Theoretical and Experimental Studies of Space-Related Plasma Wave Propagation and Resonance Phenomena

NASA Research Grant NGL 05-020-176

Semiannual Report No. 17
(1 January-30 June 1975)

and

Ten-year Summary of Research Program
[NGR 05-020-077: 1 May 1965-30 June 1970
NGL 05-020-176: 15 December 1966-30 June 1975]

Principal Investigator:
F. W. Crawford

SU-IPR Report No. 636
July 1975

INSTITUTE FOR PLASMA RESEARCH
STANFORD UNIVERSITY, STANFORD, CALIFORNIA

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Institute for Plasma Research
Stanford University
Stanford, California 94305

STAFF

NASA Research Grant NGL 05-020-176

for the period

1 January - 30 June 1975

SENIOR STAFF

Prof. F. W. Crawford (Part-time)
(Principal Investigator)

Dr. K. J. Harker (Part-time)

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GRADUATE RESEARCH ASSISTANTS

S. E. Rosenthal

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FOREWORD

From 1 May 1965 - 30 June 1970, NASA Research Grant NGR 05-020-077, on Theoretical and Experimental Studies of the Nature and Characteristics of Space-Related Plasma Resonance Phenomena, was effective at Stanford with Prof. F. W. Crawford as Principal Investigator. A second program with the same Principal Investigator, NASA Research Grant NGR 05-020-176, was initiated on 15 December 1966, and supported an Investigation of Space-related Whistler Propagation Phenomena in Laboratory Plasmas until 30 June 1970. It was step-funded from 1 July 1969 onwards, and the grant was renumbered NGL 05-020-176. Since 1 July 1970, the two programs have been combined under this research grant, initially with the NGR 05-020-077 title, but now more accurately as Theoretical and Experimental Studies of Space-Related Plasma Wave Propagation and Resonance Phenomena. During the 10.2 years since its inception, NASA support of $1.03M has been received for the total program. The present report is intended to provide a key to the resulting reports, conference papers, and publications, and to illustrate what can be accomplished with sustained support at the $100K/yr level by a small university research program. The report also represents the seventeenth semiannual report prepared under NASA Research Grant NGL 05-020-176, and covers the research carried out during the period 1 January - 30 June 1975.

CONTENTS

I. INTRODUCTION

Early in 1964, Dr. J. O. Thomas (NASA, Ames) visited the Experimental Plasma Physics Group at Stanford to discuss some puzzling cyclotron harmonic resonance phenomena that had been observed with the topside sounder satellite "Alouette". Within a few days, a simple laboratory experiment had been set up by the Principal Investigator and his colleagues, and shown intriguing cyclotron harmonic effects. Effort was diverted to the project, and support was soon sought from the NASA to sustain the program while a variety of significant developments were pursued (see Section II A). This work, carried out under NASA Research Grant NGR 05-020-077, serves to provide a clear demonstration of how laboratory and space plasma projects can interact with great mutual benefit: the relatively simple and inexpensive laboratory experiments were able to reproduce the phenomena observed with "Alouette", and to show that a mode of warm plasma wave propagation (actually predicted several years earlier, but not previously verified) was responsible. This mode was further shown to be involved in a variety of unexplained laboratory plasma noise emissions, and later analyzed as a powerful microinstability in nonMaxwellian plasmas.

In 1965, Prof. R. A. Helliwell (Radioscience, Stanford) drew our attention to a variety of unresolved problems associated with whistler excitation and propagation in the magnetosphere, about which he had just written a book. This contact stimulated us to undertake an experimental study of whistler propagation in the laboratory, and to analyze the small-signal stability of whistlers in nonMaxwellian plasmas. Again, support was sought, and received under NASA Research Grant NGL 05-020-176, and it has since been possible to shed considerable light on several of the problems stemming from observation of the magnetosphere (see Section II B).

Some laboratory observations of electron cyclotron echoes, made in 1966 with AEC support, led us to speculate on whether similar phenomena might occur in the ionosphere. Discussions with Prof. O. G. Villard, Jr. (Radioscience, Stanford) resulted in the initiation of a program aimed at the elucidation of the origins of long delayed radio echoes from the ionosphere. The mechanism that we have postulated, and on which we are currently working (see Section II C), involves the beam-plasma interaction commonly observed in laboratory plasmas.

The foregoing examples have been presented to emphasize the benefits to be derived from combining space and laboratory plasma activity. Judiciously chosen projects can lead to the strengthening of theory, by verification of detailed predictions, to the development of new diagnostic techniques, and to the stimulation of ideas for new experiments. Our present program reflects particularly the last aim: in the 1980's, the NASA Space Shuttle System is expected to carry regularly a "Spacelab" designed to perform plasma experiments; in the planning of the Spacelab facility by the NASA Atmospheric, Magnetospheric, and Plasmas-in-Space (AMPS), Science Working Group (of which the writer is a member, and chairman of the Wave Phenomena Section), studies of experiment feasibility and limitations are required [132,138,141,142]. A large part of our program is given to such studies in areas where we and others are likely to propose experiments for early missions.

In Section II, we shall summarize the results of the programs carried out under NASA Research Grants NGR 05-020-077 (1 May 1965 - 30 June 1975) and NGL 05-020-176 (15 December 1966 - 30 June 1975). Our aims are two-fold: first, to provide a key to the reports, conference papers, and publications resulting from the work (see Section IV), and second, to illustrate what can be achieved by the sustained funding of small university research programs. It is important to emphasize that this summary is not intended to be a comprehensive review of relevant developments in laboratory and space plasma physics over the last ten years or so. That would be far too great a task to accomplish in a brief report. It is simply a record of work carried out at Stanford under two particular grants, and a commentary on it. The absence of references to similar research pursued elsewhere is not intended to imply anything concerning originality, priority, or quality of the work carried out under the grants; that is for others to judge. We are simply concerned with discussing how the program has developed, and what it has been possible to undertake for an expenditure of $100K/yr.

In Section IV, we discuss the return on the investment made by the NASA in terms of personnel supported and degrees obtained. We hope that the discussion there will illustrate as well as the bibliography of results given in Section IV, how quite modest support of small university programs may pay substantial dividends to the Agency in the prosecution of its mission.

II. RESEARCH PROGRAM

A. Cyclotron Harmonic Waves [1,3-5,8-14, 17-26, 28, 31-34]

At the time when this project began, algebraic and integral expressions were available for the dispersion characteristics of warm magnetoplasma longitudinal waves for arbitrary propagation angle with respect to the static magnetic field. Detailed numerical studies had not been carried out, however, to make clear their implications. A start was made on this a year or so before inception of the grant, but it was evident that a comprehensive study would represent considerable effort. The task was undertaken by J. A. Tataronis as a Ph.D. thesis topic [25], while experimental verification of some of the theoretical predictions was undertaken by T. D. Mantei [21]. Particular emphasis was put on propagation perpendicular to the static magnetic field of cyclotron harmonic waves, since these are not subject to collisionless damping.

Although some effort was devoted by Diament to simplifying the derivation of the dispersion relations, by working in inverse velocity-space [12,17,18], and to presenting them in different forms [11], most of the effort had to be expended on sophisticated computation, particularly for oblique propagation. First, cyclotron damping and collisional damping were studied for general propagation angles [1]; in a parallel series of studies, nonMaxwellian velocity distributions were treated. This work is presented in detail in [31,32]. It was supplemented by some calculations of electron beam stimulation of CHW by Seidl [33].

Next, pulsed perpendicular propagation was studied, and for this purpose CHW group velocities were computed. This was necessary to simulate the "Alouette" resonance experiment, in which an antenna is pulsed. It was possible to use a second antenna to measure the group delay for transmission of a wave-packet; to establish that ringing occurred at the cyclotron harmonics [5,8,10,13,14], and to compute the value of the temporal decrement [26].

In bounded geometry, CHW standing waves and resonant behavior should occur. Computations were made of the RF admittance of such a magnetoplasma capacitor; first, by a highly simplified approach [3,4] which predicted sharper resonances than were observed, and later by a microscopic approach which included collisionless damping [24]. Influenced by our studies of resonance probes under another grant, CHW resonance rectification effects were sought and successfully observed [19,23]. We believe that useful diagnostic techniques can be founded on such impedance measurements, and have recently begun to study the topic again with a view to refining techniques to be used on Spacelab.

During the development of the project, several invited reviews of CHW phenomena [9,20,22], and of other plasma wave and resonance phenomena were presented [28,34]. These expressed the view that at the end of the 1960's the dispersion characteristics of most small-signal plasma modes had been verified, either in the laboratory or the ionosphere, and that the time was ripe for greatly intensified effort on the nonlinear phenomena predicted by the same basic equations. Our own work on CHW was considered as completed, and our interests progressed to the topics described later in this Section.

B. <u>Whistlers</u> [39,41,42,44,45,48-51,54,55,58,59,63,66,84,87-89,91, 98,100,118, 119, 122, 130, 133]

Ten years ago, very little attention had been given to whistler instability in nonMaxwellian plasmas. This may have been partly because longitudinal wave microinstabilities are usually very much stronger, and therefore more evident in the laboratory. There are, however, many situations in which the transverse wave whistler instability should dominate, and there was abundant evidence available from the magnetosphere that whistlers could be amplified, generated from noise, or triggered by signals injected from the ground.

Our first whistler instability computations considered various distributions of nonthermal electrons interacting with a cold plasma background [39,42,44,49,51,58,59]. This work is best summarized in [58] and the Ph.D. thesis by Lee [54]. It considered only whistler propagation perpendicular to the earth's magnetic field, but was generalized later to oblique propagation by Brinca [84], whose work included refinements to the hot plasma convective-absolute instability criterion of Derfler [100] and some useful approximations to the Fried and Conte plasma dispersion function [107].

While the instability calculations were proceeding, our experiment was set up to measure whistler dispersion characteristics, hopefully in the régime where the damping is collisionless rather than collisional. In the event, very good measurements were made in the collisional régime [45,50], but it was found that the experimental discharge was plagued with low-frequency instabilities when attempts were made to enter the collisionless régime. These observations led to a study of low frequency magnetoplasma instabilities which is reviewed in Section II E.

It had been hoped to study effects of plasma inhomogeneity and boundaries experimentally, with the aim of understanding whistler ducting better. Pressure of other projects reduced the effort to two theoretical studies: first, a general integral equation approach to inhomogeneous plasma problems [41], and second, an elucidation of a wellknown rather paradoxical result associated with whistler propagation in bounded geometry [55]. It was clear that the phenomenon of triggered whistler emissions observed in the magnetosphere would not yield to a linear theory, so nonlinear wave-wave interaction among whistlers was first examined as a possible mechanism [48]. The attempt proved unsuccessful, so study of nonlinear wave-particle interaction was taken up by Dysthe [66], and pursued intensively by Brinca [87,88,119], as part of his Ph.D. thesis work [98]. Contributions were made to understanding of the onset phase of the emissions. Brinca also extended his work on nonlinear whistler phenomena to the modulational instability [89,91].

Although our early wave-wave interaction studies of whistlers did not shed any light on triggered emissions, the results are relevant to the problem of VLF excitation: nonlinear interactions may be of value in communications [63]. We have recently extended our original analysis to include positive ion effects, and estimated the energy which could be transferred to Alfvén waves by nonlinear whistler interaction [118]. This may also be related to Pc 1 emissions.

Two alternative techniques of exciting VLF or ULF waves in the ionosphere have been examined as part of our current program: the first treats VLF excitation by helical electron and ion beams fired into the plasma from guns mounted on a satellite [130,133], and the second estimates the fields that can be produced by conventional electric and magnetic dipoles [122].

C. <u>Long Delayed Echoes</u> [27,70,128,131]

In 1965, some intriguing results on electron cyclotron echoes were published by Hill and Kaplan. These stimulated a program at Stanford supported by the NSF, and a search for corresponding phenomena in the ionosphere. Although it did not prove feasible to excite such echoes with ground-based transmitters, our ionospheric sounding program developed into a search for another effect: long delayed echoes. This phenomenon, reported nearly forty years earlier and sporadically thereafter, causes returns from the ionosphere with signal delays of up to a minute, rather than the few ms expected. The sounding program continued from 1967 to 1973, supported partly by this NASA program, and partly by the NSF. Our early observations [70] led us to the view that the delay was due to low group velocity ($\sim$ 1 km/s) propagation under conditions in which collisional damping is offset by the amplifying effect of beam-plasma interaction. The "beam" is taken to be supplied by high energy ($\sim$ keV) electrons precipitating into the ionosphere along the earth's magnetic field line.

The results of our program are summarized in a recent Ph.D. thesis by Sears [131]. So far, only conference presentations have been made [27, 128], but a major review of the area has been invited for the <u>Proc. IEEE.</u> Work on the manuscript will be completed within the next few months. The feasibility of studying the phenomenon with Spacelab will then be assessed. This is an attractive possibility, since experimentation on the topside ionosphere would free us from significant impediments to ground-based studies: on the topside there is less radio noise to contend with, and frequency usage is not constrained by FCC allocation.

Elucidation of the long delayed echo mechanism involves detailed study of beam-plasma interaction. This phenomenon has been part of the program, and our studies under other support, for many years: we have already mentioned beam excitation of CHW [33], and whistlers [42,44, 130, 133]; other basic studies [43], extending to explosive nonlinear three-wave interaction in beam-plasma systems [67,79], have also been carried

Our present interests are primarily associated with determining growth rates and group delays in the interaction region for long delayed echo wave-packets.

D. NONLINEAR WAVE PROPAGATION [48,52,53,60-63,66-69,71,72,77-79, 85,87-92,97-99,101-106,109-113,118-119,121,123,125,129, 134-137,139]

Our studies of nonlinear interaction began with three-wave parametric interaction of whistlers [48]; the analysis was later extended to include ion motions and the excitation of Alfvén waves [118], and modulational instabilities were treated [89,91]. Other combinations of transverse waves (ordinary, extraordinary, right- and left-hand polarized) were studied, first by iterative methods [52,53], and later by Lagrangian techniques [62]. Possible application to VLF communication was considered [63]. The scope was then broadened to include parametric interactions between transverse and longitudinal (Langmuir and ion acoustic) waves [60,61,68,71,72], and among longitudinal waves in active beam-plasma systems [67,79].

Interest in triggered emissions led to nonlinear wave-particle interaction studies in which sideband growth due to propagation of a large amplitude whistler was analyzed [66,87,88,119]. To obtain further insight into the processes, the corresponding large-amplitude longitudinal wave propagation problem was also studied, first analytically [78,88,111], and then by an economical low-noise computer simulation technique [112, 121,129,133,135,137]. The last project has been written up in the Ph.D. thesis by Matsuda [121]. Much of the analytical work is reviewed in that by Brinca [98].

The algebraic complexity of the nonlinear interactions referred to is very great. We have given considerable attention to the development of Lagrangian formalisms providing a more compact and informative treatment [62,92,97,101-105,123,124]. This work is described in detail in the Ph.D. theses by Kim [92], Galloway [97], and Peng [123]. It has also been applied to linear resonances in warm inhomogeneous plasmas (Tonks-Dattner resonances) [120], and to nonlinear interaction on the positive column [99].

The topics described so far have been theoretical, though applied to outstanding experimental problems. We have carried out both analysis and experiment on the nonlinear scattering from positive columns [69,77, 85]; on an associated linear problem [86], and on parametric interaction of waves propagating axially in such columns [99,139].

Much of the current interest in nonlinear wave interaction on the part of space plasma physicists has been stimulated by ionospheric heating experiments carried out in the last few years with ground-based transmitters located near Boulder, Colorado, and at Arecibo, Puerto Rico. Our work in this area [109,110,113,125,136] will be dealt with in Section II F.

E. LOW-FREQUENCY INSTABILITIES [74,80-82,95,96,108,116,117]

A plasma column confined by a static axial magnetic field is subject to a variety of low-frequency instabilities driven by charged particle drifts and instabilities, or the ionization processes involving the neutral background gas. We found it necessary to devote considerable effort to these instabilities for the highly practical reason that they impeded progress on our laboratory whistler dispersion measurements described in Section II B. They also have their counterparts in the ionosphere; for example, phenomena such as spread-F may be closely related to them.

Our first studies concerned ion acoustic instability driven by a difference between the plasma electron and ion temperatures [74,82]. Next, detailed experimental and theoretical studies of helical modes [80] and axisymmetric ionization waves [81] were carried out on positive columns, and flute instabilities were investigated in a hollow cathode arc discharge [95,117]. These projects raised subsidiary questions, which were successfully resolved, on the positive column balance when the isothermal assumption is relaxed [108], and on how to determine the convective-absolute nature of instabilities in bounded geometry [73,83]. Much of the work on these projects is described in the Ph.D. theses by Rognlien [96] and Ilić [116].

F. IONOSPHERIC HEATING AND BACKSCATTER [109,110,113,125,136]

Radar backscatter from the ionosphere is now a well-established diagnostic technique. It may be described in terms of nonlinear three-wave parametric interaction involving the up-going and down-scattered transverse waves, and up- or down-going longitudinal plasma waves in the ionosphere [110,113]. Over the last few years, ionospheric heating experiments have been carried out with ground-based, high-power transmitters [125]. The power fluxes are great enough to produce strong nonlinear effects which can be studied by backscatter techniques. Some of our effort has been given to explaining features of the backscatter spectra [109,136]. More recently, we have begun to study the feasibility of carrying a sufficiently powerful transmitter on Spacelab to produce ionospheric heating at distances of a few km from the vehicle, and of studying the resulting nonlinear phenomena by means of a backscatter radar system also carried on Spacelab. The requirements on both the heating and diagnostic systems are much less stringent than for ground-based experiments, but it is still not clear whether the experiments are feasible. We hope to contribute to elucidation of this question.

G. PULSE PROPAGATION [140]

Although the propagation of continuous waves through essentially homogeneous plasmas has been studied for over forty years, it is only in the last decade or so that transient propagation has received much attention. We have conducted the pulsed CHW studies in the laboratory described in Section II A, and it is likely that similar experiments will be performed with Spacelab as a diagnostic technique for plasma parameters. We are interested, however, in the more general problem of impulse propagation. In particular, cold plasma propagation in transverse modes (ordinary, extraordinary, right- and left-hand polarized) could be excited by effectively delta-function pulses ($\sim$ 10 ns), and should exhibit the features predicted by Brillouin and Sommerfeld around WWI, i.e. forerunners and wave-packet propagation. Warm plasma propagation in the Langmuir and ion acoustic modes should exhibit similar effects. These classical propagation features have never been fully demonstrated in the laboratory, because of instrumental difficulties involved in performing adequate experiments.

So far, we have analyzed propagation of circularly polarized transverse waves parallel to the static magnetic field [140]. We are currently extending the analysis to perpendicular propagation, and to the general case of oblique propagation. Attention will then be given to the excitation of longitudinal wave-packets propagating parallel or perpendicular to the magnetic field. It is hoped that refined experiments can be performed with Spacelab; first, to verify the basic plasma theory, and second, to provide new diagnostic techniques for ionospheric plasma parameters. Such techniques have the advantage that large volumes of plasma are sampled, effectively independent of the local plasma perturbations caused by the antennas.

III. RETURN ON THE INVESTMENT

The external funding of university research programs may be considered to have three objects. The first is to ensure the pursuit of research directions of interest to the contracting agency, in this case the NASA. The second is to provide support for senior personnel, e.g. faculty and research associates, engaged in research and the training of graduate students. The third is to enable such graduate students to follow their research studies through to the M.S. or Ph.D. levels. It may be expected that, if these objects are achieved, they will react beneficially on the activities of the contracting agency, and on scientific research and development in general. Sections II and IV indicate the scientific payoff to the NASA, and we shall not make further comments on this aspect; it is for the agency to evaluate in terms of its own criterion. In this section, we shall consider the support of research staff, and graduate research assistants working towards M.S. and Ph.D. degrees.

Table I indicates that 27 research assistants have received partial support from the program. Of these, 13 have obtained the Ph.D. degree while working in it. Some of the others have changed to other fields, and have either obtained the Ph.D. degree already, or are likely to do so. The remainder left Stanford at the M.S. stage, or are still in the program (Rosenthal, Savarino, Vidmar).

Postdoctoral research associates have always played a major role in the program. Their experience helps to keep the research moving rapidly, and they materially aid graduate students to develop research skills. Of the 16 listed, four (Brinca, Bruce, Ilić, Kim) obtained their Ph.D. degrees in the program. Eleven of the others came to Stanford from elsewhere, and contributed to the program part-time for periods of one to four years. Dr. Harker has contributed to the program since its inception, as has Adjunct Prof. S. A. Self.

TABLE 1 - STAFF SUPPORTED BY NASA RESEARCH GRANTS

NGR 05-020-077 (1 May 1965 - 30 June 1970) AND
NGL 05-020-176 (15 December 1966 - 30 June 1975)

Professorial Staff

F. W. Crawford (Professor, EE) - Principal Investigator

S. A. Self (Adjunct Professor, IPR)

Research Staff*

A. L. Brinca	K. J. Harker
R. L. Bruce	H. J. Hopman
H. Derfler	H. Ikegami
P. Diament	D. B. Ilić
K. B. Dysthe	H. Kim
T. J. Fessenden	Y-Y. Kuo
J. R. Forrest	M. Seidl
R. S. Harp	G. M. Wheeler

Graduate Research Assistants†

Electrical Engineering

L. P. Anderson	Y. Matsuda (Ph.D.)
A. L. Brinca (Ph.D.)	D. M. Mills
R. L. Bruce (Ph.D.)	T. D. Rognlien (Ph.D.)
D. B. Ilić (Ph.D.)	T. L. Savarino
H. Kim (Ph.D.)	D. M. Sears (Ph.D.)
J. C. Lee (Ph.D.)	M. M. Shoucri
S. Ludvik	J. A. Tataronis (Ph.D.)
T. D. Mantei (Ph.D.)	H. H. Weiss

Applied Physics

J. A. Edighoffer	S. L. Quilici
D. L. Fitelbach	S. E. Rosenthal
J. J. Galloway (Ph.D.)	D. L. St. John
J. M. Larsen (Ph.D.)	J. G. Small
R. R. Myers	R. J. Vidmar
Y-K. M. Peng (Ph.D.)	

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* All Postdoctoral

† The Ph.D. degrees were obtained while working in the program.

IV. REPORTS, CONFERENCE PAPERS, AND PUBLICATIONS RESULTING FROM NASA RESEARCH GRANTS NGR 05-020-077 (1 May 1965 - 30 June 1970), and NGL 05-020-176 (15 December 1966 - 30 June 1975)

A. NGR 05-020-077

Contract Year I (1 May 1965 - 30 April 1966)

1. Tataronis, J. A., and Crawford, F. W., "Cyclotron and Collision Damping of Propagating Waves in a Magnetoplasma"
*Proc. 7th International Conference on Phenomena in Ionized Gases, Belgrade, Yugoslavia, August 1965 (Gradevinska Knjiga Publishing House, Belgrade 1966), 2, 244-247.
*7th Annual Meeting of Plasma Physics Division of American Physical Society, San Francisco, November 1965
Bull. Am. Phys. Soc., 11, 578 (June 1966) [Abstract only].
IPR 27 (August 1965).

2. Crawford, F. W., "European Travel Report"
IPR 35 (October 1965).

3. Crawford, F. W., Harp, R. S., and Mantei, T. D., "RF Admittance of a Probe in a Warm Magnetoplasma"
*7th Symposium on Engineering Aspects of MHD, Princeton, N. J., March 1966.

4. Crawford, F. W., Mantei, T. D., and Tataronis, J. A., "The Plasma Capacitor in a Magnetic Field"
IPR 64 (April 1966)
Int. J. Elect. 21, 341-351 (October 1966).

5. Crawford, F. W., Harp, R. S., and Mantei, T. D., "Pulsed Transmission and Ringing Phenomena in a Warm Magnetoplasma"
*American Physical Society Meeting, Mexico City, August 1966.
Bull. Am. Phys. Soc., 11, 717 (July 1966) [Abstract only].
*IEEE International Antennas and Propagation Symposium, Palo Alto, California, December 1966.
Phys. Rev. Letters 17, 626-628 (September 1966).

Semiannual Reports:

6. No. 1 (1 May - 31 October, 1965)
IPR 39 (November 1965).

7. No. 2 (1 November 1965 - 30 April 1966)
IPR 74 (May 1966).

IPR = Stanford University Institute for Plasma Research Report.

* = Conference Presentation.

Contract Year II (1 May 1966 - 30 April 1967):

8. Crawford, F. W., Harp, R. S., and Mantei, T. D., "On the Interpretation of Ionospheric Resonances Stimulated by Alouette I"
IPR 75 (May 1966)
J. Geophys. Res. 72, 57-68 (January 1967).

9. Crawford, F. W., "Cyclotron Harmonic Waves in Plasmas"
*American Physical Society Meeting, Minneapolis, Minnesota, June 1966 (Invited paper)
Bull. Am. Phys. Soc., 11, 475 (June 1966) [Title only].

10. Crawford, F. W., "Pulsed Cyclotron Harmonic Wave Transmission"
*Gordon Research Conference on Plasma Physics, Crystal Mountain, Washington, August 1966.

11. Diament, P., "Summation of Series for Cyclotron Harmonic Wave Dispersion"
IPR 113 (October 1966)
Phys. Fluids, 10, 470-472 (February 1967).

12. Diament, P., "Magnetoplasma Wave Properties"
IPR 119 (November 1966).

13. Crawford, F. W., Harp, R. S., and Mantei, T. D., "Studies of Cyclotron Harmonic Wave-packet Transmission"
*8th Annual Meeting of Plasma Physics Division of American Physical Society, Boston, November 1966
Bull. Am. Phys. Soc. 12, 784 (May 1967) [Abstract only].

14. Crawford, F. W., Harp, R. S., and Mantei, T. D., "A Group Delay Technique for Ionospheric Diagnostics"
*Fall URSI Meeting, Palo Alto, California, December 1966.

Semiannual Reports:

15. No. 3 (1 May - 31 October, 1966)
IPR 111 (November 1966).

16. No. 4 (1 November 1966 - 30 April 1967)
IPR 167 (June 1967).

Contract Year III (1 May 1967 - 30 June 1968):

17. Diament, P., "A Convenient Model of Collisions in a Plasma"
IPR 172 (June 1967).

18. Diament, P., "Inverse Velocity Space Spectra and Kinetic Equations"
IPR 173 (June 1967)
Am. J. Phys. 35, 906-912 (October 1967).

19. Crawford, F. W., Harp, R. S., and Mantei, T. D., "Resonance Rectification Effects in Warm Magnetoplasmas"
IPR 177 (July 1967)
J. Appl. Phys. 38, 5077-5082 (December 1967).

20. Crawford, F. W., "Cyclotron Harmonic Wave Phenomena in Plasmas"
*Proc. VIIIth International Conference on Phenomena in Ionized Gases, Vienna, Austria, August 1967 [Invited paper].
Published in "A Survey of Phenomena in Ionized Gases" (IAEA, Vienna 1968), 109-127.
IPR 189 (July 1967).

21. Mantei, T. D., "Cyclotron Harmonic Wave Phenomena"
IPR 194 (August 1967) [Ph.D. Thesis].

22. Crawford, F. W., "Laboratory Observations of Microscopic Plasma Wave Phenomena"
*Conference on Plasma Waves, Culham, England, September 1967 [Invited paper].

23. Crawford, F. W., Harp, R. S., and Mantei, T. D., "Observation of Resonance Rectification Effects in a Magnetoplasma"
IPR 200 (September 1967)
Phys. Letters 25A, 627-628 (October 1967).

24. Harker, K. J., Eitelbach, D. L., and Crawford, F. W., "Impedance of a Coaxial Magnetoplasma"
*American Physical Society Meeting, Pasadena, California, December 1967
Bull. Am. Phys. Soc. 12, 1137 (December 1967) [Abstract only]
IPR 228 (March 1968).

25. Tataronis, J. A., "Cyclotron Harmonic Wave Propagation and Instabilities"
IPR 205 (December 1967) [Ph.D. Thesis].

26. Tataronis, J. A., and Crawford, F. W., "Alouette Plasma Resonance Phenomena"
*Spring URSI Meeting, Washington, D.C., April 1968
*Proc. NATO Advanced Study Institute on Plasma Waves in Space and in the Laboratory, Røros, Norway, April 1968. Published in, Plasma Waves in Space and in the Laboratory. Ed. J. O. Thomas and B. J. Landmark (Edinburgh Univ. Press, Edinburgh 1970), Vol. 2, 91-109
IPR 234 (March 1968).

27. Crawford, F. W., "A New Look at Very Long Delayed Radio Echoes"
*Spring URSI Meeting, Joint Session with AGU, Washington, D.C., April 1968
IPR 235 (April 1968).

28. Crawford, F. W., "Laboratory Plasma Wave Experiments"
*Proc. NATO Advanced Study Institute on Plasma Waves in Space and in the Laboratory, Røros, Norway, April 1968 [Invited paper]. Published in, Plasma Waves in Space and in the Laboratory Ed. J. O. Thomas and B. J. Landmark (Edinburgh Univ. Press, Edinburgh 1970) Vol. 1, 125-156.

Semiannual Reports:

29. No. 5 (1 May - 30 November 1967)
IPR 218 (December 1967).

30. No. 6 (1 December 1967 - 30 June 1968)
IPR 252 (July 1968).

Contract Year IV (1 July 1968 - 30 June 1969):

31. Tataronis, J. A., and Crawford, F. W., "Electrostatic Waves in Warm Magnetoplasma: I. Perpendicular Propagation"
IPR 325 (June 1969)
J. Plasma Phys. 4, 231-248 (May 1970).

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38. No. 10 (1 January - 30 June 1970) [Final Report]
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50. Lee, J. C., Fessenden, T. J., and Crawford, F. W., "Studies of Whistler Dispersion Characteristics"
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66. Dysthe, K. B., "Some Studies of Triggered Emissions"
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70. Crawford, F. W., and Sears, D. M., "Possible Observations and Mechanism of Very Long Delayed Radio Echoes"
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73. Rognlien, T. D. and Self, S. A., "Interpretation of Dispersion Relations for Bounded Systems"
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77. Bruce, R. L., Crawford, F. W., and Harker, K. J., "Observations of Nonlinear Scattering from a Plasma Column"
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86. Crawford, F. W., and Harker, K. J., "Energy Absorption in Cold Inhomogeneous Plasmas: The Herlofson Paradox"
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92. Kim, H., "Lagrangian Description of Warm Plasmas"
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93. No. 10 (1 July - 31 December 1972)
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95. Ilić, D. B., Rognlien, T. D., Self, S. A. and Crawford, F. W., "Low-Frequency Flute Instabilities of a Hollow Cathode Arc Discharge: Theory and Experiment"
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97. Galloway, J. J., "Lagrangian Methods in the Analysis of Nonlinear Wave Interactions in Plasma"
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98. Brinca, A. L., "Linear and Nonlinear Stability Characteristics of Whistlers"
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99. Larsen, J-M., "Nonlinear Wave Interactions on a Plasma Column"
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100. Brinca, A. L., "Generalization of the Stability Criteria for Hot Plasmas"
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101. Peng, Y-K. M., "Macroscopic Lagrangian and Hamiltonian Densities for Plasmas"
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107. Brinca, A. L., "Approximations to the Plasma Dispersion Function"
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108. Ilić, D. B., "Steady-State Theory of a Non-Isothermal Positive Column in a Magnetic Field"
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109. Kim, H., "Analysis of the Backscatter Spectrum of an Ionospheric Heating Experiment"
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110. Harker, K. J. and Crawford, F. W., "Theory for Incoherent Scatter Based on Three-Wave Interaction"
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117. Rognlien, T. D., "Low-frequency Flute Instabilities of a Bounded Plasma Column"
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121. Matsuda, Y., "Computational Study of Nonlinear Plasma Waves"
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122. Harker, K. J., "Generation of ULF Waves by Electric or Magnetic Dipoles"
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123. Peng, Y-K. M., "A Macroscopic Plasma Lagrangian and Its Application to Wave Interactions and Resonances"
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124. Peng, Y-K. M., "Microscopic Plasma Hamiltonian"
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125. Crawford, F. W., "Heating Experiments in the Ionosphere"
*Proc. APS/IEEE Second Topical Conference on RF Plasma Heating, Lubbock, Texas, June 1974 (IEEE, New York, N. Y., 1974), Paper E1, 9 pp. [Invited paper]
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127. No. 14 (1 July - 31 December 1973)
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129. Matsuda, Y., and Crawford, F. W., "Some Computational Studies of Nonlinear Plasma Waves"
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130. Kuo, Y. Y., Harker, K. J., and Crawford, F. W., "Generation of Whistler Waves by a Helical Electron Beam"
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131. Sears, D. M., "Long Delayed Radio Echoes"
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132. Crawford, F. W., "Plasma Wave and Resonance Phenomena"
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133. Kuo, Y. Y., Harker, K. J., and Crawford, F. W., "Radiation of Whistlers by Helical Electron and Proton Beams"
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IPR 607 (December 1974)
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135. Matsuda, Y., and Crawford, F. W., "Computational Study of Nonlinear Plasma Waves: II. Sideband Instability and Satellite Growth"
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136. Kim, H., Crawford, F. W., and Harker, K. J., "Analysis of the Backscatter Spectrum in an Ionospheric Modification Experiment"
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137. Matsuda, Y., and Crawford, F. W., "Some Computational Studies of Nonlinear Plasma Waves"
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138. Crawford, F. W., "Plasma Wave Experimentation Using the Space Shuttle"
*Proc. US-Australian Workshop on Plasma Waves, Australia, February 1975, Paper No. 27, 6 pp.
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139. Peng, Y-K. M., "A Comparison between Theory and Experiments on Nonlinear Three-Wave Interactions in Plasmas"
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141. Crawford, F. W., "The NASA Space Shuttle: Opportunities for Space Plasma Physics in the 1980's"
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142. Crawford, F. W., "Plasma Physics Experiments in Space"
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144. No. 16 (1 July - 31 December 1974)
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