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A FLUID MODEL FOR ESTIMATING MINIMUM SCALE SIZES IN IONOSPHERIC--ETC(U)

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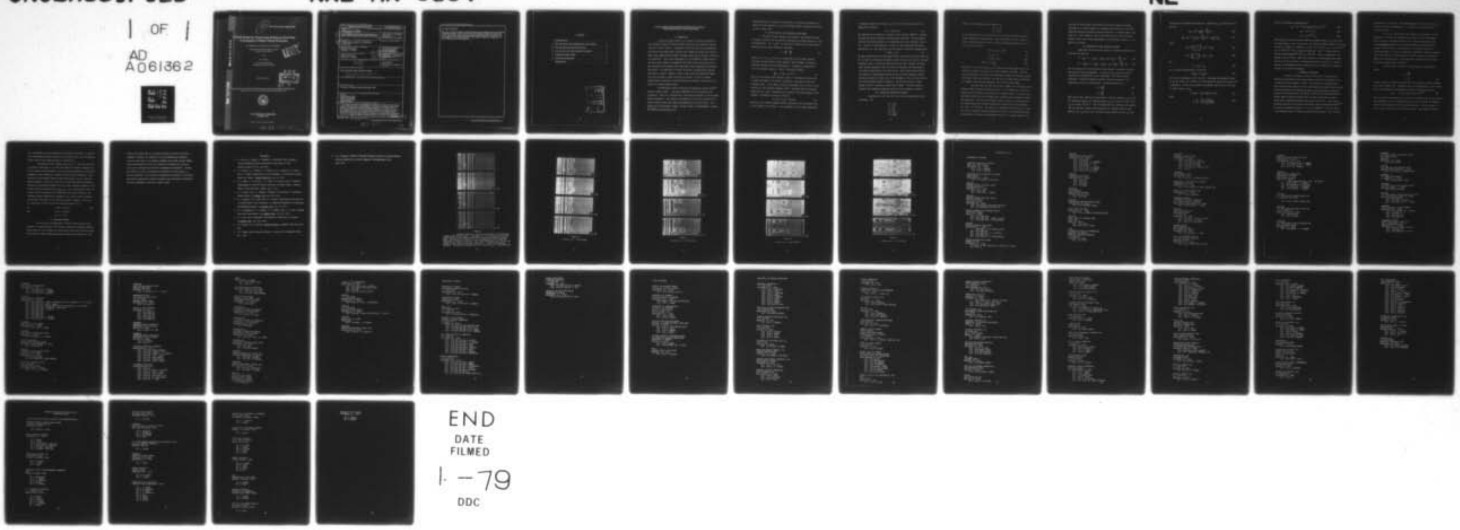

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NRL Memorandum Report 3864

LEVEL II

A Fluid Model for Estimating Minimum Scale Sizes in Ionospheric Plasma Cloud Striations

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We propose a fluid model for investigating the possibility that a small scale cut-off is present in plasma cloud striations due to particle diffusion. The model is two dimensional and perpendicular to the magnetic field, and assumes parameters applicable to the F region. The non-dimensionalized equations for the model show that the plasma motion is determined by initial plasma distribution and the value of an effective Reynolds number. Numerical simulations carried out for random phase initial conditions and maximum to minimum Pedersen conductivity ratio of 11 to 1 suggest that striation formation stops when the Reynolds number drops below

(Continues)

20. Abstract (Continued)

about 400. We calculate a diffusion constant including electron-ion collisions, which can be dominant in high altitude releases. We then scale the results of the numerical simulation and conclude that the fluid model (without kinetic corrections) predicts a minimum scale size in the range 2.4-24 m for a typical choice of ionospheric parameters. These minimum scale sizes are in agreement with project STRESS rocket in situ measurements.

CONTENTS

A FLUID MODEL FOR ESTIMATING MINIMUM SCALE SIZES IN IONOSPHERIC PLASMA CLOUD STRIATIONS

I. INTRODUCTION

Artificial plasma clouds (i.e., nuclear or barium) detonated in the ionosphere typically develop visible striations over periods of tens of seconds to tens of minutes. Propagation studies carried out simultaneously with barium cloud experiments during project STRESS have shown that line-of-sight radio communication through a striated region may be subject to 10-30 db of attenuation[1]. Thus local enhancements in the ionospheric plasma density can have a great impact on propagation when small scale structuring occurs. The resolution of the optical data from barium cloud experiments[2] and nuclear detonations is insufficient to reveal structures (irregularities) smaller than 100's of meters. However, recent in situ rocket measurements[3] suggest that structure down to meter sizes may be present. We wish to address theoretically the question of what determines the smallest structures to be found in a striated plasma cloud.

The mechanism by which striations are produced in barium clouds[4-6] and most nuclear clouds has been established to be the gradient drift instability. This is an electrostatic fluid process analogous to the Rayleigh-Taylor instability. The results of the model are in need of correction for kinetic effects below scale sizes approximating the ion gyro radius. For a barium ion in the daytime F region, the gyro radius is approximately 7 meters.

Note: Manuscript submitted August 24, 1978.

Before carrying out the kinetic corrections (to be reported elsewhere) one should ascertain whether or not the fluid model tends to generate structures on such a small scale.

II. THE ONE LEVEL, TWO DIMENSIONAL FLUID MODEL

For barium clouds released at altitudes of approximately 200 km or greater, electron and ion collision frequencies are small compared to their gyrofrequencies. As a result[7] the electrical conductivity of the plasma is dominated by the scalar (Pedersen) component,

$$\Sigma \approx n \frac{ec}{B} \frac{\nu_{in}}{\Omega_i} \tag{1}$$

where n, e, c, B, ν_{in}, and Ω_i are respectively the ion number density, electronic charge, speed of light, magnetic field strength, ion-neutral collision frequency, and ion gyrofrequency. Assuming all parameters in (1) to be constant except n, Σ obeys a continuity equation,

$$\frac{\partial \Sigma}{\partial t} = - \nabla \cdot (\underline{V} \Sigma) + K \nabla^2 \Sigma, \tag{2}$$

where $\underline{V}$ is the plasma drift velocity, and K is a diffusion constant used to model the effects of electronic collisions. The value of K will be estimated later. Let us adopt Cartesian coordinates (x,y,z), with z in the direction of the (constant) magnetic field. We assume that all variables depend only on x and y (striations are observed to be mainly magnetic field aligned). We express the electric field as

$$\underline{E} (x,y) = E_o \hat{y} - \nabla \phi (x,y) \tag{3}$$

where E_o is the constant ambient electric field and ϕ is the potential due to the presence of the cloud. It is convenient to use a frame moving with the ambient plasma drift velocity, $E_o\, c/B\, \hat{x}$. In this frame, we have a net plasma drift velocity

$$\underline{V} = - c/B\, \nabla\phi \times \hat{z} \qquad (4)$$

The equation can be viewed as a solution of the electron momentum equation in which inertia and collision terms have been neglected. The collisional correction has been included in an approximate way in the diffusion term in (2). The set of fluid equations is closed in this simple model by quasi-neutrality; i.e., the constraint that the electric current be divergenceless:

$$\nabla \cdot (\Sigma \nabla \phi) = \underline{E}_o \cdot \nabla \Sigma \qquad (5)$$

The more sophisticated two layer model[6] allows polarization currents generated by the cloud to flow along the magnetic field direction and close in the lower ionosphere, where cross-field conductivities are high. However, the lower layer becomes unimportant when the cloud's conductivity is high enough to let current loops close in the cloud itself. Some of the barium releases at altitudes of approximately 200 km are known to have integrated conductivities as high as 15 times that of the ionosphere. For such large clouds, the one-level model should be adequate. The one-level model is simple enough to allow a convenient scaling law to emerge. The small number of variables also expedites numerical solution of the equations of motion.

III. SCALING THE EQUATIONS OF MOTION

Equations (2), (4), and (5) can be put into dimensionless form as follows. Let

$$\begin{aligned} \underline{x} &= L_o\, \underline{x}' \\ t &= t_o t' \\ \Sigma &= \Sigma_o \Sigma' \\ \underline{V} &= V_o V', \\ \phi &= L_o E_o \phi' \end{aligned} \qquad (6)$$

where L_o is an arbitrary scale, length, and

$$V_o = cE_o/B,$$
$$t_o = L_o/V_o \tag{7}$$

In (6) quantities with zero subscript are dimensional constants and all primed variables are dimensionless. Upon expressing (2), (4), and (5) in terms of the dimensionless primed variables and dropping primes from x', t', Σ', $\underline{V}'$, and ϕ', we have

$$\frac{\partial \Sigma}{\partial t} = -\nabla\cdot(\underline{V}\Sigma) + K'\nabla^2\Sigma \tag{8}$$

$$\underline{V} = -\nabla\phi \times \hat{z} \tag{9}$$

$$\nabla\cdot(\Sigma\nabla\phi) = \hat{y}\cdot\nabla\Sigma \tag{10}$$

$$\text{where} \quad K' = \frac{K}{L_o V_o} \tag{11}$$

Note that K' is just the inverse of an effective Reynolds number, with the diffusion constant K in place of the usual kinematic viscosity. The fact that all quantities in (8)-(10) are dimensionless means that physical systems of different sizes will evolve in the same way, providing initial conditions and boundary conditions are analogous, and K' has the same value.

Thus the model (8)-(10) can be used to answer the following crucial question: What criterion determines whether or not structures in a striated plasma cloud will develop into structures of smaller scale? It becomes clear from (8) and (11) that as the length scale becomes smaller, diffusion becomes more important. For sufficiently small scales, we expect an equilibrium to be reached between the tendency toward finer structuring and the smoothing out effect of diffusion. Our approach to finding this scale will be to carry out a set of numerical simulations based on (2)-(5) or equivalently (8)-(10) and hopefully to identify an approximate value for K' at which diffusion is just able to halt further structuring of previously formed striations. Knowledge of a critical value of K' combined with estimates for the drift speed and diffusion coefficient allow calculation of a minimum length scale from (11). Drift speeds are fairly well known to be of order 100 m/sec. However, there are no direct measurements of the diffusion constant, so it must be calculated.

IV. CALCULATION OF THE DIFFUSION CONSTANT

Neglecting ion and electron inertia, the momentum equations for electrons and ions are

$$0 = \Omega_i \underline{V}_i \times \hat{z} - \nu_{in}\underline{V}_i + \nu_{ie}(\underline{V}_e - \underline{V}_i) + \frac{e}{m_i}\underline{E} - \frac{kT_i}{m_i}\nabla n/n \qquad (12)$$

$$0 = -\Omega_e \underline{V}_e \times \hat{z} - \nu_{en}\underline{V}_e + \nu_{ei}(\underline{V}_i - \underline{V}_e) - \frac{e}{m_e}\underline{E} - \frac{kT_e}{m_e}\nabla n/n \qquad (13)$$

For the purposes of this derivation we have adopted a coordinate system at rest with the neutral atmosphere. In (12) and (13), the $\underline{V}$'s are fluid velocities, with subscripts i and e referring to ions and electrons. Similarly, ν stands for momentum transfer collision frequency, T for temperature, and m for particle mass. The gyrofrequencies are

$$\Omega_i = \frac{eB}{m_i c} \qquad (14)$$

$$\Omega_e = \frac{eB}{m_e c} \qquad (15)$$

Note that we have retained the electron-ion collision frequency ν_{ei} in (13). For conditions typical of a 200 km release, ν_{en} is of order 10^2 sec^{-1}, and ν_{ei} is of order 10^3 sec^{-1}. This is because the ions, although less numerous than the neutrals, interact with electrons via a Coulomb cross section. However, the ν_{ie} term in (12) is typically much smaller than the ν_{in} term because of the low mass of the electron. Neglecting ν_{ie}, we find from (12) and (13)

$$n\underline{V}_i = M_i^{-1} \left(\frac{e}{m_i} n\underline{E} - \frac{kT_i}{m_i} \nabla n\right) \tag{16}$$

$$n\underline{V}_e = M_e^{-1} \left(-\frac{e}{m_e} n\underline{E} - \frac{kT_e}{m_e} \nabla n\right) + \nu_{ei} M_e^{-1} n\underline{V}_i \tag{17}$$

where

$$M_i^{-1} = \begin{pmatrix} \nu_{in} & \Omega_i \\ -\Omega_i & \nu_{in} \end{pmatrix} / \left(\Omega_i^2 + \nu_{in}^2\right) \tag{18}$$

$$M_e^{-1} = \begin{pmatrix} \nu_e & -\Omega_e \\ \Omega_e & \nu_e \end{pmatrix} / \left(\Omega_e^2 + \nu_e^2\right), \tag{19}$$

and

$$\nu_e = \nu_{en} + \nu_{ei} \tag{20}$$

Let us invoke quasineutrality in the form

$$\nabla\cdot(n\underline{V}_i) = \nabla\cdot(n\underline{V}_e), \tag{21}$$

and take the divergence of (16) and (17). We assume all parameters except n, $\underline{V}_i$, $\underline{V}_e$, and $\underline{E}$ to be constant. We also assume all vectors have only x and y components. We may then eliminate $\nabla\cdot n\underline{E}$ between (16) and (17), and find, to lowest order in ν_e/Ω_e,

$$-\nabla\cdot(n\underline{V}_i) = -\frac{c}{B} \nabla\cdot(n\underline{E}\times\hat{z}) + K\nabla^2 n, \tag{22}$$

where

$$K = \frac{\nu_e}{\Omega_e} \frac{k(T_e + T_i)/m_e}{\Omega_e + \nu_{en} \nu_{in}/\Omega_i} \tag{23}$$

We use the convenient approximations[8],

$$\nu_{ei} \approx (34 + 4.18 \log_{10}(T_e^3/n_e))\, n_e T_e^{-3/2} \tag{24}$$

$$\nu_{en} \approx 1.8 \times 10^5\, p_n \tag{25}$$

$$\nu_{in} \approx 4 \times 10^{-10}\, n_n, \tag{26}$$

where p_n and n_n are the neutral pressure and number density, T_e is in ^oK and all other quantities are in cgs units. For typical daytime conditions at 200 km, we have $T_e = 950^oK$, $T_i = 700^oK$, $p_n = 8.64 \times 10^{-4}$ erg cm^{-3}, $n_n = 7.0 \times 10^9$ cm^{-3}, $\Omega_e = 9 \times 10^6$ sec^{-1}, and Ω_i (singly ionized Ba) = 36 s^{-1}. We know that for typical barium releases[4,6] $10^6 \lesssim n_e \lesssim 10^7$ cm^{-3}. Thus K is expected to lie between 0.6 and 6 m^2/sec. When the calculation is repeated using data appropriate to 170 km and 150 km, K changes by less than a factor of 2. This is because ν_e is dominated by ionic collisions, and is insensitive to moderate changes in the neutral background.

V. NUMERICAL SIMULATION

In order to estimate a critical value for K', we have solved numerically equations (2)-(5) using diffusion constants K determined so as to give one of four desired K' values. The results to be presented here were obtained using a mesh of 162 x 42 grid points with constant grid spacing in both directions of 310 meters and doubly periodic boundary conditions. Equation (2) was advanced in time using a flux-corrected leapfrog-trapezoid scheme, which is basically second order in time, fourth order in space. Second order centered differences were used in (4) and (5). The elliptic potential equation (5) was solved iteratively using the Chebychev method[9,10]. The initial condition (t=0) was $\Sigma = 1 + 10\, e^{-(x/8km)^2} (1 + \varepsilon(x,y))$, where ε was generated from a k^{-4} power spectrum and random phases. The root mean square value of ε was 0.03. (The dimensionality of Σ may be scaled out of (2) and (5) with no consequence). B is taken to be 0.5 gauss and $V_o = cE_o/B$ = 100 m/sec.

We are not concerned here with details of relating an initial condition to a final state achieved after a long period of development. Rather we wish to determine whether or not a given configuration tends toward spontaneous generation of structure smaller than that which is present. Thus we view the time evolution to be presented here as a continuous sequence of initial conditions, hopefully at some point descriptive of structure in a striated cloud. We seek a value of the Reynold's number just low enough that a long finger-like striation will not evolve into new and smaller scale structures.

Since we hope to identify a critical value of the Reynold's number,

$$R_e \equiv \frac{V_o L_o}{K} = 1/K' \quad (27)$$

we have carried out numerical simulations so as to keep R_e constant throughout a given computer run. Throughout each run presented here, V_o is constant, and L_o is determined self-consistently from the conductivity profile:

$$L_o(t) = \{\Sigma\ (\Sigma(x,y,t)^2/\Sigma(\nabla\Sigma(x,y,t))^2\}^{1/2} \quad (28)$$

where Σ without the argument (x,y,t) refers to summation over all grid points. This definition of L_o is somewhat arbitrary, but it does have the desirable feature of being sensitive to small scale structure. Since L_o changes in time, K must change if R_e is to be held constant. Thus during a computer run, we evaluate L_o at each timestep and determine K from (27). It may be more conventional to keep K fixed and let R_e vary with L_o, but out approach allows a more direct identification of a critical R_e.

The results of four computer runs ($R_e = \infty$, 800, 400, and 300) are shown at five times (t = 0, 240, 360, 480, and 720 sec) in Figures 1-5. All four cases show the breakup of the initial slab geometry into structure elongated in the x direction. However, only the top two cases $R_e = \infty$ and 800 show a clear tendency toward further structuring. The $R_e = 400$ case appears marginal, and the $R_e = 300$ case is clearly held back by diffusion. Therefore we tentatively propose that the critical Reynold's number for the initial condition presented here ($\Sigma_{max}/\Sigma_{min} \approx 11$) is approximately 400. We intend to carry out several more simulations using finer resolution and different initial conditions to determine if $R_e = 400$ is infact universal to the short scale limit of the striation process. Using $R_e = 400$, and $V_o = 100$ m/sec. in (27), we find the following range for L_o:

For n: $10^6 - 10^7$ cm^{-3} (29)

and K: $0.6 - 6$ m^2/sec.

L_o: 2.4 - 24 m

VI. CONCLUDING REMARKS

The one level, two dimensional striation model presented here predicts, for the particular set of initial conditions considered, minimum length scales of 2.4-24 meters for large barium clouds near 200 km altitude. These scales are small enough that kinetic effects may be important. The kinetic corrections have not yet been calculated, and will be reported elsewhere. However, the tendency of the fluid mechanism to generate structures this small is in apparent agreement with recent project STRESS rocket measurements[3] and with the attenuation (probably due to strong scattering or diffraction) observed in propagation experiments[1]. Further work needs to be done to determine the sensitivity of the results to initial conditions. One should also investigate the effects of ion inertia (which may be important at higher altitudes), and electrostatic coupling to the lower ionosphere in the case of small clouds.

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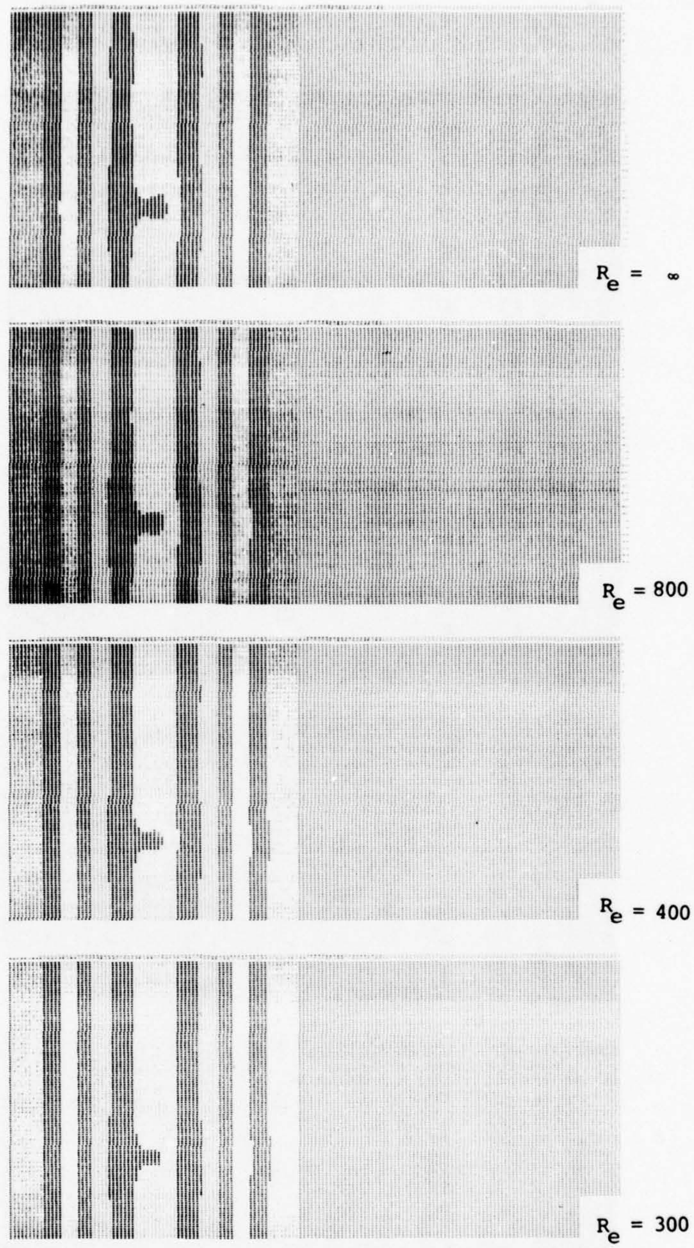

Figure 1

Initial conditions. Contours of constant Σ are boundaries between light and dark areas. A maximum Σ of 11.32 relative to the background occurs in the light vertical band containing the most noticeable bump. The vertical (y) extent of each rectangular box is 12.4 km; the horizontal (x) extent is 49.9 km. The finite difference grid is 42 by 162 points in the y and x directions respectively. Boundaries are doubly periodic. The Reynold's numbers are (top to bottom) $R_e = \infty$, 800, 400, 300.

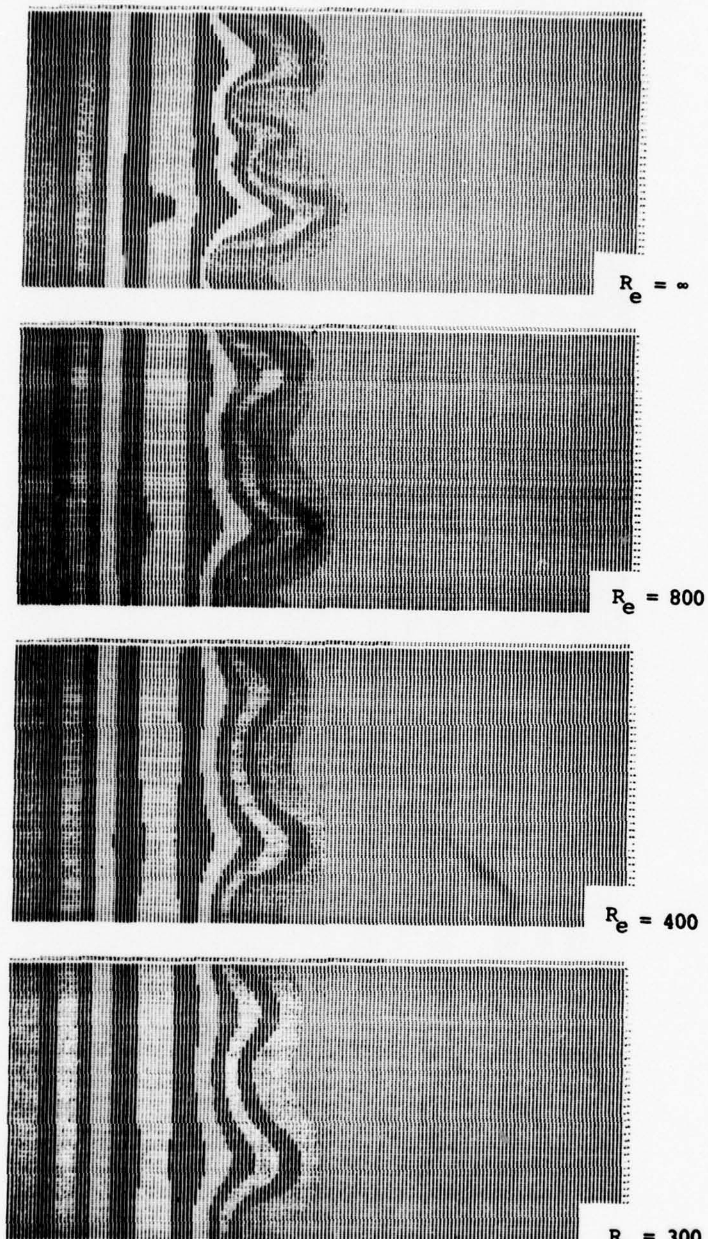

Figure 2

Σ contours at t = 240 seconds

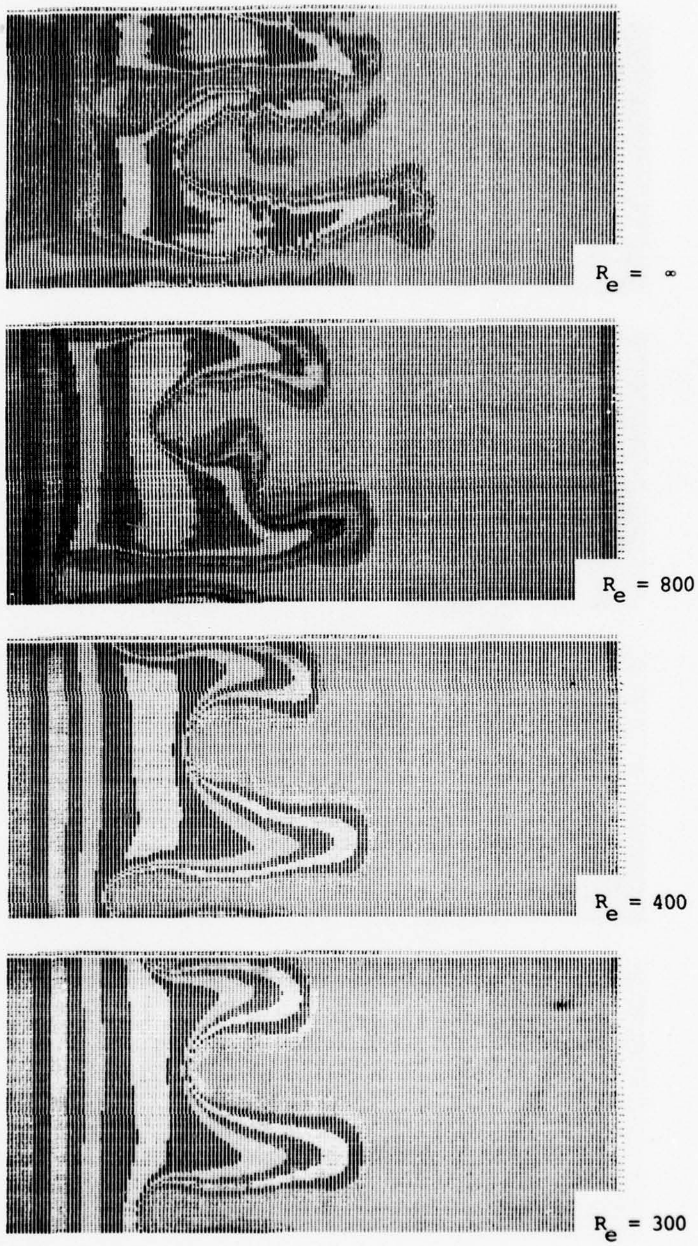

Figure 3

Σ contours at t = 360 seconds

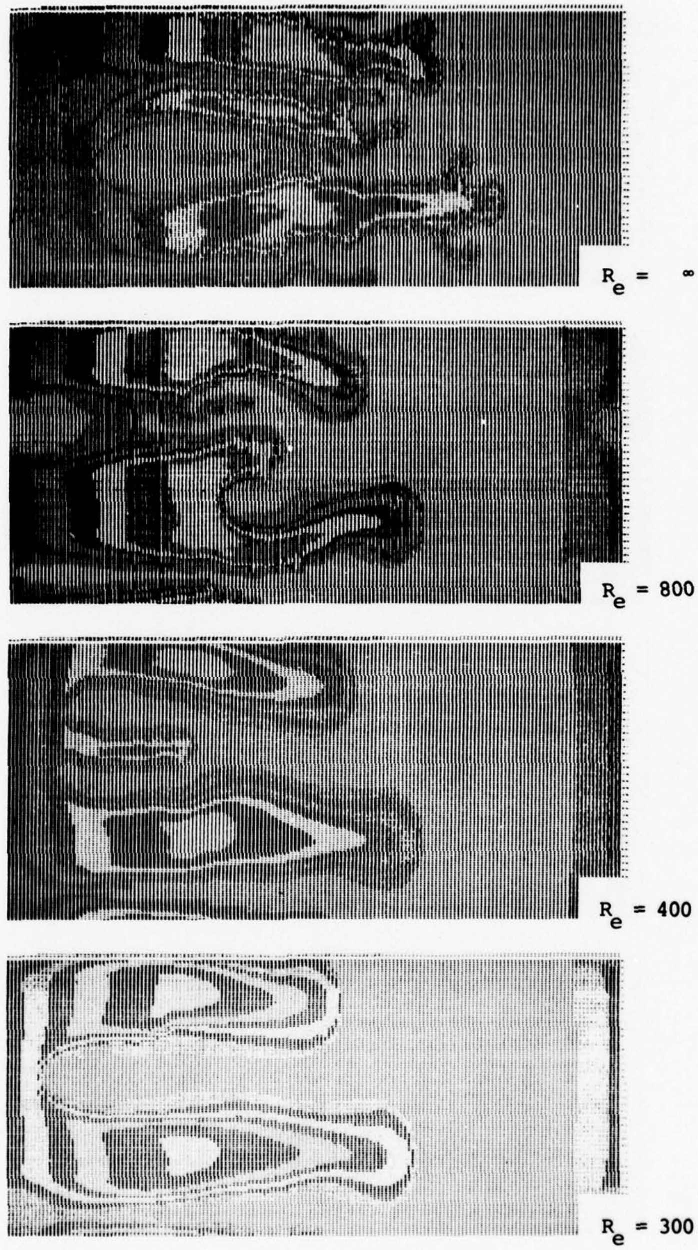

Figure 4

Σ contours at t = 480 seconds

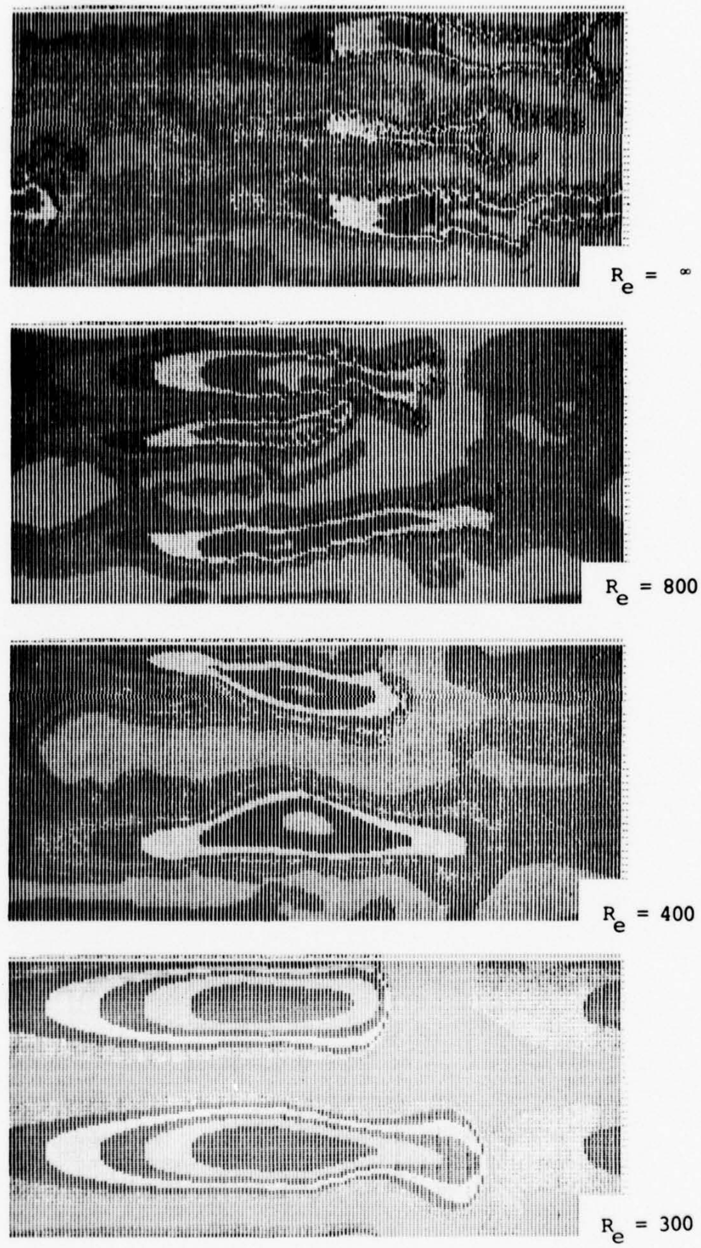

Figure 5

Σ contours at T = 720 seconds

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