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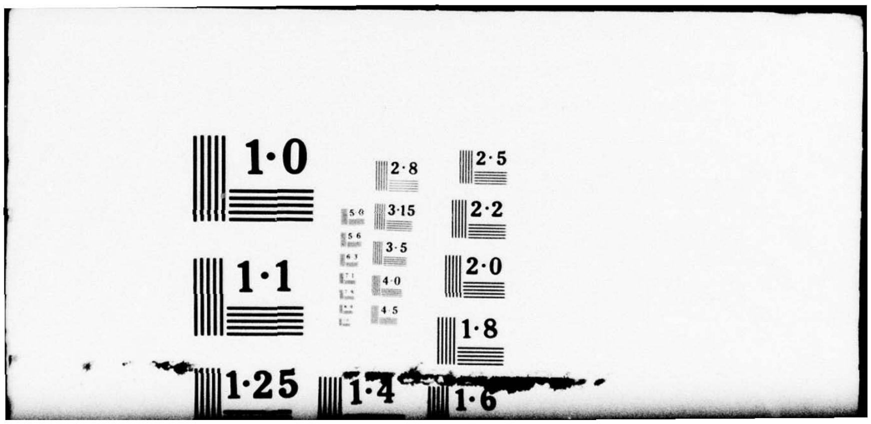
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NRL Memorandum Report 3579

Recent Results on Cleavage, Bifurcation, and Cascade Mechanisms in Ionospheric Plasma Clouds

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Plasma Dynamics Branch
Plasma Physics Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Cleavage, bifurcation, and cascade mechanisms are investigated in the evolution of striating ionospheric plasma clouds which are subject to the gradient drift instability. The numerical simulations are based on a one-level, two-dimensional model. An initially one dimensional Gaussian-like cloud with a smooth perturbation cleaves and spontaneously develops nonlinear bifurcations of the original perturbation thus forming secondary perturbations (striations). This represents a cascade from longer to shorter wavelength structures. An initially presteepened two dimensional cloud without initial perturbation cleaves and bifurcates to form a protuberance

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20. Abstracts (Continued)

in the cleavage trough. These results demonstrate that cleavage is an inherent process in the evolution of striated ionospheric plasma clouds and plays an important role in the characterization of the late-time nuclear striation power spectrum.

RECENT RESULTS ON CLEAVAGE, BIFURCATION AND CASCADE MECHANISMS IN IONOSPHERIC PLASMA CLOUDS

One of the most important problems in the late time striated nuclear environment is the characterization of the power spectrum and the decay of the structure. The ability to predict the late time striated environment is extremely important for satellite communication systems. Our understanding of the late-time striated environment has increased significantly, but there still remains some problems to be answered.

Previously we have reported (Scannapieco et al., 1976) on the late-time power spectra for striations resulting from following the nonlinear evolution of a plasma cloud coupled to the background ionosphere. There we had performed a two-level (one for the cloud, the other for the background ionosphere), two-dimensional numerical simulation of an initially one-dimensional cloud (Gaussian in one direction, uniform in the other) with random initial perturbations. The nonlinear phase of the plasma cloud development was characterized by pinching of original perturbations, production of secondary perturbations, a bubbling through of backside striations to the front side of the cloud, and appearance of image striations in the background ionosphere. Also, a power law power spectrum for the striation density fluctuations was obtained. Recently another two-level, two dimensional numerical simulation of an initially cylindrical Gaussian cloud with recombination chemistry included in the background ionosphere and an initial single long wavelength perturbation has been reported (Doles et al., 1976). In this simulation the power spectrum was not presented. However, an important result was the

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fact that secondary perturbations spontaneously grew out of the initial perturbation and this process continued to occur during the nonlinear evolution of the plasma cloud as it did in Scannapieco et al. (1976).

Some of the basic objectives of our studies are to look at the late-time power spectra at short wavelengths (in particular to account for the power law power spectra at short wavelengths) and how striations go away. Fundamental to this problem are the bifurcation, cleavage, and cascade mechanisms that produce secondary striations from primary striations (as noted in Scannapieco et al., 1976 and Doles et al., 1976). This type of study is important because the time scale for the production of secondary striations can be much more rapid than the diffusion time scales, especially for long wavelengths. Consequently, the late-time decay of striations will be very much influenced by this process. Indeed, a major contribution would be to obtain a model which describes the time it takes for striations to bifurcate and form more striations.

Figure 1 depicts schematically what it is we are trying to follow and understand. Essentially one has a steepened backside of the plasma cloud (a) which then cleaves and bifurcates (b) and keeps doing so (c and d) forming smaller and smaller wavelength structures. This in itself represents a cascade from long wavelength structures to shorter wavelength structures.

In order to better understand this phenomena we utilize a one level (plasma cloud and background ionosphere at its level, where the background ionospheric conductivity is taken to be time independent), two dimensional (perpendicular to the ambient magnetic field) model, incorporating the simplest set of equations that describe the striation phenomena. These equations are (Zabusky et al., 1973)

$$\frac{\partial \Sigma_p^b}{\partial t} - \nabla_\perp \Sigma_p^b \cdot \left(\frac{c}{B_o} \nabla_\perp \psi \times \hat{z} \right) = 0 \tag{1}$$

$$\nabla_\perp \cdot (\Sigma_p^b \nabla_\perp \psi) = \underline{E}_o \cdot \nabla_\perp \Sigma_p^b \tag{2}$$

where Σ_p^b is the magnetic field line integrated Pedersen conductivity at the cloud level, B_o is the ambient magnetic field, $\hat{z} = \underline{B}_o / |\underline{B}_o|$, $\nabla_\perp \psi = \underline{E} - \underline{E}_o$, where $\underline{E}_o$ is the ambient applied perpendicular electric field, and the subscript $\perp$ means perpendicular to $\underline{B}_o$. Equation (1) is written in the $\underline{E}_o \times \underline{B}_o$ drift frame. Also equations (1) and (2) are representative of a one level, two dimensional F region model with $\nu_b/\omega_{cb} \ll 1$ (where ν_b and ω_{cb} are the barium ion-neutral collision frequency and barium ion gyrofrequency, respectively), i.e., no Hall currents and the plasma is essentially incompressible and can be obtained from the more general equations (see for example Scannapieco et al., 1976) taking this limit and neglecting other levels.

In what follows we will show results for different initial plasma cloud configurations. In our previous study (Scannapieco et al., 1976), random initial perturbations made it difficult to follow the cleavage and bifurcation processes in detail. Consequently, when necessary, we will use single wavelength type of perturbations.

Initial 1D cloud with perturbation. The system of equations (1) and (2) was solved numerically on the Texas Instruments Advanced Scientific Computer. A two dimensional rectangular 40 x 100 grid with mesh $\Delta x = \Delta y = 1/3$ km (corresponding to approximately 13 km x 33 km in size) was chosen. In this particular simulation a Gaussian-like cloud in the y direction, uniform in x is used at $t = 0$ [similar to that found in Scannapieco et al., 1976 and the same as Zabusky et al., 1973] with a single localized perturbation of the order of two wavelengths superimposed. The Pedersen conductivity, at $t = 0$, was taken as

$$\frac{\Sigma_p^b(x,y)}{\Sigma_p^{bo}} = 32.2\left(1 - \frac{y^2}{L^2}\right)^4 [1 + \beta(x)e^{-3}] + 2.6 \qquad (3)$$

with

$$\beta(x) = \begin{cases} \cos 3\pi x/8 & , \quad |x| < 8/3\text{km} \\ 0.5\,[\cos(3\pi x/8) - 1.0] & , \quad 8/3 < |x| < 16/3\text{km} \\ 0 & , \quad |x| > 16/3\text{km} \end{cases} \qquad (4)$$

In Eq. (3) $L = 8$km and the quantity 2.6 represents the background ionosphere Pedersen conductivity so that the cloud to background ionosphere Pedersen conductivity ratio is 12.4. We take $E_o = 2$ mV/m and in the positive x direction, $\underline{B}_o = 0.5$ gauss and in the positive z direction (out of the page of Fig. 2) so that the $\underline{E}_o \times \underline{B}_o$ drift velocity is 40m/sec and in the negative y direction. Consequently, the dynamical time scale $t_D = LB_o/cE_o = 200$ sec. for this simulation.

Figure 2 depicts the iso-Pedersen conductivity contours at $t = 200$ sec after the plasma cloud has evolved according to Eqs. (1) and (2). Here we can see the type of perturbation that was put into the system at $t = 0$ (representing a primary striation or perturbation). We also note the backside growth of the perturbation. In this figure the conductivity contours are maximum at $y = 0$ and decrease as $|y|$ increases. The Gaussian like initial cloud Pedersen conductivity is confined to $|y| \leq 8$km and beyond this one has the uniform background ionosphere Pedersen conductivity. Figure 3 depicts the plasma cloud evolution at $t = 300$ sec. Clearly there is a main protuberance developing around $x = 0$ and the cleavage process has begun on either side of this. The trough and peak regions have flattened and become steep. In the cleavage region the radius of curvature tends to become infinite and in this region the divergence of the plasma flow is zero.

Figure 4 shows how the cloud has evolved at 400 sec. Clearly there is an upwelling within the trough regions which is beginning to produce secondary striations. Also perturbations are starting to form on the flanks ($4 < |x| < 6$). What we are viewing are spontaneous bifurcations of smooth striations in an evolving plasma cloud. This is a nonlinear process and is what goes on after linear theory. Clearly this is also a cascade from longer wavelength structures into shorter wavelengths. Note that the island formation depicted in Figs. 3 and 4 is due to truncation, artificial diffusion and resolution as the contours should have developed long thin necks and not broken off. In order to carry the simulation further in time this will have to be corrected.

However, the basic cleavage, bifurcation and cascade processes have been well exhibited.

Initial 2D presteepened cloud without perturbations. Once again Eqs. (1) and (2) were solved on a two dimensional mesh. However, in this case, we have employed a stretched mesh where the central 62 x 62 mesh (depicted in Figs. 5-8) is uniform, with $\Delta x = \Delta y = 8/62$ km (corresponding to 8km x 8km). Outside (not shown) an additional 11 points on each side cover an additional 7km on a side. Consequently, the total mesh is 84 x 84 covering 22km x 22km. The initial $t = 0$ plasma cloud is presteepened (hamburger shape; see Fig. 5) and no perturbations are added. The two dimensional presteepened cloud depicted in Fig. 5 is almost one dimensional in the x direction except for the roundedness for certain y values. Indeed, for most of the cloud except for $y > y_1$, $y < y_2$, $\Sigma_p^b/\Sigma_p^{bo} = 1 + 4\,[1 - (x-x_o)^2/L^2]^4$ where x_o defines the x center of the cloud and L = 2km. Here the peak Pedersen conductivity is 5.0 and the background ionosphere is 1.0 (the iso-Pedersen conductivity contours depicted range from 2 to 4.5 in increments of 0.5). In this simulation $E_o = 5$ mV/m and is in the negative y direction, $B_o = .5$ gauss and is out of the page, so that the $\underline{E}_o \times \underline{B}_o$ drift velocity is in the negative x direction. With these parameters the dynamical time scale $t_D = LB_o/cE_o = 20$ sec.

The initial cloud depicted in Fig. 5 (with no initial perturbations imposed) evolves in accordance with Eqs. (1) and (2) and Fig. 6 shows its development at t = 50 sec. Here we begin to see the start of the cleavage process on the backside of the plasma cloud (cloud appears to have a lima beam shape). Figure 7 shows the evolution of the cloud at t = 100 sec. The cleavage in the central region on the backside and the attendant bifurcation to form two fingers are now quite clear. These are the first numerical simulations of a plasma cloud spontaneously bifurcating without external perturbations imposed. We note the steepening of the contours in the two protuberances and in the cleavage trough. The trough area has become very flat such that the radius of curvature tends to become infinite. The bifurcation has to do with the initial one-dimensional nature and rounded edges of the plasma cloud which causes plasma flow around the cloud, since a purely one-dimensional cloud without perturbations is an equilibrium solution of the basic equations (1) and (2).

Figure 8 shows the cloud at t = 120 sec. The central trough region now begins to develop a protuberance (just what we now expect). The highest conductivity contour has fissioned due to truncation, artificial diffusion and resolution (this contour should have developed long thin necks). We have to refine the simulation so that we can go farther in time. However, the process presented here represents basic mechanisms which lead from long wavelengths to short wavelengths (cascade mechanism). Studies of these types are extremely important if we are going to be able to characterize the late time striated nuclear environment.

Summary. We have studied a one level, two dimensional plasma cloud (see Eqs. (1) and (2)) to investigate bifurcation, cleavage and cascade mechanisms which occur in the striated environment resulting from the gradient drift instability. These studies have been conducted using numerical simulations for different initial plasma cloud configurations.

In particular, one study was done with an initially one dimensional Gaussian like plasma cloud with initial perturbations (Fig. 2) which was then followed over the two dimensional mesh. Another study was performed with an initially presteepened two dimensional plasma with no initial perturbations (Fig. 5). The results from these numerical simulations and previous ones (Scannapieco et al., 1976; Doles et al., 1976) and our current understanding of cleavage, bifurcation, and cascade processes in plasma clouds can be summarized as follows: (1) our two level, initially one dimensional plasma cloud with random initial perturbations produced pinching of the original perturbations, production of secondary perturbations and a power law power spectrum for striations at late times (Scannapieco et al., 1976); (2) the Bell Labs (Doles et al., 1976) two level, two dimensional Gaussian-like cloud with an initial long wavelength perturbation and recombination chemistry of the second level produced cleavage and secondary perturbations (bifurcation), but the study did not delineate whether these processes were a result of the recombination chemistry, the second level, or the radius of curvature becoming large; (3) in the present study we have shown that a one level, initially one dimensional plasma cloud with an initial long wavelength perturbation spontaneously produces secondary perturbations within cleavage troughs and forms because the radius of curvature becomes infinite within those troughs; (4) our present study also shows that a one level, initially two dimensional presteepened plasma cloud (with the radius of curvature becoming infinite in one direction and having rounded edges in the other direction) <u>without</u> initial perturbations cleaves and bifurcates and so the second level and recombination chemistry are not necessary; (5) cleavage is an inherent process of plasma cloud evolution; (6) this process has nothing to do with linear theory, it is what goes on after linear theory is applicable; and (7) linear theory and diffusion processes can give a misestimate of the decay of striations, especially since cleavage and bifurcation are much faster processes than diffusion for the longer (~ 1km) striated structures. This paper should be viewed as a progress report in that we still need to investigate how much curvature is actually needed to produce cleavage and bifurcation and also we need to understand more fully the time scale for the bifurcation process.

Acknowledgment

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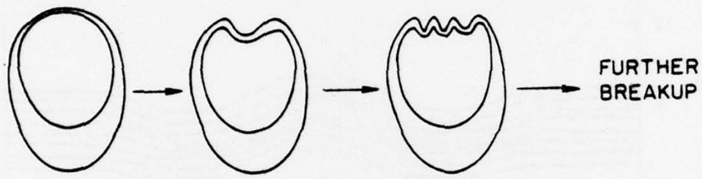

Fig. 1 — Schematic diagram depicting cleavage, bifurcation and cascade processes on the steepened backside of a plasma cloud

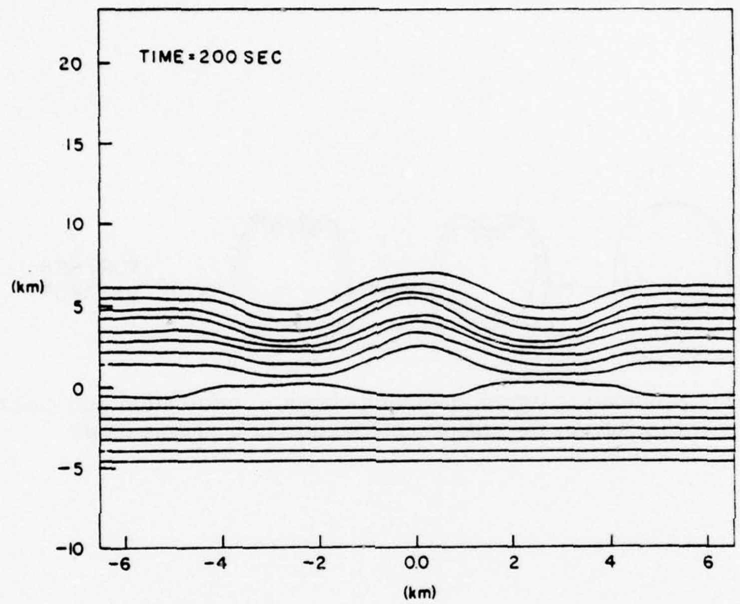

Fig. 2 — Iso-Pedersen conductivity contour plots at t = 200 sec. of an initially one dimensional Gaussian-like (in y) plasma cloud with an initial perturbation in x. The highest contour (maximum conductivity) is around y = 0 and the values decrease away from this line in both positive and negative directions. The mesh is 40 × 100 with $\Delta x = \Delta y = 1/3$ km which corresponds to approximately 13km × 33km. There is an ambient electric field of 2 mV/m in the positive x direction and an ambient magnetic field of 0.5 gauss out of the page. The gradient scale length for the initial iso-Pedersen conductivity contours in the y direction is 8 km.

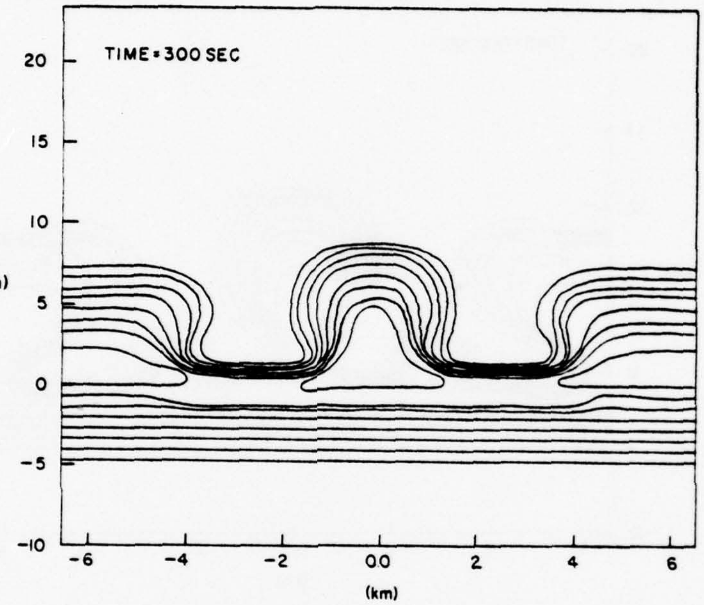

Fig. 3 — Iso-Pedersen conductivity contour plots at t = 300 sec. Note protuberance in center and cleavage troughs on each side.

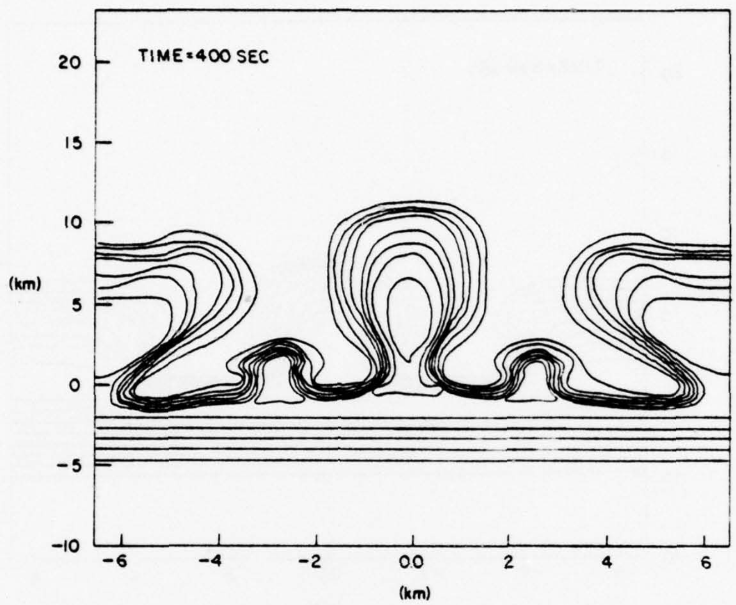

Fig. 4 — Iso-Pedersen conductivity contour plots at t = 400 sec. Note the production of secondary striations in the trough regions between the original striations and the dimpling of the original striations.

Fig. 5 — Iso-Pedersen conductivity contour plots of a plasma cloud at t = 0 (note time in upper right). These contours are ratios and represent the cloud value to that of the background ionosphere far away from the cloud. The innermost contour is 4.5 and the outermost is 2 (in increments of 0.5). The peak in the center of the cloud is 5 and the background unchanging ionosphere far away from the cloud is 1. The mesh portion shown is 8 km × 8 km (62 × 62 mesh points) with uniform spacing; however, outside there are 11 mesh (not shown) points on each side stretched covering an additional 7 km. Consequently, the total mesh is 22 km × 22 km (84 × 84 mesh points). There is an ambient electric field of 5 mV/m in the negative y direction (equivalent to an ambient neutral wind in the positive x direction); the magnetic field is 0.5 gauss and out of the paper; and the gradient scale length for the iso-Pedersen conductivity contours is 2 km in the x direction. The $\underline{E}_o \times \underline{B}$ velocity is in the negative x direction.

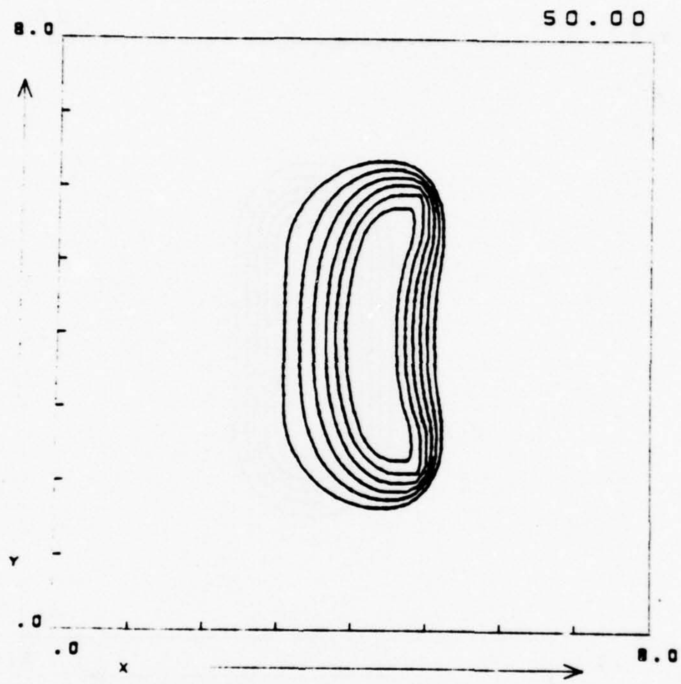

Fig. 6 — Iso-Pedersen conductivity contour plots at t = 50 sec. Note backside steepening and indentation.

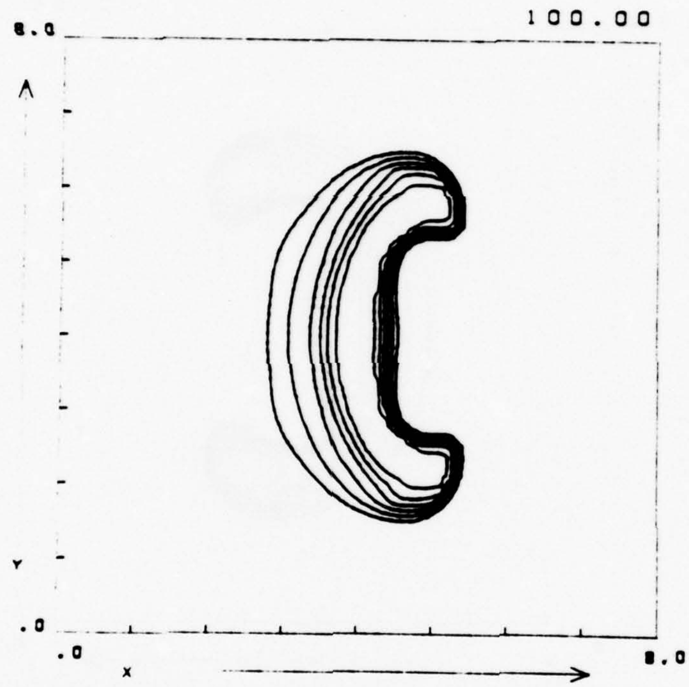

Fig. 7 — Iso-Pedersen conductivity contour plots at t = 100 sec. Note cleavage and bifurcation.

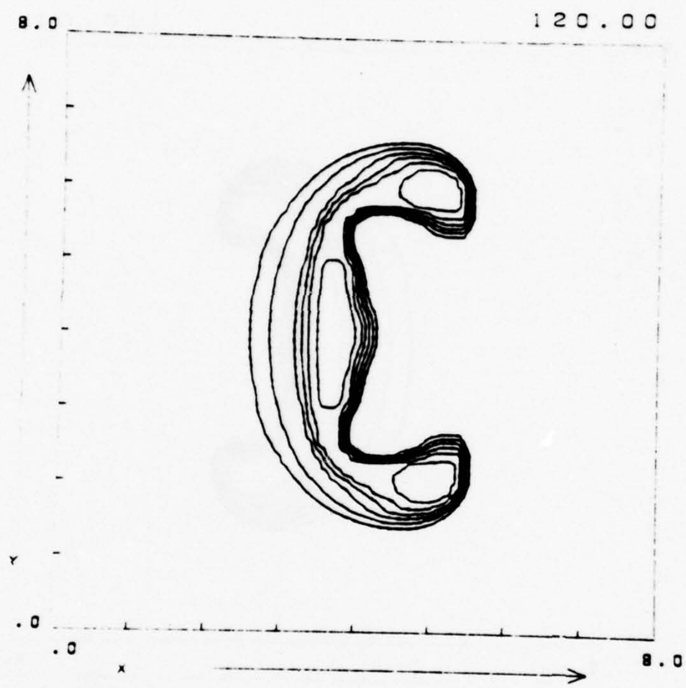

Fig. 8 — Iso-Pedersen conductivity contour plots at t = 120 sec. Note formation of protuberance in central trough region.

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