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On the existence of characteristic microscale magnetohydrodynamic fluctuations inside a corotating interaction region at 2.5 AU

H. Mavromichalaki[1], A. Vassilaki[1], X. Moussas[2], L. Marmatsouri[1], J.J. Quenby[3], and E.J. Smith[4]

[1] Nuclear and Particle Physics Section, University of Athens, Solonos Str. 104, GR-10680 Athens, Greece
[2] Astrophysics, Astronomy & Mechanics Section, University of Athens, Panepistimioupolis, GR-15783 Athens, Greece
[3] The Blackett Lab., Imperial College of Science Techology and Medicine, London SW7 2BZ, UK
[4] Jet Propulsion Lab. Mail Stop 169-506, California Institute of Technology, 1800 Oak Grove Drive Pasadena, CA 91109, USA
(xmoussas@atlas.uoa.gr)

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Abstract. A detailed analysis of small period (15-900sec) Magnetohydrodynamic (MHD) turbulence of the interplanetary magnetic field (IMF) has been made using Pioneer-11 high resolution in time data (0.75 sec) inside a Corotating Interaction Region (C.I.R.) at a heliocentric distance of 2.5 AU in 1973 (days 284-286). The methods used here are hodogram analysis, minimum variance matrix analysis and coherence analysis. Inspection of the hodogram analysis gives evidence for finite amplitude non-transverse Alfvén waves if 2min up to 8min averages of the IMF data are used. On the other hand this wave structure disappears if smaller or longer averages of the IMF data are taken under consideration. Minimum variance analysis gives evidence of linear polarized wave modes and coherence analysis shows that the field fluctuations are dominated by the magnetosonic fast modes with periods 15sec to 900sec. However it is also shown that some small amplitude Alfvén waves are present in the trailing edge of this reg ion with characteristic periods of 15 until to 200sec. The results are discussed in terms of several theoretical mechanisms.

Key words: MHD – turbulence – interplanetary medium – solar wind

1. Introduction

The interplanetary medium is a highly conducting essentially collisionless plasma with approximate equipartition between thermal and magnetic field energy densities. Thus it provides an excellent example of an astrophysical plasma where MHD waves can be studied in situ with instruments considerably smaller than the Debey length.

Early observations, identifying Alfvén waves in the trailing edge of the fast solar wind streams in the interplanetary medium are due to Coleman (1967), Belcher et al (1969) and Belcher and Davis (1971). The subject of the MHD wave modes, especially Alfvén waves, has been discussed in several reviews during the past few years (Hollweg, 197 4; 1975; 1978; Barnes and Hollweg, 1974; Völk, 1975;) all written mainly from a theoretical point of view.

Daily (1973) and Burlaga and Turner (1976) revealed that the propagation direction of Alfvén waves in the interplanetary medium, is oriented along the ambient magnetic field. Apart from these much work has been reported using spectral techniques in order to identify the wave structure of interplanetary field as well as the signatures of tu rbulence at different distances (Sari and Valley, 1976; Sari, 1977; Matthaeus et al, 1982; Roberts and Goldstein, 1987; Burlaga and Mish, 1987; Tu and Marsch, 1990)

Parker (1980) using hourly averaged data of the interplanetary magnetic field showed the predominance of the Alfvén waves over the fast and slow modes. Roberts et al (1987a; b) have used hourly averaged field plasma data in order to study the properties of interplanetery MHD fluctuations and the contribution of the compressive modes to th e interplanetary fluctuations. Mullan and Owen (1984) using ISEE-3 data for the year 1979 found signatures of outgoing Alfvén waves with duration 200-900sec. Recently Bruno and Bavassano (1991) studying the incompressible MHD fluctuations on time scales longer than 1 hour in terms of radial evolution of normalized cross helicity concluded that the local generation of Alfvén waves is not very common in solar wind and the evolution of helicity is mainly due to the continued distribution of the outward modes rather than to the presence of inward modes. Klein et al (1991) examined Voyager-2 magnetic field and plasma data (averages of 192sec) to study the evolution of the anisotropy of solar wi nd fluctuations from 1 to 10 AU. They found that on average the direction of minimum variance vectors of magnetic fluctuations are close to the mean magnetic field direction with an increasing component of the variance along the field at larger scales. On the other hand Tsurutani et al (1993) during the Ulysses fly by

Send offprint requests to: H. Mavromichalaki

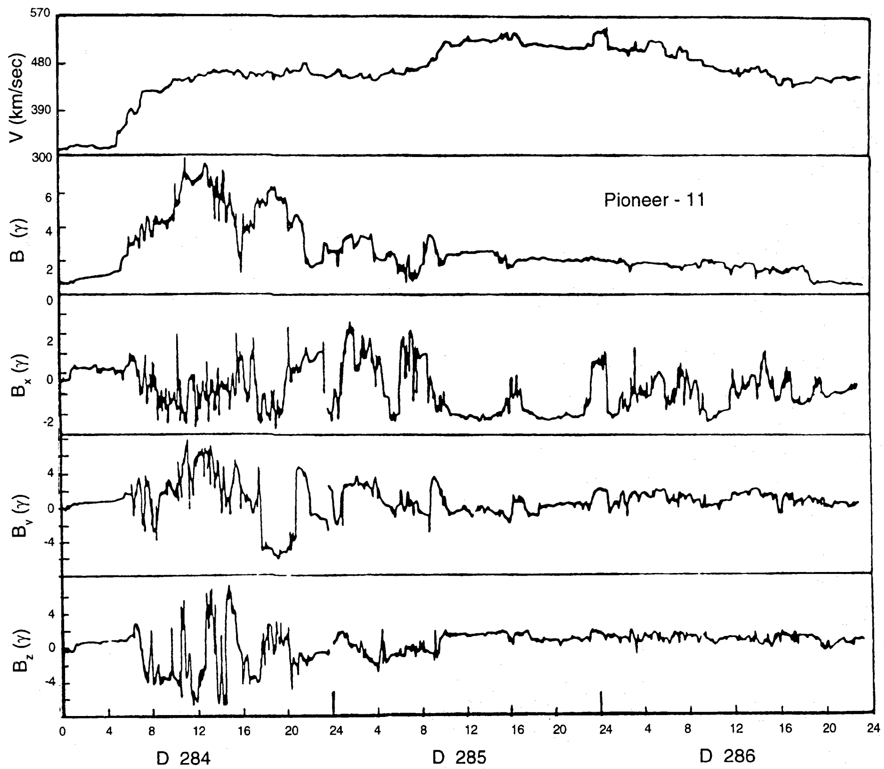

Fig. 1. Time plots of plasma velocity, field magnitude and field components of Pioneer-11 observations for 284, 285 and 286 days of the year 1973.

the Jovian foreshock, detected two predominant wave periods of 100sec and 5sec in the foreshock. The 100sec waves are non linear and steepend magnetosonic modes which sometimes have whistler packets attached and are due to 2 KeV proton beams. The authors argue that the 5sec waves are consistent with magnetosonic waves generated as by products of the whistler mode.

Moreover a detailed study of the nature of the evolution of the MHD waves in the Earth's foreshock by Malara and Elaoufir (1991) has shown that the nonlinear evolution of the one dimensional MHD wave leads to the formation of a rotational discontinuity and a compressive steepened quasi linearly polarized pulse whose structure is similar to that of a finite amplitude magnetosonic simple wave. The two dimensional evolution shows that an MHD wave is unstable against a small-amplitude long-wavelength modulation in the direction transverse to the wave propagation direction. Elaoufir et al (1990) using ISEE -1 and -2 spacecraft data investigated quantitatively the correlation between the fluctuation in electron density and magnetic field in proton foreshock. They confirmed the existence of whistler mode waves, as discrete wave packets. Besides, for appropriate value for the inperturbed magnetic field it is shown that the well known "shocklet" structure consists of finite amplitude linearly polarized, simple fast mode waves separa ted by rotational discontinuities. A region with special interest in the interplanetary space as concerns the MHD turbulence is that of a corotating interaction region. Such a case has been examined by Mavromichalaki et al (1988) using Pioneer-10 and -11 observations at 5 and 2.5 AU respectively. Hodogram analysis suggested the dominance of near plane polarized transverse Alfvénic mode fluctuations with periods between 2min and 1 hour or more. The purpose of this work is a further study of the C.I.R. at 2.5 AU during the days 284- 286 of the year 1973 in a detailed manner using Pioneer-11 observations. An attempt has been made to identify the dominant microscale MHD modes that contribute to the turbulence of this area and form its microscopic structure at that heliocentric distance.

2. Data analysis and wave structure

For our study we have used IMF and plasma data from Pioneer-11 magnetometer from the days 284,285 and 286 of the year 1973. The time resolution of the interplanetary magnetic field samples is 0.75sec while the radial plasma velocity measurements are taken every 5 minutes. Plasma velocity and interplanetary magnetic field components are plott ed in a XYZ spacecraft solar ecliptic coordinate system. The overall behaviour of the three components of the interplanetary magnetic field and the plasma velocity is shown in Fig. 1. From this figure it is obvious the presence of a large shock front at about the 6th hour of the day 284. The observed shock has a compression ratio equal to 3 which is typical of a C.I.R.

A Blackman and Tuckey (1958) power spectrum analysis and a Fourier analysis 'have been carried out on all the available magnetic field data. A set of well defined periods have been found at a confidence level of 99.9%. These periodicities extend from 1.4min - 240min, but most of them are of the order of some minutes up to 15 minutes. This fa ct leads us to investigate primarily the small periodicities in our data in order to determine their wave structure.

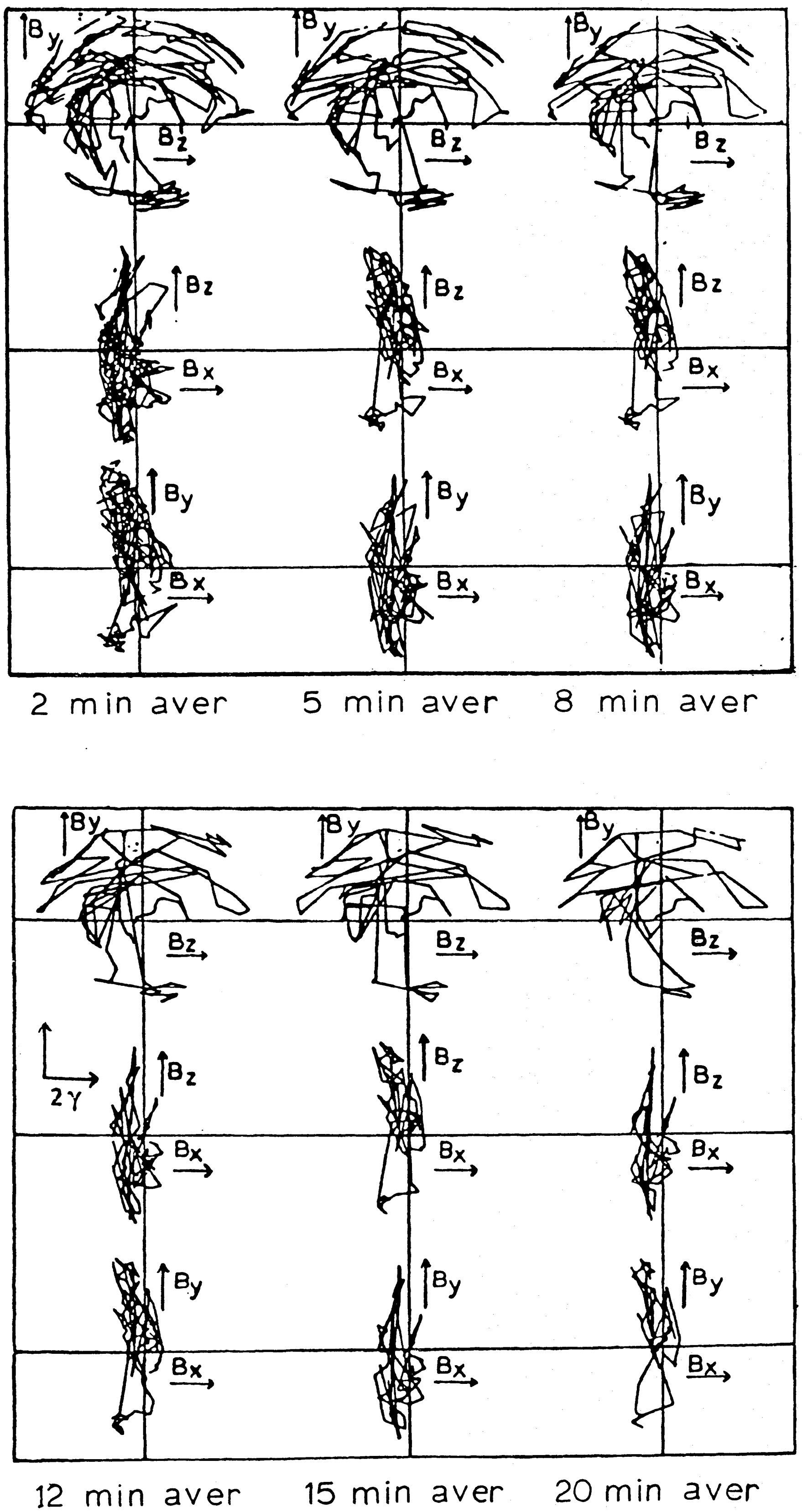

Fig. 2. Hodogram analysis of the field components (284 day). Averages over 2min up to 20min intervals.

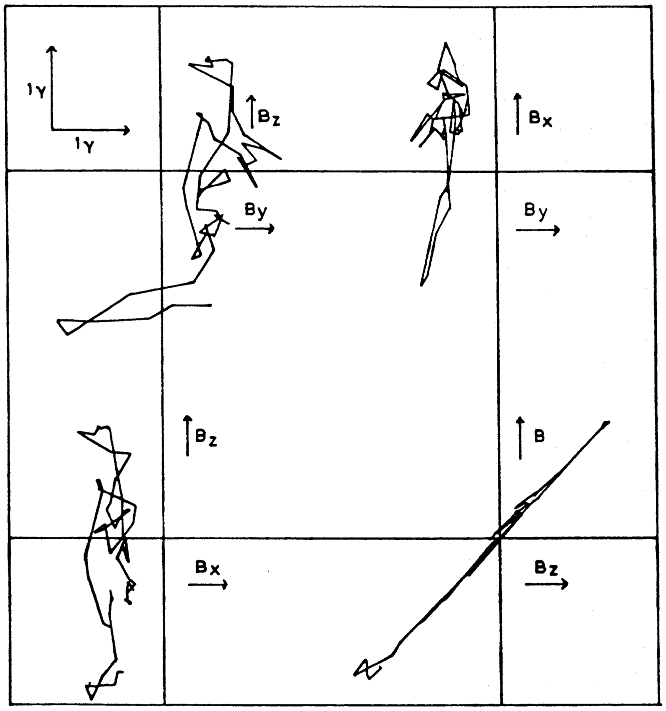

Fig. 3. Hodograms of 15sec averages during a 15min interval in day 284.

An hodogram analysis has been carried out averaging our data at different time intervals from 2min up to 20min. From this analysis it is concluded that a strong wave structure is dominant for field values averaged over 2min to 8min intervals. This wave structure disappears if longer averages are used (Fig. 2). In this figure it is clearly seen that the field vector in the YZ plane for day 284 follows circular arcs with a roughly linear relation in the XY and ZX planes (Mavromichalaki et al, 1988). For these reasons we have concentrated our interest on the small periods between a few seconds and up to 15 minutes.

We have divided our data set in 15 minute intervals and we have examined the hodogram of magnetic field vectors taking 15sec averages during each interval under consideration. Inspection of the hodograms has shown that the wave structure which dominated the 2min - 8min averages disappears. The relation between the field vectors in YZ, ZX, XY planes, as well as between the magnetic field vector and magnetic components vector becomes roughly linear. This fact is an evidence that for these time scales of 15sec the polarization is nearly linear polarization. An example of this hodogram analysis results is apparent in Fig. 3.

In order to define the polarization plane of the observed wave structure, we examine the anisotropy in the microscale fluctuations of the magnetic field data considering directions of maximum and minimum power in a preferred coordinate system according to the method employed by Sonnerup and Cahill (1967) and Siscoe et al (1969). For this purpose we estimate the variance tensor S which is defined by

$$S_{ij} = < B_i B_j > - < B_i > < B_j > \quad (1)$$

where i,j refer to x,y,z components of the magnetic field **B** and the angle brackets denote averaging over the chosen 15 minute time interval. The trace of the tensor is equal to the sum of the variances σ_s on the individual axes. It is invariant to rotation of axes and is the sum of the eigenvalues of the matrix. If $< B >$ is the average field then

$$\sigma_{\parallel}^2 = \sum < B_i > S_{ij} < B_j > / < B >^2 \quad (2)$$

$$\sigma_{\perp}^2 = \sigma_s^2 - \sigma_{\parallel}^2$$

are the variances in the magnetic field parallel and perpendicular respectively to the average field direction and is the total variance. These two variances give a measure of the fluctuations that primarily change the field strength and those that primarily change the field direction, respectively. From the calculation of these quantities for each 15min interval we find important fluctuations of the field strength ($\sigma_{\parallel}$) as well as of the field direction ($\sigma_{\perp}$) especially for days 284 and 285. This is an indication that on the time scale of 15min the fluctuations of the interplanetary magnetic field are three dimensional and the near plane polarization which dominated the 2 up to 8 min time scales was indeed disappeared.

The matrix S can be diagonalized, yielding the eigenvalues $L_1 \geq L_2 \geq L_3$ and the corresponding eigenvectors M_1, M_2, M_3 is the direction of maximum variation and is the direction of minimum variation. The relative magnitudes of the eigenvalues provide information about the anisotropy that is independent of the coordinate system used. For example, if L_1, L_2, L_3 are of approximately equal magnitude, the fluctuations are approximately isotropic in three dimensions and the directions of eigenvectors have a little significance. If L_1 and L_2 are of comparable magnitude and much larger than L_3 the fluctuations are isotropic in the plane whose normal is M_3 (near circular polarization). If L_1 is much larger than L_2 and L_3 the fluctuations are primarily in the direction M_1 (linear polarization) (Belcher and Davis, 1971).

Applying the above method in our data sets we find that in most of the cases the eigenvalue L_1 was much larger than L_2 and L_3 and consequently the IMF fluctuations are primarily in one direction, the direction of maximum variance. Thus we expect the polarization to be primarily linear. Fig. 4 illustrates the results given above by showing the eigenvalue ratios for each day under study. As we can see from this figure most of the ratios between L_2 and L_1 are found to be less than 0.2 which is a typical value for linear polarization (Burlaga and Turner, 1976). On the other hand the condition $L_2/L_1 \simeq 1$ which is typical for circular polarization, is simply not satisfied.

In order to confirm the non existence of circular polarization of the wave modes and to classify the MHD wave type, we have carried out on our data a coherency and phase lag analysis between the field components. We use this analysis to identify field fluctuations for frequencies $1.1 \cdot 10^{-3}$ to $6.6 \cdot 10^{-2}$ Hz.

It is known that MHD wave modes exhibit numerous phase relationships between the field components and mangitude fluctuations some of which will be common to more than one mode. However according to Sari and Valley (1976) and Valley (1974) there are specific phase relationships which are unique to each

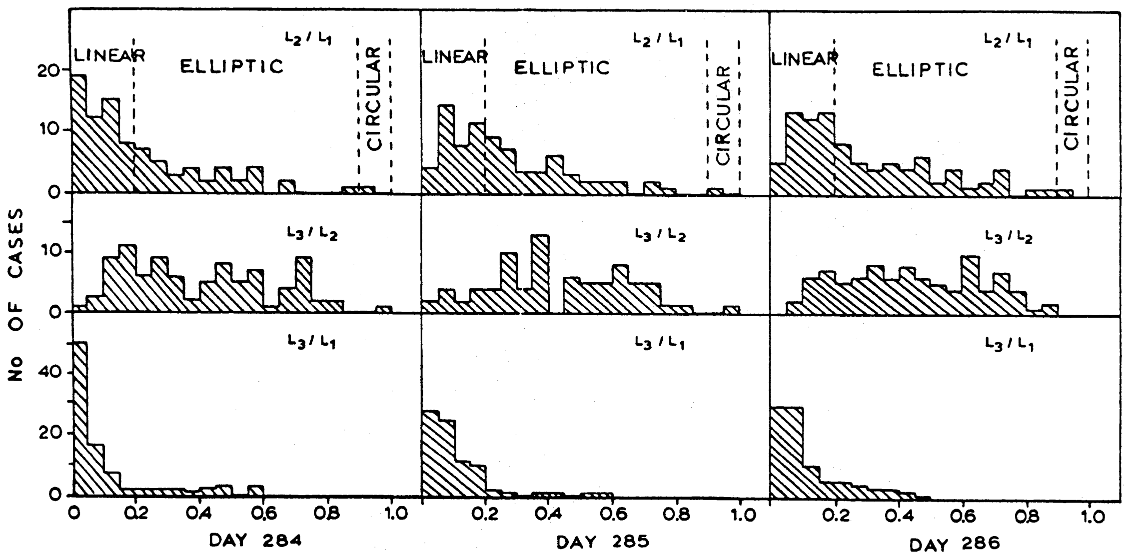

Fig. 4. Eigenvalue ratios for the three days under study.

mode and which can be determined from the analysis of the particular modes:

a) Finite Amplitude transverse Alfvén waves

b) Finite Amplitude non transverse Alfvén waves

c) Small Amplitude Alfvén waves

d) Magnetosonic waves

In order to determine which of these modes exist by applying the coherence analysis we have estimated the orientantion of the mean magnetic field for each day examined.

For this purpose we have calculated the mean angle θ between $< B >$ and z-axis as well as the mean azimuthial angle ϕ for every 15 minute interval. The polar diagrams of these estimates are shown in Fig. 5 where we can see the general tendency of the mangetic field orientation for each of the three days. The mean magnetic field on 284 day is statistically oriented towards the y-axis ($< \theta >= 94^o \pm 5^o$ and in 72% of the cases $< \phi >$ takes values close to y-axis). During the second day the orientation of the mean magnetic field statistically seems to be close to x-axis $< \theta >= 76^o \pm 2^o$ and in 77.5% of the cases $< \phi >$ takes values close to x-axis). Finally during the day 286 it is approximately oriented in the mean spiral direction which at 2.5 AU is 65^o or 155^o $< \theta >= 68^o \pm 2^o$ and in 86% of the cases ϕ = 140o). So during this day in coherence analysis we have to examine all possible combinat ions between the field componen ts for every 15min interval.

According to the above observations the criteria we have used for the existenc e of the MHD wave modes, as adopted from Sari (1977), ($< B > \parallel$ y- axis for 284 day, $< B > \parallel$ x- axis for 285 day and $< B >$ is random for 286 day) are as follow:

a) Finite Amplitude Transverse Alfvén waves, expect

1) High coherency

2) Phase relation $\pm 90^o$ between ΔB_x and ΔB_z for 284 day, between ΔB_y and ΔB_z for 285 day and all combinations for 286 day.

b) Finite Amplitude Non Transverse Alfvén waves, expect

1) High coherency

2) Phase relation 180° between ΔB_{xz} and ΔB_{xy} for 284 day, between ΔB_{xy} and ΔB_x for 285 day and all combinations for 286 day.

c) Small Amplitude Linearized Alfvén waves, expect

1) High coherency

2) Phase relation 0° or 180^o between ΔB_{xz} and ΔB for 284 day, between ΔB_{yz} and ΔB for 285 day and all combinations for 286 day.

d) Magnetosonic waves, expect 1) High coherency 2) Phase relation 0^o or 180^o between ΔB_x and ΔB, ΔB_y and ΔB and/or ΔB_z and ΔB for all days. Taking into account the above criteria the coherency and the phase lag between the three field components (ΔB_x, ΔB_y, ΔB_z) and the field magnitude ΔB are calculated for every 15 minute interval for the three days under study for the Pioneer-11 data. The same quantities are also calculated between the magnitude of the transverse fluctuations (ΔB_{xz} for the day 284 and ΔB_{yz} for the day 285) and the longitudinal fluctuations (ΔB_x, ΔB_y) and ΔB. We have a confidence level of 99.9% when the coherency was greater than 0.4 and a near stable phase over a frequency band of greater than $f_c/4$ where $f_c = 6.6 \cdot 10^{-2}$ Hz. A typical example for the coherencies and phase lags between the various field components for the 284 day is given in Table 1. It is noteworthy that there is no evidence of circular polarized wave modes. The most dominant wave modes during all days were the magnetoacoustic waves. There is an exception in day 286 where some small amplitude Alfvén waves appeared at frequencies $4.4 \cdot 10^{-3} - 6.6 \cdot 10^{-2}$ Hz. It is puzzling that there is no significant correlation between $\Delta_{\ xz}$ and ΔB_y on 284 day. This provides an evidence for the non existence of finite amplitude non-transverse Alfvén waves. Such waves can be seen on the traversal of partial arcs of circles because the longitude hodograms are at finite characteristic frequencies of the transverse fluctuations (Sari, 1977). We can

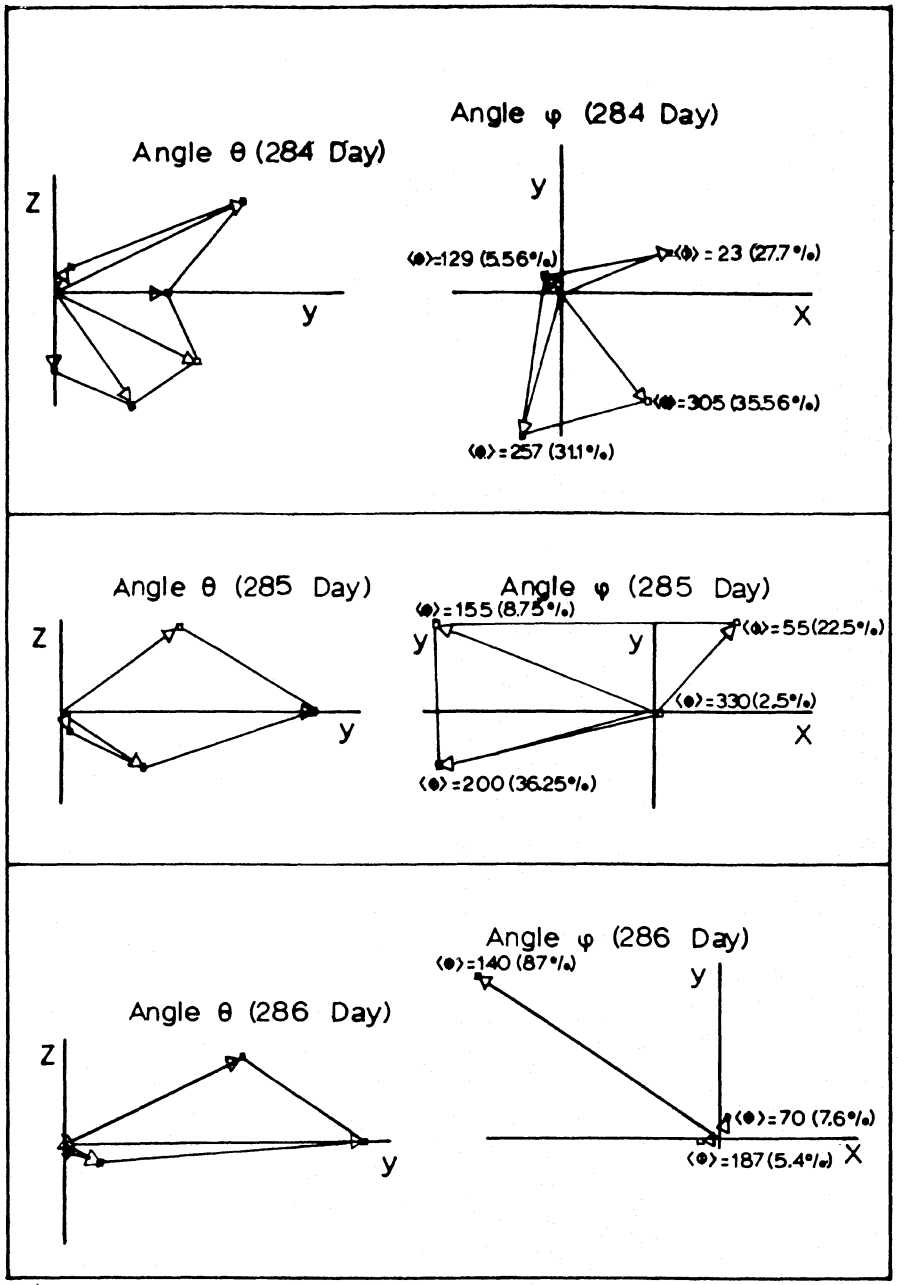

Fig. 5. Polar diagrams of the $<\theta>$ and the $<\phi>$ angles for the days 284, 285 and 286 of the year 1973.

only conclude that these waves are not significant for very short periods.

Finally we note that apart from the four above mentioned wave modes, other MHD structures such as tangential discontinuities, can't be completely dismissed. However, since the time intervals we examined here are small (15min) and the average separation between discontinuities ($> 30^o$) in the solar medium is $d = 1.5 \cdot 10^{11}$cm (about 1 hour) it is unlikely that such structures are important in our data sets (Siscoe et al, 1968; Burlaga, 1969).

3. Conclusion and discussion

From the previous section we can say that the dominant wave modes in the microscopic structure of the C.I.R. examined suggested in the hodogram, minimum variance and coherence analyses are magnetoacoustic waves with characteristic periods 15-900sec. There is no evidence of circularly polarized Alfvén waves finite amplitude Alfvén waves in this period range. A few small amplitude Alfvén waves are found at smaller characteristic periods (15-225sec) in 286 day during the trailing edge of this region.

In the last few years, there have been numerous theoretical studies shown either no substantial amount of magnetosonic waves existing in the solar wind or alternative in significant

Table 1. Typical example of the calculated coherencies and phase lags during day 284.

15-min interval	cohe-rency	phase lag	frequency range	compo-nents
65	0.95	3°	$0 < f < f_c$	By - B
68	0.98	0°	$0 < f < f_c$	By - B
70	0.83	4°	$0 < f < f_c$	By - B
70	0.76	177°	$0 < f < f_c/2$	Bz - B
71	0.88	180°	$0 < f < f_c$	Bz - B
72	0.85	180°	$0 < f < f_c$	Bz - B
73	0.82	182°	$0 < f < f_c$	Bz - B
74	0.83	180°	$0 < f < f_c$	Bz - B
77	0.67	179°	$0 < f < f_c$	Bz - B
79	0.75	179°	$f_c/4 < f < f_c$	Bz - B
80	0.76	180°	$f_c/4 < f < f_c$	Bz - B
81	0.70	186°	$f_c/4 < f < f_c$	Bz - B
82	0.74	180°	$f_c/2 < f < f_c$	Bz - B
83	0.68	180°	$f_c/2 < f < f_c$	Bz - B
89	0.80	4°	$f_c/4 < f < f_c$	Bz - B
90	0.73	4°7	$f_c/4 < f < f_c$	Bz - B

amounts of magnetoacoustic wave generation although only few cases of direct observations of magnetosonic waves in the solar wind have been made (Sari and Vall ey, 1976). For instance on the basis of theoretical works of Barnes (1967; 1974) and Hada and Kennel (1985), it is often argued that magnetosonic waves generated at the Sun will be damped out at 1 AU. On the other hand at least four mechanisms have been suggested in order to allow the local generation of these waves: Conversion of Alfvén waves to magnetosonic waves

a) through refraction in the mean spiral field (Belcher and Davis, 1971),

b) through scattering by turbulent density fluctuations (Valley, 1974),

c) by large stream-stream interactions (Belcher and Davis, 1971) and by small scale instabilities (Völk, 1975).

In the first mechanism (Belcher and Davis, 1971), although for interaction regions we expect to see all types of hydromagnetic waves, the fluctuations are primarily Alfvénic (small variance in field strength compared with large variance in components). However, even if Alfvén waves are preferentially generated, we would expect them to excite magnetosonic modes, either because of nonlinearities in the equations of motion or because geometrical considerations (a pure Alfvén wave must extend to infinity in the plane of polarization). In addition to these possibilities, Alfvén waves convected into interaction regions will see a rapid change in the average field direction across the transition into the compressed plasma. This more abrupt change in field direction as compared with the gradual spiraling, should result in enhanced anisotropies and a higher level of (rapidly damped) magnetoacoustic oscillations. Thus one may have a local mechanism of magnetoacoustic wave generation which may be attributed to the gradual conversion of Alfvén waves into magnetoacoustic waves because of refraction in the spiral field. In our observational data of Pioneer-11 a consecutive mechanism for the local generation of magnetoacoustic waves is not very likely at least during the first day of our study in which we observe the most abrupt changes in field magnitude. This is because we have no evidence of the existence of significant Alfvénic wave that convected in the interaction region at 2.5 AU. In fact there is no significant periodicity during the quiet period which lies before the formation of the shock, the 6th hour of the 284 day and consequently there are no waves that encountered the abrupt change of the magnetic field during that time period (Fig. 1)

Another possibility (third mechanism) according to Belcher and Davis (1971), is that the local generation of magnetoacoustic waves may be attributed to the large scale stream-stream interaction in the leading edges of the fast solar wind streams. It is known that the heating and high magnetic field activity found in the compression regions at the leading edges of high velocity streams were generated locally by faster streams overtaking and colliding with slower streams. Jokipii and Davis (1969) noted the importance of such stream-stream collisions as a source of wave and thermal energy in the solar wind. They noted that, if the collisions are predominant between the edges of the solar wind moving radially, the compression will be mainly in the radial direction and this will produce more fluctuations in the transverse than the radial component of the magnetic field.

Considering the fact that the C.I.R. studied here has the same characteristics as the region discussed above it is very possible that this mechanism is responsible for the generation of the magnetoacoustic waves observed in this analysis.

On the other hand Valley (1974) has shown in an analytical calculation that random density fluctuations scatter energy out of the Alfvén mode into magnetosonic mode (second mechanism). Valley's calculations demonstrated that static density fluctuations in the solar wind scatter a coherent Alfvén wave and transform it to both Alfvén and mag netoacoustic modes. Unless the wave length of the Alfvén wave is very large or the correlation function dependents on either the perpendicular or parallel directions alone, the energy in the scattered magnetosonic mode is comparable to that in the Alfvén mode. Thus, Valley concluded that significant energy may be scattered from a coherent Alfvén w ave to random magnetosonic waves, more specifically if the wavelength is smaller than the correlation length, approximately half of this lost energy goes into magnetosonic waves. A typical correlation length, L0, for the fluctuations in a C.I.R. is of the order 2 (106 km according to Jokipii and Hollweg (1970). The wave lengths corresponding to the wave observed in the power spectrum analysis of our Pioneer-11 data in the solar wind rest frame (Alfvén speed ($\simeq 60 km/sec$) are between 8.9 (102 - 5.4 (104 km. This estimated value of the wavelength is smaller than the correlation length, so there is a reasonable possibility that a large amount of Alfvén wave energy is scattered into random mangetosonic waves.

Finally another possible reason for the existence of locally generated magnetoacoustic waves lies in the small scale instabilities in plasma (the last mechanism). According to Völk (1975) since the electron current must equal the ion current in order to preserve electron neutrality of the solar wind flow, the peak of the electron distribution will thus be shifted relative to that of the ion distribution. Under these circumstances a number of resonant instabilities can be excited in particular growing magnetosonic waves travelling backwards towards the sun, in the frame of the solar wind. Perkins (1973) argued that in the case of the magnetosonic instability the wave energy may concentrated at wavelengths of the order of $2c/w_p \simeq 200km \cdot r/AU$. In our case, where Pioneer-11 is at the distance of 2.5 AU, this value is of the order of 500 km. The wavelengths of the magnetosonic waves founded here range between (545 to 900)$\cdot 10^2$ km, values much higher from those Perkin estimates. Thus it is not obvious that these waves would be a result of magnetosonic instabilities in that region.

Summarizing, we can say that the most probable explanation we can give about the magnetosonic microscopic structure of the C.I.R. under consideration, is that the fast magnetoacoustic modes, which are the dominant at periods of the order 15-900sec, are locally generated and may be attributed to the scattering of Alfvén wave energy, which constitute the dominant waves of longer periods, into random magnetosonic waves.

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