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Progress Report for Grant NAGW-2040

LANGMUIR-LIKE WAVES AND RADIATION IN PLANETARY FORESHOCKS

Period covered: 1/1/94 - 1/31/95

by

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Contents

1 Introduction

This progress report is for the first year of the renewed NASA Grant NAGW - 2040 which, with a change in title and emphasis, was renewed competitively for a 3 year period ending on 31 March 1997. The grant's basic objectives are to develop theoretical understandings (tested with spacecraft data) of the generation and characteristics of electron plasma waves, commonly known as Langmuir-like waves, and associated radiation near f_p and $2f_p$ in planetary foreshocks. (Here f_p is the electron plasma frequency.) Related waves and radiation in the source regions of interplanetary type III solar radio bursts provide a simpler observational and theoretical context for developing and testing such understandings. Accordingly, applications to type III bursts constitute a significant fraction of the research effort. The grant provides support for theoretical and observational research led by the Principal Investigator, Dr. Iver H. Cairns, at the University of Iowa. The Co-Investigators are Dr.'s P.A. Robinson, R.R. Anderson, D.A. Gurnett, and W.S. Kurth. This research has no other direct NASA sources of funds. The grant provides six months per year of Dr. Cairns' salary, as well as partial support for two other people, publication costs and professional travel.

The electron plasma waves which this grant primarily addresses are driven by energetic electrons accelerated at planetary bow shocks. These waves are of great theoretical interest and importance in many areas of plasma physics, space physics, solar physics and astrophysics. Despite electron plasma waves being studied for many years, observations in planetary foreshocks have resulted in many unexpected advances, including wave growth well below the plasma frequency f_p. Moreover, neither the observed waves themselves nor their generation of electromagnetic radiation at multiples of f_p is currently well understood. The grant's research program is intended to make further advances in analytic and numerical nonlinear plasma physics, strong turbulence theory, and numerical simulations using the Langmuir-like waves and f_p & $2f_p$ radiation observed in foreshocks and type III solar bursts. During 1994 we made very significant theoretical progress (with observational support) on nonlinear processes in foreshocks and type III bursts [Robinson and Cairns, 1994a,b; Cairns and Robinson, 1994]. Cairns [1994] also presented new observations of, and discussed the theoretical implications of, fine structures in f_p radiation generated in Earth's foreshock.

The testing of the new Stochastic Growth Theory (SGT) for type III bursts, and its extension and testing for foreshock waves and radiation, constitutes a major longterm strategic goal of the research effort. This theory was developed by Dr. Robinson in collaboration with Dr. Cairns and others. Testing SGT involves calculating probability distributions $P(E)$ for the electric field E_L of the Langmuir-like waves. One of SGT's strongest predictions is that the distribution $E \times P(E)$ should be Gaussian at small and moderate fields with either a nonlinear cutoff at high E (due to nonlinear wave processes removing wave energy) or else a power-law tail at high E if strong turbulence collapse is occurring. Since the Langmuir-like wave fields E depend strongly on position relative to the foreshock boundary (which depends on the bow shock's 3-D location and the magnetic field orientation) it is necessary to know the spacecraft's position in the foreshock when calculating $P(E)$ distributions: otherwise one might expect Gaussian distributions to result from variations in the shock location and magnetic field orientation. Accordingly a significant portion of the last years effort has gone into testing and improving upon previous models for the shock location [Cairns and Grabbe, 1994; Cairns et al., 1995] and into state-of-the-art MHD simulations with Dr. J.G. Lyon (Dartmouth College) of the shock's 3-D location as a function of the solar wind's ram pressure, MHD mach numbers, and magnetic field orientation [Cairns and Lyon, 1994]. Further research in this area is necessary in calendar 1995. Separate NASA funding for this effort has been applied for - at this time, however, the status of this request is unknown.

2 Progress in the Report Period 1/1/1994 - 1/31/1995

2.1 Foreshock Projects

The following progress was made in the area of Langmuir-like waves and radiation in foreshocks. First, a paper demonstrating the existence of electromagnetic radiation and electrostatic waves with intrinsic fine structure near harmonics $f_p + nf_{ce}/2$ in Earth's foreshock was accepted and published by JGR [Cairns, 1994]. (Here f_{ce} is the electron gyrofrequency.) Theoretical implications and explanations for the observations were also discussed. Application of a similar interpretation to fine structures in type II bursts and continuum radiation are being considered. Second, the nonlinear threshold for the electrostatic decay process $L \rightarrow L' + S$ (of a Langmuir wave L into a backscattered Langmuir wave L' and an ion acoustic wave S) was proposed to explain a monotonic trend in the maximum Langmuir fields observed in the foreshocks of Earth, Mars ... Neptune [Robinson and Cairns, 1994b]. The paper is currently being reviewed. Third, Dr. Alex Klimas is working with Dr. Cairns on 1-D, two charge species, Vlasov simulations of electron plasma waves driven by an electron beam. The simulation code is working very well. It needs to be transferred to the NCSA Cray and optimized.

- Cairns, I.H., Fine structure in plasma waves and radiation near the plasma frequency in Earth's foreshock, **J. Geophys. Res.**, *99*, 23,505, 1994.
- Robinson, P.A., and I.H. Cairns, Maximum Langmuir wave fields in planetary foreshocks determined from the electrostatic decay threshold, **Geophys. Res. Lett.**, submitted, 1994.

Additional observations of fine structures in f_p radiation from the foreshock have been obtained. They verify the identification of splitting in units of $f_{ce}/2$. Future work on these data and observations of other similar sources (e.g., type II solar bursts) will be performed and published as time permits - at a lower priority than other research. Higher priority will be reaching a state of readiness for testing SGT in 1996. This will include the identification of long periods of foreshock wave observations with slowly varying magnetic field orientation and the development of accurate models for the shock's 3-D location (see below). Vlasov simulations with Dr. Klimas will be a very high priority for the 1995 year.

2.2 Type III Projects

Progress was made on the nonlinear processes active in type III bursts, including the theoretical roles of specific generation processes for f_p and $2f_p$ radiation and the excellent ensuing agreement between observations and theory [Robinson and Cairns, 1994a], and the demonstration that the low frequency waves observed in association with intense Langmuir waves [R.P. Lin et al., Ap. J., vol. 308, 954, 1986] are indeed consistent with the electrostatic decay $L \rightarrow L' + S$ proceeding in type III bursts and being the dominant nonlinear process [Cairns and Robinson, 1994].

- Robinson, P.A., and I.H. Cairns, Fundamental and harmonic radiation in type III solar radio bursts, *Solar Phys.*, in press, 1994a.
- Cairns, I.H., and P.A. Robinson, Ion acoustic wave frequencies and onset times during type III solar radio bursts, *Astrophys. J.*, submitted, 1994.

Additional unsubmitted work was performed on strong turbulence collapse, the modulational instabilities, apparent limitation of the Langmuir wave levels, and the level of spacecraft noise backgrounds relative to predictions for various nonlinear processes. Completion of these projects and the submission of corresponding papers is our top priority for 1995.

2.3 Bow Shock Location Projects

Time variations in a spacecraft's location relative to the foreshock boundary, due to shock motions and changes in the magnetic field direction, and spatial gradients in the wave characteristics render detailed observational tests of SGT a complicated matter. A necessary first step is to know the shock's 3-D location as accurately as possible. Cairns et al. [1995] tested the standard model for the shock's standoff distance using a set of low Alfven mach number shock crossings. They found that the model needs to be modified and/or that changes in shock shape are important. Cairns and Grabbe [1994] demonstrated that the standard model is inadequate, since it does not generally follow from MHD theory (being instead a phenomenological attempt based on gasdynamic theory to create an MHD theory). They show that the standoff distance should depend strongly on field orientation and on both the Alfven and sonic mach numbers. Cairns and Lyon [1994] present state-of-the-art 3-D MHD simulations of the solar wind's interaction with a rigid magnetopause obstacle. They demonstrate enhanced standoff distances compared with the standard model, showed an important dependence on field orientation, and develop a new model that explains their simulation results with excellent accuracy.

- I.H. Cairns, D.H. Fairfield, R.R. Anderson, V.E. Carlton, K.I. Paularena, and A.J. Lazarus, Unusual locations of Earth's bow shock on 24-25 September 1987: Mach number effects, **J. Geophys. Res.**, *100*, 47, 1995.

- Cairns, I.H., and C.L. Grabbe, Towards an MHD theory for the standoff distance of Earth's bow shock, *Geophys. Res. Lett.*, *21*, 2,781, 1994.

- Cairns, I.H., and J.G. Lyon, MHD simulation of the Earth's bow shock at low mach numbers: standoff distances, *J. Geophys. Res.*, submitted, 1994.

Additional unsubmitted work also was performed: on changes in shock shape with Alfven Mach number seen in the simulations, on the details of the MHD flows in the simulations, and on extensions of the Cairns/Grabbe/Lyon models for the standoff distance. This work is expected to be completed and prepared for publication in 1995. Our goal is to have an accurate model for the shock's 3-D location available for careful and detailed evaluation and refining in 1996 of a SGT model for the foreshock Langmuir waves.

3 Work for the 1995 calendar year

Detailed justifications for the projects proposed here are given in the original proposal. Brief indications of their rationales are given in Section 2.

1. Write up the calculations demonstrating that strong turbulence theory can not explain the 1 ms 'spikes' seen by the Ulysses Fast Envelope Sampler instrument in the Jovian foreshock and the source regions of type III bursts. Alternatives will be explored further. (Foreshocks, type III bursts.)

2. Write up the work described in the 1993 report on the conditions required for the decay $L \rightarrow L' + S$ to dominate the related nonlinear process of scattering off thermal ions. The paper will compare analytic theory with published PIC simulation results and perhaps the fruits of the collaboration with Dr. Klimas. (Foreshocks, type III bursts.)

3. Collaborate with Dr. Klimas (GSFC) on state-of-the-art Vlasov simulations of Langmuir waves driven by electron beams. The Budget contains money for Goddard supercomputer time. (Foreshocks, type III bursts.)

4. Continue exploring the regimes of electrostatic modulational instabilities and three-wave processes for type III bursts (high/low Langmuir fields, narrowband or broadband Langmuir waves, large versus small ratios of electron to ion temperature, small/high beam speed). Identify the conditions under which modulational instabilities and three-wave processes dominate. (Foreshocks, type III bursts.)

5. Continue the MHD simulations and associated analytic work with Dr.'s Lyon and Grabbe in order to obtain accurate theoretical models for the bow shock's location and shape as a function of the solar wind parameters. These models are required for comparisons of SGT with foreshock data in 1996. (Foreshocks.)

6. Publish confirming observations of the radiation and plasma waves with intrinsic fine structure (spacings near half the electron gyrofrequency) near f_p in Earth's foreshock. Develop a theory for this fine structure after investigating both nonlinear Langmuir wave processes and direct cyclotron maser-style processes. (Foreshocks.)

4 Papers Supported during the Report's Period

4.1 Journal Papers

- Cairns, I.H., Fine structure in plasma waves and radiation near the plasma frequency in Earth's foreshock, **J. Geophys. Res.**, *99*, 23,505, 1994.
- Cairns, I.H., and C.L. Grabbe, Towards an MHD theory for the standoff distance of Earth's bow shock, *Geophys. Res. Lett.*, *21*, 2,781, 1994.
- Cairns, I.H., D.H. Fairfield, R.R. Anderson, V.E. Carlton, K.I. Paularena, and A.J. Lazarus, Unusual locations of Earth's bow shock on 24-25 September 1987: Mach number effects, **J. Geophys. Res.**, *100*, 47, 1995.
- Robinson, P.A., and I.H. Cairns, Fundamental and harmonic radiation in type III solar radio bursts, *Solar Phys.*, in press, 1994a.
- Cairns, I.H., and P.A. Robinson, Ion acoustic wave frequencies and onset times during type III solar radio bursts, *Astrophys. J.*, submitted, 1994.
- Robinson, P.A., and I.H. Cairns, Maximum Langmuir wave fields in planetary foreshocks determined from the electrostatic decay threshold, **Geophys. Res. Lett.**, submitted, 1994.

4.2 Conference Papers

- AGU Spring 1994 Meeting. *Fine structure in plasma waves and radiation near the plasma frequency in Earth's foreshock*, I.H. Cairns.
- AGU Spring 1994 Meeting. *MHD simulations of the location and shape of Earth's bow shock*, J.G. Lyon and I.H. Cairns.
- AGU Spring 1994 Meeting. *MHD theory of the standoff distance for the Earth's bow shock*, C.L. Grabbe and I.H. Cairns.
- APS Division of Plasma Physics Meeting.*Nonlinear processes in type III solar bursts: theoretical constraints versus observational data*, P.A. Robinson and I.H. Cairns.
- APS Division of Plasma Physics 1993 Meeting. *Langmuir wave decay versus scattering off thermal ions*, I.H. Cairns.
- AGU Fall 1994 Meeting. *Further MHD simulations of the 3-D location of Earth's bow shock*, A.M. Baldwin, I.H. Cairns, and J.G. Lyon.