradient

In a preliminary study of Pioneer 10 measurements, *Smith* [1974] found that the solar rotation most probable values of field magnitude exhibited roughly the radial dependence predicted by Parker's theory, although there were departures at each end of the distance range. As was discussed in the section on the B_ϕ gradient, there were temporal variations during the

TABLE 4. Normal Component Distance Dependence $B_\theta = A_\theta r^{C_\theta}$

Spacecraft	Radial Distance Range, AU	A_θ	C_θ	Remarks
Mariner 5	0.66–1.0	2.38 ± 0.21	−2.05 ± 0.02	B_θ (spherical coordinates)
Mariner 10	0.46–1.0	0.82 ± 0.31	−1.40 ± 0.63	B_n (SEQ coordinates)
Mariner 4	1.0–1.5	1.72 ± 0.17	−1.27 ± 0.03	B_θ (spherical coordinates)
		1.59 ± 0.11	−1.38 ± 0.02	
Pioneer 10	1.0–5.0	2.93 ± 0.31	−1.41 ± 0.12	B_θ (spherical coordinates)

analysis period which could have contributed to a lack of agreement with the steady state theory.

Musmann et al. [1977] have shown in a preliminary analysis that the combined Helios and Pioneer 10 solar rotation field magnitude data are consistent (at least between 0.3 and 3 AU) with the Parker model variation $B = 5(1 + r^2)^{1/2}/r^2$. Mariner 10 data between 0.46 and 1 AU yielded the similar best fit result $B = 4(1 + r^2)^{1/2}/r^2$. Power law models have been fitted to the magnitude data also, the result being, for example, a dependence on heliocentric distance of $r^{-1.87\pm0.07}$ for Pioneer 10 and $r^{-1.65\pm0.16}$ for Mariner 10. Since the Parker model does not predict a simple power law distance dependence for the field magnitude, it is not surprising that there is not better agreement between these results, and their usefulness is at best questionable.

Within any given solar rotation, considerable structure is usually seen in the magnitude of the interplanetary field as a function of time. As has been indicated in preceding sections, considerable variability is introduced into the IMF by high-speed solar wind streams. High-speed streams were first identified in the Mariner 2 data of 1962 [*Neugebauer and Snyder,* 1966]. Various correlations of plasma and magnetic field measurements on Imp 1 [*Wilcox and Ness,* 1965], Vela 3 [*Ness et al.,* 1971], and Mariner 2 [*Coleman et al.,* 1966] have shown that each high-speed stream has a predominant magnetic polarity, one or more streams occurring within a single magnetic sector. The magnetic field magnitude is found to be enhanced in the leading part of a stream, which is the high-density (compression) region, and reduced in the trailing part, which is the low-density (rarefaction) region. These features have been predicted in dynamical models by *Sakurai* [1971], *Matsuda and Sakurai* [1972], *Urch* [1972], and *Nakagawa and Wellck* [1973]. *Burlaga and Barouch* [1976] and *Barouch* [1977] have shown that this is primarily a kinematic effect.

The magnitude enhancement of the field in the leading portion of a typical stream increases nonlinearly with increasing r as the fast plasma tends to overtake the slow plasma. This is illustrated in Figure 6, which shows a contour map on the ecliptic plane of field magnitude enhancements related to the values of $B(r, \phi)$ that would be measured in the absence of a stream [*Burlaga and Barouch,* 1976]. This predicts that between 0.5 and 1 AU an increase in the field in the leading part

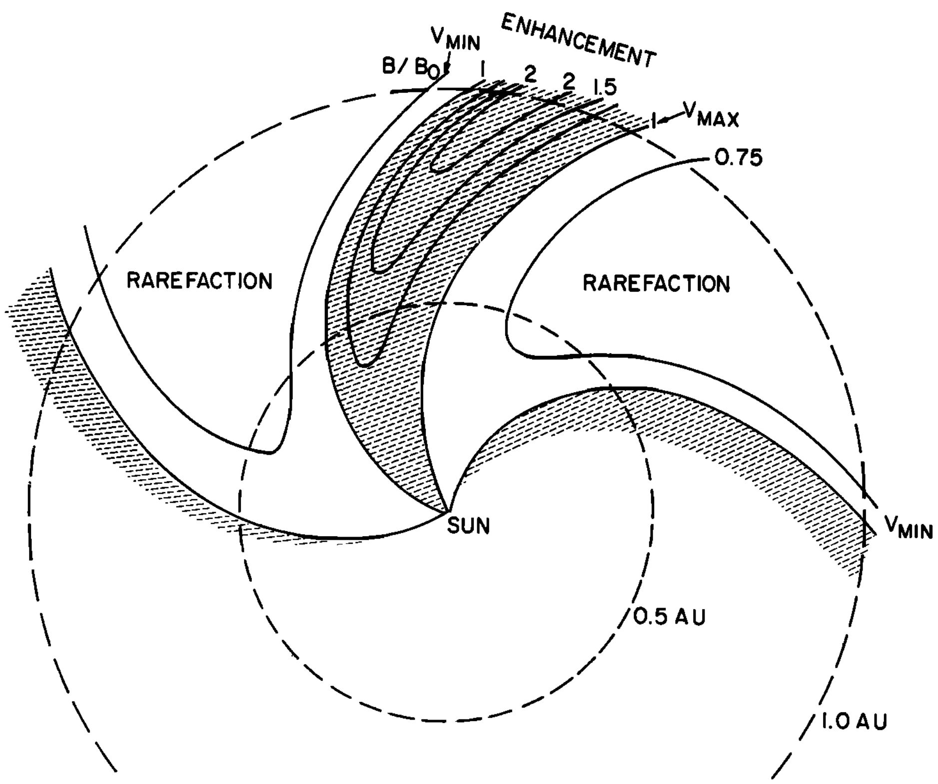

Fig. 6. Burlaga-Barouch ecliptic plane contour map of $B/B_{a=0}$ for a representative, or 'standard,' stream. $B_{a=0}$ is the value of $B(r, \phi)$ that would be measured in the absence of a stream. This shows growth of field magnitude enhancement in high-speed streams with radial distance from the sun out to 1 AU.

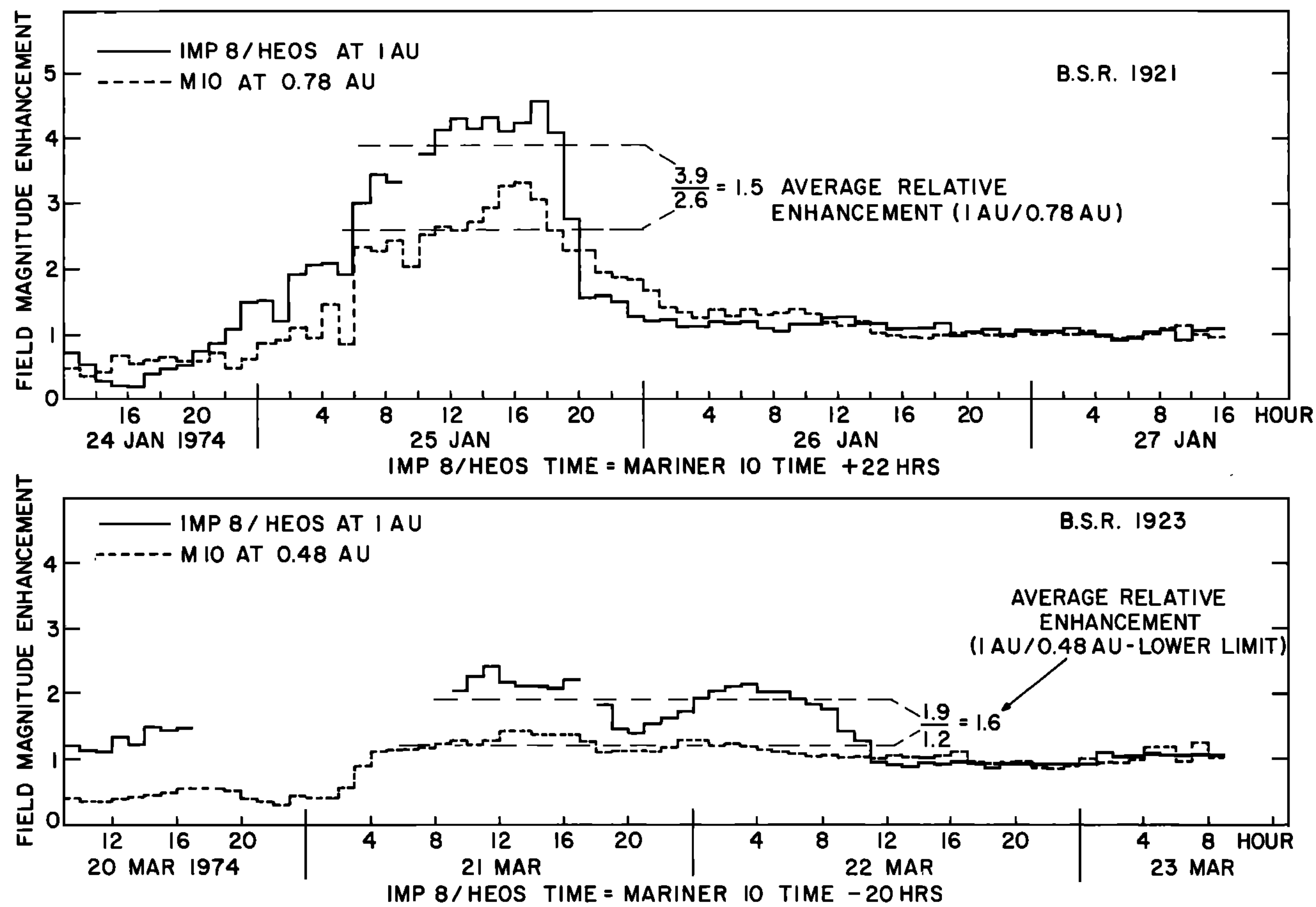

Fig. 7. Observations of the field magnitude enhancement in a recurring stream at two heliocentric distances by Mariner 10 and the same stream profile at 1 AU by either Imp 8 or Heos (1 and 2, combined data set). Enhancements are computed in each case relative to the average of a 12-hour poststream interval (the last 12 hours on each data plot). Average relative enhancements support the model of enhancement growth over the radial distance range of observation. Because of the gap in interplanetary observations by both Imp 8 and Heos during the later period, the relative enhancement for the case shown in the lower panel is a lower limit.

of a typical stream of almost a factor of 2 could be expected. Figure 7 [*Behannon,* 1976*a*] shows hourly average data from Mariner 10 and from Imp 8 in earth orbit, with small gaps being filled in by Heos data (made available by P. C. Hedgecock through the National Space Science Data Center). Two cases in which the same stream-associated magnitude enhancements were observed at widely separated heliocentric distances are shown, one when Mariner 10 was at 0.78 AU and the other at 0.48 AU. The sets of observations have been normalized by the average poststream field magnitude levels. Although this compares the change in magnitude enhancement for only two cases, in both of them the enhancement is seen to be less at the spacecraft nearer the sun, as was predicted by theory, and a ratio of enhancement at 1 AU to enhancement at Mariner 10 of at least 1.5 is found in both cases. There were more high-speed stream observations by Mariner 10 during its primary mission, but crucial data gaps occurring simultaneously at both Imp 8 and Heos make interpretation difficult.

MESOSCALE AND MICROSCALE PHENOMENA

The term 'fluctuation' has been used to describe almost every type of variation of the magnetic field relative to an average background field. As discussed by *Coleman* [1968], *Scarf* [1970], *Burlaga* [1972], *Smith* [1973*a, b*], and others, the vector field time series usually contains a mixture of stream-stream interactions, shocks, directional discontinuities, hydromagnetic waves, and higher-frequency phenomena, although the power spectrum may be dominated by one particular type of variation at a given time, the dominant type changing with time. Magnetic field time variations with periods of a few hours or less appear to be produced predominantly by waves and discontinuities, while those with periods which are relatively much longer are caused by large-scale stream interaction effects [*Coleman,* 1968; *Goldstein and Siscoe,* 1972] or by changes in solar wind stream source region conditions. The short-period phenomena are related to the large-scale structure in the sense that the colliding streams in interplanetary space probably generate at least some of the observed microscale features.

As introduced by *Burlaga* [1972], the term microscale includes events and/or structures with an observed duration or Doppler-shifted period of ≤ 1 hour or a scale length of $\lesssim 0.1$ AU. This includes directional discontinuities and shock waves and hydromagnetic and electromagnetic waves with periods of less than 1 hour ($f \geq 2.8 \times 10^{-4}$ Hz). Mesoscale phenomena (periods of 1 to ~100 hours) include long-period Alfvén waves, observed initially in the Mariner 2 data [*Unti and Neugebauer,* 1968; *Coleman,* 1967, 1968] and analyzed extensively by *Belcher et al.* [1969] and *Belcher and Davis* [1971]. Magnetic field fluctuations in the microscale and mesoscale frequency regimes have been most often studied through the computation of variances or root mean square deviations of the field magnitude and the field components (both combined, as in the Pythagorean mean, and separate). Additional techniques which have been employed are power spectrum analysis, which gives the frequency dependence of the fluctuations, and the correlation of changes in the field with changes in solar wind velocity. The latter approach has been used in attempts to identify Alfvén waves in the interplanetary medium [*Coleman*, 1966; *Belcher et al.*, 1969; *Belcher and Davis*, 1971; *Belcher and Burchsted*, 1974; *Burlaga and Turner*, 1976]. This review will consider only those experimental results which relate specifically to the variation of IMF fluctuations with heliocentric distance.

Studies of the changes in the magnetic field fluctuation spectra with heliocentric distance can indicate whether or not the interplanetary field is becoming more or less irregular on a given time (or, equivalently, length) scale with increasing radial distance [*Smith*, 1974]. This feature is important for attempts to locate the source regions of particular types of fluctuations and to determine the degree of damping of such fluctuations as they propagate in the solar wind. Interest in the damping of fluctuations has been motivated largely by discrepancies between theory and observation in studies of the heating, acceleration, angular momentum, and thermal anisotropy of the solar wind [*Hollweg*, 1975].

IMF fluctuations are of further importance in cosmic ray propagation theory. It is believed that they play the role of scattering centers for the particles, producing a spatial gradient in cosmic ray intensities as well as a modulation with solar activity (see reviews by *Jokipii* [1971], *Völk* [1975*b*], and *Moraal* [1976]). The radial variation of magnetic field fluctuations causes a corresponding variation of the particle diffusion, with an obvious bearing on the development of models of particle propagation. Studies to date (*Jokipii* [1973] and *Völk et al.* [1974]; also see *Völk* [1975*b*]) assume that only Alfvén waves of solar origin contribute significantly to cosmic ray scattering and use a WKB approximation for the spatial dependence of the wave characteristics. The results and limitations of these computations will be discussed later.

There have been several attempts at theoretical calculation of the radial variation of the relative magnetic field fluctuation amplitude, and predictably, results have varied as the complexity of the solar wind model used for the computation has increased. For a spherically symmetric solar wind, neglecting the effects of rotation and assuming that the solar wind behaves as an ideal gas, *Parker* [1965] and *Dessler* [1967] predicted that relative magnetic field fluctuations $\Delta B/B$ due to small-amplitude undamped waves would increase with distance from the sun up to a shock-limited ratio of $\Delta B/B = 1$. Here ΔB was taken as the magnitude of the perturbation $\delta \mathbf{B}$ in the azimuthal (ϕ) direction of a radial magnetic field of magnitude $B(r) = B_0(a/r)^2$. Parker suggested that such an increase would occur, under the given conditions, for compressional fast-mode waves as well as for transverse Alfvén waves. In the limiting case (particle pressure being ignored in relation to magnetic pressure), $\Delta B/B \propto r$. Thus, for example, the relative field fluctuation amplitude would be expected to double between the orbits of Mercury and earth.

In contrast, recent studies using more physically realistic models of the solar wind and IMF predict that the decreasing gradient in ΔB with increasing radial distance from the sun is sufficiently steep to limit $\Delta B/B$ to values less than one, even without damping. *Whang* [1973] constructed a model for the propagation of Alfvén waves of arbitrarily large amplitude in a spherically symmetric solar wind and spiral IMF. This model was based on the two-region solar wind model of *Whang* [1972], which included thermal anisotropy and the spiral field structure. This wave propagation model predicted that in the vicinity of 1 AU, Alfvén wave amplitudes would fall off with increasing heliocentric distance approximately as $r^{-3/2}$. It further predicted a maximum of approximately 0.5 in the relative amplitude ($|\Delta \mathbf{B}|/B$) of Alfvénic fluctuations near 1 AU and an asymptotic $r^{-1/2}$ variation at large heliocentric distances. The predicted radial distance dependence of $|\Delta \mathbf{B}|/B$ (labeled $\bar{b}/B_0$) is shown in Figure 8.

Hollweg [1974] used a simple analysis based on energy conservation to derive expressions for the spatial variation of the amplitudes of outwardly propagating undamped Alfvén waves of arbitrary amplitude in the solar wind. No special assumptions were made concerning the solar wind geometry or direction of propagation. He predicted that the energy densities in the transverse Alfvén mode should fall off as $\rho^{3/2}$, where ρ is the mass density of the plasma. *Belcher and Burchsted* [1974] concluded, on the basis of Hollweg's formulation, that if ρ falls off approximately as r^{-2} near 1 AU, then the Alfvén wave amplitude $|\Delta \mathbf{B}|$ should fall off approximately as $r^{-3/2}$, in agreement with Whang's result.

Observed Distance Dependence of IMF rms Deviations

It is customary in the analysis of magnetic field data from space to determine the intensities of fluctuations (in the form of rms deviations, variances, or power spectral density) in both the magnitude of the field and the individual orthogonal components of the field. Purely compressive mode waves produce fluctuations in the magnitude $|\mathbf{B}|$ of the magnetic field but not in its direction. In the case of pure Alfvén waves there are oscillations in direction but not in $|\mathbf{B}|$, while fast-mode waves produce oscillations in both direction and $|\mathbf{B}|$. In the latter category fall the large-amplitude elliptically polarized waves identified by *Burlaga and Turner* [1976]. They are not pure Alfvén waves because $\delta|\mathbf{B}| \neq 0$, but one cannot further determine from the available data whether they are fast-mode waves propagating nearly along B, nonlinear elliptically polarized Alfvén waves coupled to the fast mode, or possibly some other mode or combination of modes [*Burlaga and Turner*, 1976]. *Barnes* [1976] has demonstrated that purely Alfvénic plane-polarized large-amplitude disturbances cannot exist.

Fluctuations in field direction are determined from the field component fluctuations. However, the coordinate system is important for the interpretation of component measurements unless an invariant quantity such as the Pythagorean mean of the three orthogonal components is computed:

$$\sigma_c = (\sigma_x^2 + \sigma_y^2 + \sigma_z^2)^{1/2} \quad (5)$$

Although the Pythagorean mean also includes magnitude fluctuations, it is usually representative of purely directional fluctuations to a good approximation because the power in field direction fluctuations has been found in all IMF measurements to be factors of 2–10 or more greater than that in field magnitude fluctuations [*Coleman et al.*, 1969; *Rosenberg and Coleman*, 1973; *Blake and Belcher*, 1974; *Rosenberg et al.*, 1975; *Behannon*, 1976*a*; etc.]. Because of the interest in determining the relative fluctuation levels both parallel and perpendicular to the magnetic field, some studies have transformed the observations to a coordinate system in which one axis is along the average direction of the field vector [e.g., *Coleman et al.*, 1969]. Then variances parallel and perpendicular to the mean field are computed.

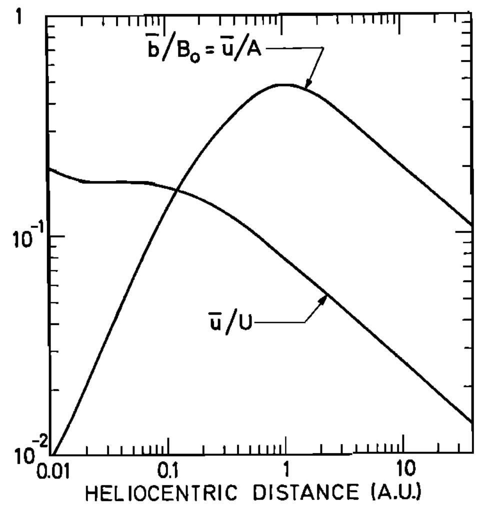

Fig. 8. Variation of the relative intensity $\bar{b}/B_0$ of Alfvénic fluctuations with radial distance from the sun, as predicted by the model of *Whang* [1973] for the propagation of arbitrary, large-amplitude, nonmonochromatic microscale waves of any polarization in a spiral interplanetary field.

One must be cautious about interpreting interplanetary directional fluctuations strictly in terms of the presence of wave modes unless tangential discontinuities or their effects are excluded from the analysis, either by judicious selection of data or by subtracting off their contributions. *Sari and Ness* [1969, 1970] have demonstrated that these discontinuities can be a major contribution to the overall level of microscale fluctuations.

The Pioneer 10 mission to Jupiter provided the first opportunity to determine the heliocentric distance dependences of fluctuations over a large range of distances. The initial analysis of the most probable daily variances for each solar rotation during the mission suggested that $\sigma^2(B_r)$ roughly followed an r^{-4} dependence on radial distance [*Smith,* 1974]. Taken with the observed r^{-2} dependence for B_r, this further suggested that $\Delta B_r/B_r$ was approximately independent of distance from the sun for the distance range studied. In a more complete analysis using 3-hour daily and solar rotation variance averages, generally weak dependences on heliocentric distance were found for both field magnitude and component fluctuations relative to the mean field magnitude [*Rosenberg et al.*, 1975]. The weakest gradient was found to be along the radial direction, consistent with the preliminary conclusion by Smith. The specific distance dependences found in each case are summarized in Table 5, together with those computed from Mariner 4 and Mariner 10 measurements.

An additional computation on Mariner 4 data yielded

$$\sigma_8(b_x)/\langle B\rangle = 0.33r^{0.75} \tag{6}$$

where $\sigma_8(b_x)$ was a measure of the power in fluctuations parallel to the mean field over solar rotation periods. This result, together with results obtained for the field magnitude, suggested a relative growth of compressional fluctuations with increasing radial distance [*Coleman et al.*, 1969]. These results were interpreted as indicating consistency with the Parker-Dessler theory predictions for undamped disturbances. A weaker relative decrease in fluctuations transverse to the mean field with increasing heliocentric distance was also found. From the combined results it was inferred that the compressive mode was becoming dominant and the Alfvén mode less significant as the distance from the sun beyond 1 AU increased. We shall return to this conclusion and its possible consequences shortly, when more supporting data are shown.

The Mariner 10 observations yielded measurements between 1 and 0.46 AU of the field component rms deviation σ_C, as defined by (5), and the field magnitude rms deviation σ_F [*Behannon,* 1976*a*]. The heliocentric distance dependences of these quantities relative to the field magnitude distance dependence, σ_C/F and σ_F/F, were determined by least squares fits to the daily averages of the hourly relative fluctuation data. The best fit distance dependences shown in Table 5 for Mariner 10

TABLE 5. Best Fit Power Law Results for Relative Field Fluctuation Distance Dependences

	3-Hour T				Daily D				Solar Rotation S			
	A	σ_A	C	σ_C	A	σ_A	C	σ_C	A	σ_A	C	σ_C
					Mariner 4							
$\sigma(B_r)/\langle B\rangle$												
All data	0.33	0.02	0.05	0.02	0.48	0.03	0.03	0.02	0.06	0.02	0.01	0.01
Quiet data	0.33	0.01	0.26	0.01	0.46	0.02	0.27	0.01	0.61	0.02	0.09	0.01
$\sigma(B_\theta)/\langle B\rangle$												
All data	0.36	0.02	0.25	0.02	0.48	0.02	0.13	0.01	0.52	0.03	0.12	0.02
Quiet data	0.40	0.02	−0.02	0.01	0.48	0.01	−0.02	0.01	0.50	0.03	0.05	0.01
$\sigma(B_\phi)/\langle B\rangle$												
All data	0.36	0.02	0.22	0.01	0.52	0.02	0.28	0.01	0.68	0.03	0.14	0.01
Quiet data	0.36	0.01	0.12	0.01	0.50	0.02	0.30	0.01	0.69	0.03	0.16	0.01
$\sigma(B)/\langle B\rangle$												
All data	0.15	0.01	0.56	0.01	0.26	0.02	0.75	0.02	0.43	0.04	0.50	0.03
Quiet data	0.16	0.01	0.38	0.01	0.28	0.02	0.70	0.02	0.39	0.02	0.71	0.01
					Pioneer 10							
$\sigma(B_R)/\langle B\rangle$	0.22	0.01	−0.08	0.06	0.35	0.02	−0.01	0.06	0.52	0.04	0.03	0.08
$\sigma(B_N)/\langle B\rangle$	0.30	0.01	−0.19	0.05	0.45	0.02	−0.09	0.04	0.58	0.06	0.08	0.13
$\sigma(B_T)/\langle B\rangle$	0.28	0.01	−0.23	0.05	0.46	0.01	−0.10	0.04	0.77	0.04	0.10	0.06
$\sigma(B)/\langle B\rangle$	0.10	0.01	−0.16	0.08	0.20	0.01	0.02	0.08	0.49	0.07	0.30	0.16
					Mariner 10							
$\langle\sigma(B_C)/\langle B\rangle\rangle_D$	0.41	0.01	−0.25	0.06								
$\langle\sigma(B)/\langle B\rangle\rangle_D$	0.09	0.01	0.36	0.13								

σ_A, σ_C are rms deviations of measured A, C values from best fit values.

suggest a slow increase in the amplitude of field magnitude fluctuations relative to the field magnitude with increasing heliocentric distance, while the relative directional fluctuation amplitude weakly decreases with increasing distance [*Behannon,* 1976*a*]. These results support some of the conclusions drawn from Mariner 4 and Pioneer 10 observations. Detailed differences may be due at least in part to different states of the interplanetary medium at the times of the various observations, although computational differences make direct comparison difficult.

To facilitate such a direct comparison of the various spacecraft observations of directional fluctuations, the individual Mariner 4 and Pioneer 10 relative (magnitude-normalized) distance dependences shown in Table 5 were evaluated at various values of radial distance between 0.5 and 5 AU, the assumption being that the measured dependences could be extrapolated beyond the actual ranges of observation. At each point of evaluation (i.e., for each value of r used) the three separate component results were combined in a Pythagorean mean according to

$$\left(\frac{\sigma_{cj}}{F}\right)_r = \left[\sum_i \left(\frac{\sigma_j(B_i)}{\langle B\rangle}\right)_r^2\right]^{1/2} \qquad (7)$$

where for Mariner 4, $i = r, \theta, \phi$ and for Pioneer 10, $i = R, N, T$. This was carried out in both cases for $j = S, D, T$, where S is the solar rotation and D and T are the daily and 3-hourly rms deviations, respectively. The relative magnitude distance dependences were also similarly evaluated for each time scale. The comparative curves are plotted in Figures 9 and 10 along with the σ_c/F and σ_F/F distance dependences found by Mariner 10. The curves are shown as solid lines only over the actual ranges of observation and as extended dashed lines outside those ranges for purposes of comparison and interpretation.

These figures suggest the following general radial distance characteristics for the magnetic field fluctuations.

1. The relative field component fluctuation amplitude (σ_c/F) increases as the fluctuation frequency decreases at all distances; the fluctuation amplitudes for periods of >1 day become greater than the mean field strength.

2. The rate of change of σ_c/F with increasing distance generally becomes less positive as frequency increases.

3. The σ_F/F data generally exhibit characteristics similar to those given in points 1 and 2 above, although there are some exceptions.

4. Mariner 4 and Pioneer 10 solar rotation statistics suggest that both σ_c/F and σ_F/F increase with increasing distance at that time scale.

5. For every pair of corresponding σ_c/F and σ_F/F curves for a given spacecraft, except for the Pioneer 10 3-hour data, σ_F/F increases at a faster rate (or decreases at a slower rate) with increasing heliocentric distance than σ_c/F.

The first of these conclusions agrees with expectations and

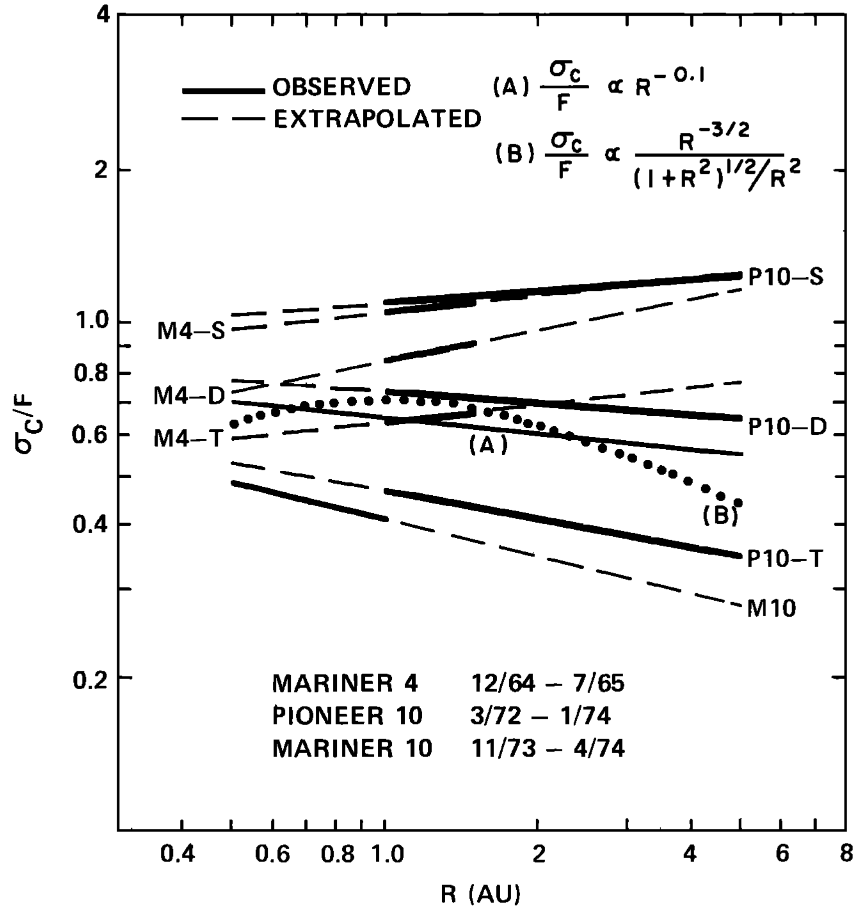

Fig. 9. Variation with heliocentric distance of the magnetic field directional fluctuation amplitude (see text) relative to the total field variation computed from observations of IMF rms deviations over solar rotation (S), daily (D), and 3-hour (T) averaging periods by Mariner 4 and Pioneer 10 and for 1-hour averages by Mariner 10. Gradients have been extrapolated to cover the range 0.5–5 AU in each case. Also shown for comparison are (1) an r^{-1} variation with distance (solid curve) and (2) a distance dependence calculated from an $r^{-3/2}$ fluctuation amplitude dependence and the observed (Parker model) field magnitude radial distance dependence (dotted curve).

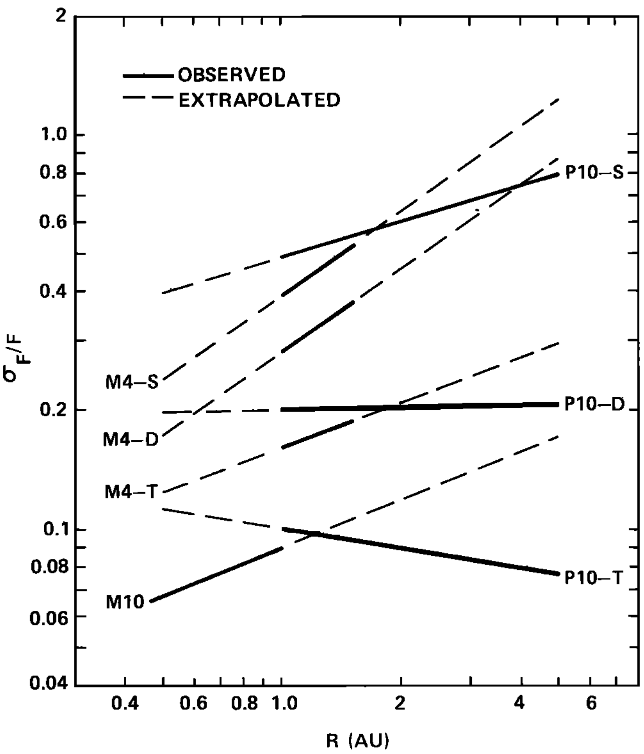

Fig. 10. Variation with heliocentric distance of magnetic field magnitude fluctuation amplitude relative to the total field variation computed from observations by three spacecraft. Gradients again have been extrapolated as those in Figure 9. Note that the longest-period fluctuations are approximately 4 times greater in relative amplitude than the shortest-period fluctuations at 1 AU.

with the results from spectral analyses and other studies. The second point simply illustrates the general decrease in relative directional fluctuation amplitudes with increasing distance except for the long-period fluctuations. From point 4 we conclude that there is generally an increase in the relative amplitude of large-scale stream-dominated fluctuations with increasing heliocentric distance for both the magnitude and the direction of the field. The fifth point provides support for the conclusion by *Coleman et al.* [1969] that the compressional mode is gaining in importance at greater radial distances relative to the directional fluctuation modes, although one must be cautious about interpretation of the field component fluctuation observations, since the studies summarized here did not attempt to separate the contributions due to propagating fluctuations from those due to static convected structures.

The fluctuations with periods of less than 1 day include the contributions from Alfvén waves. The Whang and Hollweg models for the case of little or no damping suggest that the (unnormalized) Alfvén wave amplitude varies as $r^{-3/2}$ near 1 AU. *Belcher and Burchsted* [1974] studied the radial dependence of Alfvén wave amplitudes using data from Mariner 4 and 5 and compared the results to the dependence calculated using Hollweg's model. The sum of the 3-hour variances of the three components of the field was taken as a measure of the integrated power in field fluctuations over frequencies of $\geq 9.2 \times 10^{-5}$ Hz. Data contaminated by the effects of large macroscale gradients in velocity or field strength were removed. Averages over intervals of radial distance are shown in Figure 11, the break at 1 AU indicating the separation between the two sets of measurements used in the study. They concluded that the results were consistent with nonlocally generated waves being swept away from the sun with little or no damping. That is, radial distance dependences of close to $r^{3/2}$ were found from both spacecraft for the Alfvén wave amplitude. When it is combined with the 'best fit' power law field magnitude gradient observed by both Mariner 10 and Pioneer 10, $F \propto r^{-1.4}$, the $|\Delta \mathbf{B}| \propto r^{-3/2}$ dependence gives $|\Delta \mathbf{B}|/B = \sigma_c/F \propto r^{-0.1}$. This is only slightly steeper than the gradient shown in Figure 9 from the Pioneer 10 daily relative rms (P10-D). We know, however, that the Parker model radial distance dependence of the field magnitude is not a simple power law. The dotted curve in Figure 9 shows σ_c/F versus R, an $r^{-3/2}$ dependence for the fluctuation amplitudes being assumed, with normalization by the Parker model magnitude dependence and multiplication by a suitable scaling factor for comparison. This curve suggests that the relative fluctuation versus R may not be best represented by a power law.

On the basis of the Parker-Dessler fluctuation model and the positive gradient found for $\sigma_s(B)/\langle B\rangle$ (equation (6)) from Mariner 4 observations, it was estimated by *Coleman et al.* [1969] that the shock-limited ratio of $\Delta B/B = 1$ would occur at a distance $r = 4.3$ AU. It was not observed at that distance by Pioneer 10 and 11, however. On the basis of the gradient computed from Pioneer 10 measurements it was estimated that the limit could occur at a distance of 10.7 AU if the model is correct [*Rosenberg et al.*, 1975]. These estimates were based on the very low frequency compressional fluctuations associated with solar wind stream interactions. Although the Mariner 4 and 10 observations at higher frequencies were consistent with a growth in the amplitude of field magnitude fluctuations relative to the field strength with increasing distance, the Pio-

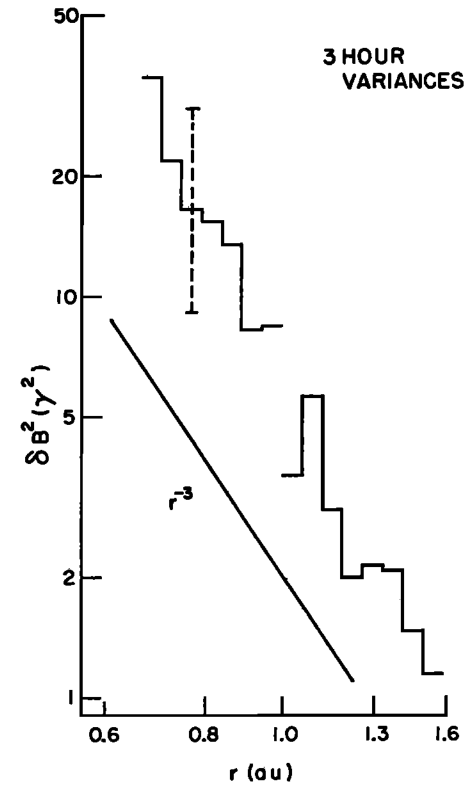

Fig. 11. Averages of the logarithm of 3-hour variances computed from Mariner 4 and 5 observations for 15 equal intervals of the logarithm of radial distance between 0.67 and 1.58 AU. The vertical dotted line is representative of the standard deviations about the average in each interval. The break in the curve separates the data from the two spacecraft.

neer 10 curves in Figure 10 suggest that the relative amplitude of compressive fluctuations with periods of only a few hours or shorter remains small in comparison with unity at all distances.

Radial Variation of IMF Power Spectra

The application of power spectrum analysis to the study of magnetic field fluctuations yields not only the power in fluctuations along various directions in space and in the total field but also the variation of that power with frequency. Such an analysis can be further augmented to provide coherence and phase information concerning the fluctuations and hence can be a valuable tool in the identification of wave modes in the data. Published power spectral studies of the IMF include *Coleman* [1966, 1967, 1968], *Ness et al.* [1966], *Siscoe et al.* [1968], *Sari and Ness* [1969], *Coleman et al.* [1969], *Russell et al.* [1971], *Sari* [1972, 1975], and *Blake and Belcher* [1974].

The first IMF power spectra that were computed that show the variation in field fluctuation power with radial distance utilized Mariner 2 data [*Coleman,* 1968]. A general increase in power across the spectrum (from 4×10^{-6} to 10^{-2} Hz) with decreasing radial distance from 1 to 0.87 AU was found for the total field, and increased power at the lowest frequencies was found for the radial component. The total power in the field magnitude increased by almost a factor of 2. Figure 12 is an example of spectral variations of the fluctuations in the total field B and radial component B_r. These spectra in the frequency range 10^{-6}–10^{-2} Hz were computed from Mariner 4 data [*Coleman et al.,* 1969]. The dashed curves represent the spectra taken nearest the sun (1 AU), and the solid curves represent the spectra computed from measurements at 1.43 AU. For both the total field and the radial component one sees a decrease in power with increasing radial distance at almost every spectral estimate. However, a greater decrease in integrated power was found for the B_r component than for the total field. In addition, decreases by more than a factor of 2 in integrated power were found for the B_θ and B_ϕ components. This was interpreted as additional support for Coleman's conclusion, drawn from the variances of the field and its components, that the compressive mode increased in dominance over the transverse fluctuations with increasing radial distance between 1 and 1.5 AU.

Blake and Belcher [1974] have computed power spectral densities for IMF fluctuations with frequencies between 1.16×10^{-5} Hz and 2.96×10^{-3} Hz using Mariner 4 and 5 168.75-s averages, with 8 days of data per spectrum. Once again, except for a general decrease in the overall power level with distance from the sun, these spectra show no striking dependence on heliocentric distance between 0.7 and 1.6 AU. Figure 13 shows the total power in components (trace of the power spectral matrix) at a frequency of 3.7×10^{-4} Hz, corresponding to a period of 45 min, as a function of radial distance. No attempt has been made to remove the effects of the high levels of fluctuation in stream-stream interaction regions. The general decrease in power with increasing distance can be seen, however. The total power in components was found to be usually an order of magnitude greater than that in field strength at all frequencies, and the power in the direction of maximum variation was found to be a factor of 2–3 greater than that in the minimum fluctuation direction. Most of the combined component (trace) spectra show a distinct break at a frequency of about 10^{-4} Hz [*Jokipii and Coleman,* 1968], with the falloff of the total power in components above that frequency roughly as $f^{-1.6}$ or slightly faster and below that frequency as $f^{-1.2}$ or slightly faster.

Figure 14 is a composite display showing spectra computed from Mariner 10 42-s, 1.2-s, and 40-ms data at three different distances from the sun [*Behannon,* 1976*a*]. One sees once again the generally observed increase in power with decreasing radial distance except at the lowest frequency estimate in the case of spectra computed at 0.6 and 0.5 AU and at the highest frequencies observed. In addition, there is a steepening of the spectrum at frequencies above about 0.4 Hz with decreasing distance. All of the spectra computed thus far in this study tend to support these characteristics of generally increasing power with decreasing distance at all frequencies up to several hertz, accompanied by a steepening fall in the spectrum at higher frequencies. A number of spectra computed for varying disturbance conditions have been examined, and one finds larger variations in power with disturbance state than with distance over the distance range 1–0.46 AU. In most cases the power in the field magnitude is roughly an order of magnitude less than that in the components below the frequency at which the steep falloff occurs. *Russell* [1972] has predicted that the slope of the IMF spectrum should be steeper than f^{-2} above 1 Hz, and on the basis of search coil observations by *Holzer et al.* [1966], *Coleman* [1968] suggested that between 0.2 and 2 Hz the spectral slope should be $f^{-3.6}$. The Mariner 10 results support those predictions at radial distances of less than 1 AU.

A comparison has been carried out of fluctuations originating at the same solar longitude but observed at different heliocentric distances by Imp/Heos at 1 AU and Mariner 10 between 0.5 and 1 AU [*Behannon and Sari,* 1977]. The preliminary results suggest that, at least over the frequency range 10^{-4}–10^{-2} Hz, there is little or no change with radial distance of the power in field component fluctuations (as given by the trace of the spectral density matrix) normalized by the total field magnitude. This is consistent with the generally weak gradient found for the rms deviation relative to the field strength.

Directional Discontinuity Distance Dependence

Directional discontinuities (DD) in the IMF have been studied and described in varying degrees of detail by *Ness et al.* [1966], *Colburn and Sonett* [1966], *Burlaga and Ness* [1968, 1969], *Siscoe et al.* [1968], *Belcher and Solodyna* [1975], *Burlaga* [1969, 1971*a, b*], *Turner and Siscoe* [1971], *Smith* [1973*a, b*], and others. These studies have shown that discontinuities pass a spacecraft at the rate of approximately one per hour at 1 AU. Both tangential and rotational discontinuities have been identified in the solar wind [*Smith,* 1973*a, b*; *Martin et al.,* 1973; *Solodyna et al.,* 1977; *Burlaga et al.,* 1977], with a predominance of tangential discontinuities in quiet low-speed regions.

From studies of Pioneer 6 data, *Burlaga* [1971*a*] demonstrated a possible radial gradient in the DD occurrence rate. Burlaga found 0.7 discontinuities per hour at 0.82 AU, 0.8 at 0.91 AU, and 1.1 at 0.98 AU. He cautioned, however, that the higher rate nearer 1 AU could be due in part or entirely to better and more continuous data coverage at 1 AU. He further concluded that the Pioneer 6 field and plasma data were not consistent with directional discontinuities originating primarily in the collision of fast streams with slower plasma, since their occurrence rate was only slightly higher in regions of increasing bulk speed than elsewhere.

From an analysis of Pioneer 8 data, *Mariani et al.* [1973]

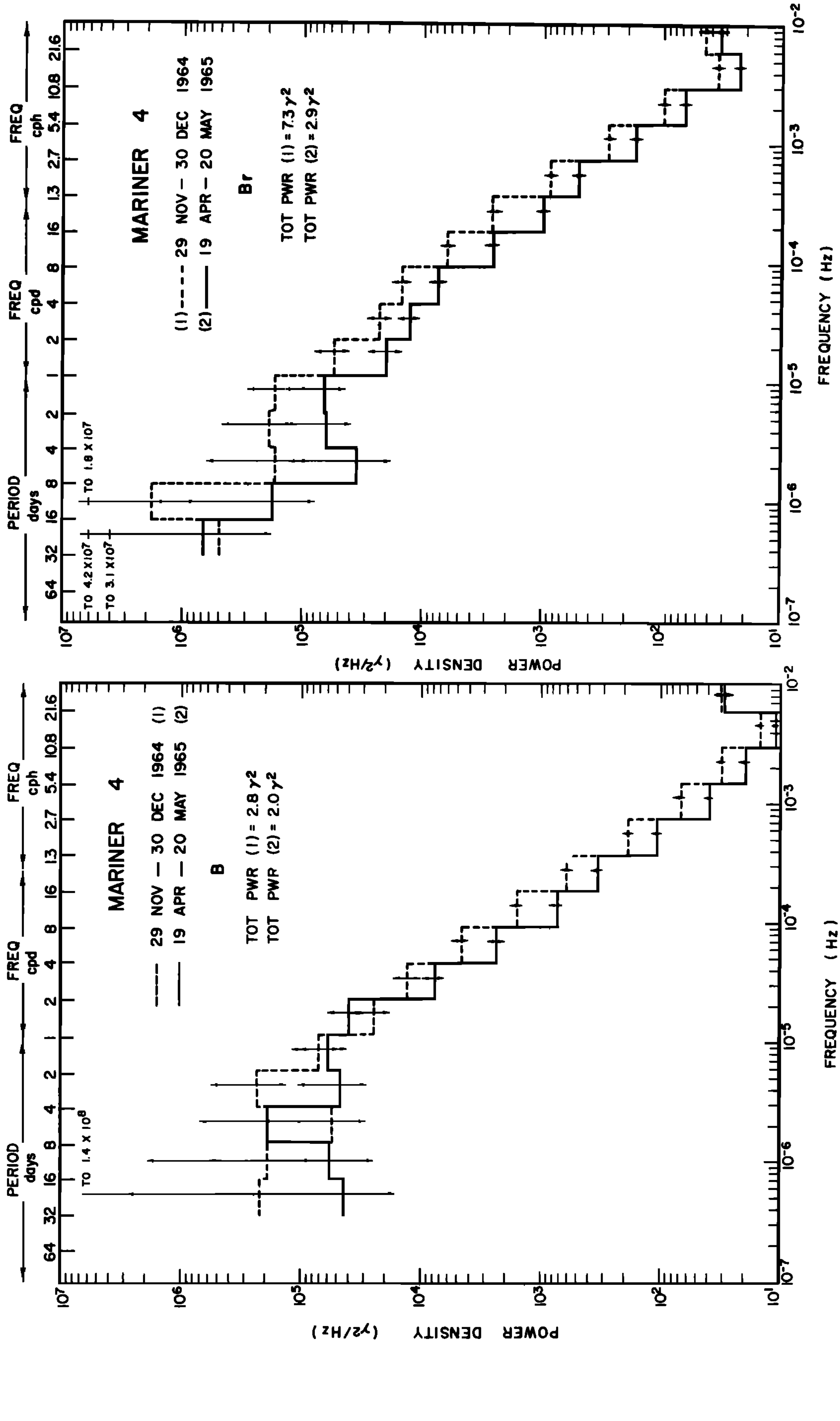

Fig. 12. Plots of power density spectra computed from Mariner 4 total magnetic field (left) and radial component (right) measurements over 32-day intervals near 1 AU (dashed curve) and 1.5 AU (solid curve).

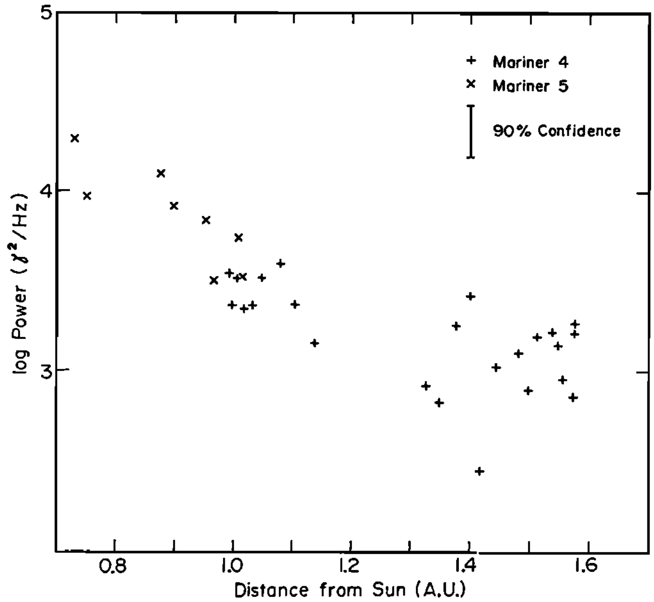

Fig. 13. A plot of the total power in field components (see text) at a frequency of 3.7×10^{-4} Hz as a function of radial distance from the sun in astronomical units, using both Mariner 4 and 5 spectra, as indicated by the symbols.

reported a possible inverse relation between radial distance and the occurrence rate of discontinuities. The linear best fit to the observations suggested a rather steep gradient, however, of 16 discontinuities/h/AU over the small range of 0.05 AU that was covered by the measurements. An alternative explanation in terms of a variation with heliographic latitude was porposed. A later, more extensive analysis using two years (1968 and 1969) of Pioneer 8 data provided additional evidence that significantly more discontinuities were being observed when Pioneer 8 was at higher solar latitudes [*Mariani*, 1975].

The results of an initial survey of the occurrence rate of directional discontinuities observed by Mariner 10 over a heliocentric distance range of 0.54 AU for 5 months [*Behannon*, 1976*a*] is shown in Figure 15. The occurrence rate is given as daily average number per hour and is plotted as a function of heliocentric distance in astronomical units. Even though there is considerable scatter in the data, a clear increasing trend with decreasing heliocentric distance is seen. As is shown, a nonlinear best fit results in a power law dependence of $r^{-1.28\pm0.35}$. Considerable structure can be seen in the occurrence rate data. Reference to the magnetic sector polarity pattern included across the top of the figure suggests that at least some of the structure in the occurrence rate is related to the large-scale structure of the interplanetary medium during this time. A comparison of the daily discontinuity counts with the hourly average field magnitude suggests that the maximum counts generally occurred during the few days immediately following the passage of compressed fields at the leading edges of high-speed streams. However, any conclusions regarding possible sources of these discontinuities must await additional analysis.

Also shown at the top of Figure 15 are the heliographic latitudes of the spacecraft during this mission. As in the case of Mariani's result, one could also argue in this case that the variation is one with latitude rather than distance. However, it is less likely with a predominately latitudinal dependence that the rate would have continuously increased as the latitude of the Mariner 10 spacecraft ranged between northern and southern extremes.

A similar dependence of the rate on distance has been found by *Tsurutani and Smith* [1975, 1976], using Pioneer 10 and 11 data. They indicate that a decrease by roughly a factor of 3 in the occurrence rate between 1 and 5 AU was found from Pioneer 11 observations, while a change by a factor of ~2 was seen by Pioneer 10. An increase in the 'thickness' of directional discontinuities by a factor of 5–10 between 1 and 5 AU was also found from the Pioneer measurements. Further analysis of the Mariner 10 data has revealed a change in discontinuity thickness between 0.46 and 1 AU that is consistent with the Pioneer 10 result [*Lepping and Behannon*, 1977].

Shock Profile Variation With Radial Distance

Interplanetary shock waves have been the subject of numerous studies, both theoretical and experimental. For general reviews, see *Burlaga* [1971*b*], *Hundhausen* [1972], and *Dryer* [1975]. It is generally believed that most interplanetary shocks observed at 1 AU originate at or near the sun, in particular, from a solar active region [*Gold*, 1955; *Hirshberg*, 1968; *Hirshberg et al.*, 1970; *Hundhausen*, 1970; *Hundhausen et al.*, 1970]. The majority of the shocks observed at 1 AU have been associated with solar flare events [e.g., *Chao and Lepping*, 1974]. They are seen much less frequently (roughly one per month) than directional discontinuities. Flare-associated shocks are predicted to propagate outward with a thickness of the order of a few proton Larmor radii during most of their passage through interplanetary space. From a study of the orientations of 22 well-determined shock normals in relation to the positions of the parent flares on the solar disk, *Chao and Lepping* [1974] suggested that a typical shock front propagating out from the sun has a radius of curvature of 1 AU at 1 AU, although any single case may vary considerably from this average.

Initial experimental evidence for the development of shock waves with heliocentric distance was presented by *Chao* [1973]. Comparing the magnetic field and plasma observations of shocklike structures at 0.98 and 0.85 AU by Mariner 5 with measurements made at 1 AU by Explorer 33, 34, and 35, Chao concluded that the observed structures were nonlinear magnetoacoustic waves that were in the process of steepening. The dominant change in the magnetic signature was the transition from a slow rise time in the field magnitude (of the order of 12 min) at 0.85 AU to a rapid rise time at 1 AU (<20 s). The 'shock' thickness at 0.85 AU was estimated to be >1000 proton Larmor radii (R_p), while at 1 AU it was $\lesssim 100\ R_p$. It has been suggested that shocks might form in the interplanetary medium as a result of the steepening of large-scale solar wind streams [*Parker*, 1961; *Dessler and Fejer*, 1963; *Sonett and Colburn*, 1965; *Razdan et al.*, 1965; *Formisano and Chao*, 1971; *Hundhausen*, 1972; etc.]. Chao showed that the shocks in this study were not close to the velocity gradient of high-speed streams and were probably associated with solar flare events.

The major recent evidence concerning the evolution of shocks with heliocentric distance has been provided by the Pioneer 10 and 11 magnetic field and plasma measurements. Except for studies of the flare-associated shocks of August 1972 [*Smith et al.*, 1977*a*], recent investigations have concentrated on the evolution of shocks associated with solar wind streams. These data show that beyond 1 AU a large fraction of the regions of interaction between fast and slow streams are accompanied by either forward shocks, reverse shocks, or forward-reverse shock pairs [*Smith and Wolfe*, 1976]. The observed characteristics suggest that solar wind speed in-

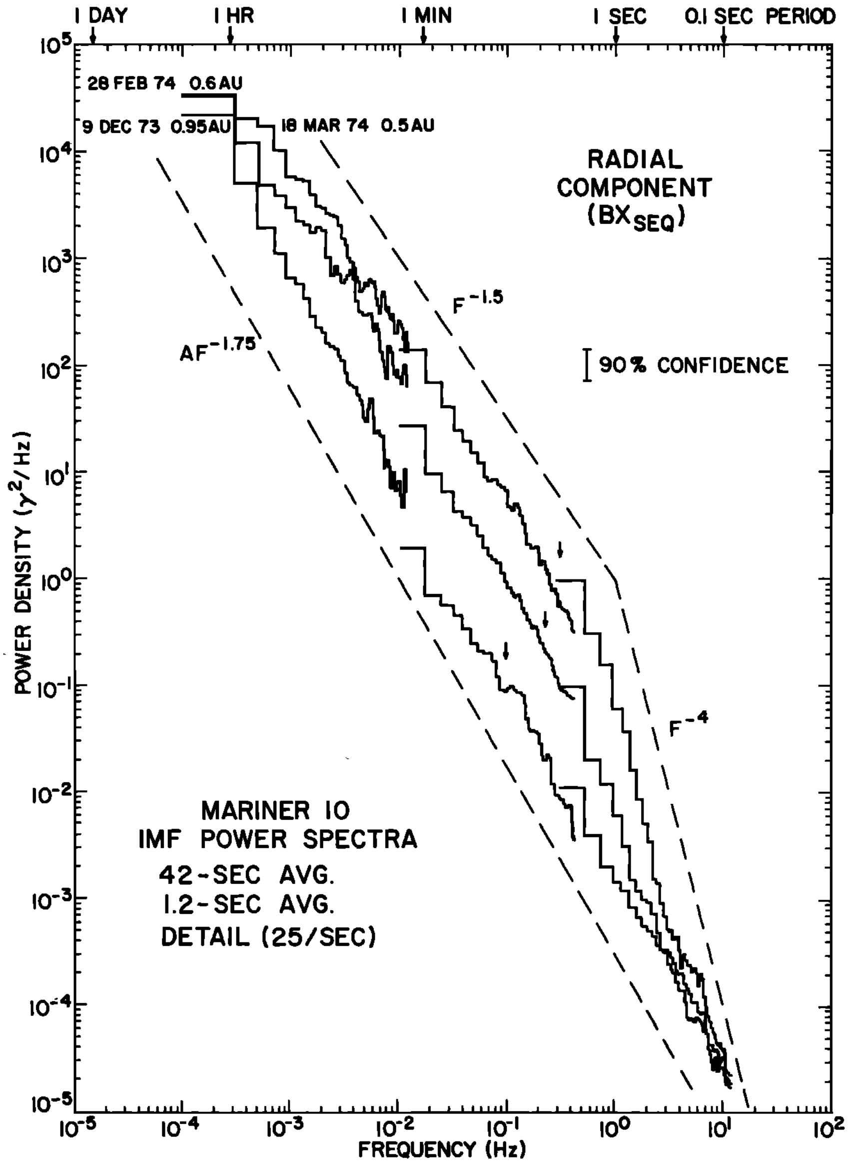

Fig. 14. Composite average radial field component spectra for 'typical' days at three heliocentric distances as measured by Mariner 10. The generally increasing power in radial fluctuations with decreasing radial distance is accompanied by a steepening of the high-frequency end of the spectrum (see text).

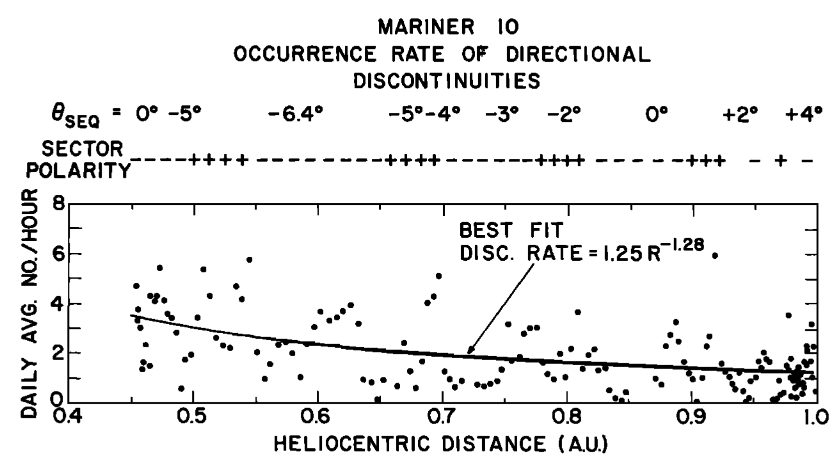

Fig. 15. Mariner 10 observations of the radial variation in the daily average occurrence rate of directional discontinuities during the 5-month cruise to 0.46 AU. The discontinuities are chosen on the basis of a change in direction of >30° in an interval of time ≤42 s. The nonlinear least squares best fit curve is superimposed on the data.

homogeneities steepen to form these shocks and that the stream amplitudes decay as the shock waves propagate outward [*Hundhausen and Gosling*, 1976; *Gosling et al.*, 1976]. Most of the observed large-scale features appear to be predicted adequately well by a simple fluid model of stream propagation which neglects all dissipation effects except those occurring at shock interfaces, although a detailed comparison of Pioneer 10 and 11 magnetic field measurements with the predictions of the model has not yet been performed.

Based on their study of flare-associated shocks observed during August 1972, *Smith et al.* [1977*a*] have concluded that the major deceleration of the shocks occurred between the sun and 0.8 AU, the heliocentric distance of Pioneer 9, with little if any additional deceleration occurring between Pioneer 9 and Pioneer 10 at 2.2 AU. These results differ from the inferences drawn by *Dryer et al.* [1975] based on the effects of the August 1972 events on comet brightness, interplanetary scintillations, geomagnetic activity, and decametric emission from Jupiter, as well as from spacecraft observations. The latter interpretation suggested that there was a piston-driven character to the shocks out to approximately 0.3–0.4 AU, followed by a continuous deceleration out to the point of decay into magnetoacoustic waves between 2 and 4 AU. In the region of deceleration the shock speed was estimated to be approximately inversely proportional to heliocentric radius. Neither the results of the study by Smith et al. nor the results of numerical simulations [*Hundhausen*, 1973; *Dryer et al.*, 1976] are consistent with the suggested power law deceleration, and Smith et al. have concluded that the likelihood of such shocks decaying into hydromagnetic waves at large heliocentric distances is small.

SUMMARY AND OUTSTANDING PROBLEMS

This review has assembled and compared the heliocentric distance dependencies obtained from spacecraft measurements of both large- and small-scale properties of the interplanetary magnetic field. The interpretation within the framework of the present state of knowledge of a generally highly structured and complexly interactive solar wind and continuously evolving solar magnetic field indicates that substantial progress has been made in understanding the average gross characteristics of the interplanetary field. However, the detailed evolution of radial gradients as functions of time within different magnetic sectors and individual solar wind streams is not understood.

As far as the large-scale IMF properties are concerned, measurements made to date are consistent in indicating that the average of the radial field component $B_r = |\mathbf{B}_r|$ varies as the inverse square of the distance. However, the data clearly show that the azimuthal component $B_\phi = |\mathbf{B}_\phi|$ is rather strongly a function of time, being influenced both by the time-dependent solar wind speed and by the fluctuation and evolution of the source field at the sun. The result is that unless the dependence on V_s is taken into account, individual sets of measurements by a single spacecraft give a B_ϕ gradient which is steeper than the r^{-1} dependence predicted from the Parker spiral model. A heliocentric distance dependence $B_\phi \propto r^{-1.8}$ was found individually for three separate spacecraft (see Table 3). A least squares best fit to the composite (five spacecraft) solar rotation average data set gives a result closer to the r^{-1} dependence. A fit to the quantity $\langle B_\phi \rangle \langle V_s \rangle$ using Pioneer 10 magnetic field and plasma observations also yields a result near the spiral model prediction, and the preliminary Helios results suggest general consistency with the spiral model. Between 1 and 0.3 AU, Helios has verified that the radial component B_r varies as r^{-2}, while B_ϕ shows large fluctuations about the theoretical r^{-1} dependence [*Mariani et al.*, 1975, 1976; *Neubauer and Musmann*, 1976; *Musmann et al.*, 1977].

All of the deep-space magnetic field measurements to date show that the field component normal to the solar equatorial plane can be sizable and nonzero for extended periods of time and that its heliocentric distance dependence is intermediate between the dependences found for the B_r and the B_ϕ components. *Coleman* [1976] has discussed how temporal variations of the solar field can result in nonzero B_θ for significant intervals of time. Studies of stream-stream interactions in the solar wind have also shown that the compressed field in the interaction region of a high-speed stream often has an enhanced normal component, which may contribute in a significant way to any long-term average.

The Helios spacecraft and future missions to the outer solar system will contribute to our knowledge of possible solar cycle variations of the radial gradients as well as to our understanding of variations within the corotating stream structure. It will be of value in such studies to separate carefully the magnetic field data into two sets corresponding to high and low solar wind speed conditions. *Bame et al.* [1977] have studied 3½ years of Imp 6 solar wind data taken separately from both high-speed (>650 km/s) and low-speed (<350 km/s) regions and have found significant differences in plasma properties between the two regimes. In particular, much more variability in properties has been found for low-speed than for high-speed streams. This contrasts with the traditional view that the low-speed state is the 'typical' state of the solar wind and magnetic field. More such studies are needed if the variability of magnetic field properties on both short and long time scales is to be completely understood.

A number of questions remain concerning the radial gradients in magnetic field fluctuations. More studies of existing measurements and perhaps also additional measurements are needed to establish the degree to which fluctuation levels are related to large-scale structure in the medium and how fluctuation levels are modulated by solar cycle effects. Additional quantitative studies with a self-consistent model of the solar wind are needed to understand fully the observed fluctuation intensity attenuation characteristics as part of the overall energy balance in the flow of the solar wind.

On the basis of the various observations of IMF radial gradients it can be concluded that relative directional fluctuations of the field are in general not increasing with radial distance from the sun, as was predicted by Parker and Dessler, except perhaps during the more active part of the solar cycle and at frequencies lower than one cycle per day. All measurements up to the present time generally support the conclusion that the ratio of relative magnitude fluctuation amplitudes to relative component fluctuation amplitudes is increasing as a function of heliocentric distance over the distance range of present observations. If compressive fluctuations are indeed increasing in importance with increasing heliocentric distance, then this could have some influence on cosmic ray propagation in the outer solar system. There would be an increase in the mirroring of particles, for example, relative to the scattering of particles from 'kinks' in the field.

There is still an incomplete understanding of the influence of IMF fluctuations on the scattering of cosmic rays as a function of heliocentric distance. *Jokipii* [1973] concluded from theoretical analysis that the coefficient for radial diffusion does not increase with r at large distances ($r \gg 1$ AU) from the sun. Cosmic ray measurements from Pioneer 10 are consistent with such a lack of a strong gradient in K_r, but *Völk* [1975*b*] has argued that there is an inconsistency in Jokipii's use of the WKB method while simultaneously assuming that the wave normal vector $\hat{k}$ always remains parallel to ⟨**B**⟩. Geometric optics (using WKB method) predicts refraction of $\hat{k}$ for MHD waves such that it is essentially radial at 1 AU if it has started out parallel to **B** near the sun [*Barnes*, 1969; *Völk and Alpers*, 1973]. The correct application of the WKB method gives a gradient in K_r which increases steeply with increasing heliocentric distance [*Völk*, 1975*b*].

The assumption of $\hat{k}$ remaining parallel to ⟨**B**⟩ was based on numerous analytical results in which the minimum variance direction for field fluctuations was found to be approximately along ⟨**B**⟩. *Solodyna and Belcher* [1976] argue that the minimum variance analysis tends to give the mean field direction rather than the direction of $\hat{k}$, and *Chang and Nishida* [1973] and *Denskat and Burlaga* [1977] have found that at 1 AU the wave vectors are in general neither along ⟨**B**⟩ nor in the radial direction. *Goldstein et al.* [1974] have shown that general Alfvénic disturbances need not have a well-defined direction of minimum variance. The recent studies by *Sari and Valley* [1976] and *Sari* [1977] show that in general the IMF fluctuations are consistent with the general nonlinear Alfvén wave solution, which has no $\hat{k}$ vector, with at times an additional admixture of compressional (magnetosonic) waves. No evidence has been found that convincingly demonstrates the existence of transverse Alfvén waves which correspond to the plane wave solution of the MHD equations. This would explain the inconsistency between the WKB calculations, which predict a steep gradient in K_r, and the observed lack of a strong gradient, since the WKB method assumes the existence of $\hat{k}$.

A decrease with increasing heliocentric distance in the number of directional discontinuities observed per unit time has been found both by Mariner 10 traveling inward to 0.46 AU and by Pioneer 10 en route to Jupiter and beyond. At the same time the thickness of these structures has been found by both spacecraft to increase with increasing radial distance, although the estimated thickness in units of proton gyroradii has been found to remain approximately constant between 0.46 and 1 AU [*Lepping and Behannon*, 1977]. The observed decrease in the occurrence rate with increasing distance is not presently understood. It could at least in part be the result of one or more effects at work during the processes (both visual and automatic) of identifying and selecting events for study. *Tsurutani and Smith* [1975] have concluded that the occurrence rate decrease found by Pioneer 10 could be a selection effect related to a combination of a fixed selection criterion and the fact that DD's increase in thickness with distance. That is not likely to be the case for Mariner 10 because thinner structures are observed inward from 1 AU. L. F. Burlaga (private communication, 1976) has suggested that the occurrence rate decrease could simply be a geometric effect whereby the space between DD's increases as the solar wind expands. Since the origin of discontinuities is still not well understood and there is at the present time no stability theory for these structures, it is not yet possible to resolve the question of whether or not some fraction of them really does physically disappear between 0.5 and 5 AU.

Variations of the IMF with latitude have been observed [*Rosenberg and Coleman*, 1969; *Rosenberg*, 1970; *Rosenberg et al.*, 1971, 1973, 1977; *Russell*, 1974; *Rosenberg*, 1975]. *Rosenberg and Coleman* [1969] found direct evidence of a heliographic latitude dependence of the dominant polarity of the IMF. *Rosenberg* [1975] and *Rosenberg et al.* [1977] have found support of that result at greater radial distances using Pioneer 10 data. *Smith et al.* [1976, 1977*b*] have found evidence from Pioneer 11 observations that the IMF sector structure essentially disappeared at a heliographic latitude of 16°N. Other recent observations and correlation studies have suggested that the solar wind and IMF come from open and diverging magnetic fields in the polar regions of the sun and a small number of such regions near the solar equator. Such observations and studies as these have pointed out the need to study the IMF and solar wind in three dimensions in order to understand fully both the large-scale structure and microscale properties of the interplanetary medium.

Solutions to outstanding problems will be facilitated by data derived both from recent and current missions and from Voyager and other future inner and outer solar system missions. Certainly, much more will be known after the next decade concerning the character of the field both nearer the sun and in the outermost regions of the solar system, and additional correlative studies between widely separated spacecraft will hopefully resolve many questions concerning the evolution of the field in both space and time.

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