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# A Study of Shock-Associated Magnetohydrodynamic Waves in the Solar Wind

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## I. Introduction

The above-named grant was used to further investigate the properties of plasma waves near the Earth's bow shock and to apply such knowledge to plasma turbulence in the interstellar medium. The principal reason for choosing this region of space is that collisionless shock waves create unstable ion and electron particle distributions. These unstable distributions create large-amplitude hydromagnetic waves. By making observations in this part of space, we are therefore close to the source of these waves. An associated argument in favor of this part of space is the extensive set of data from the ISEE spacecraft, which yields plasma measurements such as vector magnetic field measurements, plasma densities, and particle distributions. The availability of these data makes for a particularly fruitful union of theory and observations.

Three major topics were addressed by the proposal, one theoretical and two observational. These topics were: (a) an attempt to understand the evolution of the large-amplitude magnetohydrodynamic (MHD) waves in the foreshock, using a nonlinear wave equation called the Derivative Nonlinear Schrödinger equation (henceforth DNLS) as a model, (b) using the extensive set of ISEE data to test for the presence of various nonlinear wave processes which might be present, and (c) a study of plasma turbulence in the interstellar medium which might be physically similar to that in the solar wind. For these investigations we used radioastronomical techniques. Good progress was made in each of these areas and a separate discussion of each is given below.

## II. The Theory of Nonlinear Alfvén Waves with Application to the Earth's Foreshock Waves

I feel that very good progress was made during the grant period in the understanding of the nonlinear evolution of waves in the Earth's foreshock. To effectively communicate the significance of these results, a little review of the problem is in order. Magnetohydrodynamic waves are generated at shallow distances in the Earth's foreshock by unstable ion distributions. They are rapidly amplified to large amplitudes so that nonlinear processes should be important. At shallow depths in the foreshock, these waves remain relatively monochromatic and circularly polarized. A spacecraft further back in the foreshock, at a point where the waves have had a chance to evolve somewhat, sees different characteristics.

Waves deep in the foreshock show a number of differences with the monochromatic, circularly polarized wave at shallow foreshock depths. The polarization is no longer circular, the wave components show evidence of steepening, and there is the formation of high-frequency wave packets called *shocklets* in the time series.

In my opinion, the main goal of the theory of nonlinear magnetohydrodynamic waves should be to understand these characteristics, and by understand I mean the nomination of physical processes which are responsible for them, and not just their reproduction in computer simulations. The development of such an understanding has been the primary goal of my research program since 1985. The mathematical tool for this research program has been the *Derivative Nonlinear Schrödinger Equation*, a nonlinear wave equation for the magnetic field in a magnetohydrodynamic wave. This equation is

$$\frac{\partial \phi}{\partial t} + \frac{1}{2} \alpha \frac{\partial}{\partial x} \left\{ |\phi|^2 \phi \right\} - i\mu \frac{\partial^2 \phi}{\partial x^2} = 0 \qquad (1)$$

In equation (1) the complex magnetic wave field is given by $\phi = b_y + ib_z$, $x$ is the direction of (one-dimensional) wave propagation and $\alpha$ and $\mu$ are the coefficients of nonlinearity and dispersion. If a two-fluid theory is used to derive (1), $\alpha = 1/[8\pi\rho_0 V_A(1-\beta)]$. The coefficient $\mu$ is positive for RCP waves and negative for LCP waves. The magnitude of $\mu = V_A^2/\Omega_i$. The effect of wave growth and damping can be approximated in an ad hoc manner by appending a linear growth and damping term to the right-hand side of equation (1), as was done by Spangler (1986).

Equation (1), with or without terms to approximate wave growth and damping, has been used in previous papers to model the foreshock waves (Spangler, Sheerin, and Payne, Phys. Fluids **28**, 104, 1985; Spangler, Astrophys. J. **299**, 122, 1985; Spangler, Phys. Fluids **29**, 2535, 1986). At the time of the last of these papers, I felt that we had developed a good understanding of how shocklets and wave steepening might arise. My interpretation was that the *modulational instability* of circularly polarized, parallel-propagating waves was responsible. In a modulational instability, an initial amplitude modulation of a wave train will tend to grow with time. The results of the above papers, obtained using numerical solutions to the DNLS, showed that for waves with initial spatial modulation, as expected for real waves in nature, the modulational instability caused wave steepening and the formation of contracted wave pulses. Mathematically, these pulses correspond to solitons, and I identified them with the shocklets.

Within a short period of time, however, it became clear that there was a major theory derivation problem with this interpretation. The modulational instability occurs only when the product of nonlinear and dispersive coefficients $\alpha\mu < 0$. In the case of right-hand polarized waves ($\mu > 0$), which the foreshock waves are observed to be, this would indicate that wave steepening and shocklet formation occurs only when $\alpha < 0$. In the context of a fluid described above, this would require $\beta > 1$. While this condition is somewhat restrictive, it applies at least some of the time in the solar wind.

A real problem emerged from work proposed in my 1988 proposal and carried out under this grant. This paper (Spangler, Phys. Fluids B **2**, 407, 1990) showed that a kinetic theory derivation of the DNLS resulted in a nonlinearity coefficient $\alpha$ which varied rather little with the plasma $\beta$. The sign reversal necessary for the modulational instability to "go" occurred only for extreme ratios of the electron-to-ion temperature. Taken at face value, this would indicate that the evolution of upstream waves cannot be interpreted in terms of modulationally unstable wave packets and casts doubt on the utility of the DNLS as a model for such phenomena.

There are two possible interpretations of these developments. The first is that the DNLS does not have an adequate physics content to describe these types of waves. The second possibility is that there may be additional physical phenomena, absent from the analyses discussed above but able to be incorporated in a modified version of the DNLS, which could account for the observations. My viewpoint during the period of this grant was the latter.

During the grant period, I therefore considered the types of physical processes which are important in the foreshock region, but not contained in the DNLS as written in equation (1). I came up with three such processes, and a discussion of their import for solar wind magnetohydrodynamic waves was discussed in Spangler (1992; Proceedings of the Seventh Solar Wind Conference, Goslar, Germany, in press).

1. **Wave obliquity.** The foreshock waves are observed to be propagating at slight angles with respect to the static magnetic field. These angles are quite small, being of order 5° to 20° generally. Such small propagation angles motivated the approximation of parallel wave propagation which was used in my earlier work. However, a result of work carried out during the grant period showed that such small propagation angles can be quite important. This is demonstrated in a paper produced during the period of NASA support (Spangler and Plapp, Phys. Fluids B, in press, Sept. 1992). We pointed out that for obliquely propagating waves, the wave equations for $b_y$ and $b_z$ contain Korteweg-deVries type nonlinearities which vanish in the limit of purely parallel-propagating waves. Since the Korteweg-deVries equation is well known to produce steepening of wave trains, we felt that this result gave considerable insight into the nature of nonlinear wave evolution in the foreshock.

2. **Wave growth and damping.** Equation (1) conserves wave energy; wave growth and damping processes are not included. The real waves in space are being amplified due to resonant ion instabilities, and damped due to various linear and nonlinear mechanisms. As discussed in Spangler (1992), there are qualitative arguments for believing that wave growth and damping might facilitate the processes of wave steepening and shocklet formation, even when modulationally stable solutions to (1) produced no such effects.

3. **Beam modification of the wave dispersion relation.** The prediction of modulationally stable wave packet evolution in (1) is based on the dispersion relation for MHD waves in a fluid or Maxwellian plasma. In this case, for right-hand polarized waves $(\partial^2\omega/\partial k^2) > 0$, where $\omega$ is the wave frequency and $k$ is the wavenumber. This is illustrated in Figure 1 as "normal dispersion, stable." The dispersion coefficient $\mu$ is nothing other than the sign of $\partial^2\omega/\partial k^2$. For $\alpha > 0$ modulational instability and thus wave steepening cannot occur.

However, large-amplitude MHD waves near shocks in the solar system do not occur in an unperturbed fluid or Maxwellian plasma. They are found in the presence of the dense unstable beams that generated them. These beams of unstable ions typically have a number density of one to several percent of the background density. As has been pointed out by Peter Gary and others (e.g., Gary *et al.*, Phys. Fluids **27**, 1852, 1984) such dense beams can produce a major modification to the wave dispersion relation. This is illustrated in Figure 1 by the line indicated as "beam-modified dispersion," and is a stylized version of the results presented in Gary *et al.* (1984). As may be seen, the beam-modified dispersion relation includes a range of wavenumber in which $(\partial^2\omega/\partial k^2) < 0$. While a rigorous study of modulational instability including the effects of beam modification has not been carried out, the heuristic ideas mentioned above suggest that modulational instability and wave steepening might be expected.

The first two of these possibilities were quantitatively and rigorously examined during the course of the grant period. The computer code for solving the DNLS subject to arbitrary initial conditions used in the investigations of Spangler, Sheerin, and Payne (1985), Spangler (1985), and Spangler (1986) was modified to simultaneously investigate the effects of oblique propagation and growth and damping. In Figure 2 we present the results of a

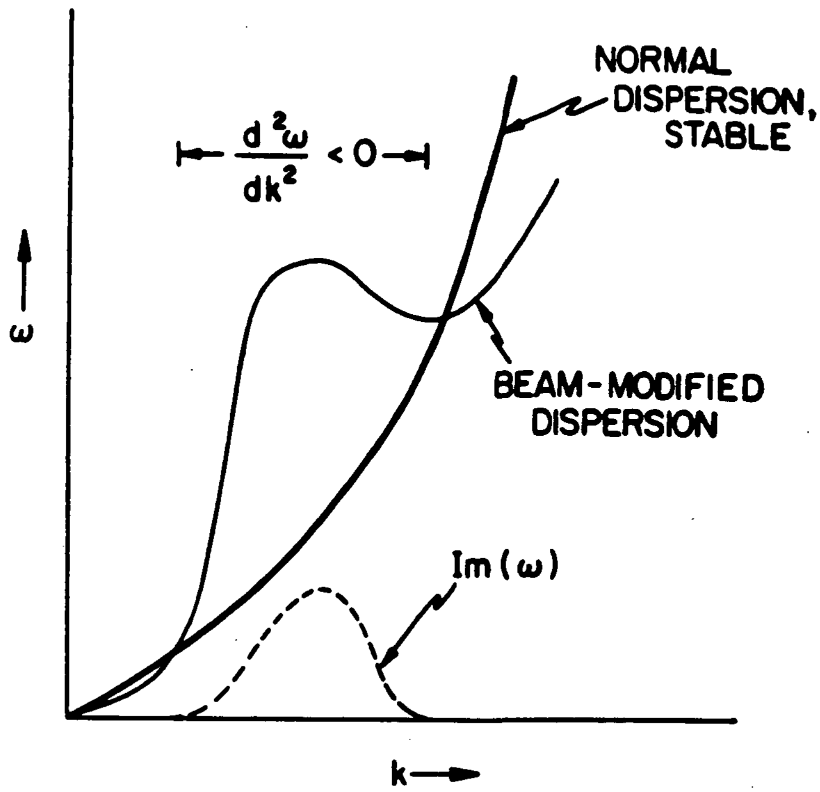


Figure 1. Stylized representation of the effect of an unstable ion beam on the dispersion relation $\omega(k)$ for magnetohydrodynamic waves. The heavy solid line gives the dispersion relation for right-hand polarized waves in a fluid plasma. The dashed line gives the imaginary part of the dispersion relation (growth rate) given an unstable ion distribution. The light solid line shows the corresponding real part of the dispersion relation in this case. It shows substantial differences with the fluid dispersion relation, including an apparent reversal in the sign of $\partial^2\omega/\partial k^2$ near the wavenumber where $\mathrm{Im}(\omega(k))$ is a maximum.

sample calculation. The upper row shows the initial conditions in wave intensity $b_y^2 + b_z^2$, $y$ component of the wave field, and spatial power spectrum. The wave packet then evolved subject to oblique propagation at an angle (typical for the real waves) of 11.5°, and growth at the primary wavelength of $\gamma_{\max} = 0.005\Omega_i^{-1}$. The state of the wave train at a time of $100\Omega_i$ is shown in the bottom row of Figure 2.

The remarkable feature of this plot is that it shows essentially *all* of the major observed features of upstream waves, such as steepening of the wave packet (most clearly visible in the plot of wave intensity), shocklet formation (plot of $b_y$), polarization evolution (clearly apparent in a comparison of the plots of $b_y$ and $b_z$), and spectral transfer of wave energy to higher wavenumbers (plot of power spectrum).

The conclusion to be drawn from this and other calculations is that the DNLS, despite its somewhat limited physics content, seems capable of describing the main observed characteristics of upstream waves. Use of the DNLS also allows identification of the physical processes responsible for this evolution, which are (a) the DNLS nonlinearity, which causes a spectral transfer of wave energy, (b) obliquity of propagation, which causes polarization

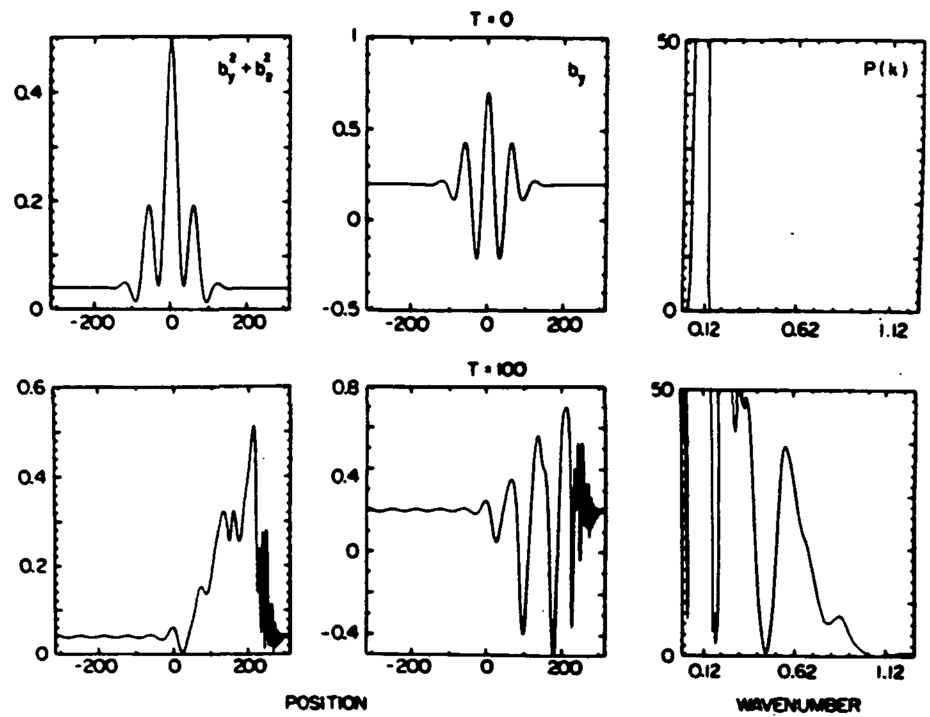


Figure 2. Evolution of a spatially modulated, obliquely propagating wave packet. Upper row shows initial condition, bottom row shows wave field at $t = 100/\Omega_i$. The columns show, from left to right, respectively, wave intensity, one component of the wave field, and the spatial power spectrum. The units of wave intensity and field are $B_0^2$ and $B_0$, respectively, while the units of the power spectrum are arbitrary.

evolution and, through the Korteweg-deVries nonlinearities, a tendency towards wave steepening, and (c) wave growth, which via linear processes keeps the wave amplitude large so that effective spectral transfer can occur, thus offsetting the demodulation and reduction in wave amplitude which occurs in the absence of growth and damping.

The status of publication of these results is as follows. A preliminary report of all this material was presented as an invited talk at the Solar Wind 7 Conference and will appear in the published conference proceedings. As mentioned above, a paper discussing the properties of obliquely propagating nonlinear Alfvén waves is in press in the Physics of Fluids B. Finally, in the course of the next few months, I plan to write a paper for the Journal of Geophysical Research, which will be an expanded version of the Solar Wind 7 Conference proceedings paper.

## III. Observational Studies of Large-Amplitude MHD Waves in the Earth's Foreshock

One of the major areas of research supported by grant NAGW-1594 was an extensive investigation of wave observations made by the ISEE spacecraft when it was in the Earth's ion foreshock. This project has been intended as a major expansion of the study of Spangler *et al.*, J. Geophys. Res. **93**, 845, 1988. Like Spangler *et al.* (1988), a major emphasis is to deduce the presence of various linear and nonlinear wave mechanisms through the presence of density compressions, but the investigation is far more general and has discovered a number of properties of these waves which were hitherto unnoticed. This work comprised the Ph.D. thesis research of Dr. James Leckband, who successfully defended his thesis in April 1992.

The data consist of 20 "episodes" chosen as times when the ISEE spacecraft was in the Earth's foreshock, when large-amplitude wave activity was visible on survey plots, and when all wave and plasma characteristics appeared to be time-stationary for periods of at least 30 minutes. Wave data consisted of magnetometer data with temporal resolution of 4 seconds, plasma density data with a resolution of 4 (high data rate mode) or 12 (low rate mode) seconds, plus information on average electron and ion temperature for each period. An example of a data interval is shown in Figure 3. The top three panels show the three components of the wave magnetic field, and the bottom panel shows the plasma density. The $x$ component (top panel) is the *variable* magnetic field in the direction of the static magnetic field, while the $y$ and $z$ components comprise the transverse wave field. In the case of a parallel-propagating plane wave, all fluctuations would be in the $y$ and $z$ components.

From this figure one can readily see that the properties of the magnetic fluctuations in the $y$ and $z$ components are quite different from those in the $x$ components. From the bottom panel, one can see also that these waves are quite compressive, with a typical density modulation index $\equiv \sigma_n/n$ of order 15%. One of the principal goals of this research program has been to understand the mechanisms responsible for these density fluctuations.

The work carried out in this program has consisted of computing and studying autospectra, cross spectra, and cross correlations of the data series shown in Figure 3, e.g., cross correlation and cross spectra of $b_y$ with $n$. This analysis has yielded a host of interesting results which will be published in the papers resulting from Dr. Leckband's Ph.D. thesis. A brief synopsis of some of these results is given below.

- Upstream solar wind magnetic field and density data from IMP 8 were used to estimate the "pristine" solar wind fluctuations in these quantities. These calculations allowed us to calculate, for each of the 20 episodes, the frequency and thus length scale at which foreshock turbulence began to dominate that of the undisturbed solar wind. This typically occurred at or slightly below a frequency of 0.01 Hz, corresponding to a wavelength of about 40 thousand kilometers.

- Power spectra of the transverse magnetic field components typically show a well-defined spectral maximum corresponding to the dominant frequency of the waves. In a new result, we found that the falloff of spectral power with frequency above this peak is almost always power law with a spectral index of about 2.5. This is considerably steeper than the value of 5/3 corresponding to the one-dimensional reduction of a Kolmogorov spectrum.

- A careful study was made of the dependence on frequency of the angle of propagation with respect to the static magnetic field, $\theta_{kB}$. This investigation also featured a rigorous consideration of the errors involved in these propagation angles. It was found that these angles typically ranged from about 5° to 15°. This information is directly relevant to the theory presented in Section II.

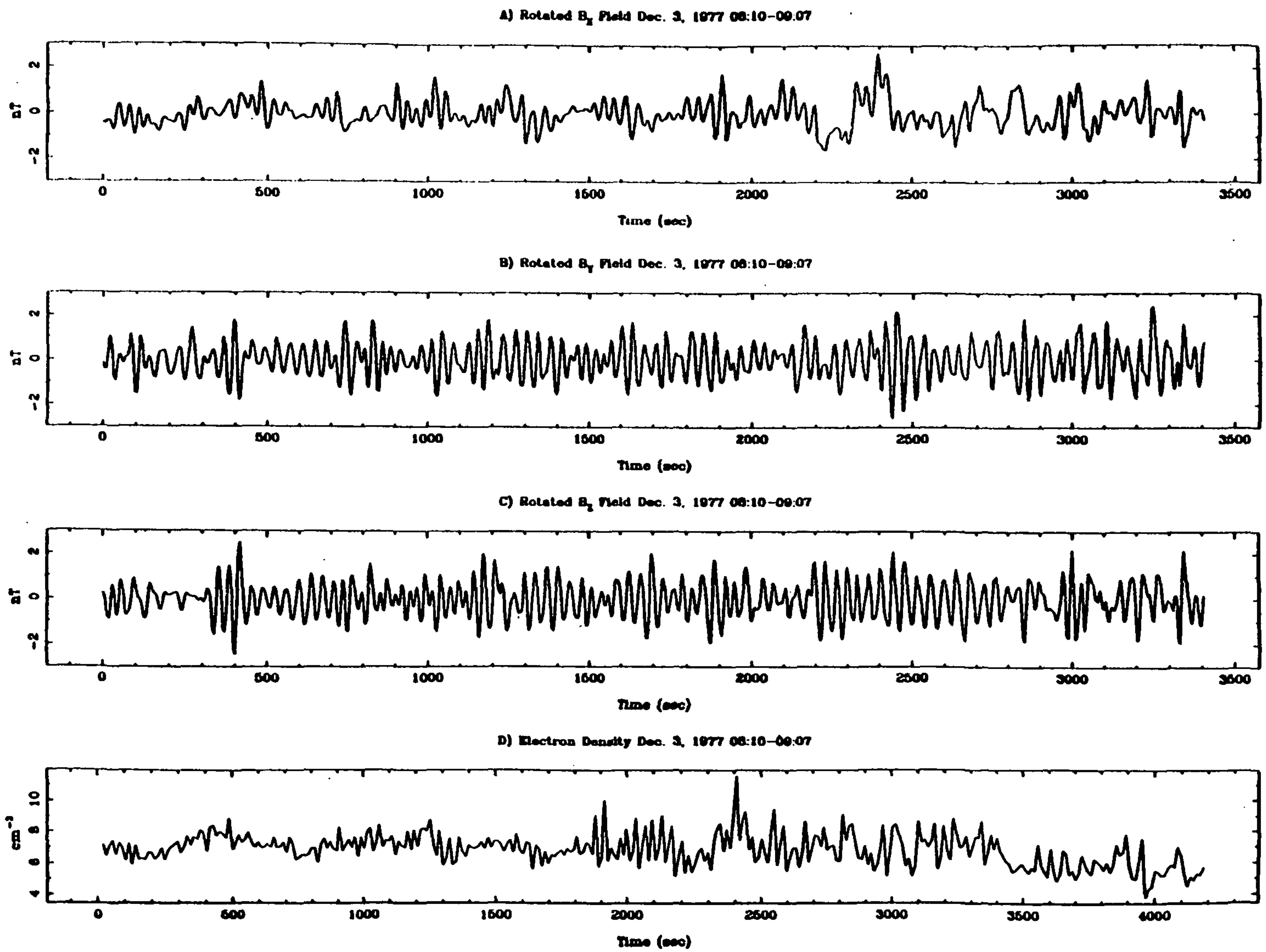


Figure 3. Plot of MHD wave data during a 57-minute interval on Dec. 3, 1977. Magnetic field components are defined in a frame in which one axis is aligned with the large-scale interplanetary field. From top to bottom the frames show, respectively, $x$ (static field-aligned), $y$, and $z$ component of the wave magnetic field, and plasma density (from Ph.D. thesis of James Leckband).

- The principal finding of this study has been the existence of a very strong correlation between $\delta n$, the fluctuation in density, and $b_x$. This correlation was strong and present in each of the episodes, with correlation coefficients ranging from about 40 to 70 percent.

- From study of power spectra and the angle of wave propagation $\theta_{kB}$, we believe that there are two classes of waves in the foreshock MHD turbulence. Typically, the "wave band" magnetic field fluctuations from about 0.014 Hz to 0.030 Hz are propagating in a more or less parallel manner. Typical propagation angles are $5^\circ - 20^\circ$. However, at low frequencies between about 3 and 10 mHz, where the foreshock turbulence still dominates over the pristine solar wind, the propagation angles are consistent with nearly perpendicular propagation. We thus identify this second class of wave as low frequency (at frequencies perhaps one-third or one-fourth of the wave band frequency) and of perpendicular propagation.

- Dr. Leckband interprets these low-frequency waves as the result of a decay or filamentation instability in which parallel-propagating MHD waves decay, producing perpendicular-propagating daughter magnetosonic waves. This theory has recently been presented in a paper by Viñas and Goldstein (J. Plasma Phys. **46**, 107, 1991). Dr. Leckband finds agreement between the frequencies predicted by the Viñas-Goldstein theory and the observed second class of foreshock waves.

- Using a novel method of data display for MHD waves, i.e., a dynamic spectrum method, we have found cases in which there is slight evidence for the presence of the three-wave decay instability in which an initial parallel-propagating MHD wave decays into a forward-propagating ion-acoustic wave and a backward-propagating MHD wave.

We believe these results are of considerable value in obtaining a better understanding of the foreshock waves. These results have been presented at a number of AGU meetings, and as a poster at the Solar Wind 7 meeting. In the coming months we will be writing a major paper for the Journal of Geophysical Research using the results of this thesis.

## IV. A Radioastronomical Study of MHD Turbulence in the Interstellar Medium

One of the benefits of research in space plasma physics is that it can help us understand plasma processes in more remote astrophysical plasmas, in which important phenomena such as the acceleration of cosmic rays and formation of stars maybe occurring.

This viewpoint, adopted in my research program in which theoretical and observational studies of turbulence in the solar wind, is used to provide insight into the turbulent plasma in the interstellar medium.

The observational technique used is radio wave scintillation, in which we look for phase and amplitude fluctuations in radio waves which have been induced by propagation through a medium with a stochastically varying plasma density.

Considerable progress in this area was made during the period of support by grant NAGW-1594. Some of the highlights are as follows.

- We continued our development of a "scattering map" of the galaxy, obtaining a measurement of a quantity related to the path integral of the electron density variance. These measurements showed that the intensity of turbulence is far greater in the inner galaxy than at the location of the sun, indicated that there are "clumps" of intense turbulence which are of size a few parsecs or less, and indicated that galactic regions of intense turbulence might be associated with regions of star formation (Fey, Spangler, and Mutel, Astrophys. J. **337**, 730, 1989; Fey, Spangler, and Cordes, Astrophys. J. **372**, 132, 1991).

- We pointed out that previously published observations indicated that the inner scale of the turbulence in the interstellar medium is of order 50–200 km. We noted that this is of the order of the ion-inertial length in the warm ionized phase of the interstellar medium. This result strengthens the analogy of the interstellar medium with the solar wind, where the inner scale is also of the order of the ion-inertial length. This result also provides information on the phase (density and temperature) of the interstellar medium in which the plasma turbulence resides. This result was published in Spangler and Gwinn (Astrophys. J. **353**, L29, 1990).

- I continued my investigation, in a collaboration with colleagues at the Italian Institute for Radio Astronomy, of the phenomenon called low-frequency variability of extragalactic radio sources. A new investigation was carried out utilizing data on intensity scintillations and measurements of the brightness distribution of those sources. The results of this investigation are the most compelling information to date that low-frequency variability is indeed an interstellar scintillation phenomenon, and furthermore indicated that such measurements must provide a means of determining the velocity of the density irregularities responsible for interstellar scintillations. The results of this investigation have been written up, submitted to Astron. Astrophys., favorably reviewed, revised and resubmitted. We expect publication in late 1992 or early 1993.

- An investigation was made of the heating of the interstellar medium by dissipation of irregularities (plasma waves) responsible for interstellar scintillations. In contrast to some previous investigations, I found that there need not be a thermodynamic embarrassment in which wave heating exceeds the cooling capability of the medium, provided that the irregularities responsible for scintillations are in envelopes of H II regions, which have a substantial cooling capability. Nonetheless, wave heating may be a significant energy input in parts of the interstellar medium. A distinctive feature of this study was the consideration of a number of nonlinear wave dissipation mechanisms, such as the parametric decay instability and wave steepening which have been widely discussed in the context of solar wind turbulence, but never previously in association with interstellar turbulence. This work is presented in Spangler (Astrophys. J. **376**, 540, 1991).

## V. Publications Resulting from NASA-Supported Research During the Period of Grant NAGW-1594

During the grant period of grant NAGW-1594, a number of papers were produced in the fields of the theory of nonlinear Alfvén waves, observed characteristics of waves near the Earth's foreshock, and radioastronomical studies of plasma turbulence in the interstellar medium. These papers are indicated below.

1. A. L. FEY, S. R. SPANGLER, and R. L. MUTEL
VLBI Angular Broadening Measurements in the Cygnus Region
*Astrophys. J.* **337**, 730–738, 1989

2. S. R. SPANGLER
Kinetic Effects on Alfvén Wave Nonlinearity I: Ponderomotive Density Fluctuations
*Phys. Fluids B* **1**, 1738–1746, 1989

3. S. R. SPANGLER
Kinetic Effects on Alfvén Wave Nonlinearity II: The Modified Nonlinear Wave Equation
*Phys. Fluids B* **2**, 407–418, 1990

4. S. R. SPANGLER and C. R. GWINN
Evidence for an Inner Scale to the Density Turbulence in the Interstellar Medium
*Astrophys. J. Lett.* **353**, L29, 1990

5. T. J. LAZIO, S. R. SPANGLER, and J. M. CORDES
Faraday Rotation Measure Variations in the Cygnus Region and the Spectrum of Interstellar Plasma Turbulence
*Astrophys. J.* **363**, 515, 1990

6. S. R. SPANGLER and R. J. REYNOLDS
A Comparison of H Alpha Intensity and Radio Wave Scattering on Eight Low-Latitude Lines of Sight
*Astrophys. J.* **361**, 116, 1990

7. A. L. FEY, S. R. SPANGLER, and J. M. CORDES
VLA and VLBI Angular Broadening Measurements: The Distribution of Interstellar Scattering at Low Galactic Latitudes
*Astrophys. J.* **372**, 132, 1991

8. S. R. SPANGLER
The Dissipation of MHD Turbulence Responsible for Interstellar Scintillation and the Heating of the Interstellar Medium
*Astrophys. J.* **376**, 540, 1991

9. J. M. CORDES, J. M. WEISBERG, D. A. FRAIL, S. R. SPANGLER, and M. RYAN
The Galactic Distribution of Free Electrons
*Nature* **354**, 121, 1991

10. S. R. SPANGLER and B. B. PLAPP
Characteristics of Obliquely Propagating Nonlinear Alfvén Waves
*Phys. Fluids B* [in press, September 1992]

11. S. R. SPANGLER, W. A. EASTMAN, L. GREGORINI, F. MANTOVANI, and L. PADRIELLI
Refractive Interstellar Scintillations and Low Frequency Variability: A Detailed Analysis Using Measured Source Structures
*Astron. Astrophys.* [submitted]