RELATIVELY STABLE, LARGE-AMPLITUDE ALFVÉNIC WAVES SEEN AT 2.5 AND 5.0 AU

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Abstract. Pioneer 11 and 10 observations of the wave structure seen in a corotating interaction region at 2.5 AU on day 284 of 1973 and 8 days later at 5 AU reveal large-amplitude Alfvénic structures with many detailed correlations seen between their features at the two radial distances. Hodogram analysis suggests the dominance of near plane polarized, transverse Alfvénic mode fluctuations with periods between 2 min and one hour or more. Some wave evolution close to the Corotating Interaction Region (CIR) shock is noticed, but waves towards the centre of the compression seem to propagate with little damping between the spacecraft observation positions.

1. Introduction

The interplanetary medium provides an excellent example of an astrophysical plasma where magnetohydrodynamic waves can be studied in situ with instruments considerably smaller than the Debye length. Knowledge of the detailed wave structure is also important in understanding energetic particle propagation within the solar wind.

Early observations identifying Alfvén waves in the interplanetary medium are due to Coleman (1966, 1967), Belcher, Davies, and Smith (1969), and Belcher and Davis (1971), all of whom concentrated on the trailing edges of fast solar streams. Apart from the shock, rotational and tangential discontinuities, a particularly distinct form of large scale field variation is the magnetic cloud. This helical or closed loop field structure has been identified relatively recently by Klein and Burlaga (1980).

Barnes (1966) discusses the theory of hydromagnetic waves in the IMF (Interplanetary Magnetic Field) and shows that the Alfvén mode should persist while the magnetosonic mode should be strongly damped. Development of the theory for the non-symmetric wind situation is carried out by Hollweg (1974) for the transverse Alfvén mode with arbitary direction for the propagation vector **k**. The results apply to non-compressive, $|\mathbf{B}|$ = constant waves of arbitary amplitude if circularly polarized and

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of small amplitude for any polarization. Belcher and Burchsted (1974) analyse waves between 0.7 and 1.6 AU and show the radial dependence of their energy to follow the Hollweg (1974) prediction, indicating little dissipation or generation within that region. Sari (1977) finds at these distances that the dominant fluctuation power lies in finite amplitude Alfvén waves with arbitary **k** vectors, thus allowing finite variations parallel to the mean field direction. In the analysis of Burlaga and Turner (1976) most fluctuations are similarly found to be of large amplitude (typical $\delta B/B \approx 0.4$) at periods of about 1 hour, propagating in the outward direction but with **k** aligned near the $\langle \mathbf{B} \rangle$ direction. A related result of Belcher and Solodyna (1975) shows most directional discontinuities to be rotational rather than tangential and are outwardly propagating in periods of IMF fluctuation which are predominantly Alfvénic.

On a larger spatial scale, > 0.1 AU, investigation of the magnetic helicity by Matthaeus and Goldstein (1982) suggests the dominance of outwardly propagating Alfvénic fluctuations at low frequency although some inward propagation is indicated. This large-scale structure may signify the existence of twisted flux tubes comprising big eddies embedded in the solar wind. Bruno, Bavassano, and Villante (1985) also discuss the detection of long wavelength ($0.3 \rightarrow 1$ AU) Alfvén waves at the Helios 1 and 2 orbits.

The problem of the evolution of IMF fluctuations with radial distance remains open. Burlaga (1983) poses the question; are Alfvénic fluctuations a superposition of non-interacting Alfvén waves or the result of turbulence in which energy cascades to smaller wavelengths? More recent experimental work suggests the latter. Bavassano *et al.* (1982) measuring between 0.3 and 0.9 AU find from 3×10^{-4} Hz to 2×10^{-3} Hz that the power spectrum of fluctuation steepens from f^{-1} to $f^{-1.6}$ although it is unchanged at $f^{-1.6}$ at higher frequencies. The radial power dependence is $r^{-3.2}$ at lower frequencies but $r^{-4.2}$ at higher frequencies. WKB undamped propagation theory yields approximately r^{-3} and thus wave evolution seems to occur within 1 AU. Further out from the Sun between 1 and 5 AU, Bavassano and Smith (1986) find $f^{-1.7}$ for $3 \times 10^{-4} < f < 8 \times 10^{-3}$ Hz with the power proportional to $r^{-3.5}$, both laws being frequency independent. Again a slow attenuation of the turbulence is revealed with a typical damping length of 8 to 10 AU.

Various theoretical models for the decay of Alfvén waves with distance have been advanced. Derby (1978) investigates the Sagdeev–Galeev decay instability of large amplitude circularly polarized waves and finds a decay time proportional to the observed, Doppler shifted, period of the waves. An observed period of 45 min corresponds to a 1 AU damping distance. Bavassano *et al.* (1982) consider the nonlinear interaction between a large flux of outwardly propagating waves and a small flux of inwardly propagating waves, a process rather similar to that of Derby (1978) since the latter predicted the production of backward going transverse waves by the instability. Bavassano *et al.* (19 find a steepening of the power spectrum at low frequencies with distance and a radial dependence, $r^{-3.6}$ for the region below 1 AU, in qualitative agreement with experiment. However, Bavassano and Smith (1986) note three other theories for the evolution of Alfvén waves with distance. Dobrowolny and Torricelli-Ciamponi (1985) consider linear Landau damping of oblique Alfvén waves. Hollweg

(1975) finds $r^{-3.5}$ for the fluctuation power rather than r^{-3} in the rarefaction region expected behind CIR's and Matthaeus and Goldstein (1982) point out the flow of energy from large-scale structures to high-frequency waves in a turbulent cascade. Production of waves via instabilities within high-speed streams has been considered by Bavassano, Dokrowolny, and Moreno (1978), an opposing evolutionary process or by shear within the CIR (Coleman, 1968).

It is the purpose of this paper to identify the dominant wave structure within a particular CIR and to consider the stability of the waves as a function of distance from the Sun.

2. Analysis of the Wave Mode in a Corotating Interaction Region at 2.5 and 5.0 AU

In this work, we study the magnetic structure of a CIR which has been observed at 2.5 and 5.0 AU heliodistance, employing, respectively, Pioneer 11 and 10 magnetometer data. High time resolution, 0.7 s and 0.37 s field samples are available. The time periods covered are days 284 to 286 of 1973 for Pioneer 11 and days 292 to 296 of 1973 for Pioneer 10. Five min samples of the radial plasma velocity have also been provided.

Since the plasma velocity resolution available is inadequate for detailed study of $\Delta \mathbf{V}$ (velocity) and ΔB (magnetic fluctuation) correlations, we concentrate on an interpretation of the magnetic fluctuations alone. Hodogram analysis provides a useful approach. Magnetic vectors are plotted in a spacecraft solar ecliptic coordinate system taking the radial direction to the Sun $\mathbf{x}$, $\mathbf{z}$ towards the north and $\mathbf{y}$ completing the right-handed set. The hodograms, or plots of the positions of the end points of the vectors (Bx, By), (By, Bz), and (Bz, Bx) show significant structure within the CIR at both 2.5 and 5.0 AU.

Figures 1(a) and 1(b) illustrate the overall behaviour of the three field vectors and the plasma velocity as seen at Pioneers 10 and 11 for the complete passage of the CIR, observed successively at 2.5 and 5.0 AU. Before the shock, denoted by the sharp increase in $\mathbf{V}$ and $\mathbf{B}$, lack of wave activity is noticed. However, some Alfvénic fluctuations characterized by $|\mathbf{B}| \approx$ const. are revealed as precursors just pre-shock at both distances on detailed analysis.

Figure 2(a) displays hodograms for days 292 to 296 at 5 AU, based upon 2 min field averages. A post-shock region of intense activity is seen, followed by a slow decline towards the trailing edge of the CIR. Separate plots for the (x, y), (x, z), and (z, y) planes are provided. Similar information is given in Figure 2(b) for days 284 to 286 at 2.5 AU.

To interpret the hodograms, reference is first made to the theory of large amplitude hydrodynamic waves as developed by Barnes and Hollweg (1974). Since $|\mathbf{B}|$ is relatively constant while large fluctuations occur in the field components, it is reasonable to restrict the discussion to Alfvénic disturbances. The transverse mode of finite amplitude as defined by Barnes and Hollweg (1974) is incompressible and with both $|\mathbf{B}|$ and $|\mathbf{B}_1|$ constant where $\mathbf{B}_1$ refers to fluctuations perpendicular to the propagation direction. The propagation vector, $\mathbf{k}$, and the mean field $\langle \mathbf{B} \rangle$, can be at any angle and we consider

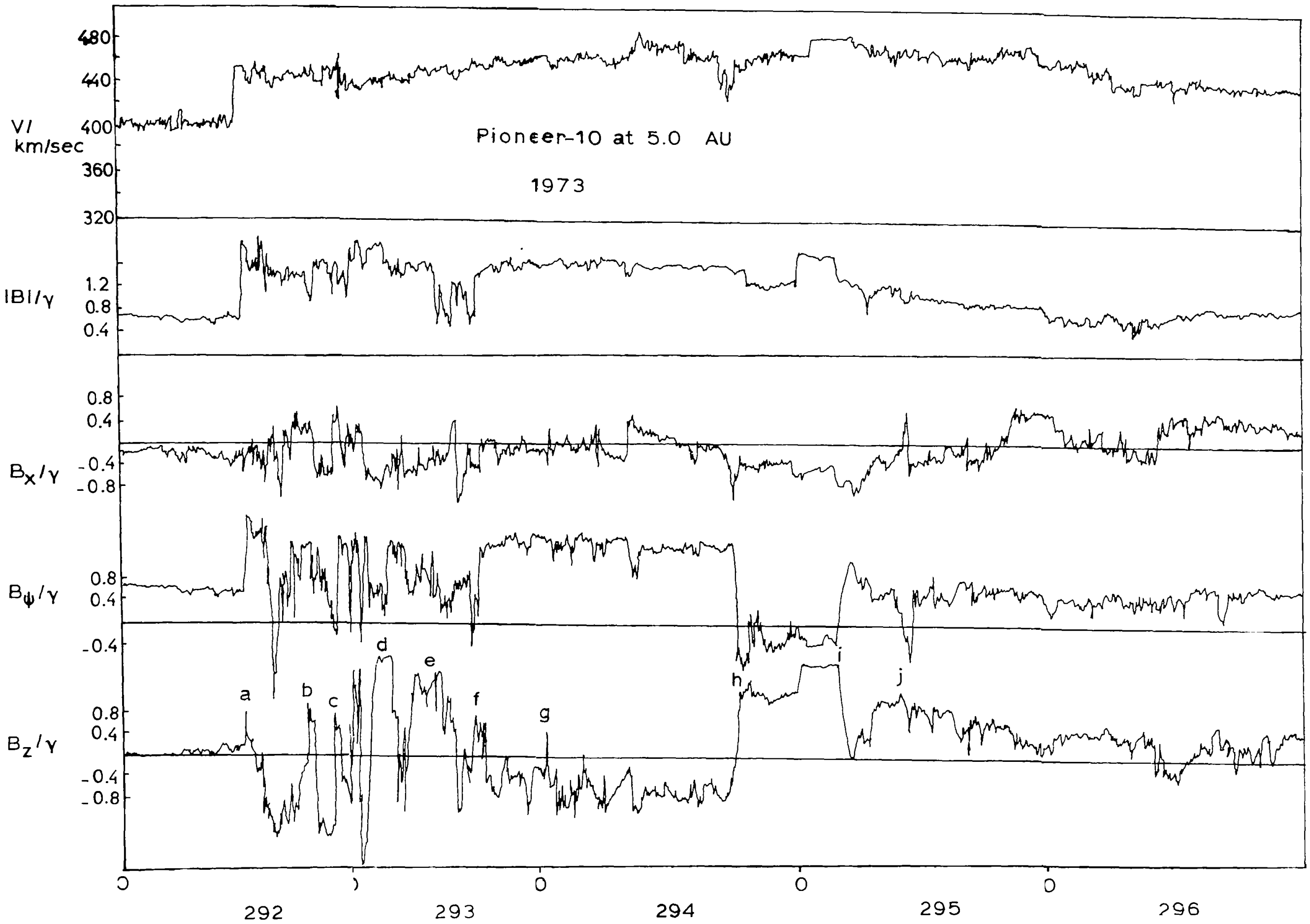

Fig. 1a. 2-min average values of the three magnetic field components, the magnetic field and the plasma velocity versus time for the days 292 to 296 of 1973 for Pioneer 10. Individual Alfvénic fluctuations seen in the Pioneer 10 waveform which appear to have counterparts in the Pioneer 11 results are labelled $a \rightarrow j$.

the case where **k** is in the z' direction while the y' direction lies in a plane containing $\langle \mathbf{B} \rangle$ and **k**. $\mathbf{B}_1$ corresponding to circular polarization describes a circle in the (x', y') plane for $\mathbf{k} \parallel \langle \mathbf{B} \rangle$. The situation where **k** is not parallel to the mean field may result in **B** moving along the partial arc of a circle in the (x', y') plane, provided one component has a sinusoidal variation. In this latter case, the (x', y') plane is not perpendicular to $\langle \mathbf{B} \rangle$. Barnes and Hollweg (1974) showed that in the small amplitude limit of the general $\mathbf{k} \nparallel \langle \mathbf{B} \rangle$ case, the transverse Alfvén wave is approximately linearly polarized. This is despite the restriction $\nabla \cdot \mathbf{B} = 0$ which, as demonstrated by Barnes (1976) prevents the existence of large amplitude plane polarized Alfvén waves. More general solutions of the finite amplitude wave equation allow propagation with no characteristic **k** direction and, hence, no particular (x', y') plane may be identifiable within the data (Goldstein, Klimas, and Barish, 1974; Barnes, 1976).

Figure 3 illustrates two extreme cases, the first corresponding to circular polarization (A) and the second to near plane polarization (B). Planes with directions of minimum, intermediate or 'mid' and maximum variance are used to exhibit the expected field

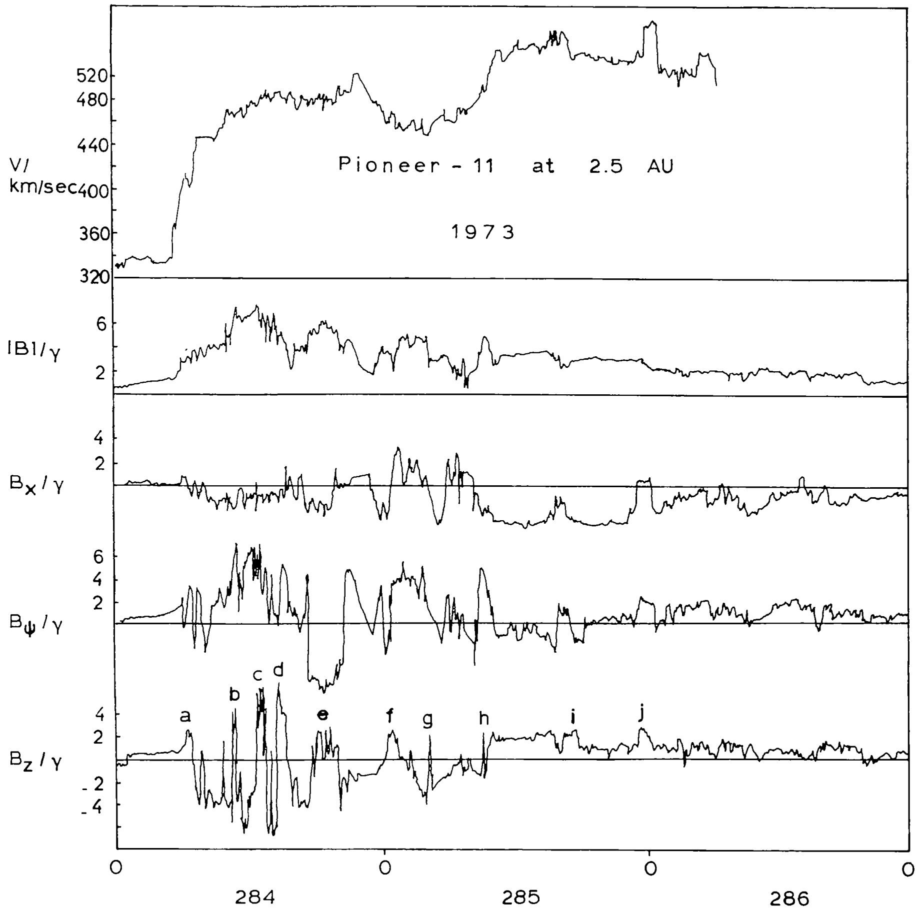

Fig. 1b. The corresponding with the Figure 1(a) time series plots for the days 284 to 286 of 1973 for Pioneer 11.

component variations. For circular polarization, the typical hodogram is a straight line in the plane containing the 'min' and 'max' variance directions while it is a circle in the 'mid' and 'max' variance plane. In the near-plane polarized case, the 'min'–'max' variance plane provides a straight line hodogram while the 'mid'–'max' plane shows the magnetic vector describing the arc of a circle. It turns out that the chosen spacecraft coordinates planes correspond reasonably closely to the ideal planes of Figure 3 for most of the time.

Both Figures 2(a) and 2(b) clearly show the vector in the (y, z) plane on most days to follow circular arcs with a roughly linear relation in the (x, y) and (z, x) planes. Now the mean field direction at the distances where the measurements are obtained is expected to be close to $\hat{\mathbf{y}}$ and indeed the y component of the field is dominant in the data. We, therefore, interpret the hodograms as revealing the presence of large amplitude Alfvén waves propagating at large angles to $\langle \mathbf{B} \rangle$. In fact, since the plane of polarization is approximately (y, z), the $\mathbf{k}$ vectors must be directed nearly radially ($\pm \hat{\mathbf{x}}$ direction). Some motion of the $\mathbf{B}$ vector end points over a sphere is clearly allowed by the data, but an approximation to a plane polarized situation is occurring.

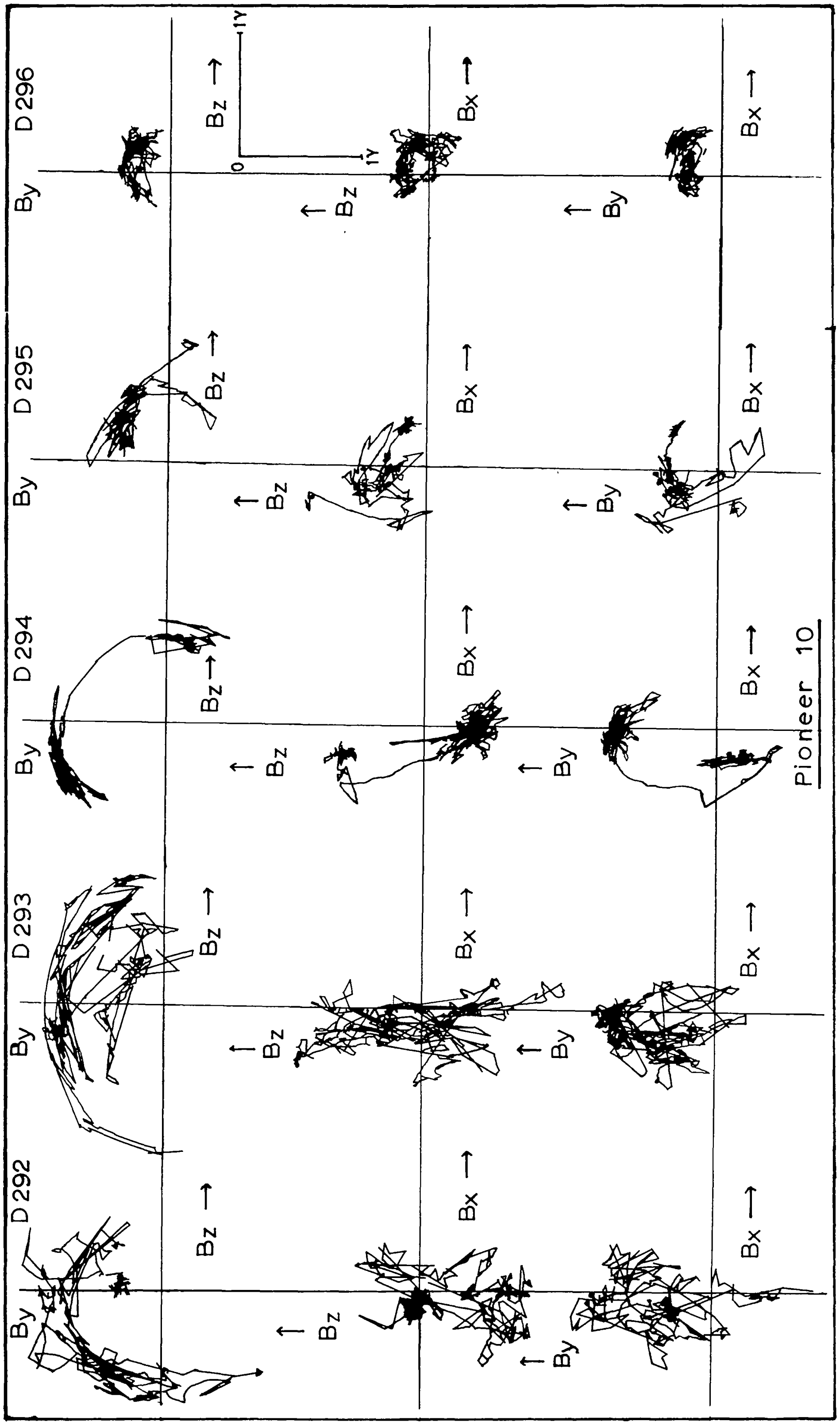

Fig. 2a. Scatter plot diagrams of 2-min average field vectors for days 292 to 296 for Pioneer 10. Separate plots for the (x, y), (x, z), and (z, y) planes show a type of waves oscillating mainly in the (y, z) plane (solar ecliptic components).

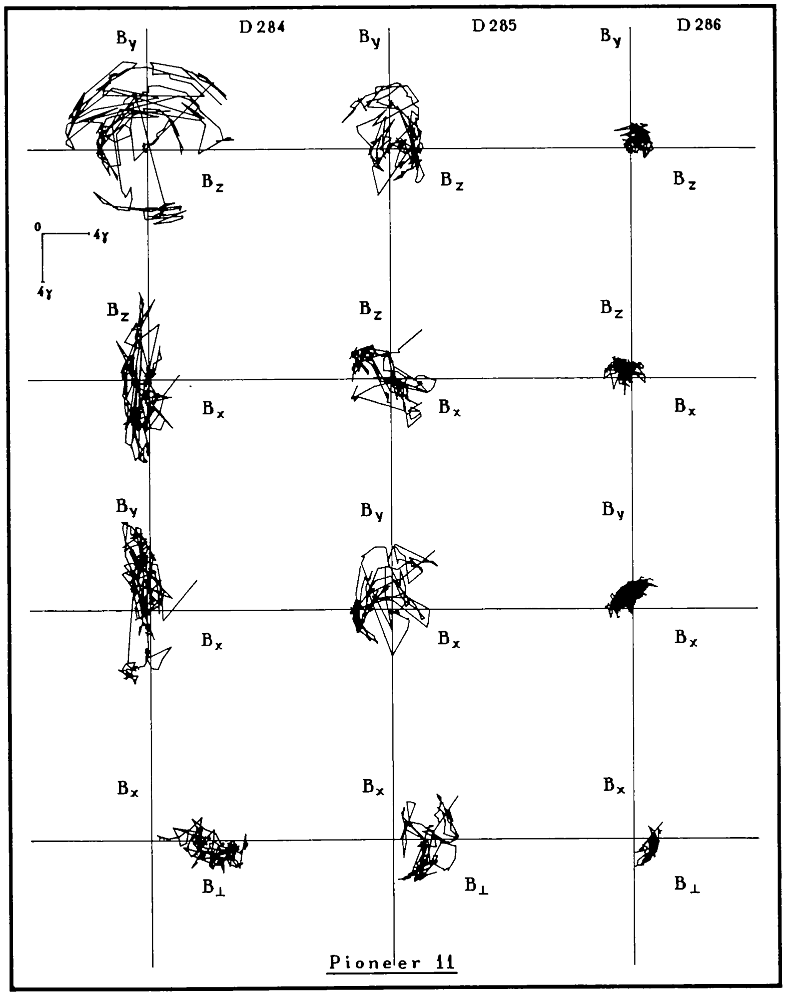

Fig. 2b. Hodograms similar to those in Figure 2(a) based upon 2-min field averages for days 284 to 286 of 1973 for Pioneer 11. Also similar plots of the positions at the end points of the vectors ($B_\perp$, B_x) for the above days are provided. ($B_\perp$ refers to the fluctuations in the plane (y, z) perpendicular to the propagation direction.)

Various other interpretations of the hodograms seem less probable. For example, high-frequency, circularly polarized waves sampled at a near-integer multiple of their frequency might simulate the plane polarized behaviour. Alternatively, each wave seen may be one of a group of large-scale helical structures within the IMF, for instance twisted flux tubes. The additional hypothesis is then required that the spacecraft always happends to sample the same restricted region of phase within the 2π rotation of the field. In other words the same part of the circle in the 'mid'–'max' hodogram of Figure 3, circular polarization is always seen.

Figures 4(a) and 4(b) are hodograms in which the same data is selected as for one day of Figures 2(a) and 2(b), but 12, 28, and 60 min field averages are instead employed. The well-defined circular arcs in the (y, z) planes become less obvious with longer averaging periods, illustrating the importance of the 2–12 min range. However, the near plane polarized, large-amplitude wave behaviour tends to persist out to at least a 1 hour period.

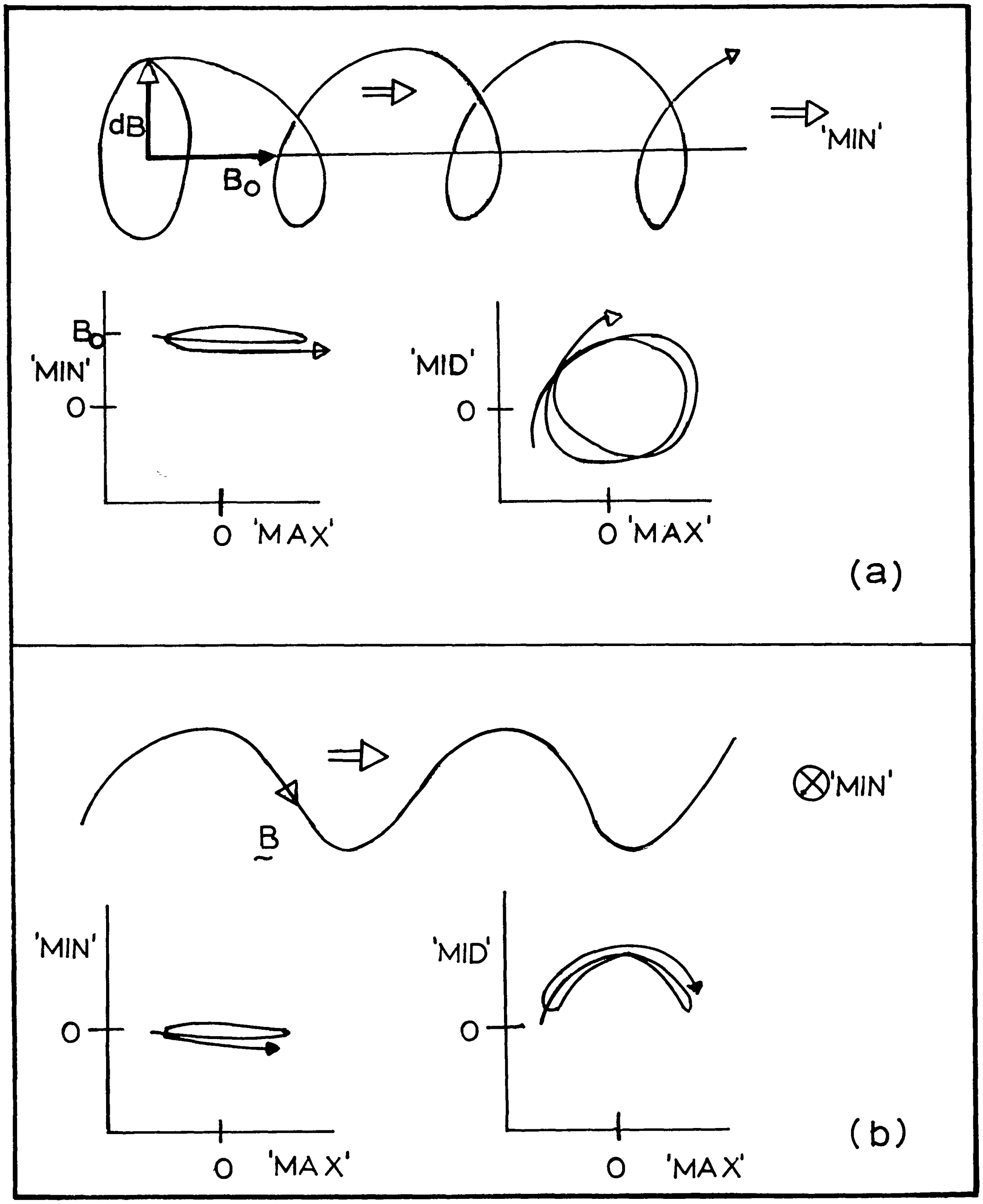

Fig. 3. An example of two extreme cases for (a) transverse circularly polarized Alfvén waves and (b) non-transverse plane polarized Alfvén waves.

In conclusion to this section, it may be said that our analysis lends support to previous workers who have identified Alfvénic finite amplitude structures within the IMF which propagate near radially. We do not, however, necessarily confirm the presence of twisted flux tubes appearing as circular polarization varying on a time-scale of minutes to hours.

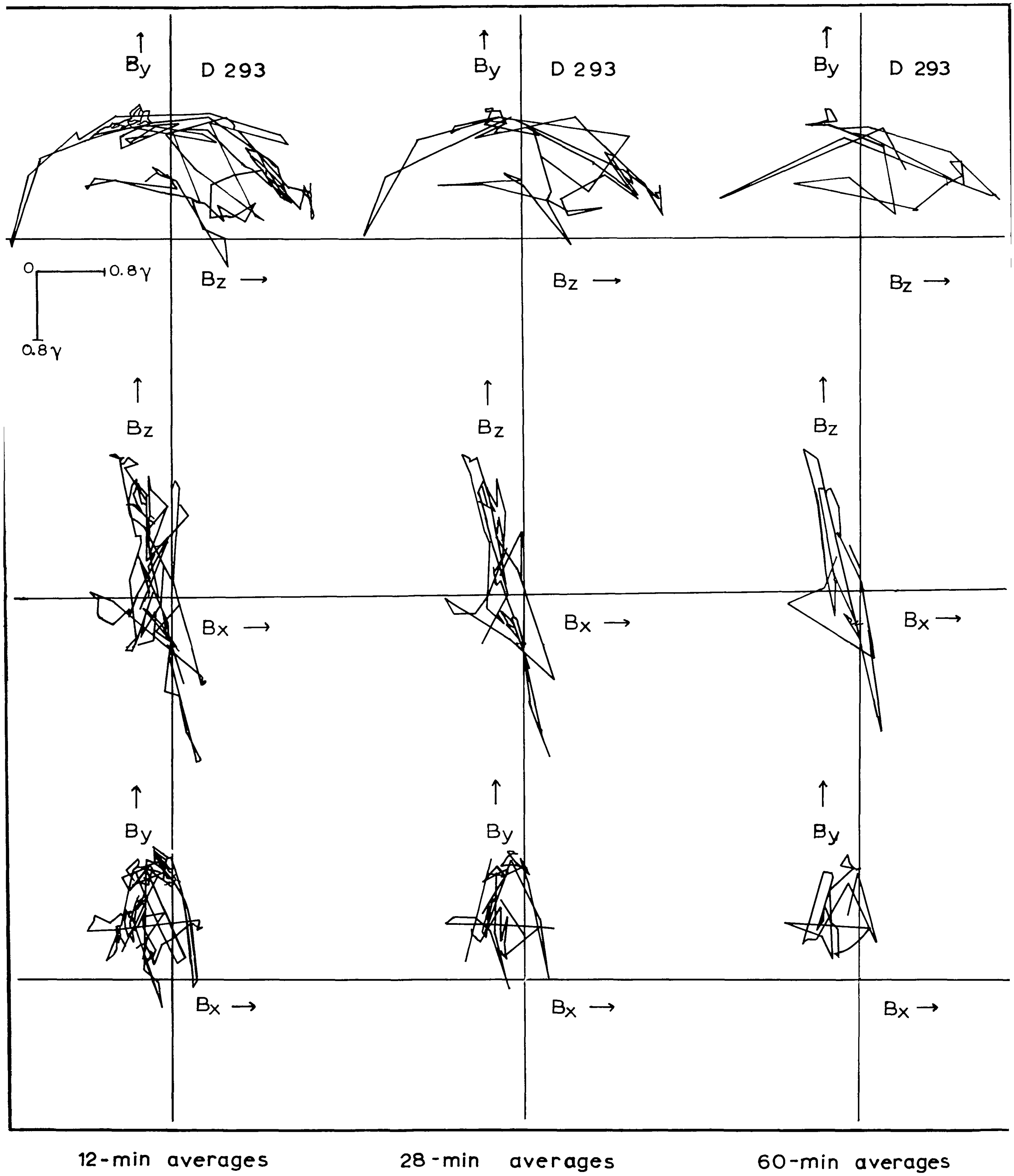

Fig. 4a. Hodograms of the field vectors for the day 292 of 1973 for Pioneer 10 based upon 12-, 28-, and 60-min field averages.

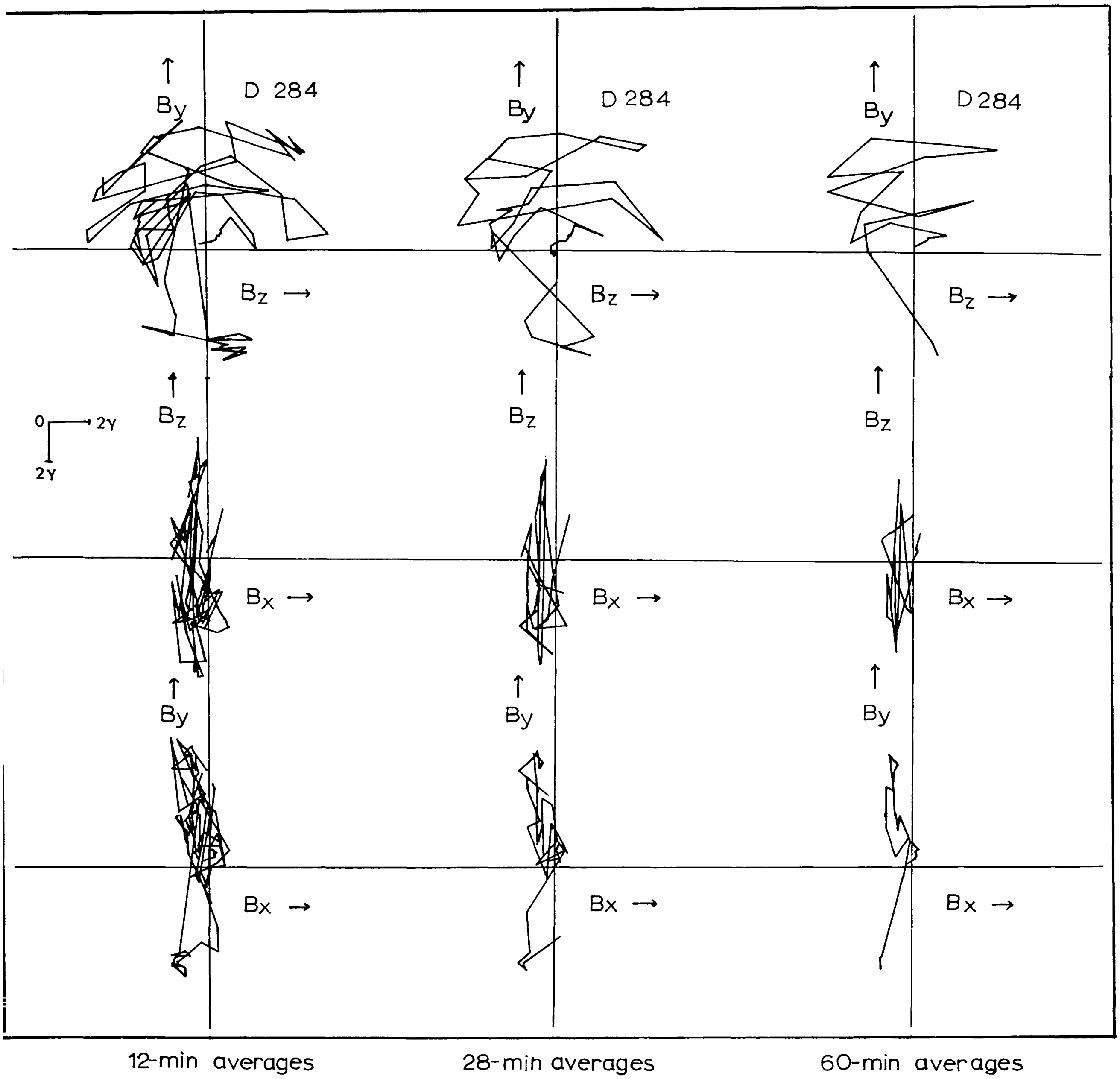

Fig. 4b. Hodograms of the 12-, 28-, and 60-min field averages for one day (D284) of the same data of Pioneer 11.

3. Evolution of Large Waves between 2.5 and 5 AU

Because the observations discussed here are concerned with the same CIR seen at two distances within 8 days of each other and nearly co-aligned in solar longitude, it is worth attempting a detailed study of the evolution of individual features which may be detectable at both spacecraft. Comparison of the field fluctuations seen in Figures 1(a) an 1(b) suggests a similar appearance in the relative positions and shapes of various peaks and, therefore, a non-local origin for the variations. Within the data set, 10 peaks are noticed at 2.5 AU which appear to have counterparts at 5 AU and these are labelled $a - j$ on the graphs.

The field changes $h - j$ may include discontinuities and will be neglected in the subsequent analysis. Tangential discontinuities tend to show step-like change in both $|\mathbf{B}|$ and the field components while rotational discontinuities tend to exhibit step-like changes in the components while $|\mathbf{B}|$ remains near constant. Fluctuations $a - g$ are wavelike with relatively constant $|\mathbf{B}|$ and are, therefore, likely to be large examples of the transverse mode discussed in Section 2. Moreover, they must contribute significantly to the long period arc structures of Figures 2 and 4.

The spatial stability of the CIR wave region may be discussed in terms of the expansion of its size between 2.5 and 5.0 AU. While the region encompassing the waves identified in Figures 1(a) and 1(b) covers a radial distance $\Delta r \simeq 0.4$ AU at 2.5 AU, it is seen covering $\Delta r \simeq 0.73$ AU at 5 AU. This expansion is consistent with movement at a speed of 65–70 km s^{-1}, close to the expected Alfvén speed.

Some structural changes within the stream have taken place if the detailed peak identifications at the two distances are correct. The waves or discontinuities labelled f, g, h occupy a relatively larger region at 5.0 AU than at 2.5 AU when compared with the radial extent of the waves a to f. However, a heliolatitude effect may give the appearance of relative expansion. Note also the peak a at 5 AU which is likely to be the merger of three separate peaks a at 2.5 AU. Steepening and merging of waves within the shock surface, which this evolution of a seems to represent, are predicted phenomena.

Although the positions at which the CIR overtook the Pioneer 10 and 11 spacecraft were located close in solar longitude a significant shift in time occurred due to the radial separation. The waveform similarity between the observations would be unlikely without a large scale coherence to the structure of the fluctuations within the flux tubes of the stream. Furthermore, relative stability over 2.5 AU argues for a solar origin for these waves. Since the periodicities imposed on the plasma at the source are short compared with the time of passage of the stream, it is reasonable to be able to identify the amplitude of each wave component at the two spacecraft.

To quantify the evolution of the large-scale waves, the amplitudes of the y and z components of the waves a, b, c, d, e, and f have been measured. The means of the ratios of these fluctuations at the two distances are then found, i.e.,

$$\left\langle \frac{\delta \mathbf{B}_{y,\,z,\,10}}{\delta \mathbf{B}_{y,\,z,\,11}} \right\rangle .$$

The results are

$$\left\langle \frac{\delta \mathbf{B}_{y,\,10}}{\delta \mathbf{B}_{y,\,11}} \right\rangle = 0.34 \pm 0.26 \, ; \quad \left\langle \frac{\delta \mathbf{B}_{z,\,10}}{\delta \mathbf{B}_{z,\,11}} \right\rangle = 0.21 \pm 0.10 \, .$$

Errors quoted are the standard deviations obtained from the individual ratios. The mean ratio for the two components is 0.28 ± 0.16. A mean ratio has thus been established to about 60% accuracy.

To put the above ratio in context, note that WKB theory for undamped propagation of small amplitude waves of arbitary $\mathbf{k}$ predicts $|\delta \mathbf{B}| \sim r^{-1.5}$ or a ratio 0.35:1 while the nonlinear wave interaction theory of Bavassano *et al.* (1982) predicts an $r^{-1.8}$ dependence or a ratio of 0.29:1 at small radial distance. Our results cannot distinguish between the undamped or lightly damped radial dependencies for wave propagation and are also consistent with the 8–10 AU damping length found by Bavassano and Smith (1986) at 10^{-3} Hz. The large amplitude waves discussed here, however, have frequencies $\sim 10^{-4}$ Hz and so do not exactly correspond to the fluctuations studied previously, either by theory or experiment.

4. Implication for Energetic Particle Propagation

An important motivation for carrying out the analysis described has been to gain better physical insight into the nature of the waves responsible for scattering and perhaps accelerating low-energy cosmic rays and solar energetic particles within selected solar wind regions. In particular the work is relevant to the well-known discrepancy between the value of the particle diffusion mean free path deduced by the application of quasi-linear scattering theory to a power spectral representation of the field fluctuations and the values deduced from the observed intensity-time profiles following flare particle injections (Quenby, 1984, and references therein). The latest progress in reducing the discrepancy as reported by Valdes-Galicia *et al.* (1987, 1988) involves numerical trajectory integrations in a field model derived from spacecraft data during the solar particle event analyzed.

An additional effect in reducing the scattering as calculated from the field values can lie in the relative ineffectiveness of large-scale, coherent wave structures within a magnetic flux tube followed by energetic particles. Such a structure can produce a longer diffusion mean free path than that expected for a random field model based upon a Gaussian correlation function (Webb and Quenby, 1974; Valdes-Galicia *et al.*, 1988). The actual sign of magnetic helicity within the large-scale structure can also be important (Goldstein and Matthaeus, 1981) since the wave-particle resonance occurs with only one sense of field rotation, depending upon the sign of the particle's charge. The implication of this work in identifying likely large scale and coherent wave structures within a CIR is that future modelling of energetic particle propagation should not rely on simple general turbulent field representation. Instead, details of the field fluctuation ocurring during the particle events must be taken into account.

5. Conclusions

(1) Large-amplitude Alfvénic disturbances are abundant within a CIR seen successively by Pioneers 11 and 10 at 2.5 and 5.0 AU.

(2) The waves observed are identified as in the large-amplitude transverse mode with propagation vectors orientated at large angles to the mean field direction but close to the radial direction. The magnetic vector fluctuates approximately like a plane polarized wave. Periods between 2 min and 1 hour are involved, the higher frequency waves being superimposed upon those of lower frequencies.

(3) Radial expansion of the post-shock region of the CIR where the large amplitude waves are found is at a speed consistent with Alfvénic propagation.

(4) The largest amplitude waves observed show relative stability in their structure between 2.5 and 5.0 AU. Their evolution is consistent with either the WKB theory of undamped propagation or theories of wave decay with damping scale sizes greater than, or of the order of 2.5 AU.

(5) There is some evidence for the merging of waves seen close to the shock with that interface as the CIR propagates outwards between 2.5 and 5.0 AU.

(6) Towards the trailing edge of the CIR, the distinction between waves and discontinuities and their possible evolution is difficult to discern from the data considered.

(7) Since the observed wave structures involve the superposition of quasi-periodic smaller amplitude, higher frequency waves upon larger amplitude, lower frequency disturbances, it is concluded that employment of 1 hour interplanetary field averages can conceal significant 'micro physics' of the medium.

(8) The large-scale coherence, implied in the analysis, between the field structures at 2.5 and 5.0 AU requires some effect at the coronal hole source of the CIR to imprint the pattern on the plasma flow.

(9) Future analysis of energetic particle propagation within CIR structures should take into account the specific form and distribution of the waves present and not rely on a random turbulence model.

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