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MESOSCALE IONOSPHERIC PHENOMENA -- Lower Hybrid Collapse, Caviton Turbulence, and Charged Particle Energization in the Topside Ionosphere and Magnetosphere

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28 March 1993

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13. ABSTRACT *(Maximum 200 words)*

In 1981, Chang and Coppi [*Geophys. Res. Lett.*, **8**, 1253] suggested that lower hybrid turbulence could be the prime candidate for the acceleration of ions and generation of "ion conics" in the high-latitude ionosphere and magnetosphere. Subsequently, Retterer, Chang and Jasperse [*J. Geophys. Res.*, **91**, 1609 (1986)] demonstrated that nonlinear wave interactions near the lower hybrid frequency through modulational instability, such as the collapse of waves into soliton (caviton) turbulence could play a key role in the energization of both the ambient ions and electrons. Recent sounding rocket observations in the source region of the topside auroral ionosphere seem to confirm the details of such predictions [Kintner et al., *Phys. Rev. Lett.*, **68**, 2448 (1992); Arnoldy et al., *Geophys. Res. Lett.*, **19**, 413 (1992)]. In this paper, the scenario of this interesting micro/meso scale, nonlinear wave-wave and wave-particle interaction plasma process in the auroral ionosphere/magnetosphere is briefly reviewed.

14. SUBJECT TERMS
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FIGURE CAPTIONS

SYNOPSIS OF ACTIVITIES

During the past year, we have made substantive progress toward the goals set forth in our research proposal: "Mesoscale Ionospheric Phenomena." In the research area, we have succeeded in developing the basic understanding of the mesoscale processes of lower hybrid collapse, caviton turbulence and charged particle energization in the topside ionosphere and magnetosphere, We have also made considerable advance in the study of the polar wind and ion cyclotron resonance heaing of central plasma sheet heavy ions. A number of these theoretical findings have recently been confirmed by experimental data collected by polar-orbiting satellites as well as high altitude sounding rockets. As a gauge of recognition of the group's quality of research by its peers, our group presented a total of 16 invited and review lectures during the year at various national and international conferences and research institutions.

In January of 1992, we organized an annual Symposium on the "Physics of Space Plasmas". Professor Eugene Parker of the University of Chicago was the Awardee of the 1992 Alfvén Lectureship and delivered an Opening Lecture on the subject matter of: "Spontaneous Discontinuities and Stellar X-Rays." We also organized a 1992 Cambridge Workshop on Theoretical Geoplasma Research. The theme of the workshop was "Controversial Issues and New Frontier Research in Geoplasmas." This activity was participated by over 125 research scientists and graduate students from all corners of the world. During the year, we also participated in the scientific sessions at the Spring and Fall AGU Meetings, the Plasma Physics Meeting of the American Physical Society, the Third Huntsville Workshop on Magnetosphere/Ionosphere Plasma Models, the Western Pacific Geophysics Meeting, the Nineteenth IEEE International Conference on Plasma Science, the Chapman Conference on Micro-Meso Scale Phenomena in Space Plasmas, and the 28th Annual Meeting of the Society of Engineering Science.

In this report, we provide a comprehensive review of our contribution toward the understanding of lower hybrid ion heating processes in Earth's ionosphere and magnetosphere. This review is prepared by Tom Chang for the forthcoming Special Issue of Invited Lectures of Physics of Fluids B, Vol. 5.

1. INTRODUCTION

In this review, we consider an interesting plasma physics phenomenon that occurs rather frequently within the Earth's magnetosphere. The Earth's magnetosphere is a cavity carved out from the solar wind by the Earth's magnetic dipole (Figure 1). The plasma density of the magnetosphere is quite low (of the order of one particle per cubic centimeter) and most of the particle population of the magnetosphere resides in a region called the "Plasma Sheet." The plasma sheet is quite dynamic, expanding and contracting aperiodically in time. Frequently, field-aligned energetic (keV) electrons have been detected streaming toward the Earth's ionosphere near the boundary layer region of the plasma sheet (Figure 2). In addition to being responsible for the production of the visible discrete auroral display in the E-region of the ionosphere, these energized electrons are also the culprit for a suite of plasma waves that are observed along the auroral field lines. In particular, intense electrostatic lower hybrid turbulence has been detected[1] near the topside ionosphere and the suprauroral region where the plasma beta is very low (Figure 3).

The particle populations in the suprauroral region are generally quite anisotropic. For example, ion distributions strongly peaked in pitch angle are routinely observed[2] (Figure 4). The conic shape of these distributions indicates some form of heating transverse to the ambient magnetic field. The generally accepted scenario for such transverse acceleration is some sort of wave-particle interaction. In this picture (Figure 5), the ions are energized perpendicularly to the geomagnetic field lines by energy-carrying plasma waves. One can then account for the conic form of the distribution by realizing that the magnetic field strength decreases with altitude. Thus, the adiabatic motion of the ions drifting to higher altitudes transforms the heated distribution into one that is more field-aligned, i.e., a **conic**[3].

It was suggested by Chang and Coppi[4] in 1981 that the intense lower hybrid waves that are detected along the discrete auroral field lines could be the prime cause for the ion acceleration process. It is known that electron beams such as the precipitating energetic auroral electrons can provide the free energy to generate waves in the whistler range of frequencies (VLF waves for supraauroral/auroral parameters) including the lower hybrid waves[5]. Since the observed lower hybrid waves were generally broad band, a quasilinear diffusion operator was used to estimate the average energy transfer from a steady state of waves populating a portion of the field line. It was found that typically 1-eV ions could be raised in energy to tens or hundreds of eV and beyond by lower hybrid waves of moderate intensity along the discrete auroral field lines where electron beams were detected (Figure 6). As the heated ions drift upward along the field lines due to the "mirror" geometry of the Earth's magnetic field, they eventually leave the primary heating region. Thus, the heating process was found to be self-limiting.

However, we are confronted with the dilemma that the lower hybrid waves initially excited by the linear instability of the energetic auroral electrons are of high phase velocity, they would resonantly interact only with energetic ions, which are few in number in the topside ionosphere. In this review, we shall describe a scenario (first introduced by Retterer, Chang, and Jasperse (RCJ)[6] in 1986) utilizing the convective nature of the waves and ensuing nonlinear mode-coupling processes that can result in the collapse of the lower hybrid modes to shorter wavelengths to achieve the resonance matching with the tail region of the cold ionospheric ion distribution. The theory also predicts the simultaneous occurrence of counterstreaming electrons that are commonly observed[7] in conjunction with the ion conics in the suprauroral region. These theoretical predictions, including the eventual generation of lower hybrid caviton turbulence due to the phenomena of collapse through modulational instability have been confirmed by recent high-altitude sounding rocket experiments[8-13], utilizing innovative high-time resolution wave and particle detectors.

2. THE THEORY OF RETTERER, CHANG, AND JASPERSE (RCJ)

The commonly observed geometry of discrete aurorae in the high latitude ionosphere is that the auroral arcs are sufficiently extended in the longitudinal direction but narrowly confined in the latitudinal direction. This indicates that the regime containing the energetic precipitating electrons above a discrete auroral arc (the suprauroral/auroral region) must also be similarly confined in the latitudinal direction. The density within the suprauroral region is generally less than that of its immediate neighborhoods with appreciable perpendicular (outward) and parallel (downward) density gradients. The propagation characteristics of the relevant plasma waves that are excited by the energetic electron beam at high altitudes depend crucially on the inhomogeneous density structure of the depleted suprauroral region. It has been shown by Maggs[14], Maggs and Lotko[15], and Retterer et al.[16], using ray-tracing calculations, that for typical plasma parameters in the suprauroral region, convective modes at frequencies much higher than the lower hybrid frequency will generally propagate out of the region in the latitudinal direction shortly after they are generated, leaving only those modes close to the lower hybrid frequency, which have group velocities nearly parallel to the magnetic field, to continue to propagate and grow along the field-aligned direction. These lower hybrid modes can stay within the suprauroral region and grow to very large amplitudes leading to the nonlinear coupling of modes and collapse of waves to shorter wavelengths near the topside ionosphere (Figure 7).

It has been demonstrated by Retterer, Chang and Jasperse[6] (RCJ) that such type of nonlinear coupling process may be understood in terms of the phenomenon of modulational instability based on the warm fluid approximation for the ions and electrons. (Similar ideas have been considered by other authors in other plasma applications[17-18] and in the laboratory[19].) Assuming that the high frequency (lower hybrid) fluctuations are modulated by the low frequency (acoustic) components, the resulting equation governing the amplitude of the lower hybrid electric field for propagations restricted at an angle characterized by the square root of the mass ratio ($\mathbf{k} \bullet \mathbf{B} \approx (m_e/m_i)^{1/2}$) is a cubic nonlinear Schrödinger equation (NLSE). (The assumption of one-dimensional propagations is a physically realistic approximation. Due to the narrowness of the suprauroral region in the latitudinal direction, other nonlinear mode-coupling processes that are neglected in this approximation entail the **ExB** drift of the electrons and therefore can not support the continued growth of the ensuing instabilities. The choice of the particular angle given above facilitates the growth of waves near the lower hybrid frequency.)

In addition to the nonlinear coupling process of wave-wave interactions, concomitant wave-particle interactions control the evolution of the lower hybrid turbulence in the topside ionosphere RCJ[6] suggested that the dominant wave-particle plasma interaction process could be modeled by the consideration of instantaneous Landau damping of the waves by the various particle species (i.e., the beam electrons, the background ambient ions and electrons) which at the same time are scattered by the lower hybrid waves through resonant interactions. The resulting coupled equations characterizing both the nonlinear wave-wave and wave-particle interactions given below have been solved numerically[6] for typical suprauroral conditions near the topside ionosphere.

$$i\partial E_k/\partial t = Dk^2 E_k - C\sum_{k',k''} E_{k'}E^*_{k''}E_{k+k''-k'} + i\gamma_L(k)E_k \tag{1}$$

$$\partial f_s(v)/\partial t = \partial/\partial v\left[D_s(v)\partial f_s/\partial v\right] \tag{2}$$

where E_k is the Fourier component of the lower hybrid electric field fluctuations, C and D are the coupling and diffusion coefficients expressible in terms of the plasma parameters, γ_L is the instantaneous Laudau damping rate, and f_s are the distribution functions. Because the average intensities of the waves are sufficiently low and the spectrum is broad-band, RCJ used the quasilinear diffusion operator for the scattering of particles by the waves. This approximation is quite adequate except during the initial transitional regime from linear to the saturation state. It is to be noted that using the quasilinear diffusion operator is not the same as assuming quasilinear plateauing. The turbulence is strong and is governed by Eq.(1). Quasilinear theory would have entailed a linear growth equation for E_k^2.

The bottom panel of (Figure 8) gives the calculated evolution of the lower hybrid wave energy density as a function of elapsed time. It is seen that the wave energy grows linearly during the initial stage of excitation and then saturates due to nonlinear mode-coupling processes. The result compares favorably with that obtained from an equivalent PIC simulation. The top panel of (Figure 8) gives the time evolution of the ion energy density. It is noted that the ions are heated only after nonlinear mode coupling has set in. At later stages of the evolution when the waves are saturated, the ions are seen to continue to gain their energy. The lower hybrid waves now simply play the role of a conduit, transferring energy from the electron beam to the ions. If mode-coupling processes are not allowed to take place (quasilinear theory), then the waves will continue to grow until quasilinear plateauing of the beam electrons sets in and the ions cannot be heated. Figure 9 compares the ion velocity distribution at the end of a PIC simulation with the theoretical prediction based on the hybrid kinetic/NLSE model of RCJ. Note that the tail regions of an initial Maxwellian ion distribution have been heated by the nonlinear coupling process.

Figure 10 presents the evolution of the wave spectrum in a one-dimensional PIC simulation. It is seen that the wave energy cascades continually from the k-values of the linearly unstable modes toward larger k-values indicating the collapsing process toward shorter wavelength lower hybrid waves. Figure 11 depicts the evolution of the amplitude of the electric field in real space and time based on the RCJ model[20]. At the beginning, the amplitude of the electric field grows uniformly. Eventually, when wave collapse sets in, the electric field intensity begins to concentrate aperiodically and in narrow spatial regions. These localized structures (cavitons, because they correspond to sharp localized density depletions) are seen to propagate at speeds much less than the ambient ion thermal velocity and should appear as stationary structures if detected by in situ electric field measurements. **The onset of caviton turbulence is expected from the model equations since it is known that the cubic NLSE can support such type of solitary structures[21].**

3. CONFIRMATION OF THE RCJ THEORY BY ROCKET OBSERVATIONS

Recent rocket experiments[8-13] (MARIE and TOPAZ 3) carried out by Kintner, Yau, Labelle, Arnoldy, and their co-workers have obtained wave-particle data in the topside ionosphere, that are in remarkable agreement with the predictions of the RCJ theory.

For example, electric field data from both the MARIE and TOPAZ 3 satellites have obtained irrefutable evidence of caviton turbulence in the topside ionosphere with each individual caviton exhibiting the characteristic envelope solitary structure as predicted by the cubic NLSE and the RCJ theory, (Figures 12-13). 12-13. The intense cavitons are clearly seen in Figure 12 as spiky structures[8] with high intense electric field intensity (50-100 mV/m for the MARIE satellite). These structures have been christened "Lower Hybrid Spikelets" by LaBelle et al.[8] A typical example of one of these spikelets is displayed in expanded time scale in Figure 13; the envelope structure with characteristic lower hybrid oscillations is clearly displayed[8]. The frequency of the peak of the spectral density of one of the typical spikelets was around 10 kHz and a wavelength of approximately 20 m, giving a characteristic phase velocity of waves at 200 km/s[22]. Similar events are routinely seen by the TOPAZ 3 satellite[10,12] with peak intensities at 300-400 mV/m or beyond when the instrument is saturated.

That these structures are cavitons are clearly seen in Figures 14-15[10-11] where the lower panels give Langmuir probe measurements indicating highly rarefied regions corresponding to the locations of the electric field spikelets (third panels from the top). Simultaneous with the observation of cavitons, the ions are seen accelerated in the 90 degree pitch angle direction. In Figure 15, one of the ion events (at 577.1 seconds) is not accompanied by the simultaneous observation of a caviton structure. The interpretation by Arnoldy et al.[11,13] is that the ions are not exactly at 90 degrees and are, therefore, probably coming from a region below the spacecraft. This indicates that it is the cavitons that accelerate the ions rather than the ions producing the waves; for otherwise, cavitons should always be present when transversely accelerated ions are seen.

Figure 16 gives typical particle distributions obtained by the TOPAZ 3 satellite[11]. The top three panels are phase space plots when transverse heating is not observed. The lower panels are phase plots when transverse heating is observed. At $t = 577.5$ sec., the oxygen population is tailed heated with the tail emanating from $v_\perp$ approximately equal to 10 km/s. Simultaneously, the hydrogen population is also heated. For lower hybrid heating, the hydrogen population should again be heated from $v_\perp = 10$ km/s. This is consistent from the near bulk heating signature of the phase space plot. We defer the discussion of electron signatures in a later section.

Generally, the ions will receive many kicks by the cavitons. The integral effect on the ion distribution by the ensemble of cavitons is the diffusion of ions in velocity space, which can be estimated from the ensemble statistics of the numerical solution of Eqs. (1) and (2). Alternatively, the perpendicular velocity diffusion coefficient may be estimated from the saturated k-spectrum such as those given in Figure 10. Based on such spectrum forms, Crew and Chang[23] suggested the following form for the velocity dependence of the diffusion coefficient:

$$D_{\perp} = (q/m)^2 S_{E0}(v_{\perp}/v_0)^{\beta}\left[1+(v_{\perp}/v_0)^{\beta+3}\right]^{-1} \tag{3}$$

where S_{E0} is a reference value of the electric field spectral intensity, v_0 is the reference phase velocity and β is a parameter which depends on the shape of the spectrum curve.

Recently, Retterer, Chang and Jasperse[20] used the above form of the diffusion coefficient to estimate the energization of ions by the caviton turbulence observed by the MARIE satellite[8-9]. The values of S_{E0} and v_0 are chosen as (7 mV/m)^2/kHz and 200 km/s, respectively based on estimates from typical wave measurements on MARIE. Using Monte Carlo techniques originally developed by Retterer, Chang and Jasperse[24] in 1983 and with a judicious choice of initial conditions, it was shown that the simultaneously observed hydrogen data[9,20] may be effectively reproduced, provided the shape parameter β is chosen to be unity (Figures 17-18).

4. ELECTRON SIGNATURES

Turning our attention to the electrons, we first note that the collapse process characterized by Eqs. (1) will generate short wavelength lower hybrid waves with phase velocities symmetrically in both positive and negative directions along the angle characterized by $\mathbf{k} \bullet \mathbf{B} = (m_e/m_i)^{1/2}$.. Thus, we expect the ambient electrons to be energized both upward and downward along the field lines. This type of counterstreaming electrons have been observed in the magnetosphere in conjunction with ion conics[7] (Figure 19). In addition, of course, we expect to see a flattened (N.B., not quasilinear plateaued) component of the beam population. However, unlike the ions, the electron population is also affected by VLF or lower hybrid waves at angles other than that characterized by the square root of the mass ratio. Thus, a two-dimensional simulation or analysis is needed to study the full effect of the VLF waves on the electron population. Such types of simulations have been performed by Retterer et al.[16,25] (Figure 20).

The calculated electron population is very similar to that is displayed in the left panels of Figure 15 of the TOPAZ data.. We expect to see the flattened electron beam population nearly everywhere within the discrete auroral region and not solely in conjunction with the observation of cavitons. Same holds true for the bi-directional energization of the ambient population. Measurements have also detected short-lived (the order of seconds) dispersive bursts of cold electrons anti-correlated with the transversely accelerated ions. Their role in the totality of the wave-particle interaction process within a discrete auroral arc is not clear. The flattened electron population in Figure 15 also has a pitch-angle scattered component. This could be accomplished by anomalous Doppler resonance as suggested by Kadomtsev and Pogutse[26] and Parail and Pogutse[27]. It has been suggested by Omelchenko et al.[28] that such type of fan-like electron distribution could enhance the local production of lower hybrid waves.

5. SUMMARY AND RECENT ACTIVITIES

In this review, we have described an extremely interesting plasma physics phenomenon in the magnetosphere/ionosphere; namely, transverse ion acceleration by localized intense lower hybrid cavitons. The theoretical research was initiated in 1981[4] in response to the curious observations of ion conics in the suprauroral region of discrete arcs. This was followed by a daring theoretical prediction (RCJ)[6] which, by noting that the relevant plasma process is micro/meso scale in nature, suggested that all the important actions must initiate from the topside ionosphere. The theoretical predictions were verified by a series of recent innovative rocket experiments[8-13] carried out in the source region. Definitive evidence of the existence of intense lower hybrid spikelets (or cavitons) were detected. Concrete evidence was collected indicating that it is these cavitons that initiate the transverse energization of ionospheric ions in a discrete aurora. Ensemble-averaged diffusion calculations[9,20] of the ions in this region gave further credibility of the feasibility of energizing ionospheric ions to magnetospheric energies by broad band lower hybrid waves.

Since the reporting of the in-situ measurements of cavitons and transverse ion acceleration, a number of new developments have emerged. For example, higher dimensional theories and simulations have been performed[16,25,29-31]. It is now understood that when the extra dimensions are taken into consideration, the cavitons are actually cigar-shaped structures of finite extension. The major axis of each individual caviton is aligned with the magnetic field and the aspect ratio is related to the square root of the mass ratio. The absolute dimensions of these creatures depend on the details of the wave-particle interactions and the ambient parameters. Electron dynamics are understood more fully in higher dimensions[16,20,29-31]. Limited study has also been made for multi-ion plasmas[16,25]. Some of these recent calculations are performed with free energies other than that of the electron beam, for example the fan instability or ion ring distributions[28,29,31,32]. Applications have been made to the particle energization processes in other phenomena in space plasmas; e.g., cusp ions[32] and solar flares where a relativistic description is necessary[29]. It has also been suggested that conversion to short wavelength lower hybrid waves could be accomplished by linear conversion[33] and/or scattering of waves over prescribed plasma irregularities[34].

We end this review by providing three additional comments. The first comment is that it is not always necessary to have lower hybrid collapse before transverse ion energization can take place. The important thing is that there is a resonance matching between the phase velocity of the waves and the particle velocity of the ions. This point is demonstrated rather vividly by the two recent studies of Ergun et al[35] and Ganguli et al.[36].

The second comment is that transverse ion energization can be accomplished by other plasma processes, such as electromagnetic[37-42] and electrostatic[43] ion cyclotron resonance heating, multiple-cyclotron resonance heating[44], oblique double layers[45], stochastic heating for coherent waves[46], and nonresonant heating[47]. In space applications, these alternative ideas have been reviewed recently by Lysak[48], Chang et al.[49], and Chang and André[50], among others.

Finally, most of the particle energization processes and wave-particle interaction phenomena are mesoscale in nature. Self-consistent calculations that address both the background inhomogeneous plasma and the microscopic interactions are ultimately needed. Some calculations aiming in that direction have been made recently[36,51].

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REFERENCES

1. D.A. Gurnett, R.L. Huff, J.D. Menietti, J.L. Burch, J.D. Winningham, and S.D. Shawhan, *J. Geophys. Res.*, **89**, 8971 (1984).

2. (a) D.M. Klumpar, in *Ion Acceleration in the Magnetosphere and Ionosphere, AGU Monograph No. 38*, edited by T. Chang, M.K. Hudson, J.R. Jasperse, R.G. Johnson, P.M. Kintner, M. Schulz, M. Schulz, and G.B. Crew, (American Geophysical Union, Washington, D.C., 1986), p. 389, and references contained therein. (b) J.D. Winningham and J. Burch, in *Physics of Space Plasmas (1982-4)*, edited by J. Belcher, H. Bridge, T. Chang, B. Coppi, and J.R. Jasperse, (Scientific Publishers, Inc., Cambridge, MA, 1984), **Vol. 5**, p. 137. (c) W.K. Peterson, H.L. Collin, M.F. Doherty, and C.M. Bjorklund, *Geophys. Res. Lett.*, **19**, 1439 (1992).

3. D.J. Gorney, S.R. Church, and P.F. Mizera, *J. Geophys. Res.*, **87**, 10479 (1982).

4. T. Chang and B. Coppi, *Geophys. Res. Lett.*, **8**, 1253,(1981)

5. (a) B. Coppi, F. Pegararo, R. Pozzoli, and G. Rewoldt, *Nuclear Fusion*, **16**, 309 (1976). (b) J.E. Maggs, *J. Geophys. Res.*, **81**, 1707 (1976). (c) K. Papadopoulos and P.J. Palmadesso, *Phys. Fluids*, **19**, 605 (1976).

6. J.M. Retterer, T. Chang, and J.R. Jasperse, *J. Geophys. Res.*, **91**, 1609 (1986).

7. C.S. Lin, M. Sugiura, J.L. Burch, J.N. Barfield, and E. Nielsen, *J. Geophys. Res.*, **89**, 8907 (1984).

8. J. LaBelle, P.M. Kintner, A.W. Yau, and B.A. Whalen, *J. Geophys. Res.*, **91**, 7113 (1986)

9. A.W. Yau, B.A. Whalen, F. Creutzberg, and P.M. Kintner, in *Physics of Space Plasmas (1985-7)*, edited by T. Chang, J. Belcher, J.R. Jasperse, and G.B. Crew, (Scientific Publishers, Inc., Cambridge, MA, 1987), **Vol. 6**, p. 77.

10. P.M. Kintner, J. Vago, S. Chesney, R.L. Arnoldy, K.A. Lynch, C.J. Pollock, and T. Moore, *Phys. Rev. Lett.*, **68**, 2448 (1992).

11. R.L. Arnoldy, K.A. Lynch, P.M. Kintner, J.L. Vago, S.W. Chesney, T. Moore, and C. Pollock, *Geophys. Res. Lett.*, **19**, 413 (1992).

12. J.L. Vago, P.M. Kintner, S.W. Chesney, R.L. Arnoldy, K.A. Lynch, T.E. Moore, and C. Pollock, *J. Geophys. Res.*, **97**, 16935 (1992).

13. R.L. Arnoldy, K.A. Lynch, P.M. Kintner, and J. Vago, *Physics of Space Plasmas (1992)*, **12**, 73 (1993).

14. J. Maggs, *J. Geophys. Res.*, **83**, 3173 (1978).

15. J. Maggs and W. Lotko, *J. Geophys. Res.*, **86**, 3439 (1981).

16. J.M. Retterer, T. Chang, and J.R. Jasperse, in *Physics of Space Plasmas (1989)*, edited by T. Chang, G.B. Crew, and J.R. Jasperse, (Scientific Publishers, Inc., Cambridge, MA, 1990), **Vol. 9**, p. 119.

17. V.K. Tripathi, C. Grebogi, and C.S. Liu, *Phys. Fluids*, **20**, 1525 (1977).

18. S.L. Musher and B. Sturman, *JETP Lett.*, English Translation, **22**, 265 (1976).

19. R. McWilliams, R. Koslover, H. Boehmer, and N. Rynn, in *Ion Acceleration in the Magnetosphere and Ionosphere, AGU Monograph No. 38*, edited by T. Chang, M.K. Hudson, J.R. Jasperse, R.G. Johnson, P.M. Kintner, M. Schulz, M. Schulz, and G.B. Crew, (American Geophysical Union, Washington, D.C., 1986).

20. J.M. Retterer, T. Chang, and J.R. Jasperse, *J. Geophys. Res.*, ***99***, 13189 (1994); J.M. Retterer, T. Chang, and J.R. Jasperse, in Research Trends in Physics, *Nonlinear Space Plasma Physics*, edited by R. Sagdeev, et al, (American Institute of Physics, NY, 252, 1993).

21. M. Goldman, *Rev. Mod. Phys.*, **56**, 709 (1984).

22. J. LaBelle and P.M. Kintner, *Rev. Geophys.*, **27**, 495 (1989).

23. G.B. Crew and T. Chang, *Phys. Fluids*, **28**, 2382 (1985).

24. *J.M. Retterer, T. Chang, and J.R. Jasperse, Geophys. Res. Lett.*, **10**, 583 (1983).

25. J.M. Retterer and T. Chang, in *Physics of Space Plasmas (1988)*, edited by T. Chang, G.B. Crew, and J.R. Jasperse, (Scientific Publishers, Inc., Cambridge, MA, 1989), **Vol. 8**, p. 309.

26. B.B. Kadomtsev and O.P. Pogutse, *ZhETF*, **53**, 2025 (1967).

27. V.V. Parail and O.P. Pogutse, *J. Plasma Phys.*, **2**, 125 (1976).

28. Yu. Omelchenko, V.D. Shapiro, V.I. Shevchenko, M. Ashour-Abdalla, and D. Schriver, *J. Geophys. Res.*, **99**, 5965 (1994).

29. J.J. Su, J.M. Dawson, R. Bingham, D.A. Bryant, D.S. Hall, and K.McClemens, *EOS, AGU Trans.*, **73**, 82 (1992); *Bull. APS*, **37**, 1369 (1992).

30. V.I.Shevchenko, V.D. Shapiro, G.I. Solovev, V.P. Kalinin, R. Bingham, R.Z. Sagdeev, M. Ashour-Abdalla, *Bull. APS*, **37**, 1403 (1992).

31. R. Bingham, J.J. Su, J.M. Dawson, V.D. Shapiro, V. Shevchenko, V.N. Tsytovich, *Bull. APS*, **37**, 1359 (1992).

32 M.K. Hudson and I. Roth, in *Ion Acceleration in the Magnetosphere and Ionosphere, AGU Monograph No. 38*, edited by T. Chang, M.K. Hudson, J.R. Jasperse, R.G. Johnson, P.M. Kintner, M. Schulz, M. Schulz, and G.B. Crew, (American Geophysical Union, Washington, D.C., 1986), p.271.

33. T. Stix, *Phys. Rev. Lett.*, **15**, 878 (1965).

34. T. Bell, D. Lauben, U.S. Inan, and R.A. Helliwell, *EOS, AGU Trans. Supplement*, **72**(44), 409 (1991).

35. R. Ergun, G.T. Delory, E. Klementis, C.W. Carlson, J.P. McFadden, I. Roth, and M. Temerin, *J. Geophys. Res.*, **98**, 3777 (1993).

36. G. Ganguli, M.J. Keskinen, and H. Romero, *Bull. APS*, **37**, 1479 (1992). (b) H. Romero and G. Ganguli, *Bull. APS*, **37**, 1479 (1992).

37. T. Chang, G.B. Crew, N. Hershkowitz, J.R. Jasperse, J.M. Retterer, and J.D. Winningham, *Geophys. Res. Lett.*, **13**, 636 (1986).

38. J.M. Retterer, T. Chang, G.B. Crew, J.R. Jasperse, and J.D. Winningham, *Phys. Rev. Lett.*, **59**, 148 (1987).

39. G.B. Crew and T. Chang, *Phys. Fluids*, **31**, 3425 (1988).

40. G.B. Crew, T. Chang, J.M. Retterer, W.K. Peterson, D.A. Gurnett, and R.L. Huff, *J. Geophys. Res.*, **95**, 3959 (1990).

41. M. André, H. Koskinen, L. Matson, and R. Erlandson, *Geophys. Res. Lett.*, **15**, 107 (1988).

42. M. André, G.B. Crew, W.K. Peterson, A.M. Persoon, C.J. Pollock, and M.J. Engelbretson, *J. Geophys. Res.*, **95**, 20809 (1990).

43. M. Ashour-Abdalla and H. Okuda, *J. Geophys. Res.*, **89**, 2235 (1984). (b) R.L. Lysak, M.K. Hudson, and M. Temerin, *J. Geophys. Res.*, **85**, *678 (1980)*.

44. M. Temerin and I. Roth, *Geophys. Res. Lett.*, **13**, 1109 (1986). (b) L. Ball, *J. Geophys. Res.*, **94**, 15257 (1989), (c) L. Ball, *Aus. J. Phys.*, **42**, 493 (1989). (d) L. Ball and M. André, *J. Geophys. Res.*, **96**, 1429 (1991).

45. J.E. Borovsky, *J. Geophys. Res.*, **89**, 2251 (1984).

46. (a) K. Papadopoulos, J.D. Gaffey, and P.J. Palmadesso, *Geophys. Res. Lett.*, 7, 1014 (1980). (b) N. Singh, R.W. Schunk, and J.J. Sojka, *Geophys. Res. Lett.*, **8**, 1249 (1981).

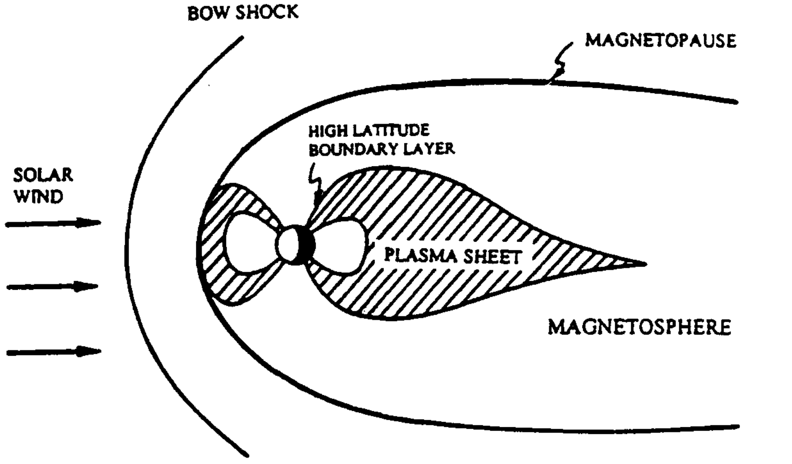
47. (a) R. Lundin and B. Hultqvist, *J. Geophys. Res.*, **94**, 6665 (1989). (b) R. Lundin, G. Gustafsson, A.I. Eriksson, and G. Marklund, *J. Geophys. Res.*, **95**, 5905 (1990).

48. R.L. Lysak, in *Ion Acceleration in the Magnetosphere and Ionosphere, AGU Monograph No. 38*, edited by T. Chang, M.K. Hudson, J.R. Jasperse, R.G. Johnson, P.M. Kintner, M. Schulz, M. Schulz, and G.B. Crew, (American Geophysical Union, Washington, D.C., 1986), p. 261.

49. T. Chang, G.B. Crew, and J.M. Retterer, *Computer Phys. Comm.*, **49**, 61 (1988).

50. T. Chang and M. André, in *Auroral Plasma Dynamics, AGU Monograph*, edited by R.L. Lysak, (American Geophysical Union, Washington, D.C., to be published.)

51. D.G. Brown, G.R. Wilson, and J.L. Horwitz, *EOS, AGU Trans. Supplement*, **73**(43), 474 (1992).



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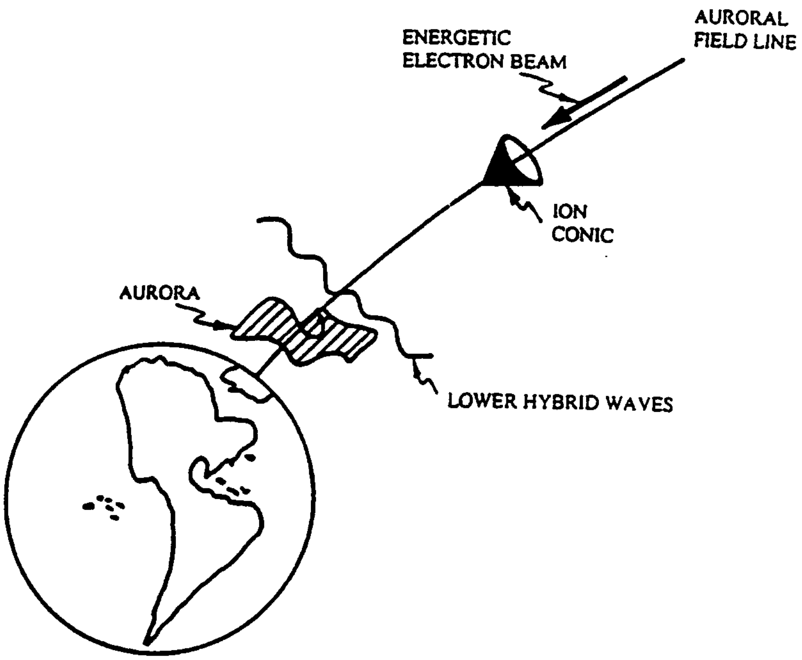

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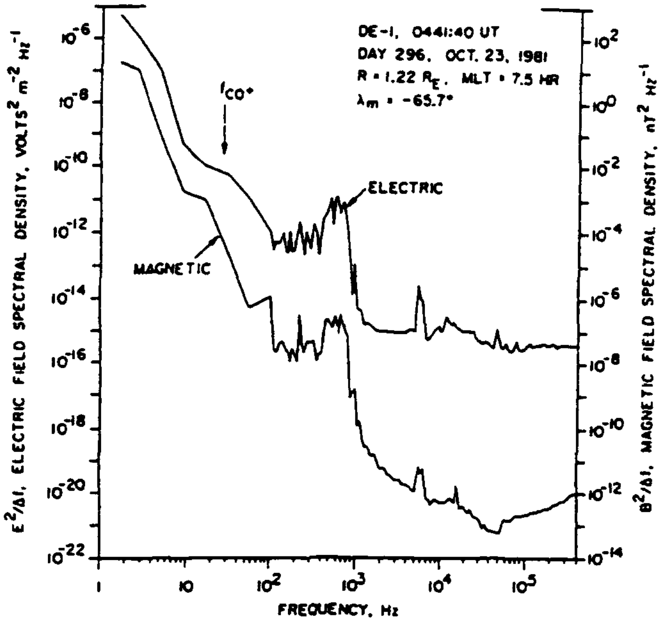

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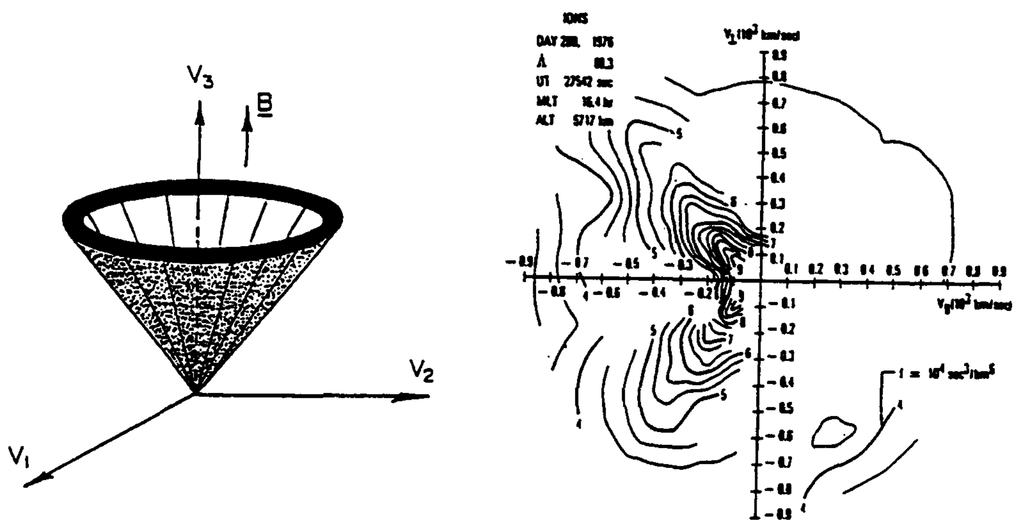

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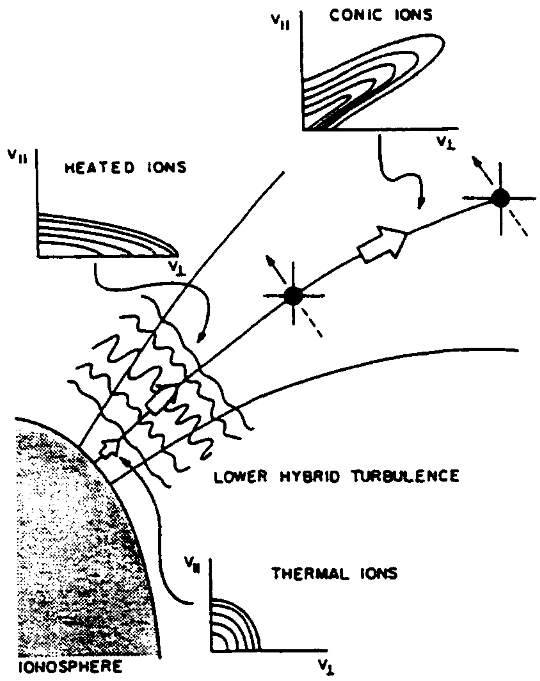

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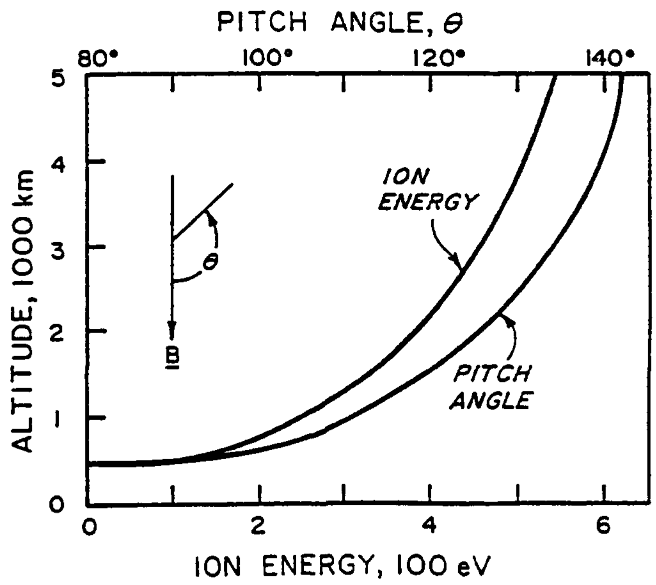

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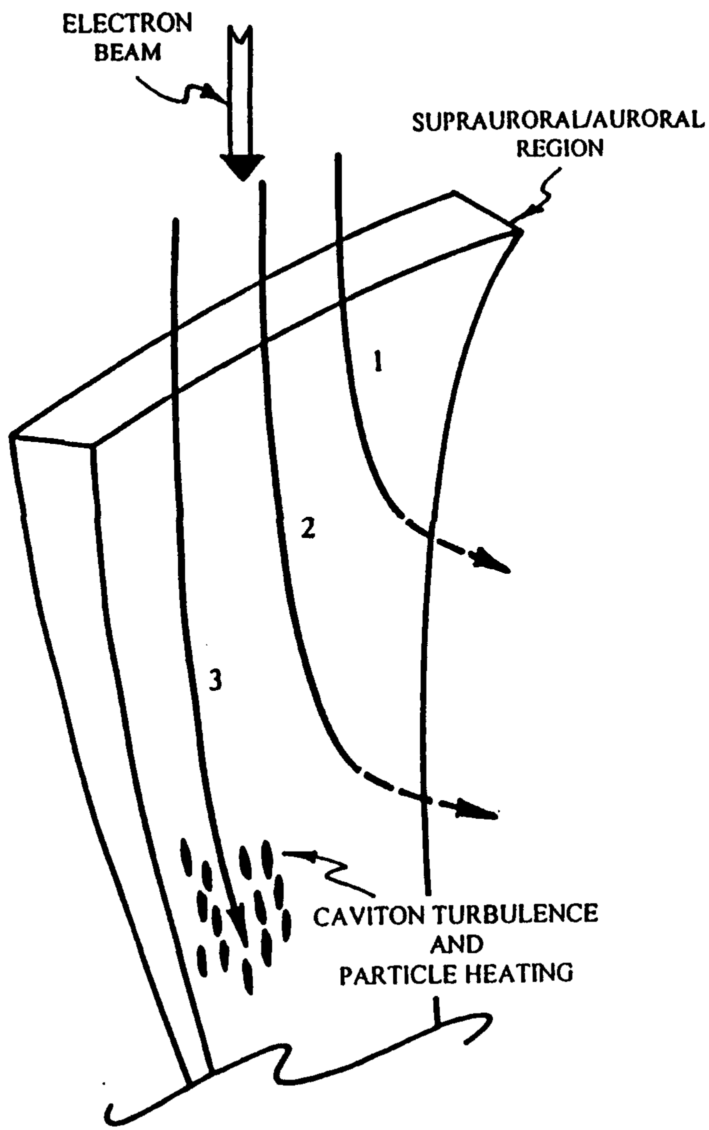

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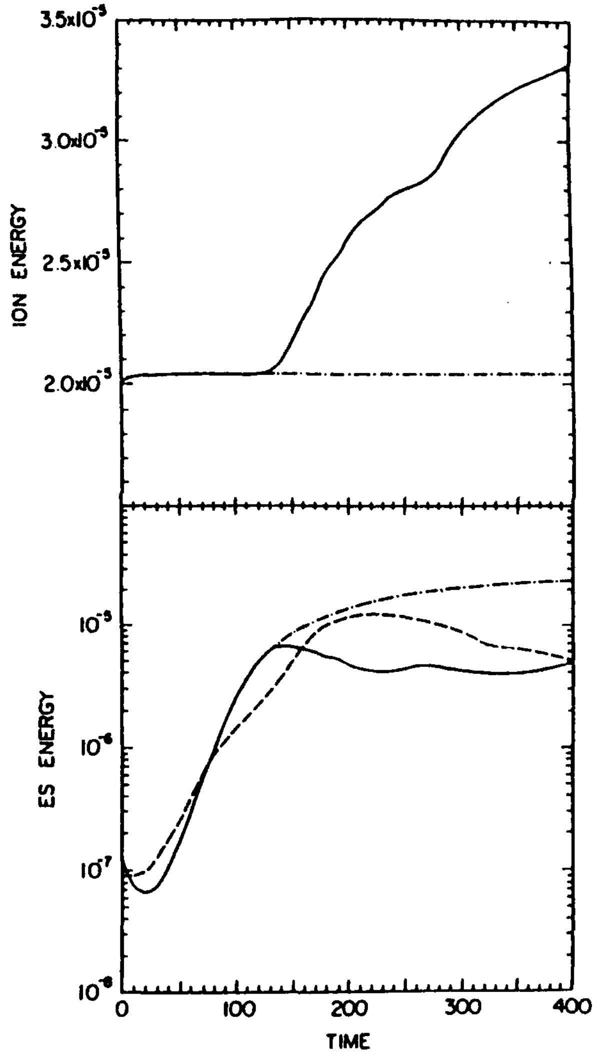

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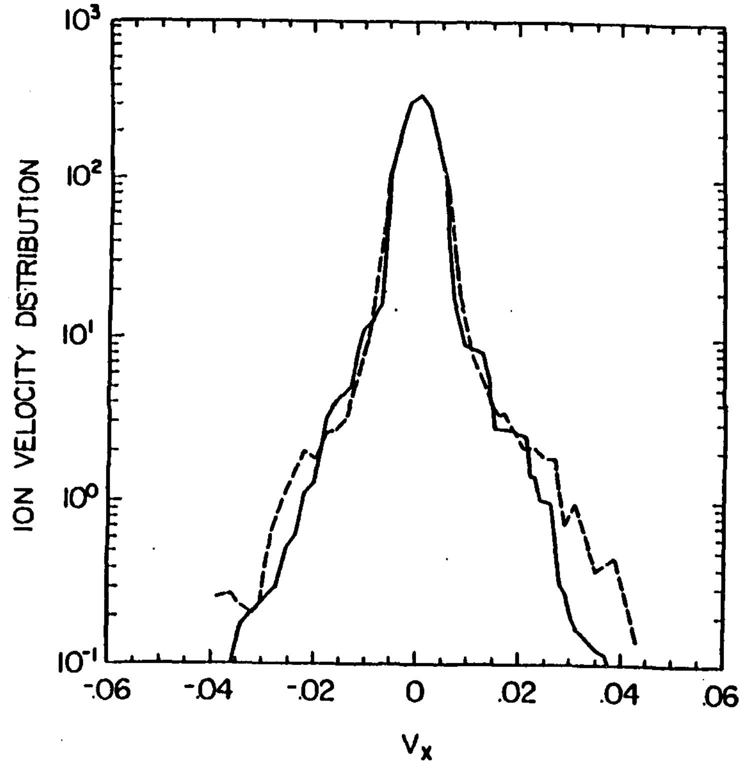

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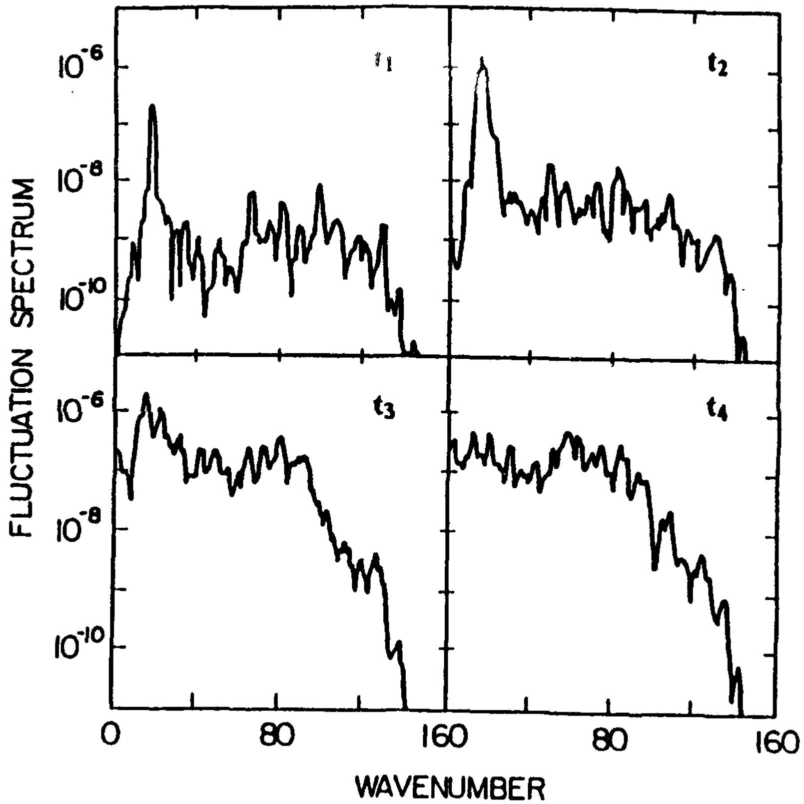

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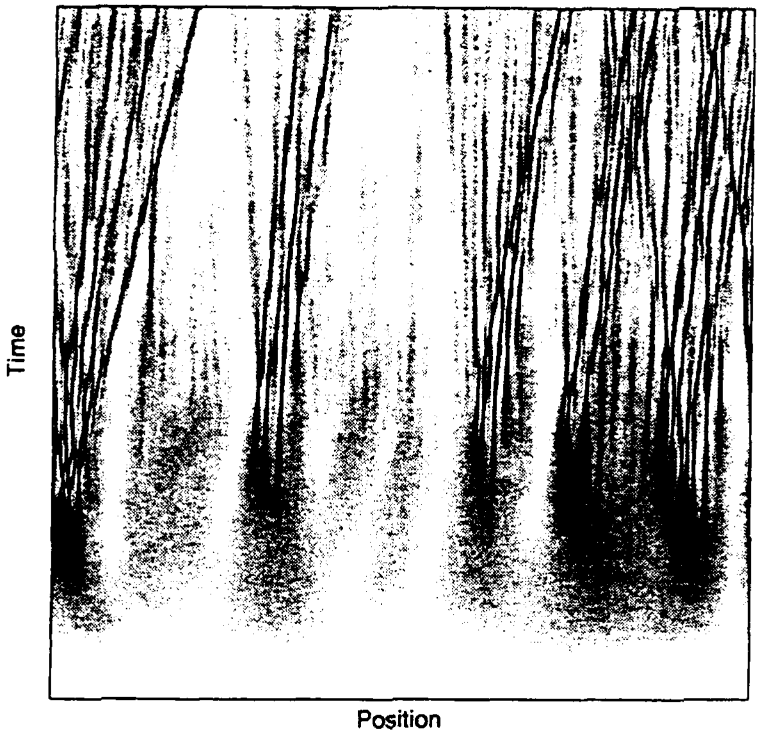

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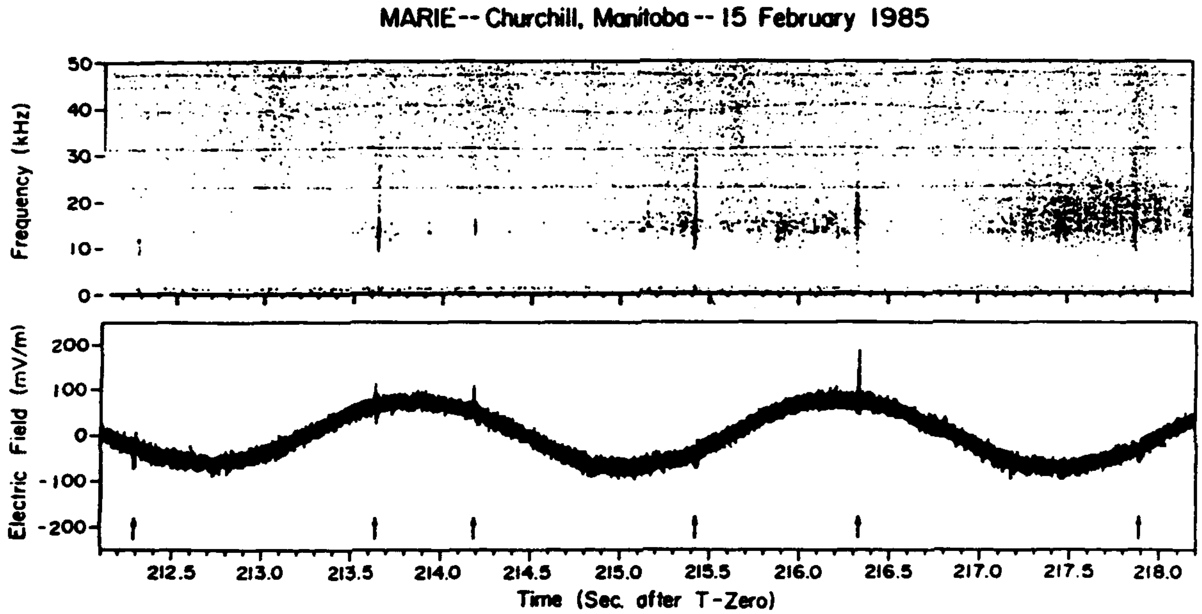

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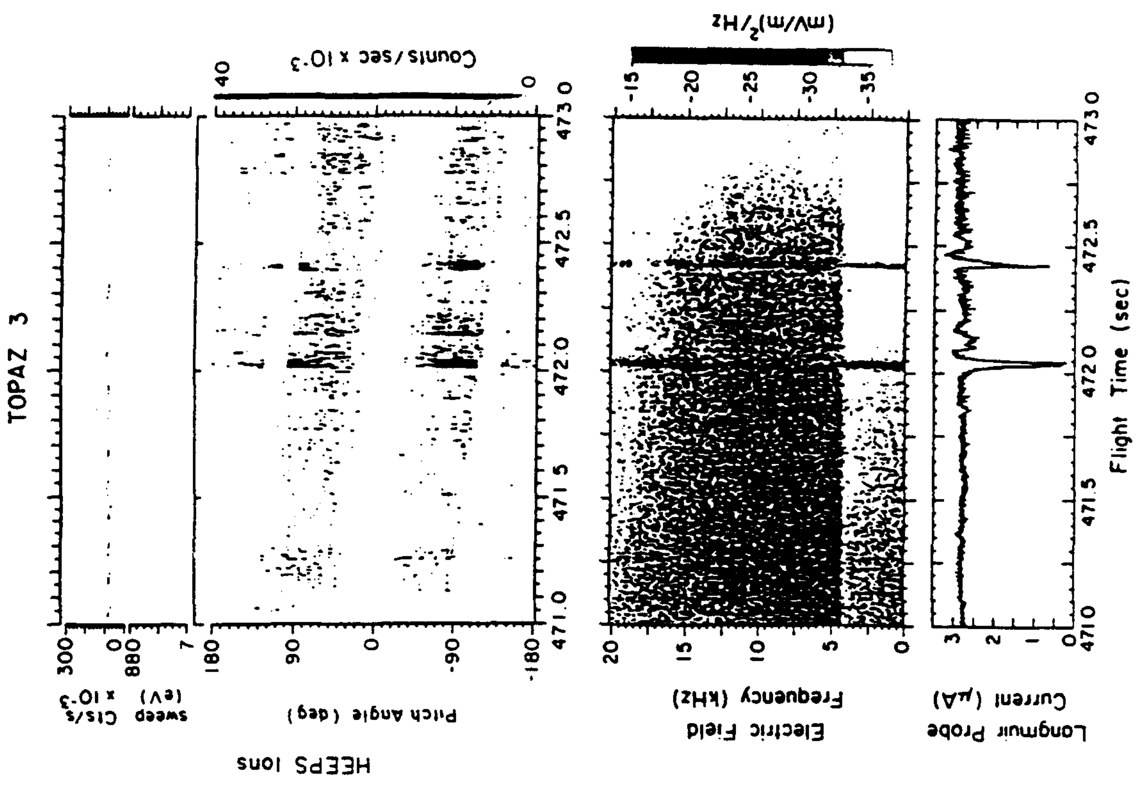

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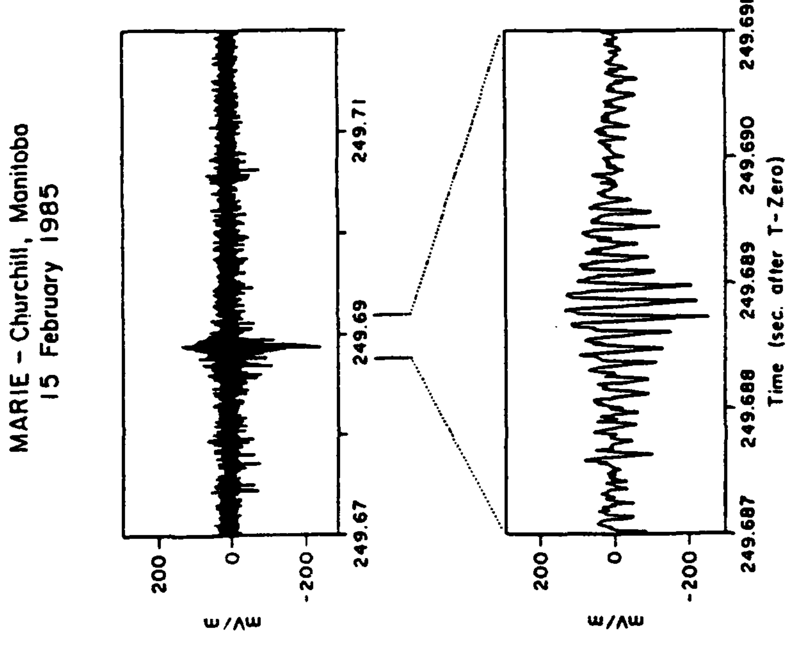

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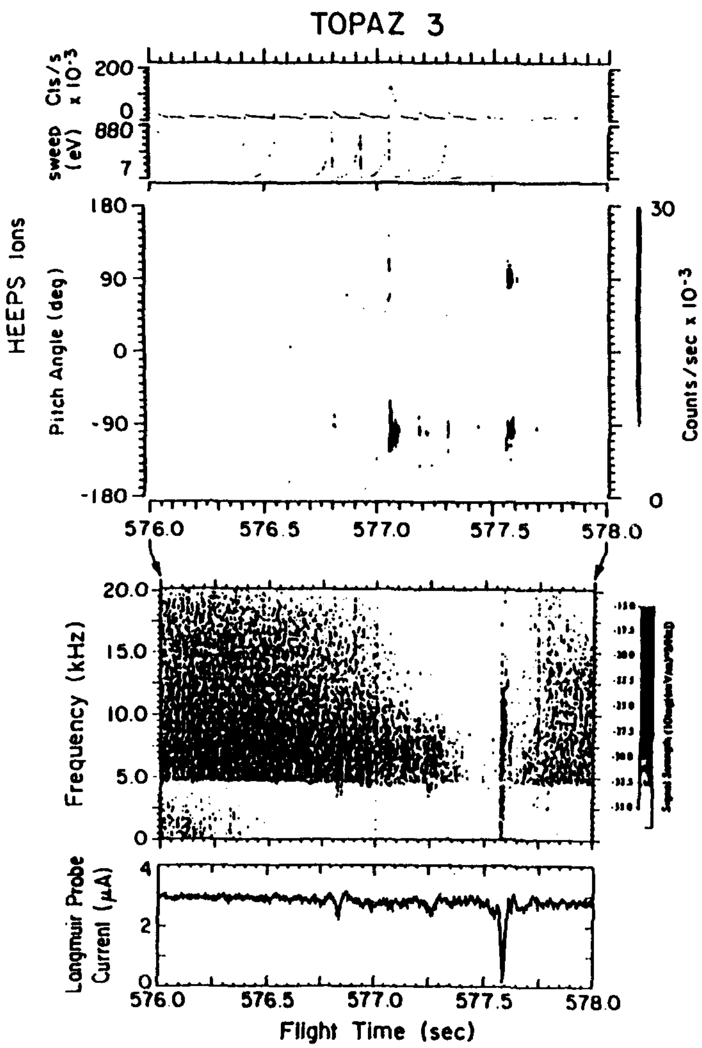

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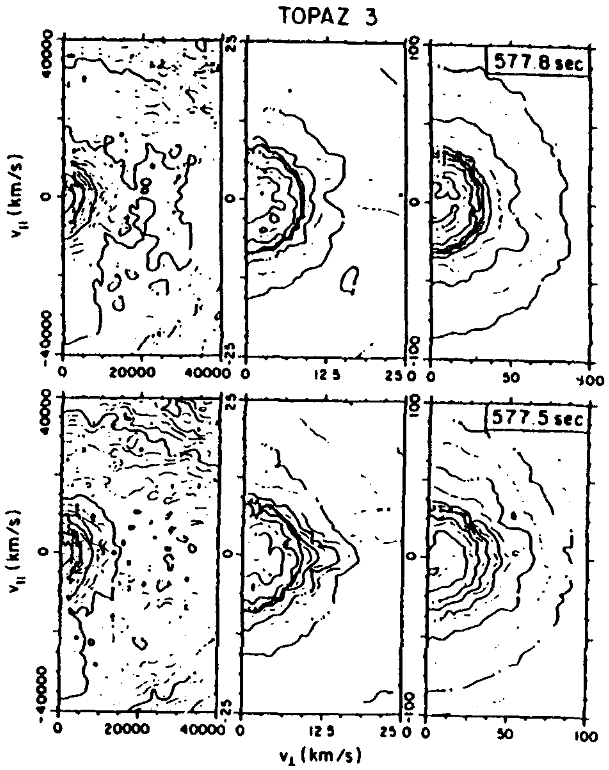

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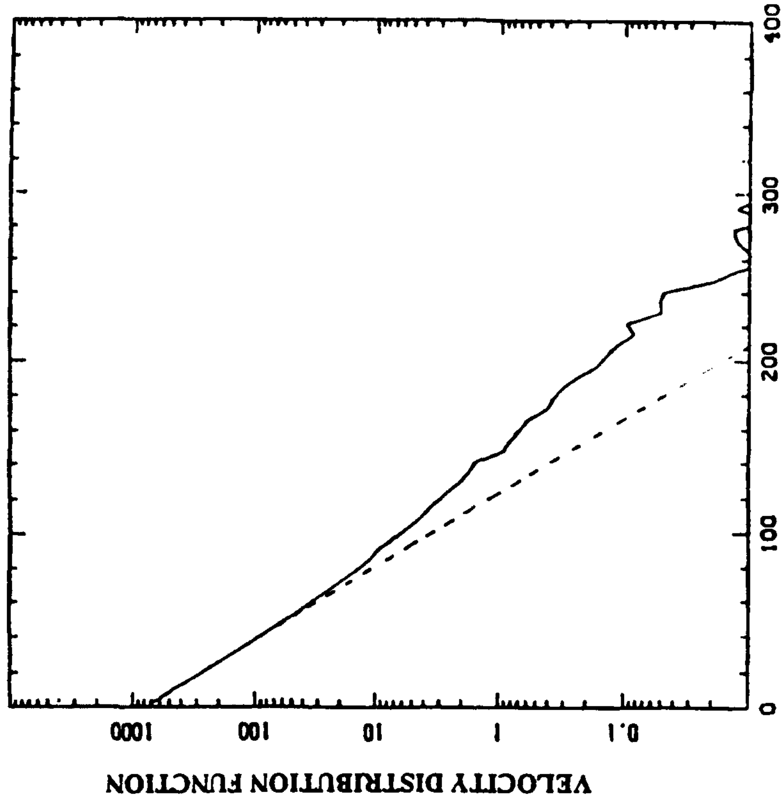

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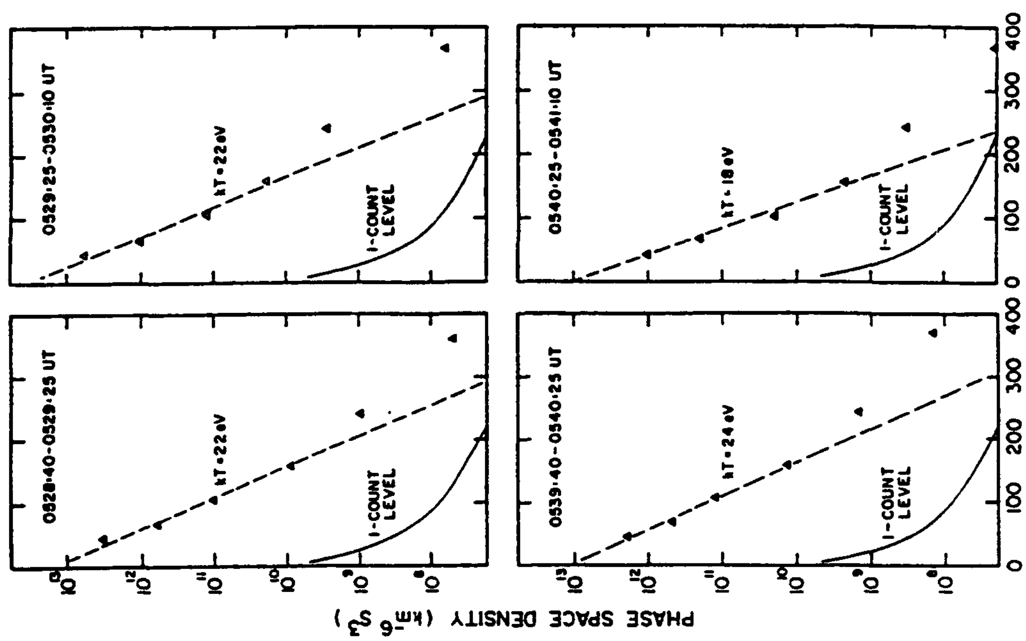

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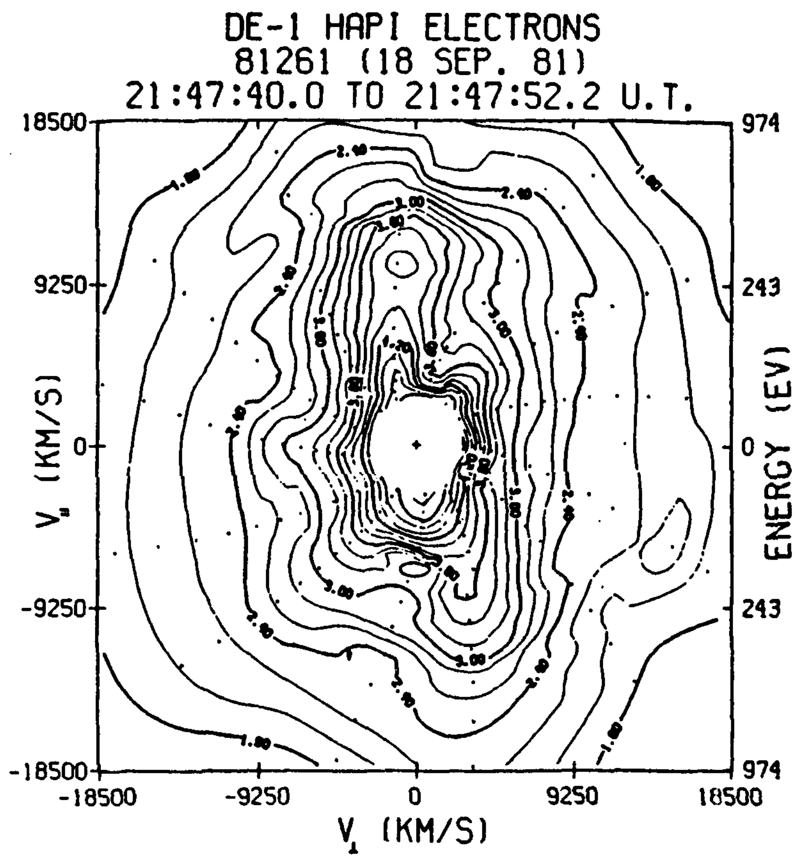

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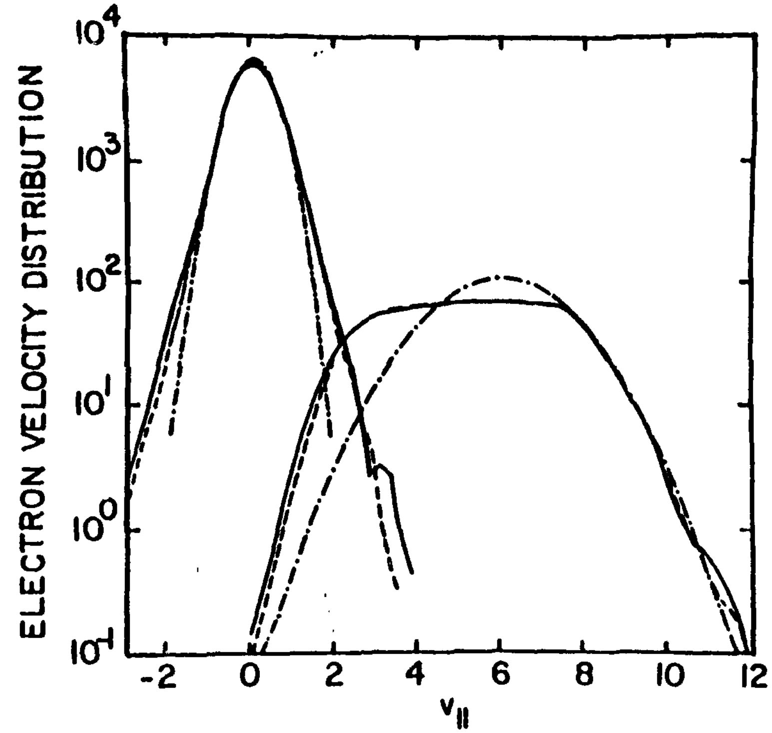

Figure 20