SPATIAL DEPENDENCES IN THE DISTANT SOLAR WIND: PIONEERS 10 & 11

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ABSTRACT

Pioneer 10, 11 observations of the solar wind and magnetic field between 1 and 20 AU are reviewed. Spatial dependences, which are emphasized, must be inferred in the presence of large temporal variations including solar cycle effects. The separation of spatial and temporal dependences is achieved principally through the use of multipoint observations including baseline measurements at 1 AU. Measurements of the solar wind parameters (radial speed, flux, proton temperature) and of the magnetic field magnitude and components are compared with two theories, the Parker theory which assumes radial, azimuthally symmetric flow and the Goldstein-Jokipii theory which includes effects associated with stream-stream interactions. The observed radial gradients in the proton density and velocity and the magnetic field are consistent with the Parker model. The temperature falloff is not adiabatic which reveals the strong heating effect of stream interactions. The second order effects anticipated by the Goldstein-Jokipii model are obscured to a large extent by the much larger time variations. However, they cannot be present to the extent implied by the specific input conditions assumed in their numerical model near the sun which correspond to overly strong streams. A qualitative dependence of field magnitude on heliomagnetic latitude, i.e., referred to the observed location of the heliospheric current sheet, has been derived. The field strength has been found to decrease with distance from the current sheet. The identification of effects of the interstellar gas, e.g. mass loading, has been made difficult by the time variations and by the continuing strong influence of stream-stream interactions.

Introduction

The solar wind conferences come at convenient intervals for reviewing progress in many research areas, among them our understanding of heliospheric structure. This article is a review of Pioneer 10, 11 observations of the solar wind and magnetic field in the outer heliosphere. Pioneer 10 is now beyond 25 AU and is proceeding in the general direction of the tail of the heliosphere. Pioneer 11, after having spent several years crossing the solar system enroute to Saturn from Jupiter, is now beyond 10 AU and is travelling toward the nose of the heliosphere. This enormous extension of the limits of observation over the past decade is revealing how the heliospheric properties vary with distance from the sun.

Knowledge of spatial dependences, however, must be extracted from large temporal variations occurring over a broad range of time scales. During the time taken for the Pioneers to reach their current locations, the solar cycle has varied between the minimum in 1974 to the recent maximum of 1979. The source regions on the sun from which the solar wind originates appear to have changed significantly, e.g., from large polar coronal holes to the lower latitude sites of flares and coronal transients. These solar cycle changes may have resulted in changes on shorter time scales that are qualitatively different during the minimum and maximum in solar activity. Various attempts are being made to cope with time variations in an effort to distinguish them from spatial dependences. When this separation is successful, useful information is obtained on both types of dependences.

Scientific interest in large scale spatial dependences derives from attempts to understand the evolution of the solar wind, its interaction with the local interstellar gas and its effect on galactic cosmic rays. As the solar wind propagates into the outer heliosphere, it not only expands radially but is strongly affected by the interaction between fast and slow streams (Hundhausen, 1973; Smith and Wolfe, 1976; Hundhausen and Gosling, 1976; Smith and Wolfe, 1977; Dryer et al., 1978). The two Pioneers are now reaching distances at which the solar wind interaction with the inflowing interstellar neutrals might become evident. An understanding of how the properties of cosmic rays are modified when they reach the inner heliosphere depends on the medium through which they have travelled (Fisk, 1979; McDonald et al., 1979; Van Allen, 1980; Webber and Lockwood, 1981; McKibben et al., 1982).

The results presented in this review complement earlier Pioneer reports on spatial dependences, some of them prepared in conjunction with past solar wind conferences (Collard and Wolfe, 1974; Smith, 1974; Parker and Jokipii, 1976; Rosenberg et al., 1978; Mihalov and Wolfe, 1978; Smith and Wolfe, 1979; Collard et al., 1982). The results are also complementary to corresponding studies based on Voyagers 1 and 2 (Gazis and Lazarus, 1982, 1983; Burlaga et al., 1982).

Theoretical Background

The simplest, physically reasonable model against which to compare the observations is based on spherically symmetric, time stationary solar wind flow (Parker 1963, Hundhausen 1972). The solar wind properties are derived from the hydrodynamic equations, which express the conservation of flux of mass, momentum and energy, combined with Maxwell's equations. These equations lead to expressions for radial gradients in the solar wind flux and in the magnetic field components. The behavior of the temperature, which is only one term among several in the energy equation, is generally more complicated. The assumption that the solar wind expands adiabatically leads to the simplest dependence of temperature on distance (Parker, 1963) although other formulations exist that include the effect of thermal conduction (see review in Hundhausen, 1972). This model involves serious limitations, specifically the complete disregard of those dependences that lead to solar wind streams and their interactions.

Some of these basic limitations are overcome in the model of Goldstein and Jokipii (1977). They write the hydrodynamic equations in a general form in which longitudinal dependences and time variations are explicitly included. Their expressions for the radial gradients of the principal conserved parameters then show their dependence on space and time. The equations of motion are solved numerically for several different cases corresponding to different solar wind properties at a base level above the corona. In one model for a high speed stream, the speed, v, and density, n, are anti-correlated since this feature of solar wind streams is commonly observed at 1 AU. Other models involve radially symmetric but time dependent streams as well as streams in which n and v are uncorrelated. Basic solar wind parameters derived numerically from the model are then averaged over a solar rotation and their evolution with radial distances studied. In this way, the effect of stream-stream interactions on the radial gradients is exhibited.

One of the principal limitations associated with the Goldstein-Jokipii model is the extent to which the solar wind is driven by fast streams. The specific values for their input functions correspond to very strong streams with the consequence that the interaction effects are exaggerated. For example, compression ceases at ~ 5 AU and is followed at greater distances by a re-expansion of the solar wind (an effect referred to as a "rebound"). The data to be presented below do not show such behavior, certainly not at distances of 5 AU, so that the scale on which stream effects are occurring is significantly greater than implied by the model. Nevertheless, the model is useful in assessing the qualitative effects of stream-stream interactions on the radial gradients and provides a good baseline against which to compare the observations.

The predictions of these two models are summarized in Table 1. The gradients of principal interest are those involving the radial component of the solar wind velocity, v_r, the particle flux, nv_r, the isotropic temperature, T, and the radial and azimuthal field components, B_r and B_ϕ. The Goldstein-Jokipii model includes other parameters, including those representing angular momentum flux, however, they have not been compared systematically with the observations and are not included in the table.

In addition to models which deal with the evolution of the solar wind with distance, there are a number of models of the interaction of the solar wind with the inflowing interstellar gas (Axford, 1972, 1973; Holzer, 1972, 1977; Fahr et al., 1978; Wallis, 1978). The principal consequences of this interaction are charge exchange ionization of the interstellar neutrals by solar wind protons leading to so-called mass loading and a deceleration and heating of the solar wind. In face of the obvious strong effects of stream-stream interactions, the solar wind interaction with the interstellar gas has thus far received much less attention in published studies of spatial dependences.

Observations and Analysis

This section is a review of the most recent analyses of Pioneer 10, 11 observations as they pertain to spatial dependences. Most analyses have emphasized radial dependences. Suppression of longitudinal dependences, and by inference the effect of stream-stream interactions, has been attempted by averaging over an integral number of solar rotations. With few exceptions, possible latitude dependences have been ignored, presumably because the latitude differences are small compared to changes in radial distance. Care must be exercised to avoid confusing spatial with long-term temporal dependences. Multi-point observations have been used to make this distinction and to assess the extent to which time variations are present.

A study of the radial dependences of the basic solar wind parameters has recently been carried out by Kayser et al. (1983). Pioneer 10 and 11 observations of v, nv, n and T have been analyzed both separately and as a composite date set. In the following, the results obtained from the joint Pioneer 10, 11 analyses are presented. In general, these results are in good agreement with those resulting from analyzing the data from each spacecraft. Least squares fits to the observations were obtained using averages over three successive solar rotations.

TABLE 1

RADIAL GRADIENTS

PARAMETER	RADIAL DEPENDENCE	
	PARKER	GOLDSTEIN-JOKIPII[a]
V_r	~ constant (slight increase)	slight decrease, then increase (Figure 1)
nV_r	r^{-2}	$\sim r^{-2}$ (Eq. 6)
T	$r^{-\alpha}$ $o < \alpha < 4/3$	minimum at ~ 1 AU, then increase (Figure 4)
B_r	r^{-2}	$\sim r^{-2}$ (Eq. 7)
$B\phi$	r^{-1}	$V_r B_\phi \sim r^{-1}$, rB_ϕ: secondary maximum (Fig. 3)

a - The figures and equations in this column are to be found in the article by Goldstein and Jokipii.

The least squares fit to the solar wind speed leads to a result:

$$v\ (\text{km sec}^{-1}) = (468 \pm {}^{18}_{17})\ \ r_{**}\ (-0.03 \pm .02),$$

where the double star is the usual Fortran symbol for "raised to the power as follows". There is little, if any, statistically significant dependence of the solar wind speed on radial distance. The Parker theory predicts a slight increase in speed with distance as the basic acceleration associated with the conversion of thermal into convective energy asymptomatically approaches zero. The Goldstein and Jokipii model (for the case in which v and n are anticorrelated at the source) leads to a slight decrease in v as a result of the transfer of momentum from the faster moving, but less dense, stream to the slower moving, more dense stream. Neither effect appears to be present in the observations to a significant degree. Thus, the average solar wind speed appears to be independent of distance.

Figure 1 shows the Pioneer 10 speeds averaged over intervals of three solar rotations from launch in 1972 through 1980. The solid curve represents corresponding averages from several spacecraft making simultaneous observations near 1 AU as compiled by King (1979). A preliminary attempt was made to accommodate radial

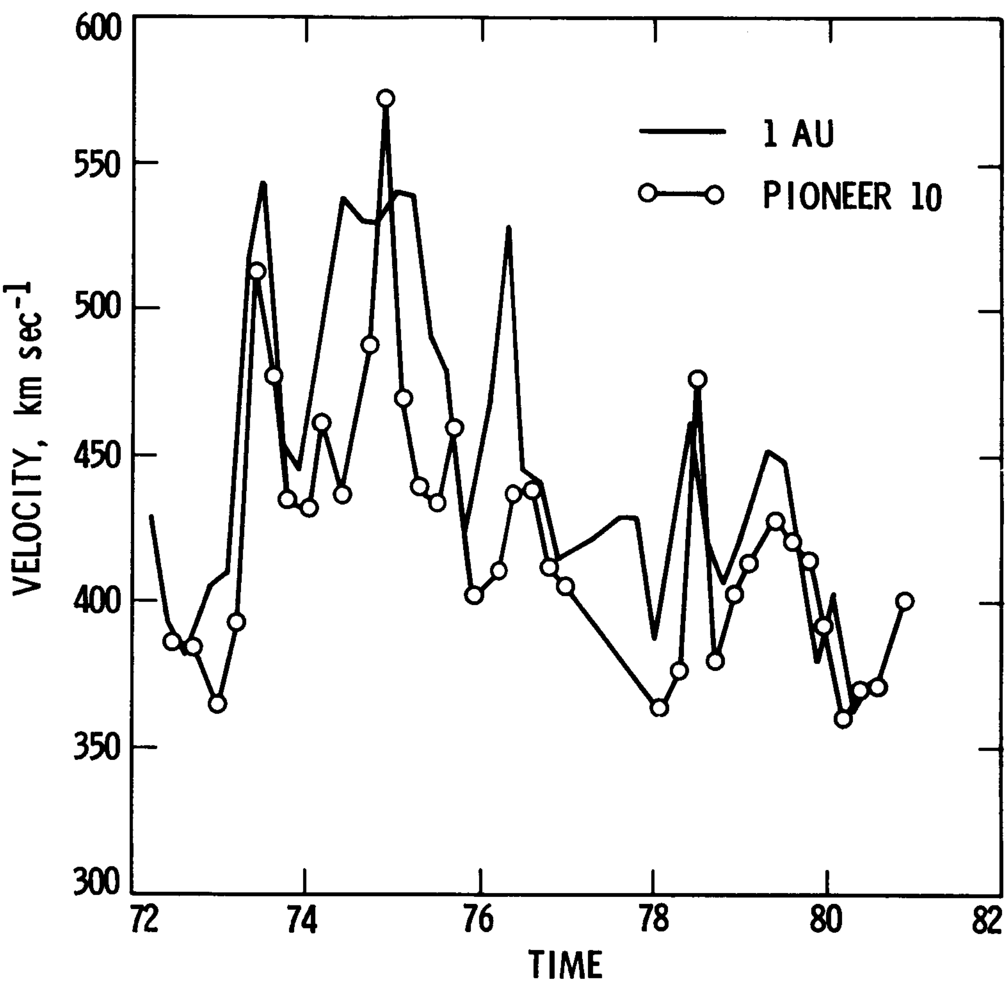

Figure 1. Solar wind speed at 1 AU and as observed by Pioneer 10. The solid line shows the variation in solar wind speed at 1 AU from 1972 (launch of Pioneer 10) to solar maximum in 1980. The well documented increase in speed during solar minimum is evident as well as the gradual decrease toward solar maximum. The open circles connected by straight lines are average Pioneer 10 speeds measured between 1 and 10 AU corotated back to 1 AU. In general, the average speed at large distances is well correlated with the solar wind speed at 1 AU. (J. A. Slavin carried out the analysis and prepared this figure.)

and azimuthal delays and to account for propagation of the solar wind from 1 AU to Pioneer. Undoubtedly, a more accurate correction for the delays is possible and desirable, but the essential features of the comparison are evident in the figure.

The figure shows the extent to which significant time variations are present. The average values vary between maximum and minimum by ~ 150 km sec^{-1}. In addition to large variations from year-to-year, a secular variation is evident with high speeds prevailing near solar minimum (1974-76) and low speeds being observed near solar maximum. There is a reasonably close correspondence between the speed variations at 1 AU and at large distances, Pioneer 10 having reached 25 AU in 1982. Clearly, a small radial dependence in speed could be masked by the relatively large temporal variations.

Figure 2 is a plot of proton flux, nv, one of the parameters that is conserved in the equations of motion. A least squares logarithmic fit to these data (Kayser et al., 1983) leads to

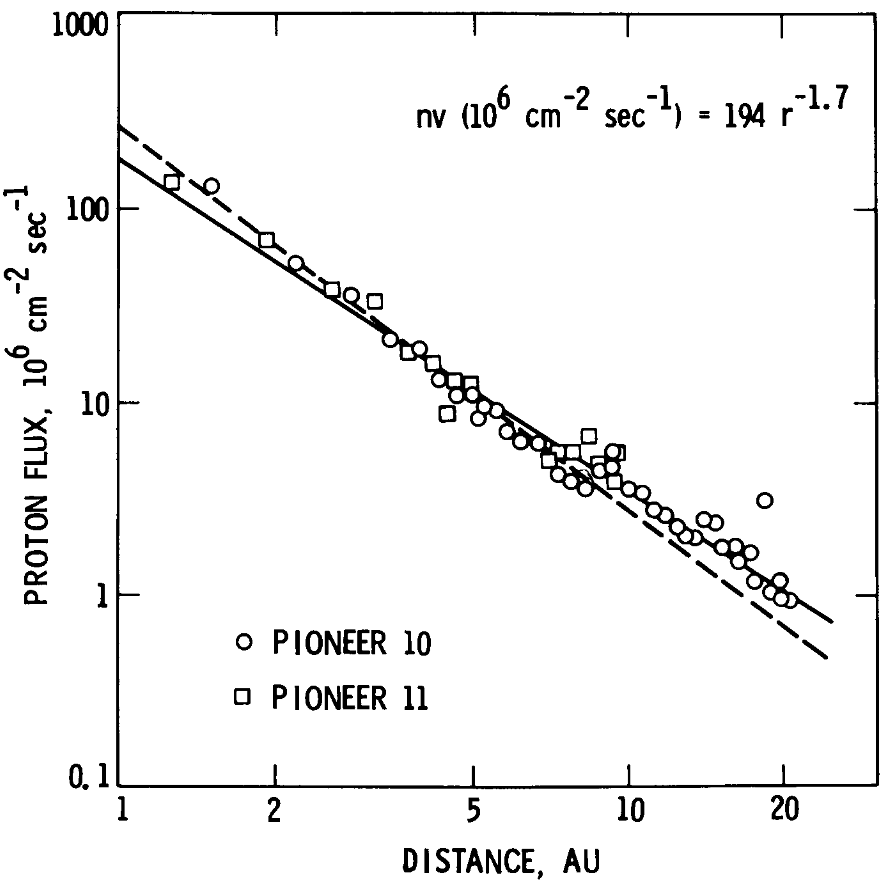

Figure 2. Solar wind proton flux as a function of radial distance from 1 to 20 AU. The flux, averaged over three successive solar rotations, is shown for both Pioneer 10 and 11. The dashed line passing through the data points corresponds to a dependence of r^{-2}. The solid line is a least squares fit to the observations. The scatter about this straight line fit appears to be substantially less than for n or v alone presumably as a consequence of the anticorrelation between n and v.

$$nv\ (10^8\ cm^{-2} sec^{-1}) = (1.9 \pm 0.2)\ r_{**}\ (-1.74 \pm .04).$$

Both theoretical models predict an r^{-2} dependence implying the observed decrease is less rapid than expected. This deviation is attributed to an increase in solar wind flux, specifically an increase in n since v is decreasing, during the approach to solar maximum. An analysis of n similar to that which leads to Figure 1 does reveal a significant increase in density in 1977-78 in both the 1 AU and the Pioneer data. Again, although the results appear consistent with an r^{-2} dependence if the flow had been radially symmetric, second order radial dependences could be masked by time variations. With a more careful, quantitative comparison, it might be possible to reduce this uncertainty significantly.

The radial gradient in the proton temperature is shown in Figure 3. The least squares fit to these data, obtained by Kayser et al. (1983), yields:

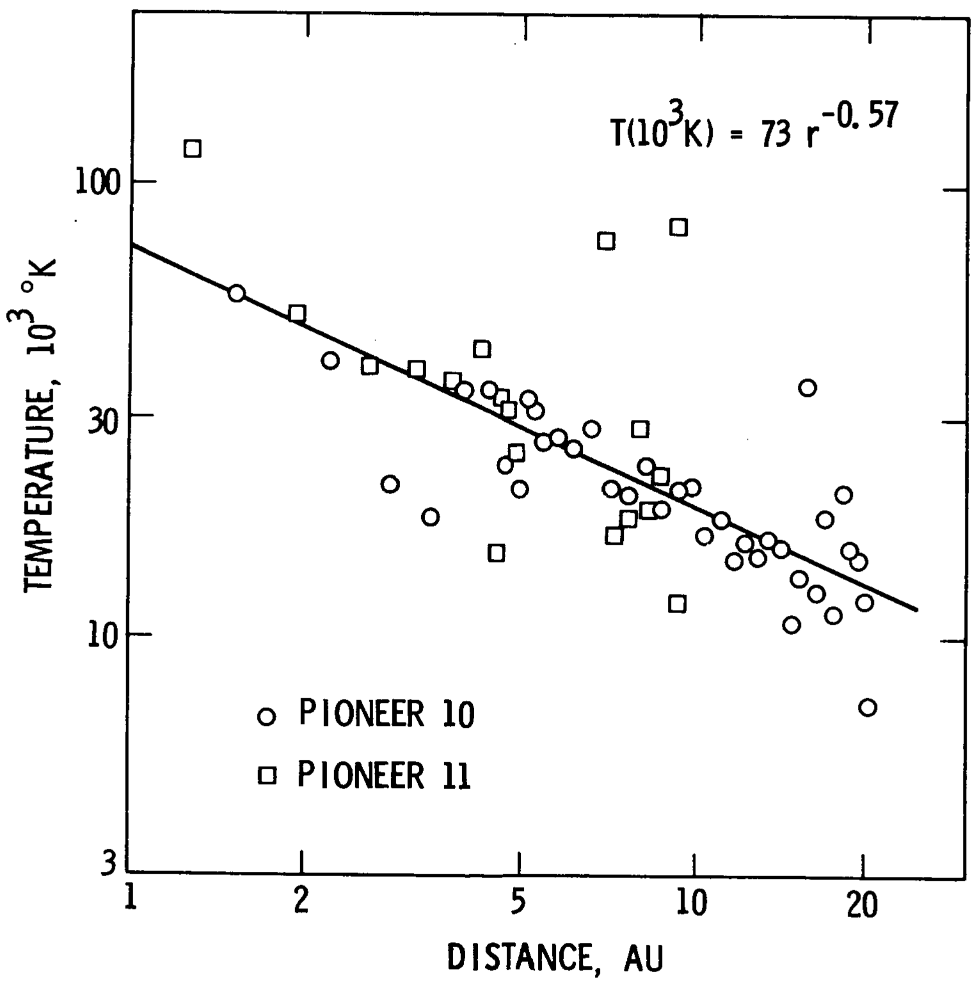

Figure 3. Proton temperature dependence on distance. The temperatures derived from both Pioneers, averaged over three solar rotations, are shown between 1 and 20 AU. The straight line is a least squares fit to the observations. A large amount of scatter is apparent in the data and seems to be correlated with simultaneous large variations in solar wind speed (shown in Fig. 1).

$$T(10^3 k) = \left(73 \pm {}^{1.1}_{1.0}\right) \; r_{**} \; (-0.57 \pm .07).$$

This result is clearly inconsistent with $r^{-4/3}$ and with a simple adiabatic expansion of the solar wind. The temperature dependence is qualitatively consistent with the Goldstein-Jokipii model in which heating is a significant accompaniment of the stream interactions. However, it does not agree quantitatively with their model which predicts an actual reversal in the gradient inside 5 AU leading to a temperature maximum near 5 AU. This feature of the model is one aspect of the solar wind being driven too hard as a result of the choice of input function.

Earlier analyses of the dependence of the magnetic field parameters on radial distance have been extended recently by Thomas et al. (1983). The field strength is a particularly appropriate parameter to study because typical interplanetary field fluctuations over intervals of minutes to hours tend to conserve B. Figure 4 shows magnetic field magnitudes from Pioneers 10 and 11 averaged over spatial intervals of 0.5 AU. The averages have been multiplied by a factor of $[(r^{-2} + r^{-4})/2]^{-1/2}$ which is appropriate to the Parker model and which adjusts the observations to the equivalent field strength to 1 AU. The least squares straight line fit implies that, on the average, the field magnitude reproduces the expected relation very closely. In addition, the average value of ≈ 6 nT corresponds well with long-term averages of the field strength at 1 AU.

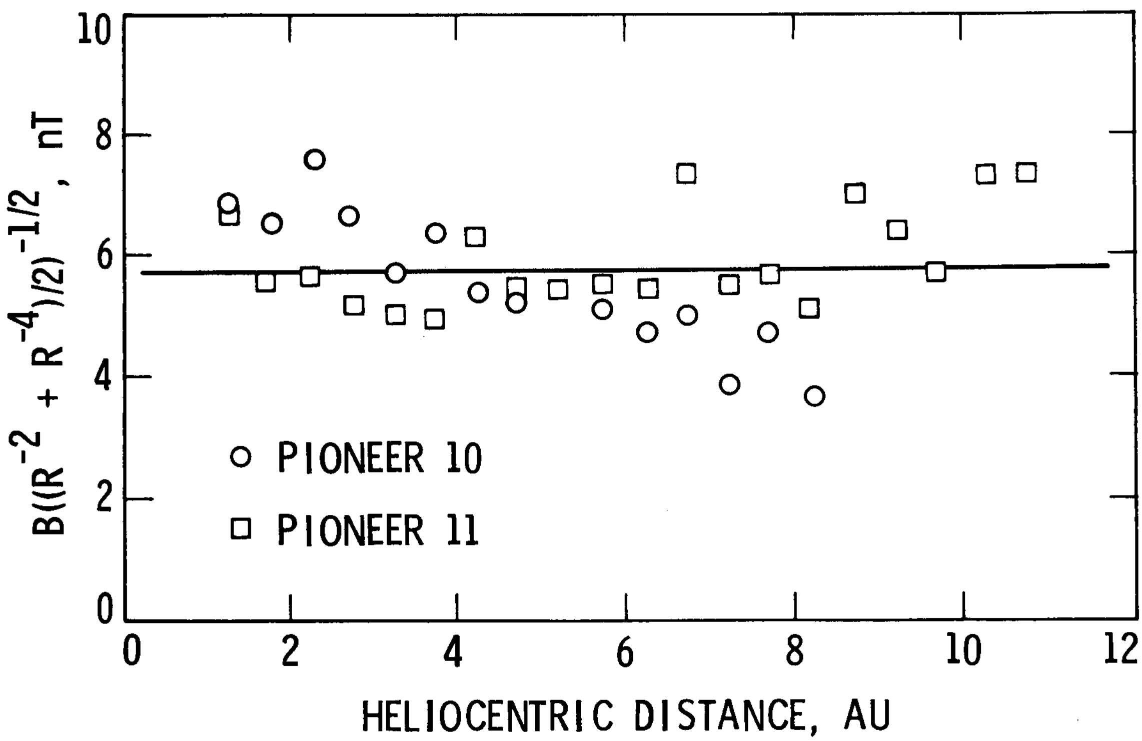

Figure 4. Interplanetary magnetic field magnitudes observed by Pioneer. The measured field strengths were averaged over successive distance intervals of 0.5 AU. They were then multiplied by a factor of $[(r^{-2} + r^{-4})/2]^{-1/2}$, derived from the Parker spiral field model, to produce the equivalent field strength at 1 AU. The values were then plotted against distance as shown. The straight line is a least squares fit to the composite data set. The absence of a significant slope shows that the decrease in B is consistent with the Parker model.

Significant departures from the average are evident in Figure 4 and these have been investigated with the results shown in Figure 5 (Slavin et al., 1983) The adjusted field magnitude from Pioneer 11 is shown as a function of time and is superposed on the annual averages as measured at 1 AU. In spite of somewhat greater variability in the Pioneer averages, the general trends and the values at 1 AU are reproduced reasonably well. The latter show the decrease in B near solar minimum, previously identified by King (1979), as well as a significant increase during the approach to solar maximum identified recently by Slavin and Smith (1983). Thus, the secular variation at 1 AU is matched by corresponding changes at large radial distances. The tendency for the field at Pioneer to be systematically less than the field at 1 AU may be attributable to a latitude dependence. This hypothesis is consistent with an analysis presented below and is presently under study.

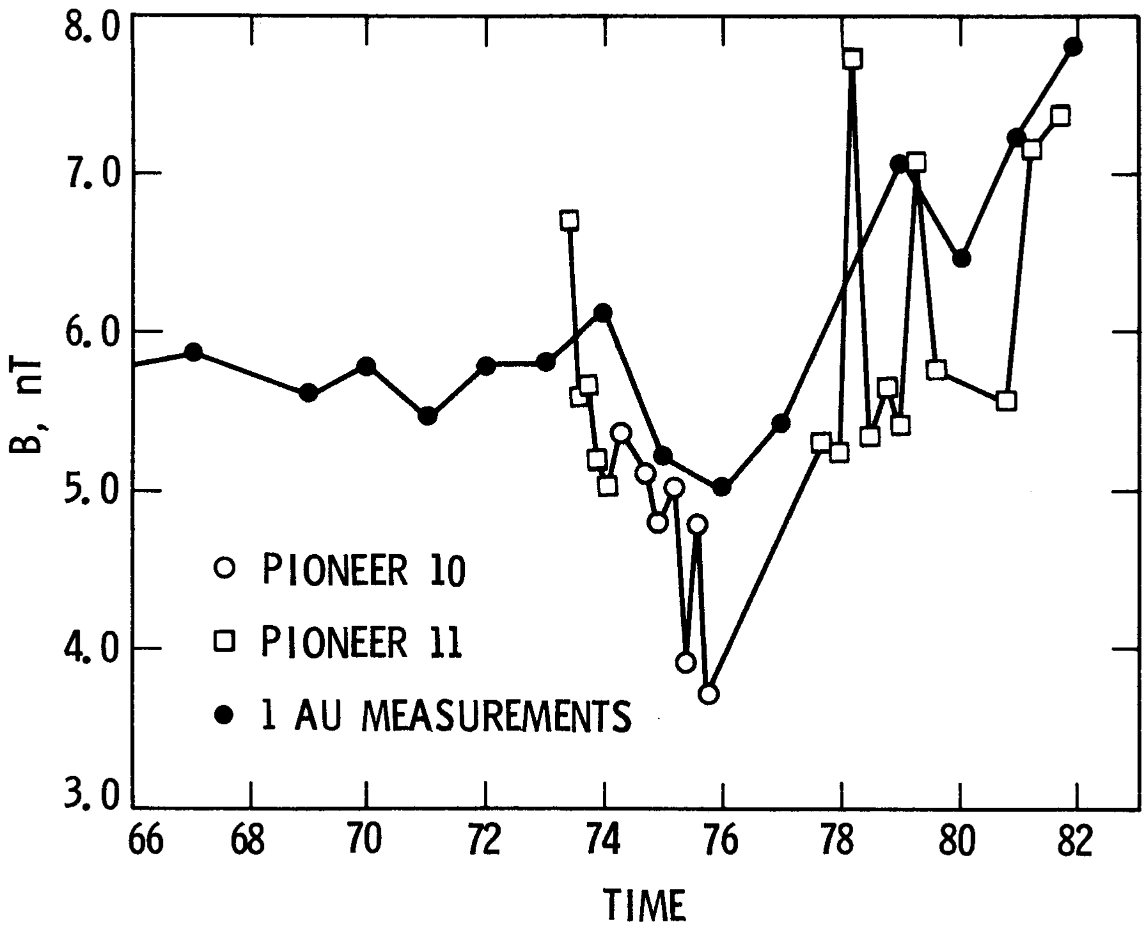

Figure 5. Variation in magnetic field magnitude at 1 AU and at Pioneer. The solid line corresponds to measured fields at 1 AU. The decrease in B near solar minimum (~ 1975) shows up at both 1 AU and at the larger distances in the Pioneer 10 and 11 data. The Pioneer field values appear to be systematically lower, a feature that is discussed in the text.

The azmuthal field component, B_ϕ, has also been studied in a similar analysis. Figure 6 shows values of B_ϕ, averaged over 0.5 AU intervals, after being multiplied by the corresponding radial distance. According to the Parker model, rB_ϕ should be constant, a prediction which is fulfilled very well as shown by the straight line representing a least squares fit to the observations. This result contrasts somewhat with the Goldstein-Jokipii model which for some cases implies a slightly more rapid decrease of $B\phi$ than r^{-1}. The equivalent azimuthal component at 1 AU is only about 3 nT on the average. This value is low compared to the more typical value of about $6/\sqrt{2} \approx 4.4$ nT. This tendency is one aspect of the lower than anticipated average for B noted above and may be caused by Pioneer being persistently at a higher latitude than the spacecraft orbiting at 1 AU.

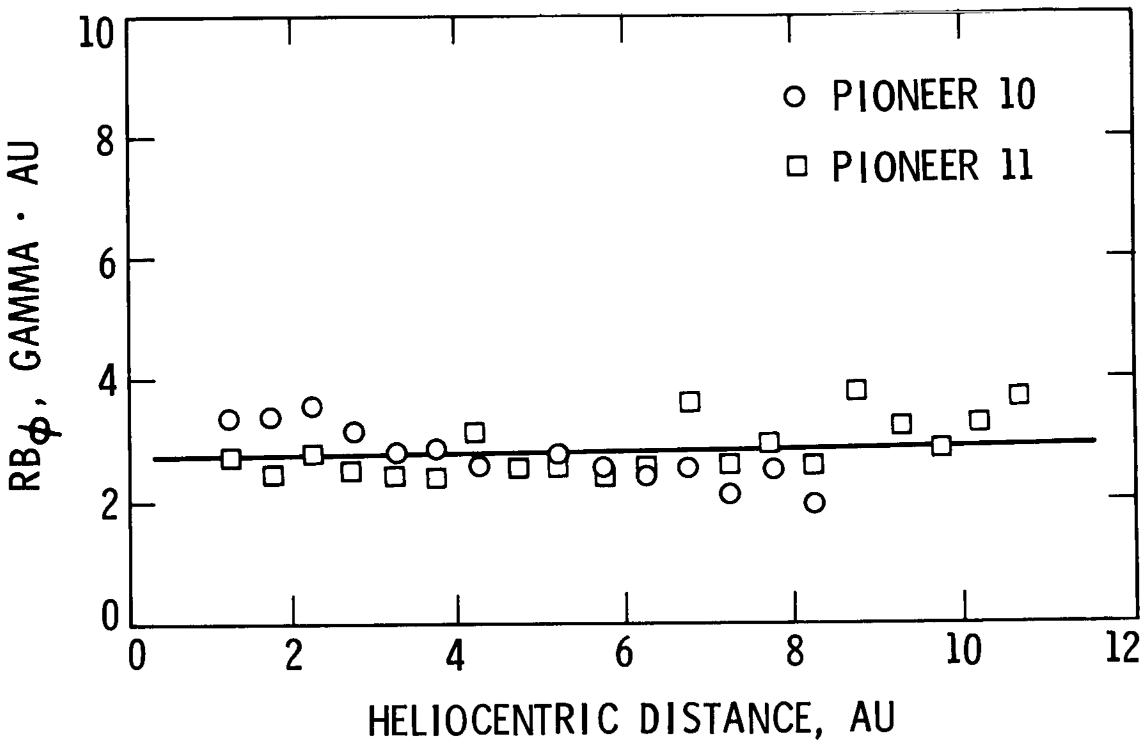

Figure 6. Azimuthal field component as a function of distance. Pioneer 10, 11 measurements of $B\phi$ were averaged over distance intervals of 0.5 AU. They were then multiplied by the average radial distance at which the data were acquired to obtain a value corresponding to the equivalent field component at 1 AU. The resulting points do not show any significant dependence on r (as attested to by the least squares straight line whose slope is approximately zero). Thus, on the average, $B\phi$ decreases as r^{-1} between 1 and 11 AU.

The radial component has been investigated and has been found to be consistent with an r^{-2} dependence as predicted by both theoretical models. The analysis of $r^2 B_r$ vs r shows much greater variability than for B or $B\phi$. Enhanced variability is attributable to B_r tending at large distance to become orthogonal to the average field direction, and, hence, susceptible to the interplanetary field fluctuations, and to the very low average values at large distances. The latitudinal or north-south field component, B_θ, has also been studied and the long-term average has been found to be zero within statistical uncertainty.

The agreement of B_r, B_ϕ, and B with the Parker model implies that, on the average, the field is along the Parker spiral. In a previous analysis, the observed field was rotated into a reference frame with one axis along the spiral direction. Histograms of the azimuth angle of the field, ϕ_B, showed a close correspondence with the two angles (0° and 180°) corresponding to the spiral from 1 to 8.5 AU and during solar minimum conditions (Thomas and Smith, 1980). The study of individual regions also showed a good correspondence with the spiral direction, especially within interaction regions.

Possible dependence of field magnitude on latitude has also been investigated by Thomas et al. (1983). Figure 7 shows the adjusted magnitude as a function of "heliomagnetic" latitude rather than heliographic latitude. Since the heliospheric current sheet (sector boundary) constitutes a basic "plane" of symmetry, the distance of the observations above or below the current sheet was considered more appropriate to a search for latitude dependences than the distance referred to the solar equator. This possibility was tested by using the sector structure, during a particularly stable interval, to obtain a qualitative measure of magnetic latitude.

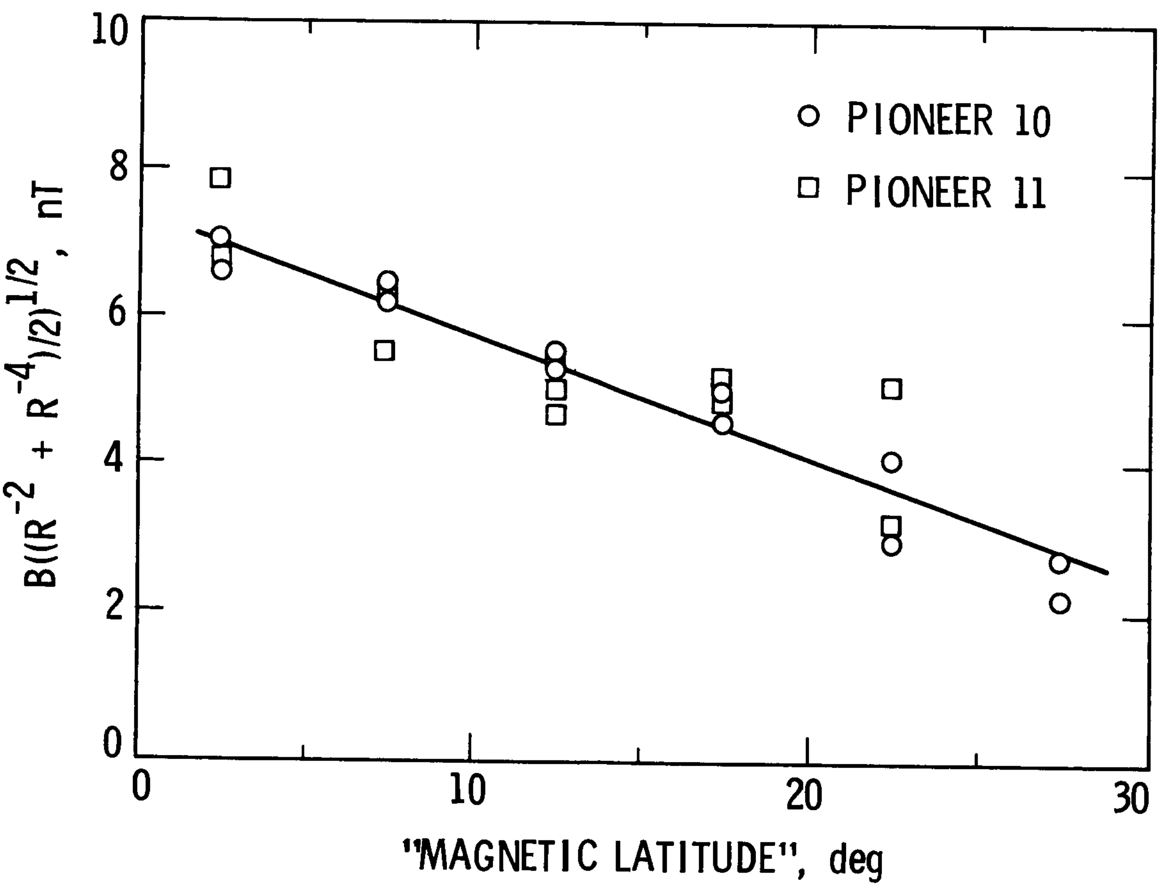

Figure 7. Interplanetary field strength as a function of heliomagnetic latitude. The adjusted magnitude of the field is plotted against a qualitative measure of the distance from the heliospheric current sheet or "magnetic latitude". The latter was basically derived from knowledge of the current sheet location (observed twice per solar rotation as a reversal in field polarity) and the assumption that the distance from the current sheet varies sinusoidally with time.

The result (Figure 7) shows a decrease in B with increasing latitude. This finding is consistent with less tightly spiraled fields at high latitude (alternatively, decreasing B_ϕ) as well as with an increase in solar wind speed with latitude (since $B_\phi = B_r \Omega r/v$). Since the current sheet (the heliomagnetic equator), is typically found inside interaction regions, which are compression regions of enhanced B, the data inside and adjacent to interaction regions were analyzed separately. The magnetic latitude effect was also found in the rarefaction regions.

Discussion

As the Pioneer observations have been extended outward, to beyond 25 AU in the case of Pioneer 10, many properties of the solar wind, averaged over one or more solar rotations, continue to agree with the simple Parker model. This result holds for the solar wind speed and proton flux and for the magnetic field magnitude and components. Although Parker pointed out the consequences of an adiabatic decrease on temperature, his analysis was based on the more general polytrope relation and he made the point that non-adiabatic behavior would not be surprising. In fact, the proton temperature is strongly affected by local heating at stream-stream interfaces.

The principal limitation on comparison between theory and observation is associated with the large time variations occurring from month-to-month, year-to-year and over the solar cycle. These variations introduce a large amount of scatter into the basic data and may be obscuring departures from the simple theory which would otherwise be apparent. The deviations from the Parker model associated with stream-stream interactions, or interactions with the interstellar gas, are clearly of low order as can be seen in the predictions of the appropriate models. Thus, although the solar wind is strongly overdriven in the Goldstein-Jokipii model, the perturbations are still relatively small. Basically, the solar wind momentum and energy fluxes are dominated by the convective terms, nmv^2 and $1/2\ nmv^3$, on which small perturbations are superposed.

The effort to distinguish small perturbations in the presence of the large time variations has barely begun. The obvious approach is to make greater use of multipoint observations. In addition to comparisons with baseline observations near 1 AU, much more needs to be done in comparing Pioneer and Voyager observations. However, progress will inevitably depend on analyzing differences in parameters measured at two locations or differences between theory and observation. Such studies will ultimately have to face issues relating to the accuracy of the basic measurements, a problem that is undoubtedly more acute for the plasma measurements, especially n and T, than for the magnetic field measurements.

Progress in identifying the effect of the interstellar gas has been slow in the face of the continuing strong influence of stream-stream interactions. It may be that the interstellar interaction will only become evident at sufficiently large distances that the stream effects have died out. The latter is undoubtedly occurring, the most obvious evidence being the wearing away of solar wind streams as the high and low speeds are progressively eliminated. It may be that the stream effects are quenched nearer the sun during solar minimum than during solar maximum (Smith et al., 1983). Thus, the approaching minimum may provide a favorable opportunity for studying the interstellar interaction.

Another approach to discriminating against stream interactions would be to concentrate on the solar wind properties within rarefaction regions, i.e., the trailing portions of high speed streams. It may prove simpler to identify and eliminate rarefraction effects than compression effects, especially since the former may be opposite in sense to the heating and deceleration presumably caused by the interstellar gas. Clearly, much analysis remains to be done before an assessment can be made of the extent to which the interstellar gas is affecting the solar wind properties.

An aspect of the observations that also needs more study is the nature of the correlations between the various solar wind and magnetic field parameters such as v & T, n & B, etc. (Jokipii, 1976). Such correlations, which appear to be present on different time scales, are important to studies of the internal solar wind dynamics as well as to the study of spatial dependences. Such correlations are an important aspect of the Goldstein-Jokipii model and are a potentially useful means of identifying stream interaction effects. According to the theory, they represent signatures of compression and rarefaction (including the possible rebound phenomenon).

At present we find ourselves with a network of four spacecraft proceeding into the outer heliosphere in various directions and at significantly different latitudes. A decade ago, none of us would have expected to be confronted with such a fortunate situation. However, we can expect, from this embarrassment of riches, to obtain answers in the not too distant future to many of the questions with which we are now struggling.

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