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ON THE EXISTENCE OF FINITE AMPLITUDE, TRANSVERSE ALFVÉN WAVES IN THE INTERPLANETARY MAGNETIC FIELD

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ABSTRACT

Interplanetary magnetic field data from the Mariner 10 spacecraft are examined for evidence of small and finite amplitude transverse Alfvén waves, general finite amplitude Alfvén waves, and magnetosonic waves. No evidence for transverse Alfvén waves is found. Instead, the field fluctuations are dominated by the general finite amplitude Alfvén wave. Such wave modes correspond to non-plane-wave solutions of the nonlinear magnetohydrodynamic equations.

Large amplitude ($\Delta B/B \sim 1$) Alfvén waves have been observed in the interplanetary magnetic field [1,2] and are assumed to occur in numerous laboratory and astrophysical plasmas. These waves are expected to obey the nonlinear magnetohydrodynamic (MHD) equations[3,4] for which the magnitude of the total magnetic field, $|\vec{B}_{o_z} + \Delta\vec{B}|$, is constant; the fluid fluctuations are incompressible and are related to the magnetic field fluctuations by $\Delta\vec{v} = \pm\Delta\vec{B}/(4\pi\rho)^{1/2}$; and the field fluctuations satisfy the vector equation, $(\vec{B}_{o_z} \cdot \vec{\nabla})\Delta\vec{B} = \pm (4\pi\rho)^{1/2}\, \partial(\Delta\vec{B})/\partial t$. Such waves are generally studied in terms of transverse or plane wave solutions to the equations[5], because of simplifications resulting from Fourier decomposition. However, non-transverse or non-plane-wave characteristic solutions exist[6,7] which permit more general, and more complex, fluctuations. It is not clear that transverse waves need occur naturally, since they correspond only to special cases of the MHD equations.

The turbulent interplanetary plasma provides an ideal environment to study MHD waves. This study's results were obtained from six second averages of Mariner 10 magnetometer data[8] taken at heliocentric radii from 0.5 to 1.0 AU. Twenty-six periods of from one to four hours in length were chosen for analysis when the mean interplanetary magnetic field was stable and directed along the heliocentric radius. During these times[9], ambiguities associated with such structures as discontinuities[10,11] were eliminated. Phase and coherency spectral analyses were used to identify the field fluctuations for frequencies $0 < f < 8.3 \times 10^{-2}$ Hz, or for equivalent spatial wavelengths $\lambda = V_w/f \geq 5 \times 10^8$ cm.

In the spacecraft frame (considered stationary in the solar wind), the MHD wave modes will exhibit numerous phase relationships between the field component and magnitude fluctuations, some which will be common to more than one mode. There exist, however, specific phase relationships which are unique to each mode and which can be determined by analysis of the particular modes:

1) Finite Amplitude, Transverse Alfvén Wave

$$|\vec{B}_{o_z} + \Delta\vec{B}| = \text{const}, \quad B_{o_z} = \text{const}, \quad B_x^{\,2} + B_y^{\,2} = \text{const}$$

This case consists of two modes, depending on whether the phase vector, $\vec{k}$, is or is not parallel to the mean ($\vec{B}_{o_z}$) magnetic field. For $\vec{k} \parallel \vec{B}_{o_z}$ (circular polarization), $\vec{B}$ will revolve in a circle in the xy plane. In the spacecraft frame, a phase relationship between the transverse components of Phase $\Delta B_x\ \Delta B_y = \pm 90°$ will be observed.

For $\vec{k} \nparallel \vec{B}_{o_z}$, $\vec{B}$ is confined to move along a partial arc of a circle in the xy plane[5]. As a result, no specific phase relation between ΔB_x and ΔB_y will be observed, since their characteristic frequencies will be multiples of each other. However, since $B_x^{\,2} + B_y^{\,2} = \text{const}$, the magnitude of the transverse components will satisfy Phase $\Delta B_x^{\,2}\ \Delta B_y^{\,2} = 180°$. (Note that the phase relations for $\vec{k} \parallel \vec{B}$ will also satisfy the phase relation for $\vec{k} \nparallel \vec{B}$).

2) Finite Amplitude, Non-Transverse Alfvén Wave

$$|\vec{B}_{o_z} + \Delta\vec{B}| = \text{const}, \quad B_z \neq \text{const}$$

This mode, not being transverse, has no characteristic $\vec{k}$, but the wave group velocity propagates in the mean field direction. Moreover, the field fluctuations will have a fluctuating longitudinal component, ΔB_z. In order that $|\vec{B}_{o_z} + \Delta\vec{B}| = \text{const}$, it can readily be demonstrated that ΔB_z will, to first order, vary exactly out of phase with the magnitude of the transverse field fluctuations: Phase $(\Delta B_x^{\,2} + \Delta B_y^{\,2})\Delta B_z = 180°$. This result implies that the longitudinal field fluctuations will occur at twice the characteristic frequencies of the transverse field fluctuations.

3) Small Amplitude, Linearized Alfvén Wave

$$|\vec{B}_{o_z} + \Delta\vec{B}| \neq \text{const (in second order)}$$

This mode satisfies the linearized MHD equations[4]. $\Delta\vec{B}$ is normal to the plane containing $\vec{k}$ and $\vec{B}_{o_z}$. Hence, to second order, $|\vec{B}| \neq$ const (except for circular polarization); this gives rise to an in-phase relation between the magnitude of the transverse field and the field magnitude fluctuations: Phase $(\Delta B_x^2 + \Delta B_y^2)\ |\Delta B| = 0°$.

4) Magnetosonic Waves

These are compressive modes occurring in both the linearized and finite amplitude MHD equations[5]. For $\vec{k} \nparallel \vec{B}_{o_z}$ (i.e., not degenerate with the planar, linearized Alfvén wave with $\vec{k} \parallel \vec{B}_{o_z}$), the transverse field fluctuations can be shown to vary exactly in or out of phase with the field magnitude fluctuations: Phase $\Delta B_x\ |\Delta B|$ and $\Delta B_y\ |\Delta B| = 0°$ or $180°$. A similar relation between $\Delta B_z\ |\Delta B|$ is expected, but this coherency can (and was observed) to be broken by the presence of case (2) fluctuations.

The simultaneous presence of all four wave modes can be detected, as a result of the phase relationships unique to each mode. Note that without knowledge of all the plasma parameters, the presence of other MHD structures (e.g. tangential discontinuities) can not be completely dismissed. However, as stated above, the selection of stable, radial field periods would tend to rule out such structures in the data.

The phase and coherency relationships in this study were obtained in a field aligned coordinate system ($\vec{z} \parallel \langle\vec{B}\rangle$) using cross and co-spectral analyses[12] at an equivalent of 150 degrees of freedom.

For the periods examined, no significant coherencies at the 90 per cent confidence level were found between $\Delta B_x\ \Delta B_y$ and $\Delta B_x^2\ \Delta B_y^2$ (transverse finite amplitude Alfvén). Instead, for all periods, coherencies between 0.6 and 0.9 were found for $(\Delta B_x^2 + \Delta B_y^2)\Delta B_z$ at exactly 180° phase lag for $0 < f < 8.3 \times 10^{-2}$ Hz (non-transverse finite amplitude Alfvén). A typical coherency-phase relation is shown in Figure 1. The anticorrelation between $(\Delta B_x^2 + \Delta B_y^2)$ and ΔB_z is observed in the time domain as well, as exhibited in another typical period in Figure 2. The existence of such fluctuations is not obvious in general plots of the data, because of the lack of specific phase relations between ΔB_x and ΔB_y and because the characteristic ΔB_z fluctuations occur at twice the ΔB_x and ΔB_y frequencies.

Only one statistically significant instance of a small amplitude Alfvén wave was noted, for which Phase $(\Delta B_x^2 + \Delta B_y^2)\,|\Delta B| = 0°$. Most periods also exhibited coherencies between 0.3 and 0.4 for either $\Delta B_x\ |\Delta B|$ and $\Delta B_y\ |\Delta B|$ with phase lags of 0° or 180°. These results would imply the existence of a small admixture of magnetosonic fluctuations, and this is consistent with previous analyses[9].

The above results would indicate that except for discontinuities in the interplanetary magnetic field[13,14,15] the fluctuations are dominated by finite amplitude, non-transverse Alfvén waves. Observations consistent with a small percentage of magnetosonic waves were found; such waves are expected to Landau damp in the solar wind[16], but a number of mechanisms for generating them have been proposed[17,18,19]. Finite amplitude, transverse Alfvén waves, if they exist in the solar wind, exist in such small quantities as to be non-detectable within our levels of statistical confidence.

The lack of transverse Alfvén waves can be readily explained in the absence of a mechanism to convert transverse Alfvén waves to non-transverse Alfvén waves. The transverse case corresponds to only two characteristic modes of the MHD equations, whereas the non-transverse case corresponds to an infinity of characteristic modes. Given a situation of random wave excitation, it would be highly unlikely that the transverse wave should occur. These results might be generalized to finite amplitude Alfvén waves for other laboratory or astrophysical situations, and would imply that the assumption of planarity for such fluctuations may, at best, be an approximation.

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FIGURE CAPTIONS

Figure 1 Coherencies and phase lags for $(\Delta B_x^2 + \Delta B_y^2)\Delta B_z$ typical for the Mariner 10 data periods.

Figure 2 Mariner 10 magnetometer data giving the field magnitude and standard deviation, $F(\gamma)$ and $\sigma(\gamma)$, ($1\gamma = 10^{-5}$ Gauss), solar ecliptic field longitude, ϕ, and latitude, θ. Also plotted are the magnitude of the transverse field fluctuations and the longitudinal field fluctuations whose anticorrelation is consistent with the existence of wave packets of finite amplitude non-transverse Alfvén waves.

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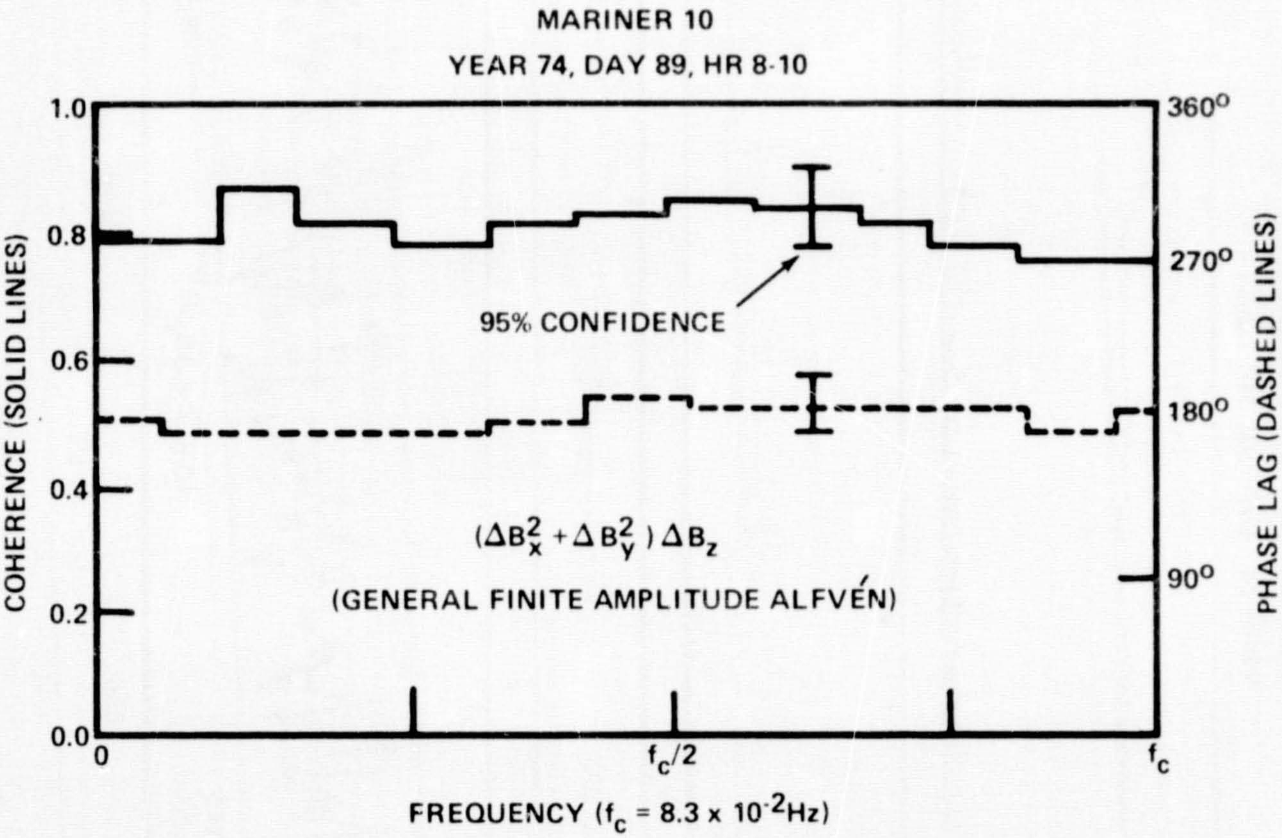
MARINER 10
YEAR 74, DAY 89, HR 8-10
1.0
0.8
0.6
0.4
0.2
0.0
360°
270°
180°
90°
COHERENCE (SOLID LINES)
PHASE LAG (DASHED LINES)
95% CONFIDENCE
$(\Delta B_x^2 + \Delta B_y^2)\,\Delta B_z$
(GENERAL FINITE AMPLITUDE ALFVÉN)
0
$f_c/2$
f_c
FREQUENCY ($f_c = 8.3 \times 10^{-2}$Hz)

Figure 1

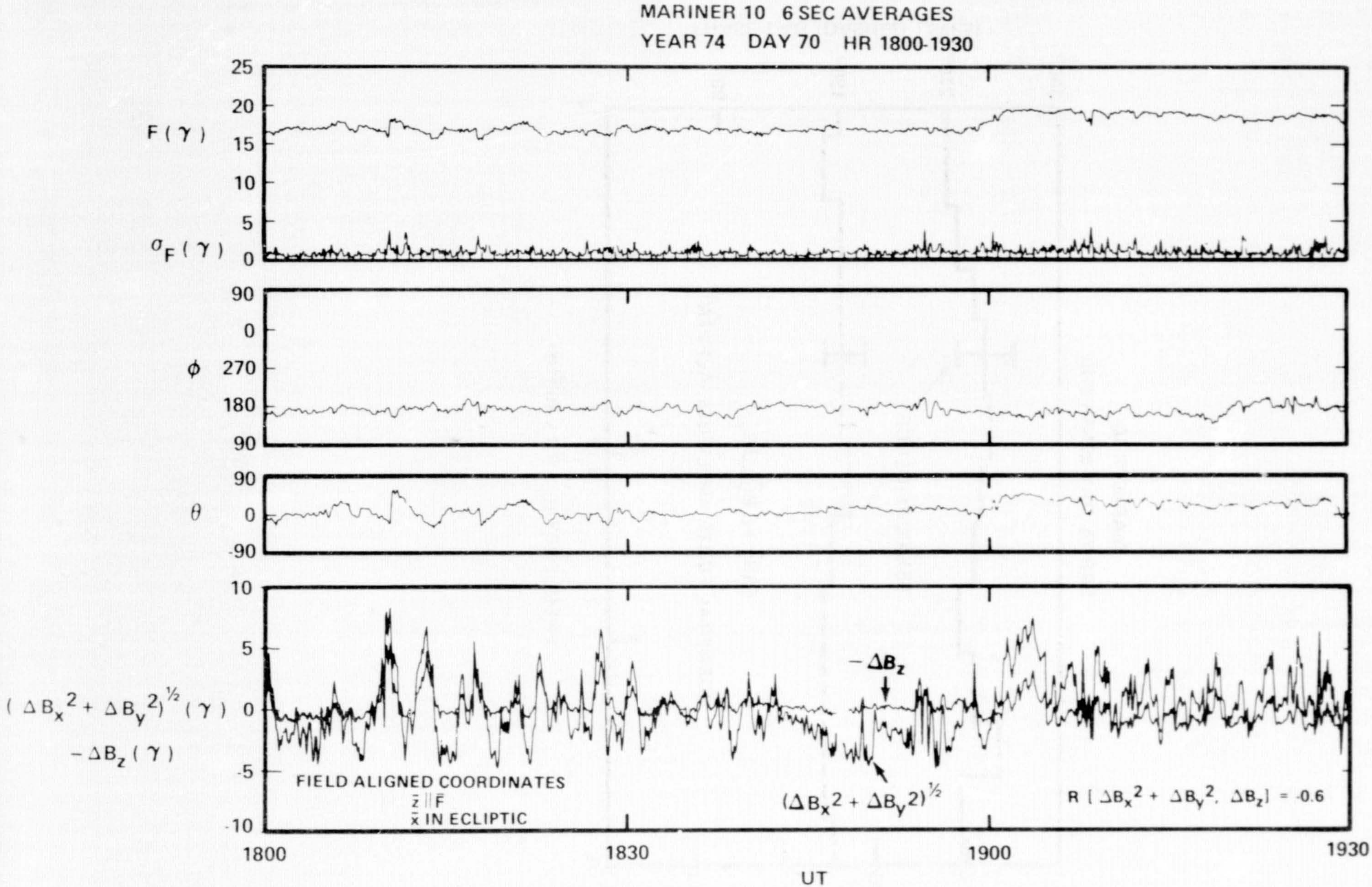
MARINER 10 6 SEC AVERAGES
YEAR 74 DAY 70 HR 1800-1930
F (γ)
σF (γ)
φ
θ
(ΔBx2 + ΔBy2)½ (γ)
− ΔBz (γ)
FIELD ALIGNED COORDINATES
z || F
x IN ECLIPTIC
− ΔBz
(ΔBx2 + ΔBy2)½
R [ΔBx2 + ΔBy2, ΔBz] = -0.6
1800
1830
1900
1930
UT

Figure 2