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The Parker Spiral Configuration of the Interplanetary Magnetic Field Between 1 and 8.5 AU

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An analysis is presented of the magnetic field data obtained by the Pioneer 10 and 11 spacecraft. The purpose is to provide a quantitative picture of the overall configuration of the interplanetary magnetic field in the outer heliosphere. The field directions observed between 1 and 8.5 AU are found, on average, to conform to the Parker spiral directions within both quiet regions and interaction regions to an overall accuracy of 1.1°. The average latitude angle of the field is shown to be zero within a similar accuracy. The included angle between the inward and outward sectored field directions is found to be very close to 180° and displays no solar cycle dependent trends, such as have been previously reported. The field direction is shown to display greater variability in quiet regions than in interaction regions, a fact which is important in terms of the effect of interaction regions on the propagation of energetic particles. The fractional polarities for observations below 10° heliographic latitude are shown to be dominated by temporal variations; however, dual-spacecraft studies have allowed a significant latitudinal gradient to be extracted. This result is qualitatively consistent with the almost complete disappearance of the inward sector at 16° heliographic latitude, although it is suggested that the latter effect may be due to a lower than average current sheet inclination in 1976. The sector structure is shown to extend occasionally to these high latitudes during this time, implying a deflection of the equatorial current sheet, in association with individual interaction regions. It is suggested that the fast streams associated with interaction regions may move the current sheet to higher heliographic latitudes when the source of the fast plasma is in the southern solar hemisphere.

INTRODUCTION

This paper presents an analysis of the magnetic field data obtained by the Pioneer 10 and 11 missions with a view to providing a quantitative picture of the overall configuration of the interplanetary field in the outer heliosphere. Such a picture is important if the internal processes occurring in the solar wind are to be understood. The average configuration and the degree of variation on both long and short time scales are relevant to an understanding of the motion of energetic particles in the interplanetary magnetic field. In particular, the results have direct relevance to the modulation of cosmic rays, although the details of this relationship will be covered in later publications.

Pioneer 10 was launched in March 1972, and Pioneer 11 just over 1 year later. Many observations concerning the interplanetary magnetic field, some predictable and others unexpected, have been presented previously. The reader is referred to recent reviews by *Smith and Wolfe* [1979] and *Behannon* [1978]. Of direct relevance to the work presented here are the observations that high-speed solar wind streams evolve into corotating interaction regions (CIR's) often characterized by forward and reverse shocks and high field magnitudes [*Smith and Wolfe,* 1976], the almost complete disappearance of inwardly directed magnetic field sectors at 16° heliographic latitude [*Smith et al.,* 1978], and the radial gradients of the interplanetary magnetic field components [*Smith,* 1974]. The result of the latter work is that the interplanetary magnetic field components diminish in qualitative agreement with the predictions of Parker's model [*Parker,* 1958]. A more recent analysis [*Rosenberg et al.,* 1978] has suggested that the components display small but significant departures from the predictions of the Parker model.

In this study we have concerned ourselves with the field directions rather than with the individual components in an attempt to obtain quantitative measurements of the field configuration in the outer heliosphere. All reduced data from Pioneer 10 and 11 have been used in the analysis. The field directions are compared with the theoretical model as a function of heliocentric distance, within interaction regions, quiet regions, and fast and slow stream regions. Further evidence for a latitudinal dependence of the sector structure is presented.

DATA PRESENTATION

The most probable field configuration in a given region of the heliosphere is determined by displaying the hourly average vector field angles as histograms, in a way similar to the methods used previously near 1 AU [i.e., *Hedgecock,* 1975*a*]. For our purposes, however, the usual heliographic coordinate system is unsuitable for expressing the field angles, since the heliocentric distances of the spacecraft are varying and thus the Parker spiral angle is expected to change. To compensate for this variation in the expected field configuration, a coordinate system is used which has one axis along the predicted spiral direction. This is achieved by rotating the usual heliographic coordinate system (R, T, N) about the N axis such that the R axis points along the outward Parker spiral direction. Thus R' points outward along the Parker spiral, N lies in a solar meridian plane (positive northward), and T' makes up a right-handed set. In this coordinate system a field vector which conforms to the predicted orientation will have an azimuthal angle of either 0° or 180°. By histograming the observed hourly average field directions in these coordinates one may seek to confirm Parker's hypothesis or alternatively to display any substantial departures from the assumed directions. For the purposes of this work the Parker spiral angle is taken to be that which is consistent with an angle of 45° at 1 AU (implying a constant solar wind velocity of 429 km/s).

To reduce the number of hours in which a sector boundary crossing occurs, which can clearly corrupt the average direction (particularly if the crossing occurs near the middle of the

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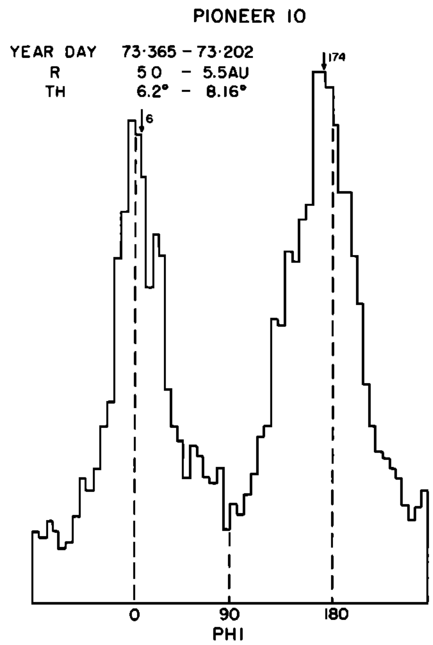

Fig. 1. Histogram of field azimuth angle in spiral coordinates (defined in text) derived from hourly vector field averages of Pioneer 10 data when the spacecraft was moving between 5- and 5.5-AU heliocentric distance. (The Parker spiral angles in these coordinates are 0° and 180° by definition.)

hour), a rejection criterion is used which demands that the vector average magnitude should exceed 67% of the scalar average magnitude. In this way, even the noisiest data are accepted, but the majority of sector boundary crossings are rejected. It is estimated that the residual contamination constitutes less than 0.5% of the data set.

Observations

Figure 1 is a histogram of hourly average field azimuth angles using a limited quantity of data. The data are those obtained by Pioneer 10 as it traversed a region between 5- and 5.5-AU heliocentric distance. The two peaks clearly correspond to the inward and outward sector field directions. The medians of the two halves of the distribution are at 6° and

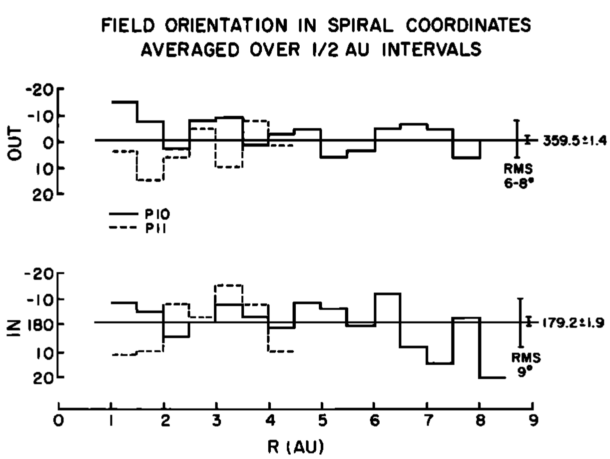

Fig. 2. Plots of 0.5-AU average directions (as defined in the text) of the interplanetary field, expressed as deviations from the Parker spiral direction, against heliocentric distance. The top panel displays deviations for the outward sector directions, and the bottom panel for the inward sectors.

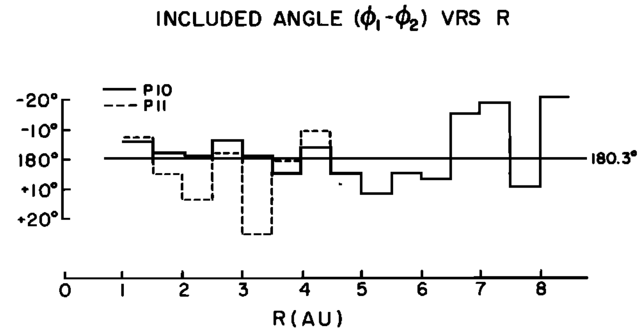

Fig. 3. Included angle (angle between inward and outward average directions) plotted against heliographic distance.

174°, respectively. These represent deviations of 6° from the assumed direction in each case, and the included angle differs substantially from 180°. The histograms are arbitrarily normalized, but it is clear from the degree of scatter between adjacent bins that these angles do not represent significant departures from the Parker spiral directions.

To seek for systematic variations, similar histograms were produced for each 0.5-AU interval by using data from both Pioneer 10 and 11 outbound. The medians of the two peaks were determined in each case, and their departures from the spiral directions are displayed in Figure 2. The top panel represents departures for the outward sectors, and the bottom panel for the inward sectors. The average departure, rms deviation, and standard error of the mean are displayed to the right of each panel. It is clear that within the statistics there are no systematic departures from the assumed Parker spiral direction. It should be noted at this point that the inward sector displays a larger rms scatter and the deviations for this panel appear to be larger at greater heliocentric distances. Figure 3 displays the included angle between the two peaks (clockwise from the outward peak). The average of the distri-

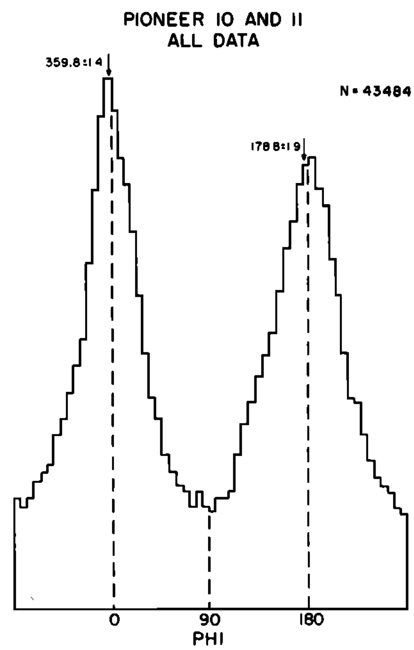

Fig. 4. Histogram of field azimuth angles in spiral coordinates using all reduced data from Pioneer 10 and 11. The errors on the median are those deduced from Figure 2. N is the total number of hourly averages.

bution is very close to 180°. It has been reported that the included angle displays a solar cycle dependent variation near 1 AU [*King*, 1976]. No similar trends are apparent in this analysis.

Having established that no systematic departures from the Parker spiral direction appear in the data, it is now justifiable to display a single histogram using all data. This is shown in Figure 4. The larger quantity of data and the correspondingly improved statistics are apparent from the greatly reduced scatter between adjacent bins. The medians of each peak are shown and are in good agreement with the Parker hypothesis. Combining the two medians into a single result, one can state that the average deviation from the Parker spiral angle between 1 and 8.5 AU is $-0.6 \pm 1.1°$. Thus the Parker spiral angle is found to be a very good approximation over the heliocentric distances covered. The spiral angle at 8.5 AU is ~83°, and thus substantial departures are unlikely to be found beyond these distances, as the field becomes almost azimuthal. It should again be noticed that the inward peak is broader than the outward, indicating that larger fluctuations are present in inward sectors. The authors believe this to be a latitudinal effect. The area below each peak (number of vectors) is, in fact, almost identical, indicating almost equal observations of inward and outward sectors. We will return to these points in the next section. There are a substantial number of vector averages which are perpendicular to the Parker spiral direction. The trough in this distribution has a height of 17% of maximum. In the next section the area below each peak is used to define the fractional polarities of the interplanetary magnetic field. This is clearly an approximation, as the classification of sector direction in the trough is somewhat arbitrary. It is not expected that this procedure will lead to a significant error.

Figure 5 displays the histogram of the latitude angle of hourly vector averages (normalized to constant solid angle) using the same data set used in Figure 4. There is clearly no significant departure from the expected angle of 0°. The distribution is much more sharply peaked than that for the azimuthal angles, and indeed, there are no vectors for which the hourly field average is either exactly north or south. This is a result similar to that obtained at 1 AU [*Hedgecock*, 1975*a*].

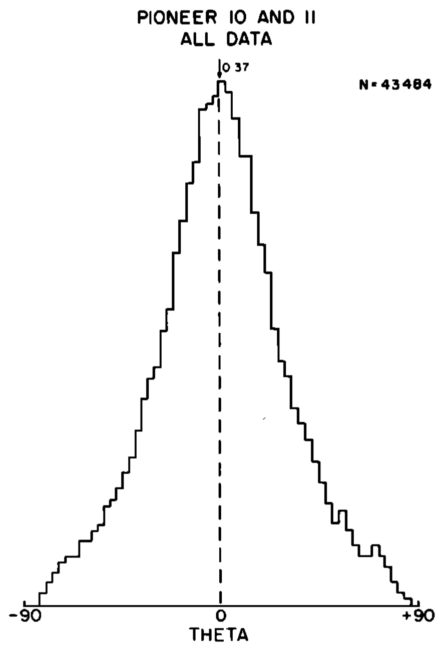

Fig. 5. Histogram of the latitude angle of hourly vector averages (normalized to constant solid angle) using the same data set used in Figure 4.

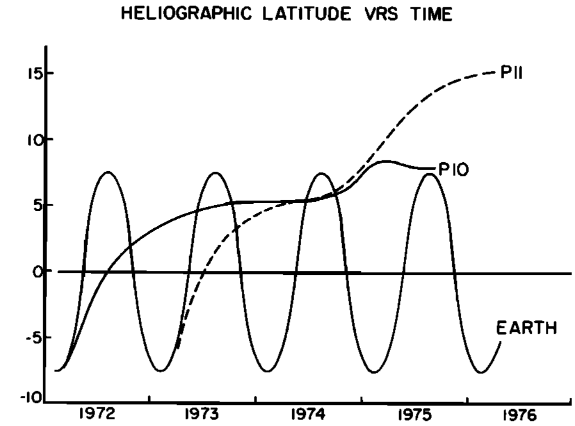

Fig. 6. Heliographic latitude plotted against time for Pioneer 10 and 11 together with the earth.

LATITUDE DEPENDENCE

Figure 6 displays the heliographic latitude of the two Pioneer spacecraft during the period 1972–1976, together with the heliographic latitude of the earth. It was noted in the previous section that there was no apparent preponderance of one sector configuration over the other. This is contrary to expectation, as both Pioneer spacecraft spend most of their time substantially above the heliographic equator. According to the tilted equatorial current sheet hypothesis, which at this time is fairly well established [*Schulz*, 1973; *Hedgecock*, 1975*b*; *Smith et al.*, 1978], outward sectors (during this solar cycle) might be expected to predominate at positive latitudes.

The larger fluctuations apparent in the inward sectors may well be a latitudinal effect. For a tilted equatorial current sheet a spacecraft above the heliographic equator will be in closer proximity to the current sheet during inward sectors

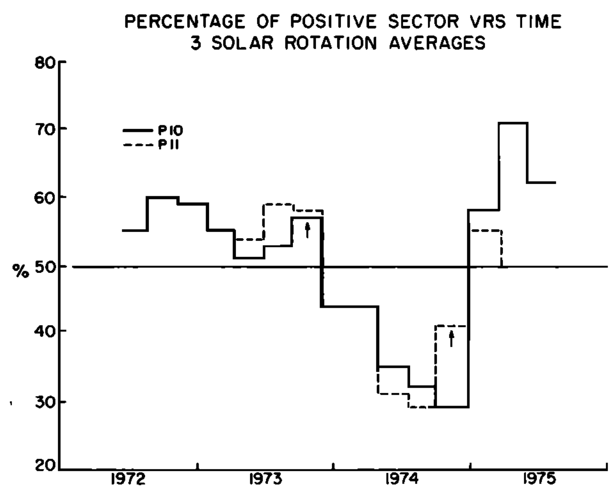

Fig. 7. Fractional positive polarities observed by Pioneer 10 and 11, expressed as percentages of the total (derivation defined in text), plotted against time. Account is taken of appropriate delays such that Pioneer 10 and 11 are observing approximately the same solar wind structures.

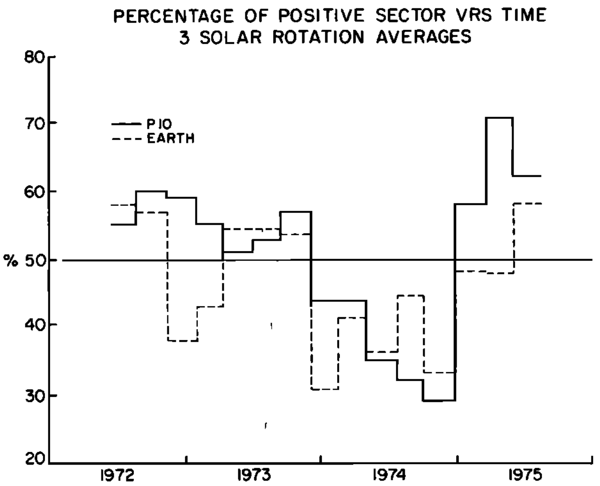

Fig. 8. Similar to Figure 7 but using data from Pioneer 10 and earth-orbiting satellites.

than during outward sectors. Thus waves or other fluctuations in the current sheet might be expected to have a greater influence on the field directions in inward sectors.

A more detailed presentation of the ratio of positive (outward) to negative sectors is given in Figure 7. The fractional polarities are determined from the areas below the two peaks of histograms constructed from data obtained during exactly three solar rotations. Appropriate time corrections for azimuthal and radial separations are used such that Pioneer 10 and 11 are looking at approximately the same solar rotations. The arrows in the figure refer to the two Jovian encounter periods when the average for the appropriate spacecraft is performed over only two solar rotations. All Pioneer 10 data are represented, while Pioneer 11 data are displayed only through early 1975, after which there is a data gap of several months. The subsequent higher-latitude Pioneer 11 data are considered separately.

It should first be noticed that the percentage of positive sector bears little relationship to the heliographic latitude of the Pioneer spacecraft (Figure 6). Second, the two spacecraft display very similar variations despite substantial spacial separa-

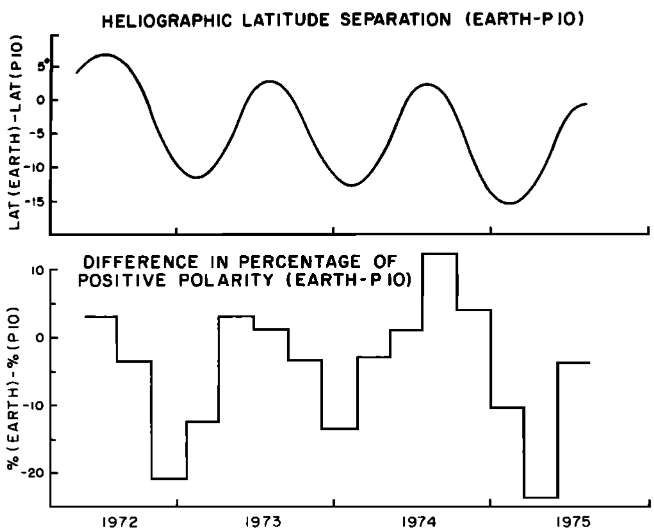

Fig. 9. Differences between the positive sector preponderances observed by Pioneer 10 and near the earth as a function of time. The top panel gives the heliographic latitude separation of Pioneer 10 and earth.

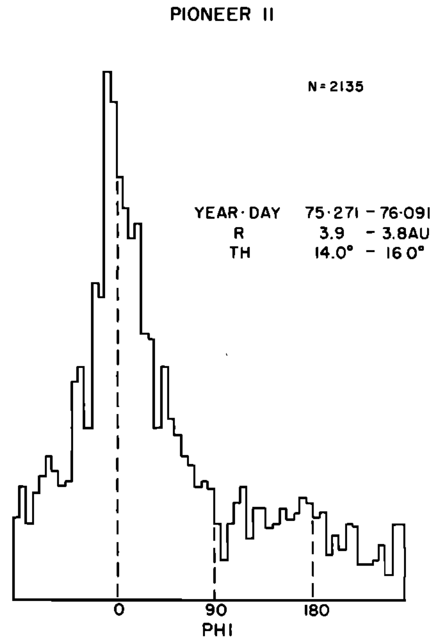

Fig. 10. Histogram of field azimuth angles in spiral coordinates using data obtained by Pioneer 11 when the spacecraft is above 14° heliographic latitude.

tions. It is clear that the fractional polarities at these latitudes are dominated by temporal variations and any latitudinal dependence is hidden. The close agreement between the two spacecraft suggests that the sector structure is convected outward by the solar wind and is essentially unmodified in the intervening distance (2–3 AU).

It is clear in the above comparison that the latitude differences of the two spacecraft are insufficient to allow latitudinal dependences to be separated from the temporal variations. However, the close agreement between the two spacecraft, despite the large radial separations, suggested that dual-spacecraft comparisons may be productive between Pioneer 10 and observations near the earth. Thus a similar comparison has been performed between Pioneer 10 data and data from earth-orbiting satellites. The data used are a compendium of solar wind parameters collected from several near-earth satellites between 1963 and 1975 [*King*, 1977]. The results will be subject to errors due to gaps in the available data. The average time coverage over the period studied was 78%. It is anticipated that the errors will be small, since the data gaps rarely exceed 1 day in duration (apart from a particularly bad period late in 1974).

Figure 6 displays the heliographic latitude of the earth and Pioneer 10. Figure 8 displays the percentages of positive sector orientations, again averaged over three solar rotations for both Pioneer and near-earth data. In this case there are significant differences between the two sets of observations (although similar temporal trends are apparent).

Figure 9 displays the differences between the two data sets. The top panel gives the latitudinal separation of Pioneer 10 and the earth, and the bottom panel the difference between the observed sector preponderances. The subtraction has removed much of the temporal variation, and the data now display a clear latitudinal dependence. The correlation coefficient is 0.61, which has a 98% confidence on a distribution of 15 points. Thus approximately 60% of the Pioneer 10–earth differences can be explained by the latitude separation. The result is qualitatively consistent with a previous study between Pioneer 10 and Heos data [*Rosenberg et al.,* 1977].

After its Jovian encounter, Pioneer 11 returned across the inner heliosphere, reaching a heliographic latitude of ~16° in 1976. A data gap exists during the middle of 1975, during which time the spacecraft rose from ~10° to ~14° heliographic latitude. The few months of currently reduced data that are available after this time enable us to look at higher heliographic latitudes.

Figure 10 displays the histogram of field azimuth angles for Pioneer 11 when the spacecraft was between 14° and 16° heliographic latitude. In this case the inward field sectors have almost disappeared, leaving only one clearly discernible peak in the distribution. The fractional positive polarity is ~0.9. As was suggested previously, Pioneer 11 is now above the current sheet for most of the time. Thus to reconcile this observation with the large temporal variations observed at lower latitudes, one is led to infer the presence of large waves or other deflections in the current sheet which dominate the sector structure below 10° heliographic latitude but which do not reach latitudes of 15°.

However, it should be pointed out that the almost complete disappearance of the negative sector at these latitudes may be unrepresentative. Figure 11 shows the fractional polarities of the interplanetary magnetic field inferred from ground-based magnetograms, together with the heliographic latitude of the earth.

The reliability of polarities inferred from ground-based measurements is a little uncertain, but the qualitative features are correct. The period before 1976 has already been considered. Of interest is the behavior during 1976. The inferred fractional polarities are in good correlation at this time with the heliographic latitude. When the earth reaches its highest latitude of 7.25° in the middle of 1976, the inferred fractional positive polarity is ~0.8. If this estimate is reliable, it is unusually high. The earth is at a latitude nearly 10° lower than Pioneer 11, which at this time was recording fractional polarities of ~0.9. Thus the possibility exists that a change in the current sheet inclination at this time caused untypically high positive sector occurrences over a wide range of northern latitudes during 1976. This observation is in agreement with an earlier analysis [*Svalgaard and Wilcox,* 1974] which indicates that the inclination of the current sheet is lower at solar minimum than at other periods of the solar cycle. Further discussion of this and other related effects is left to a later publication [*Thomas and Smith,* 1980].

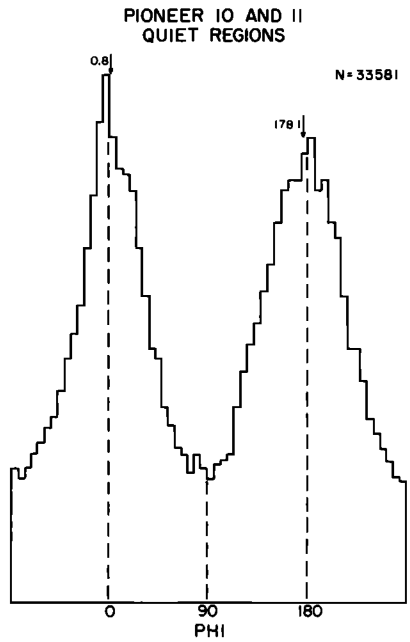

Fig. 12. Histogram of field azimuth angles in spiral coordinates using all Pioneer 10 and 11 data but excluding interaction regions.

FIELD CONFIGURATION WITHIN INTERACTION REGIONS

Having looked at the overall configuration of the interplanetary field, we now display data which have been divided into quiet regions and interaction regions. The interaction regions have been identified in the data using the much larger field magnitudes observed within these regions. Figure 12 dis-

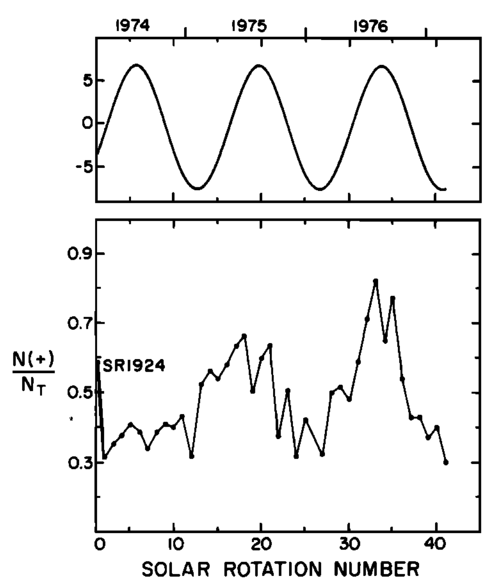

Fig. 11. Interplanetary field polarities inferred from geomagnetic variations plotted against time. The top panel gives the heliographic latitude of the earth (reproduced from *Smith et al.* [1978]; note that a labeling error in the original has been corrected).

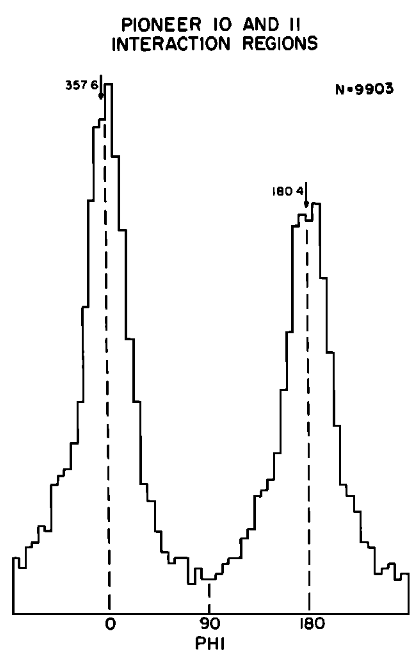

Fig. 13. Histogram of field azimuth angles in spiral coordinates using all Pioneer 10 and 11 data obtained within interaction regions.

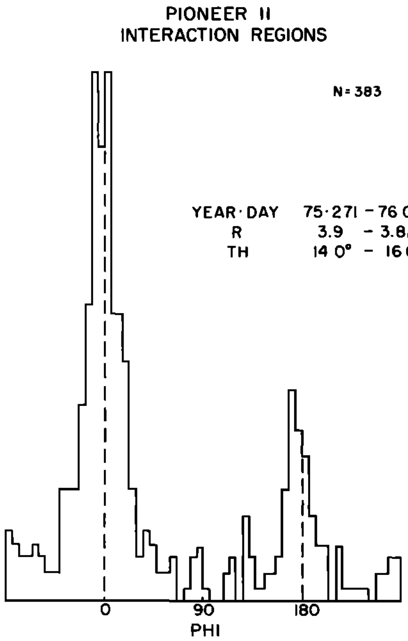

Fig. 14. Histogram of field azimuth angles in spiral coordinates from the same data set as that used for Figure 11 but using only data obtained within interaction regions.

plays the data obtained by Pioneer 10 and 11 during all quiet periods. The two peaks are still very clear but are broader than those in the corresponding histogram displayed in Figure 5. The height of the trough in this distribution represents 25% of maximum compared to 17% previously. Conversely, Figure 13 displays the data from all interaction regions. The peaks are much more clearly defined, and the height of the troughs has fallen to 5% of maximum, contrary to what might naively be expected. The field direction in interaction regions is considerably less variable than in quiet regions. In both regions, however, the average departures from the Parker spiral are small and are not statistically significant. It should be noted that the field orientations within interaction regions display similar fluctuations in both inward and outward directions. The area below the outward peak is substantially larger than that below the inward peak, representing 55% of the total. The result differs from the almost equal areas observed for the whole data set (Figure 4) and is more consistent with the concept of a tilted equatorial current sheet. It may be that the fractional polarities observed within interaction regions are less subject to temporal variations than those observed within the interlying quiet regions.

The substantially lower fluctuations in field direction observed within interaction regions imply less relative power transverse to the average magnetic field within these regions (associated with variations on a time scale of 1 hour). This has important consequences for the propagation of high-energy particles within and across interaction regions. A similar result is obtained when these histograms are produced by using daily averages (i.e., angular fluctuations are significantly lower within interaction regions). The consequences of these observations are beyond the scope of this paper. The reader is referred to a forthcoming publication which presents a full power spectral analysis of the Pioneer 10 and 11 magnetic field data (B. T. Thomas and E. J. Smith, manuscript in preparation, 1980).

The high-latitude Pioneer 11 data displayed in Figure 10 have been similarly divided into quiet regions and interaction regions. The histogram for the quiet regions is not displayed. It is similar to Figure 10, but the negative sector signature is even more clearly absent. Figure 14 displays the data for interaction regions, and it is seen that the inward sectors are still clearly visible. The implication is that the equatorial current sheet extends at times to higher latitudes within interaction regions than within the interlying quiet regions.

These observations are consistent with the hypothesis that interaction regions associated with fast streams originating at southern latitudes on the sun may push the current sheet upward toward northern heliographic latitudes. An earlier analysis [*Smith et al.,* 1978] also made this point as a speculation. This deflection could occur near the sun and then propagate outward unmodified. However, a ridge of high-pressure plasma associated with CIR's has been reported by *Siscoe et al.* [1972] which could provide a mechanism for subsequent deflection. A recent theoretical paper [*Pizzo,* 1978] supports the idea of a meridional mass transport driven by these pressure gradients. More recent work using Pioneer 11 particle data [*Cherneff et al.,* 1980] has shown that high-latitude interaction regions can be divided into two types according to the signature of accelerated protons associated with them. They classify them as northern and southern hemisphere interaction regions.

FAST AND SLOW STREAM REGIONS

The average solar wind velocity within interaction regions is not greatly dissimilar to the overall average solar wind velocity. In view of this it is perhaps not surprising that both interaction regions and quiet regions have similar average field configurations. However, the velocity behind interaction regions will, in the main, be higher than the velocity in front, and one might expect to find different field orientations in these regions. For the purpose of this study, fast stream regions have been arbitrarily defined as data obtained within 60

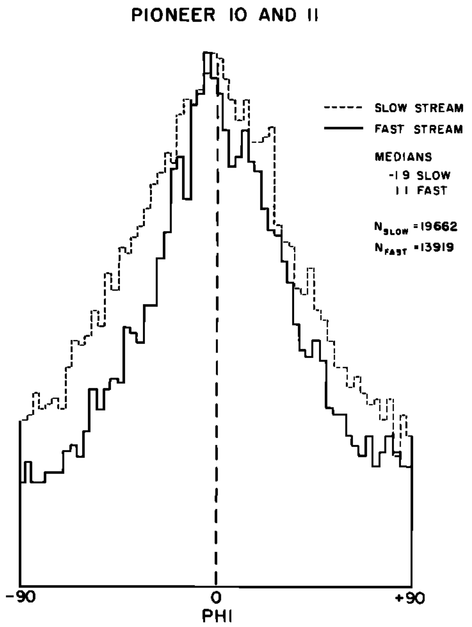

Fig. 15. Histogram of azimuth angles in spiral coordinates. Here the inward and outward peaks have been added together to produce a single peak respresenting both the inward and the outward sector directions. The data have been divided into fast and slow stream regions (as defined in the text).

hours after the passage of an interaction region past the spacecraft. Slow stream regions are taken to be data obtained more than 60 hours after its passage. The interaction regions themselves are rejected. To improve the statistics, the two peaks observed in previous histograms have been added together to produce a single peak representing both outward and inward spiral directions.

Figure 15 displays the data for both fast and slow stream regions simultaneously. First, it can be seen that the fluctuations are larger in the slow stream regions. A similar result has been reported for solar wind plasma [*Bame et al.,* 1977]. Second, one notices that the peaks are no longer symmetrical. The slow stream distribution has an asymmetry to the left (implying a more wound up configuration), and the fast stream distribution is asymmetric to the right. The actual separation of the medians of the distributions is barely significant, but it is worth noting that it corresponds to an average solar wind velocity difference of ~20% (e.g., the difference between 400 and 500 km/s) based on the average heliocentric distance of all the data being 3.8 AU.

CONCLUSIONS

It has been shown that the field directions observed by Pioneer 10 and 11 between 1- and 8.5-AU heliocentric distance conform on average to the predicted Parker spiral directions to an accuracy of approximately 1°.

The variability in field directions is shown to be substantially greater within quiet regions than within corotating interaction regions. This has significant consequences for the propagation of cosmic rays and other energetic particles in the heliosphere.

Although of doubtful statistical significance, the field directions are shown to differ somewhat between fast and slow solar wind streams in a way which is qualitatively consistent with expectation.

The sector pattern is observed to be dominated by temporal variations below 10° heliographic latitude, although a clear latitudinal dependence emerges from dual-spacecraft studies. This is qualitatively consistent with the observation that the inward sector virtually vanishes at 16° heliographic latitude in 1976, when Pioneer 11 is believed to be above the current sheet most of the time. However, it is suggested that the 90% positive sector preponderance at this latitude may be associated with a solar cycle effect. The inferred interplanetary sector structure near the earth indicates a fractional positive polarity of ~0.8 when the earth is at 7.25° heliographic latitude. This value is substantially higher than the typical value of 0.68 [*Rosenberg and Coleman,* 1969]. It is probable that a lower than average inclination of the equatorial current sheet has led to unusually high percentages of positive sector over a wide range of northern heliographic latitudes during 1976 (sunspot minimum).

During this interval, when Pioneer 11 is at ~15° heliographic latitude, the negative sector signature is found to persist within interaction regions. The positive sector preponderance associated with interaction regions at this time is 75%. This implies that the equatorial current sheet extends to higher heliographic latitudes in association with at least one corotating interaction region over this period. It is suggested that the fast stream plasma associated with the formation of interaction regions may move the current sheet to higher latitudes when the source of the fast plasma is at southern solar latitudes (and vice versa).

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