Final Report for Period: 07/2001 - 06/2003

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Principal Investigator: Dimant, Yakov S.

Award ID: 0196417

Organization: Boston University

Title:

Theoretical Studies of Low-Frequency Instabilities in the Ionosphere

Project Participants

Senior Personnel

    Name: Dimant, Yakov

    Worked for more than 160 Hours: Yes

    Contribution to Project:

    The Principal Investigator, Y. S. Dimant, supervised the project, performed the theoretical work, formulated the tasks for the numerical simulations, and analysed the results.

Post-doc

Graduate Student

Undergraduate Student

    Name: Ray, Licia

    Worked for more than 160 Hours: No

    Contribution to Project:

    Undergraduate student Licia Ray was involved in the development of linear theory for the combined Farley-Buneman/ion-thermal instabilities. She checked analytical formulas and discussed the underlying physics.

Technician, Programmer

Other Participant

    Name: Smirnov, Alexandre

    Worked for more than 160 Hours: Yes

    Contribution to Project:

    Professor Alexandre P. Smirnov from Moscow State University (Moscow, Russia) developed a three-dimensional code for the description of the modified two-stream (Farley-Buneman) instability in the electrojet. He worked as a Visiting Scientist for one month during the first year of the project (funded by the project) and currently continues to work on the topic of the project in his home institution, being supported by his own funding.

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

The PI closely collaborated with Prof. M. Oppenheim from Boston University, Dr. G. Milikh from University of Maryland (College Park). He also had joint publications on the topic of the project with Drs. E. Burns, X. Chao, A Sharma, K. Papadopoulos, C. Goodrich*, T. Rosenberg, A. Weatherwax from University of Maryland (College Park), Dr. J. Lyon from Dartmouth College, and Dr. J. Fedder from George Mason University and had non-formal contacts with Drs D. Farley, D. Hysell and M. Kelley from Cornell University, Drs. J. Foster and E. Mishin** from MIT Haystack Observatory.

* Currently at Boston University

** Currently at Boston College

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<u>Activities and Findings</u>

Research and Education Activities:

The reported project was originally funded by NSF Award ATM-9812679 at Cornell University. On July 01, 2001, the PI moved to Boston University, where he joined the research group led by Professor M. Oppenheim, and transferred the reported project to the new institution. The transferred project at Boston University is currently funded by NSF Award ATM-0196417.

The objective of the current project is to provide a theoretical basis for better understanding of numerous radar and rocket observations of density irregularities and related effects in the lower equatorial and high-latitude ionospheres. The research focused on: (1) continuing efforts to develop a theory of nonlinear saturation of the Farley-Buneman instability; (2) revision of the kinetic theory of electron-thermal instability at low altitudes; (3) studying the effects of strong anomalous electron heating in the high-latitude electrojet; (4) analytical and numerical studies of the combined Farley-Buneman/ion-thermal instabilities in the E-region ionosphere; (5) studying the effect of dust charging in Polar Mesospheric Clouds.

(1) For theoretical study of the nonlinear saturation of the Farley-Buneman instability, the PI has further developed and extended analytical and numerical description based on the three-wave mode-coupling dynamical model. For possible future numerical studies, he developed a simplified hybrid set of continuous equations which combines a fluid description of electrons with kinetic description of ions. Simulations based on continuous equations have an advantage compared to particle-in-cell (PIC) simulations because they have no noise problem and can properly describe nonlinear dynamics of the instability excited near its threshold. In close collaboration with the PI, Prof. A. Smirnov from Moscow State University (Moscow, Russia) has written a 3-D code based on those equations and started testing it. We collaborated with Prof. Smirnov during his brief visit to the US (funded by the project) and we are currently continuing to collaborate via E-mail communications. Except that visit, the work by Prof. Smirnov at his home institution is covered by his own funding.

(2) The electron thermal-driven instability in the upper D/lower E regions of the high-latitude ionosphere was theoretically predicted earlier by the PI in collaboration with Prof. R. Sudan (Cornell University) based on the kinetic [Dimant and Sudan, JGR, 100, 14,605 (1995)] and fluid [Dimant and Sudan, JGR, 102, 2551 (1997)] theories. Evidence for the new instability was found in datasets of rocket and radar measurements [Blix et al., GRL, 23, 2137 (1996); Tsunoda et al., GRL, 24, 1215 (1997)]. In the framework of the reported project, the PI has revised the kinetic theory of this instability based on a more accurate account of the velocity dependence of the electron energy loss rate.

(3) In close collaboration with Dr. G. Milikh (University of Maryland, his work there is supported by his own funding), as well as in contact with other researchers, we studied the effect of strong anomalous electron heating in the high-latitude electrojets and its implications for observations. The effect of strong anomalous heating in the ionosphere observed by radars during the events of strong magnetospheric perturbations cannot be explained by standard Joule heating alone. The effect is currently believed to be mainly due to fully developed FB turbulence. A popular 2-D theory of turbulent heating based on the concept of anomalous electron-plasmon 'collisions' [Robinson, JATP, 48, 417 (1986)] shows reasonable agreement with observations, but is physically inconsistent. This incited us to develop a model of anomalous heating which would make accurate predictions and, at the same time, would be based on correct physical principles. To this end, we developed a heuristic analytical model of nonlinearly saturated Farley-Buneman turbulence and used it as an input source for numerical simulations of the electron heating based on energy balance equations and a specialized kinetic code developed in the University of Maryland (College Park).

(4) In close collaboration with Prof. M. Oppenheim (Boston University, this work is supported by his own funding) we have started fully kinetic, 2- and 3-D particle-in-cell (PIC) numerical simulations of the E-region instabilities. These simulations take advantage of modern, massively parallel supercomputers and have no analog in the world. Encouraged by the first results, with assistance of undergraduate student Licia Ray (Boston University), we have developed a fluid-model linear theory of the combined Farley-Buneman/ion-thermal instabilities in the E-region ionosphere. This work has been an important educational activity for the student.

(5) In close collaboration with Dr. G. Milikh, the PI has also developed an analytical/numerical model of dynamical charging of polar mesospheric dust affected by strong HF heating.

As a result of the project, we have published or submitted 8 papers in peer-peviewed Journals. Several more papers are currently under preparation for submission. Results of the project have been also presented at the Annual Meetings of the American Physical Society, (1999,2001,2002, abstracts published in the Bulletin of American Physical Society), Spring Meetings of the American Geophysical Union, (1999-2002, abstracts published in the EOS Supplements), at the Annual CEDAR Workshops, (Boulder/Longmont, Colorado, 1999--2003, invited talks), Annual Ionospheric Interactions Workshops, (Santa Fe, New Mexico, 1999--2002), 21st IUPAP International Conference on Statistical Physics (2001), (Cancun, Mexico, 2001), The World Space Congress (COSPAR & IAC, Houston, Texas, 2002) with publications in the appropriate Proceedings.

Findings:

(1) For the generic three-wave mode-coupling model of nonlinear saturation, we have found the exact criteria in the full parameter space for wave-amplitude saturation (boundedness of attractors). We have classified in the parameter space fundamentally different kinds of asymptotic behavior of the wave triad and assessed the average wave amlitudes in the nonlinearly saturated space.

The analysis of an extended three-wave mode-coupling model to a multi-wave model have shown that waves with largest oscillation amplitude have a tendency to be excited at a margin of linear stability. We studied the case of marginal linear stability in detail both analytically and numerically. Via developing of a nonlinear theory based on the perturbation approach, we have found an approximate analytical solution of the nonlinearly coupled ordinary differential equations (ODE) at the marginal linear stability/instability. This solution describes a regime of nearly-periodic sawtooth amplitude oscillations of the mode with the largest amplitide and synchronous amplitude spikes of the two other modes. Numerical solutions of the ODE fully confirmed the analytical predictions. These studies give a new insight into nonlinear saturation of the Farley-Buneman (FB) instability near the instability threshold and can also be applied to similar processes in other media.

(2) A revision of the kinetic theory of the electron thermal (ET) instability caused by strong ambient DC electric field in the upper D/lower E regions of the high-latitude ionosphere has provided more accurate estimates of the linear threshold of the instability. The analysis has also shown that the short-wavelength limit of the linearly unstable band (down to two meters) is shorter than was predicted before. This is of importance for correct interpretation of radar observations. We believe now that radar signals observed by 50MHz radars may detect irregularities fully or partially excited by the ET instability in the linearly unstable range.

(3) In our studies, we have shown that the observed extreme temperature elevations (by an order of magnitude, up to 3000K) in the high-latitude E region during strong magnetospheric perturbations cannot be accounted for by frictional heating by the dominant electric field components (DC or turbulent), which are perpendicular to the geomagnetic field. It is a relatively small component of the FB turbulent electric field which can heat electrons to the extreme temperatures. Because the full 3-D theory of the FB turbulence had not been completed and no consistent 3-D simulations of the FB instability had been conducted, we have developed a model of nonlinearly saturated FB turbulent electric field, which is based on simple physical reasonings and comparison with some rocket observations. As a result, we obtained the root-mean-square (rms) components of the turbulent electric field as functions of the convection DC electric field at different altitudes and used them as the heating source in appropriate energy balance equations. This resulted in a coupled set of nonlinear equations for the rms turbulent electric field, electron and ion temperatures. The temperature-dependent electron-neutral collision frequency and cooling rate were calculated by the specialized kinetic code because they are strongly affected by non-Maxwellian deviations of the electron energy distribution function (EDF).

Due to significant non-Maxwellian EDF deviations, the electron temperature retrieved from radars may differ from that determined via the average thermal energy of electrons. By using kinetic theory, we have derived the relation between the two temperatures. This is of importance for accurate interpretation of the radar measurements. We have compared the numerical results of anomalous electron heating with available radar measurements and made quantitative predictions of the effect for a broad range of ionospheric conditions. A good agreement with observations supports the physical ideas underlying the model.

The heuristic equations of the turbulent electric field with adjustable parameters may serve as a skeleton for more accurate equations, which may be used for reliable and accurate predictions of the effect of strong anomalous electron heating under various conditions. Appropriate analytical relations can even be included in future global ionosphere-magnetosphere models. New and presumably more complete data of rocket measurements of turbulent electric fields, as well as anticipated results of future 3-D simulations, may help improve the model. At present, our model can be used for prompt estimates of the effect of electron heating at different altitudes in the electrojet.

(4) To model nonlinear saturation of the FB instability and turbulent heating of electrons by direct simulations, we have started 2- and 3-D fully kinetic PIC simulations of the FB instability. Surprisingly, the first 2-D simulations have demonstrated that for driving electric field well above the FB instability threshold, ion thermal (IT) driven effects (usually disregarded by the E-region ionospheric community) dominate the development of the FB instability. In such regimes, the nonlinearly saturated state demonstrates a remarkably coherent structure of ionospheric irregularities with the clear offset of the predominant wavevector from the direction of the electron E X B drift. This feature, as well as the analysis of phase shifts between the temperature and density perturbations, has allowed us to interpret such regimes as driven predominantly by the IT instability. These results also indicate that results of some previous fully kinetic or hybrid simulations, in which a similar wavevector offset was observed, were probably misinterpreted.

For driving electric field closer to the FB instability threshold, we observed regimes when the FB instability dominates. Unlike the predominantly IT driven regimes, these regimes show significantly turbulent, mode-coupling character of nonlinearly saturated state with no clear offset from the E X B-drift direction, as should be for the FB instability. Some thermal effects, however, showed up in these regimes as well.

First 3-D simulations in the IT dominated regimes showed no significant structure in the direction parallel to the geomagnetic field, B. We

conjecture that this is because such regimes are saturated by purely thermal mechanisms with no mode coupling to the third dimension parallel to B. We expect such coupling, which may lead to possible structuring along B and related heating effects, in 3-D simulations of the FB dominated regimes which can only be saturated via mode coupling. These regimes, however, require much more computer resources and much longer computational time, so that we have not yet been able yet to conduct such simulations. We are currently continuing this work (supported by other funding) and look forward into a significant progress in this direction.

Following our predictions of the ET instability (see above), Kagan and Kelley [JGR, 105, 5291 (2000)] recently hypothesized a neutral-wind driven IT instability (with the driving mechanism similar to that of the ET instability) at higher E-region altitudes. Their linear theory, however, has some inconsistencies and appears to significantly exaggerate the efficiency of the IT driving mechanism. The results of our PIC simulations described above inspired us to revise the linear theory of the IT instability.

Because all driving meachanisms should coexist, we have developed linear theory of the combined instability, including all driving mechanisms (except spatial gradients): IT, FB, and ET driving terms. The results of the linear theory (based on fluid equations) have given us the predictions of the threshold electric fields, linear growth rates, and the preferred wavevectors at different altitudes, as functions of the DC electric field. Within the electrojet altitudes, these results show general dominance of the FB driving mechanism, in some disagreement with our PIC simulations. For a more accurate comparison, however, we need nonlinear theory. This will be a subject of future activities.

(5) Previous models of discrete dust charging [e.g., Cui and Goree, IEEE Trans. on Plasma Science, 22, 151 (1994); Rapp and Lubken, Earth Planets Space, 51, 799 (1999)] were based on numerical simulations of charge distributions over dust grains. In framework of the reported project, we have found a general analytical expression for the stationary discrete charge distribution. We also developed a dynamical model of temperature-dependent variations of the average dust charge distribution along with the free-electron density.

The density variations are sensitive to the parameters of the dust such as the grain size and composition. High-power HF heating facilities like HAARP (Gakona, Alaska), EISCAT heating facility (Tromso, Norway), and Sura (Russia), may rapidly heat free electrons at mesospheric altitudes. Applying modulated heating, one may modulate the mesospheric dust charge and hence the free-electron density at the heated area. By observing from the ground the free-electron density variations and comparing them with model calculations, one may deduce such parameters as the mean grain size, dust density and photoemission rates.

Our dynamical model predicts possible strong variations of the free-electron density in one-second or longer duration range of modulations. Meauserements of the small free-electron density in the D region represent real experimental challenge. We have proposed some possible measurement techniques.

It is also possible to use the effect of Polar Mesosphere Summer Echoes (PMSE) which is also related to the mesospheric dust. The radar signal associated with the PMSE should be proportional to the free-electron density at the dust layer altitudes, so that modulations of the density should also result in modulations of the PMSE signals. Recent experiments involving HF heating of dust clouds [Belova et al., JGR, 108, DOI: 10.1029/2002JD002385 (2003)] showed fast (tens milliseconds) disappearance of the PMSE during heater turn-on and equally fast recovery after heater turn-off. These temporal characteristics suggest that the effect was caused by some physical mechanism probably not associated with the dust charging. We hope that future experiments will provide observational evidence for dust charging effects.

Training and Development:
Undergraduate student Licia Ray (Boston University) was involved in the theoretical studies of the project. She assisted us in the development of linear theory of the combined FB-IT instability. She checked the derivation of all equations starting from the original fluid equations. During this work, she learned all the underlying physics, which improved her basic knowledge of ionospheric and plasma physics.

The PI included some materials of the project studies in his one-semester course on Advanced Plasma Physics, which he taught for gradiate and undergraduate students at Cornell University during the Spring Semester of 2001.

Outreach Activities:
The PI has given several lectures/talks on topics close to the reported project for students and researchers from different communities: in the University of Maryland at College Park (2000-2002), Haystack Observatory (2000), Boston University (2001), University of Western Ontario (London, Canada, 2003), and PARS Summer School, Alaska (2003).

Journal Publications

Y. S. Dimant, "Nonlinearly saturated dynamical state of a three-wave mode-coupled dissipative system with linear instability", Physical Review Letters, p. 622, vol. 84, (2000). Published

G. M. Milikh, Y. S. Dimant, X. Shao, P. N. Guzdar, A. S. Sharma, K. Papadopoulos, E. M. Burns, C. C. Goodrich, T. J. Rosenberg, A. T. Weatherwax, M. J. Wiltberger, J. G. Lyon, and J. A. Fedder, "Modeling ionospheric absorption modified by anomalous heating during substorms", Geophysical Research Letters, p. 487, vol. 28, (2001). Published

G. M. Milikh and Y. S. Dimant, "Kinetic model of electron heating by turbulent electric field in the E region", Geophysical Research Letters, p. 1575, vol. 29, (2002). Published

Y. S. Dimant and G. M. Milikh, "Model of anomalous electron heating in the E region, I: Basic theory", Journal of Geophysical Research, p. , vol. , (   ). Accepted

G. M. Milikh and Y. S. Dimant, "Model of anomalous electron heating in the E region, II: Detailed numerical modeling", Journal of Geophysical Research, p. , vol. , (   ). Accepted

Y. S. Dimant and G. M. Milikh, "Effect of radio wave heating on polar mesospheric clouds", Advances in Space Research, p. , vol. , (   ). Accepted

Y. S. Dimant and M. M. Oppenheim, "Ion-thermal effects on E-region instabilities: linear theory", Journal of Atmospheric and Solar-Terrestrial Physics, p. , vol. , (   ). Submitted

M. M. Oppenheim and Y. S. Dimant, "Ion-thermal effects on E-region instabilities: 2-D kinetic simulations", Journal of Atmospheric and Solar-Terrestrial Physics, p. , vol. , (   ). Submitted

Books or Other One-time Publications

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Contributions

Contributions within Discipline:
The Earth's ionosphere is a conducting layer of partially ionized plasma created by Solar ultra-violet radiation in the upper atmosphere. This transition region between the neutral atmosphere at low altitudes and the highly ionized magnetosphere at high altitudes is of great importance for Solar-Terrestrial interaction. The Earth's ionosphere is also of significant practical importance because of its effect on radio wave propagation and satellites.

The part of the ionosphere located roughly between 90 and 150 km of altitude is named E region. A low-ionized region slightly below it is named D region. These two are crucial regions where cross-field conductivities can be high enough to allow magnetospheric and ionospheric currents to close across geomagnetic field lines. In the high-latitude and equatorial regions, the E region forms strong electric currents called electrojets. These electrojets commonly develop plasma instabilities and often become irregular and turbulent. Investigating these instabilities and other physical processes in the E/D regions is of importance for deep understanding of the natural processes in the near-Earth environment and for practical purposes.

While E-region waves and instabilities have been studied for over 40 years, there are still many outstanding questions. Among them: What physical processes dominate turbulence at different altitudes in the lower ionosphere, and what observational effects do they create? What is the average amplitude and 3-D spectral characteristics of the nonlinearly saturated turbulence? What consequences does this turbulence have on the temperatures and conductivities of the lower ionosphere and can we develop predictive relationships useful in large-scale analytic and computer modeling? What information about the ionosphere can be retrieved from radar/rocket measurements of ionospheric irregularities?

The reported project is a continuing theoretical study of the E/D-region plasma instabilities and of other related phenomena with the objective of enhancing our understanding of the natural processes in the lower ionosphere and improving the community's diagnostic and predictive capabilities. As a result of the project, we have significantly improved our qualitative and quantitative understanding of the physical processes in the E/D-region ionosphere. The results of the project have helped to answer some of the above questions and have created a basis for further

research and educational activities.

Among the major contributions within the field:

Our research has shown that thermal driving mechanisms should play an important role in the lower ionosphere, resulting in the development of the electron thermal (ET) instability in the upper D/lower E regions and of the ion-thermal (IT) instability at the top of electrojet and higher. Besides, thermal factors may significantly affect the development of the Farley-Buneman (FB) instability in the middle of the electrojet. This new understanding changes dramatically the previous view of ionospheric processes and is of importance for physical interpretation of radar and rocket observations. Linear theory of the combined (ET+IT+FB) instability, which covers all relevant altitudes in the ionosphere, provides a novel way to predict the instability threshold under various ionospheric conditions.

The developed heuristic model of nonlinearly saturated turbulence with adjustable parameters may serve as a skeleton for more accurate analytical models if future three-dimensional simulations and observations provide more material for a detailed comparison. The analytical/numerical model of strong anomalous heating based on the heuristic model represents a new predictive tool for the ionospheric community. It allows prompt estimating anomalous temperature elevations and their possible effect on the ionospheric conductivities at different altitudes for different amplitudes of the driving electric field. The recently derived relation between the electron temperature retrieved from radars and that determined by the mean thermal energy of electrons will help more accurate interpretations of the radar measurements.

The new stationary theory of discrete charging of mesospheric dust grains at the D-region altitudes provides an explicit analytical expression for the dust grain distribution over discrete charges. This general expression has a rather universal applicability and can be applied to similar processes in other space and laboratory dust-in-plasma. This analytical expression agrees with previous particular numerical results and it is easy to use. The dynamical theory of dust charging based on a time-dependent discrete-charge kinetic equation can be used for the analysis of dust plasma interactions in fastly changing processes (like varying dust charging caused by modulated HF heating). The proposed measurement technique based on this theory can be potentially used as a complementary diagnostic tool for mesospheric dust parameters.

Contributions to Other Disciplines:

Dissipative dynamical systems are widely present in many areas of science and technology. Among them, rather common are systems with linear instabilities saturated by nonlinearity. Understanding of this process and finding quantitative characteristics of the nonlinearly saturated dynamical state represents a fundamental problem, which is very complicated mathematically. The analysis may be simplified in cases when linearly unstable systems evolve to turbulent states with a restricted number of dominant wave perturbations. Such nonlinearly saturated states can be modeled by attractions of truncated sets of coupled ordinary differential equations (ODE).

For systems with quadratic nonlinearity, three-wave mode coupling models may reasonably describe key features of actual turbulence, especially in linearly unstable systems near the equilibrium. The most typical and representative example of such a system is the three-wave mode-coupling model extensively studied in the framework of the reported project. The corresponding (or equivalent) set of nonlinearly coupled ODE arise in plasma physics, nonlinear optics, fluid mechanics, etc.

The major contribution to other fields is the following:

The general results on the dynamical three-wave mode-coupling model obtained in the project are applicable to any problem reducible to this model and could be employed to other fields of research routinely studied by methods of nonlinear dynamics (mechanical and electrical engineering, chemistry, biology, social studies, etc.). In particular, exact analytical results on nonlinearly saturated state of the three-wave model obtained in terms of generalized dimensionless parameters and the novel mathematical approach to finding such relations may be directly applied to relevant problems in other disciplines.

Contributions to Human Resource Development:

Theoretical approaches developed during the project studies and some results can be used as a teaching tool for students in the areas of plasma physics, space physics, and nonlinear dynamics. Some materials of the project were already used by the PI to teach students during a one-semester course on Advanced Plasma Physics at Cornell University (Spring, 2001).

By using the project studies as an educational tool, we have used an opportunity to teach a female undergraduate student Licia Ray. The work on assisting us with the analytical research has helped her to improve her knowledge of ionospheric and plasma physics and improve her general mathematical skills. Licia Ray was accepted recently as a graduate student at the University of Colorado (Boulder, Colorado).

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

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