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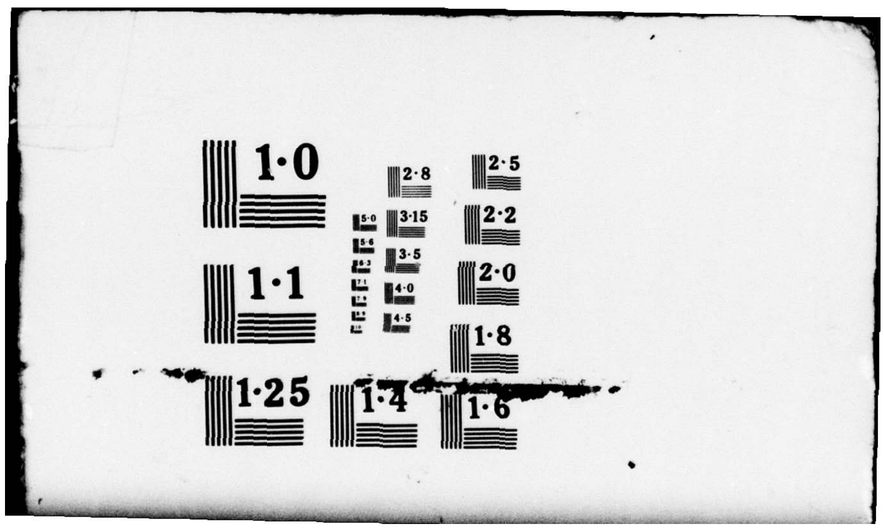
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SOLAR ATMOSPHERIC DYNAMICS

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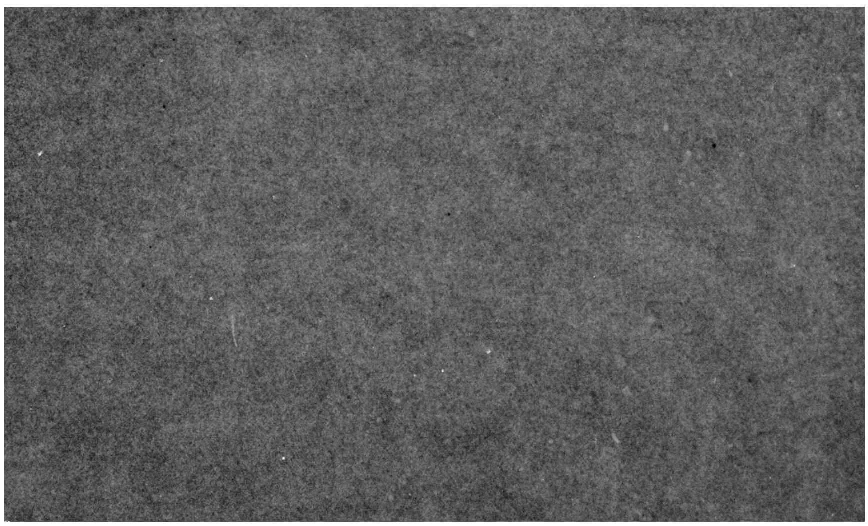

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

We have studied the heating of the solar chromosphere and corona, and the propagation of acoustic waves through the transition region between the chromosphere and corona. In order to place an upper limit on the effectiveness of acoustic waves in heating, we have written and tested a computer program to accurately calculate the propagation and dissipation of vertically travelling acoustic waves which includes thermal conduction and radiative transfer. In order to study heating by other possible waves, in particular magneto-acoustic-gravity waves, we have written and are now testing a compu-

ter program which approximately includes horizontal motions. In order to study the effects of horizontal inhomogeneities we have started developing a three-dimensional fluid dynamic computer program.

We have also studied the propagation of acoustic waves through the solar transition region. We find that waves with velocity amplitudes compatible with observations near the temperature minimum ($<\pm 1$ km/s) transmit too little flux through the transition region ($<2 \times 10^4$ erg/cm^{2}s) to heat the corona.

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SOLAR ATMOSPHERIC DYNAMICS

I. INTRODUCTION

The goal of this research is to study the driving of the solar atmospheric oscillations and their role in heating the chromosphere and corona. Although many models of the solar atmosphere have been constructed with acoustic waves as the energy source, their ability to transport sufficient energy has recently been questioned. We made accurate calculations for the most favorable case of vertically propagating acoustic waves. We found that they can not supply sufficient energy to heat the corona. Further calculations with an accurate treatment of radiative transfer are necessary to answer the question for the upper chromosphere. A program to perform such calculations was prepared and they will be carried out this coming year. If acoustic waves can't transport the needed energy to the corona, can other types of waves? It is clear that coronal heating depends critically on the magnetic field. Hence the role of magneto-acoustic-gravity waves should be studied. Because magnetic waves can propagate at a faster speed than acoustic waves in a strong magnetic field, magnetic waves with velocity amplitudes consistent with observations may transport the required energy. We continued our development of a "modal" fluid dynamic code to calculate the propagation and interactions of these waves. We also began development of a fully three-dimensional fluid dynamic code that will in addi' on be able to include horizontal inhomegeneities.

II. RESEARCH

A. Heating of the Chromosphere and Corona

Three different attacks were made on the problem of how the chromosphere and corona are heated. First, the heating by vertically propagating acoustic waves was investigated including effects of radiation transfer and conduction. This provides an upper limit to possible acoustic heating. Second, investigation of heating by non-vertically propagating magneto-acoustic-gravity waves was continued using an approximate treatment of variations in the horizontal direction. This provides a more realistic analysis of sources of mechanical heating by other than acoustic waves and of the interaction of the waves with the mean atmospheric structure and each other. Third, development of a truly 3-dimensional dynamic code was begun in collaboration with Richard Klein (Kitt Peak National Observatory) and Lawrence Auer (High Altitude Observatory). Eventually such a code will be able to calculate models with horizontal inhomogeneity. Progress was made using all three approaches, and work is still in progress.

1. Vertically Propagating Acoustic Waves

Acoustic waves are generated dynamically by coupling to the convective motions below the photosphere and also by overstability in the top of the convective region (see review by Stein and Leibacher, 1974, Ando and Osaki, 1975). Can they heat the chromosphere or corona? There is doubt both observationally (Athay and White, 1978; Brunner and McWhirter 1978) and theoretically (Jordan, 1977). Vertically propagating acoustic waves suffer no refraction and stand the best chance of dissipating their energy high in the solar atmosphere. The main energy loss mechanisms for such waves is radiative and conductive damping. A careful treatment of these effects is needed to assess theoretically the possible role of acoustic waves.

For this purpose a one-dimensional fluid dynamic code was written which includes radiative and conductive heating and cooling in the energy equation and the transfer equation for radiation in the gray - LTE approximation. As in previous 1-D dynamic calculations, the code is Lagrangian with the mass column density the independent variable. The velocity, position and density are first solved for explicitly from the equations of motion, definition of velocity and mass conservation (continuity) equations (Richtmyer and Morton, 1969). Then the energy, Saha and transfer equations are solved implicitly and simultaneously for the temperature, degree of hydrogen ionization, and mean radiation intensity using Newton-Raphson iteration (complete linearization) (see Richtmyer and Morton, 1969 and Klein, Stein and Kalkofen, 1976). The opacities used are those of Robert Kurucz and the thermal conductivity is taken to be $5\times10^{-7}T^{5/2}$ erg/cm K, without limiting the flux because of maximum electron velocity. The usual treatment of the transfer equation, using a finite differenced form of the Feautrier equation

$$\frac{J_{i+3/2} - J_{i+1/2}}{\Delta\tau_{i+1}} - \frac{J_{i+1/2} - J_{i-1/2}}{\Delta\tau_i} = \frac{\Delta\tau_{i+1/2}}{\mu^2}\left(J_{i+1/2} - B_{i+1/2}\right), \quad (1)$$

alternates a complete linearization to get first order corrections to variables and then a formal solution to obtain the radiation field for the given temperature structure. The elimination procedure in the formal solution was slightly modified, in order to include very small optical depths in the corona. The straightforward Gaussian elimination scheme would lose all significance from the samil term $\Delta \tau J$ compared to the large term $\Delta \tau^{-1} J$. It was therefore necessary to modify the method of formal solution of the transfer equation as follows: The transfer equation has the form

$$A_i J_{i-1} + B_i J_i + C_i J_{i+1} = -D_i . \tag{2}$$

The usual procedure is to calculate elimination matrices

$$E_{i+1} = (B_i + A_i E_{i-1})^{-1} C_i \tag{3}$$

and

$$F_{i+1} = -(B_i + A_i E_{i-1})^{-1} (D_i + A_i F_{i-1}), \tag{4}$$

where these are then used to back substitute for the

$$J_i = E_i J_{i+1} + F_i . \tag{5}$$

At small optical depth the radiation field is nearly constant and E_i nearly the identity matrix 1. It is therefore possible to gain accuracy by working with a matrix ε_i equal to the difference between E_i and 1.

That is, let

$$\varepsilon_i = 1 - E_i \tag{6}$$

$$J_i = (1 - \varepsilon_i) J_{i+1} + F_i \tag{7}$$

The relations to calculate ε_i and F_i are found by substituting equation 7 into the difference equation 2. The result is

$$\varepsilon_i = \left[B_i + A_i - A_i \varepsilon_{i-1} \right]^{-1} \left[B_i + A_i + C_i - A_i \varepsilon_{i-1} \right] \tag{8}$$

$$F_i = - \left[B_i + A_i - A_i \varepsilon_{i-1} \right]^{-1} \left[D_i + A_i F_{i-1} \right] \tag{9}$$

The large terms in the sum $B_i + A_i + C_i$ are cancelled analytically. Using this procedure it is possible to calculate to an optical depth 10^{-n} where n is the number of significant digets in the computer word.

The computer code was written and tested at NCAR. As soon as the link between Michigan State University and NCAR is established (within the next few months) calculation of models will begin. These models will start with a solar atmosphere in radiative equilibrium. Waves will be generated below the top of the convection zone by a piston whose motion will have a power spectrum like that calculated for waves generated by the lighthill mechanism (Stein, 1968) plus the "300 second" oscillation. The calculation will be allowed to run until a statistically steady state atmosphere is obtained. This atmosphere will have a self-consistent structure for the acoustic wave heating - gray LTE radiative losses plus conduction, included in the calculation. The maximum extent to which acoustic waves can produce a chromosphere and corona will then be apparent. I anticipate that for the low chromosphere and possibly the upper chromosphere the model atmosphere will accurately reproduce the observed solar atmosphere. Where these models reproduce the observed solar atmospheric structure they will be used to investigate the detailed effects of acoustic waves on line profiles in collaboration with Richard Shine (NASA Goddard Space Flight Center.)

2. Magneto - Acoustic - Gravity (M.A.G.) Waves

Acoustic waves generated below the photosphere are in fact not vertically propagating, so they suffer refraction, which prevents them from reaching the corona (Kopp, 1968). Furthermore, they propagate in the presence of a magnetic field which changes their character. Finally, the observed heating of the solar atmosphere clearly depends sensitively on the magnetic field strength (Withbroe and Noyes, 1977). In order to study the propagation and dissipation of these M.A.G. waves the development of an approximate 3-dimensional "modal" code was begun in 1975 with the support of AF contract F19628-75-C-0013. The essence of this approach is to separate all the variables into a mean and a fluctuating part. The mean part is uniform on horizontal planes and the fluctuating part is expanded in a complete set of horizontal modes with amplitudes a function of height and time. For simplicity the expansion is truncated to a single hexagonal horizontal mode of some given length scale. When this expansion is substituted into the equations of motion and transfer, the result is a set of one-dimensional partial differential equations in z and t for the mean variables and fluctuating mode amplitudes, but with horizontal variations included via the imposed hexagonal horizontal structure. In this way it is possible to study non-longitudinal and non-vertically propagating waves, but still include non-linear interaction of the wave with itself in the vertical direction, and still only integrate one-dimensional partial differential equations using standard Eulerian techniques. This idea comes from Gough, Spiegel and Toomre (1975) who used a similar method to study convection.

The equations were derived in collaboration with Shyu-Hsien Hsieh. They were coded by Robert Wolff, using Richtmyers (1969) two-step Lax-Wendroff method to solve the difference equations, with a flux correction scheme for eliminating numerical instabilities (Book, Boris and Hain, 1975). Testing of the code was begun by Robert Wolff. So far only tests of the one-dimensional propagation terms have been made, with mixed results. Piston driven longitudinal compression waves do form shocks properly. Far from the piston the mean flow develops into a sawtooth pattern with half the period of the driving piston. This is because the piston is not in phase over the horizontal plane but has a hexagonal pattern and produces wave trains 180^{o} out of phase with each other at the center of the hexagonal cell and its edge. Both wave trains develop into shocks and the horizontal average has shocks coming twice as fast as in a single wave train. The fluctuating component of the fluid variables develops a square wave profile. This too is reasonable, because when the square wave fluctuating component is added with appropriate sign to the saw tooth mean component, a saw tooth shock train with the full wave length results, but those shocks at the cell edge are displaced a half wave length in height relative to those at the cell center. On the other hand, we have not yet been able to verify that the code conserves energy properly. Further work on finding and correcting the bugs in this program is being carried out.

3. Three - Dimensional Fluid Dynamics

Neither one-dimensional nor even "modal" calculations can include effects of horizontal inhomogeneity in the mean structure of the solar atmosphere. To do that at least two-and preferably three-dimensional calculations are needed. Drs. Auer, Klein and myself began development of a three-dimensional fluid dynamic computer code.

Our approach is to represent the three-dimensional difference operator for the fluid dynamic equations as the product of one-dimensional operators. Consider for example the continuity equation

$$\frac{\partial \rho}{\partial t} + \Sigma_i \frac{\partial}{\partial x_i} (\rho u_i) = 0 \qquad (10)$$

Let L_i represent the operator

$$\rho^{n+1/6} = \rho^n - \frac{\Delta t}{6} \frac{\partial}{\partial x_i} (\rho u_i) \qquad (11)$$

The operators for different directions don't commute so the operator for a full time step is taken to be

$$L_x L_y L_z L_z L_y L_x \qquad (12)$$

This method of "time-splitting" reduces the complicated three-dimensional differencing problem to a product of simple one-dimensional difference algorithms. An additional bonus is the somewhat larger time step permitted by the Courant condition.

The scheme actually used to transport the fluid variables in time is that devised by MacCormack (1971). This is similar to the two-step Lax-Wendroff method of Richtmyer and Martin (1969) but (i) always uses the same grid points (so there is no staggering in space) and (ii) changes the direction of spatial differencing between predictor and corrector, so one is always upstream and the other downstream. This increases the dissipation and makes the scheme very stable. Additional non-linear stabilization is provided where needed by the Flux Corrected Transport (FCT) algorithm of Boris (Book, Boris and Hain, 1975). In their method extra diffusion is added to the transport scheme to make all variables vary smoothly. This extra diffusion is then cancelled out everywhere except where that would lead to ripples. The process of limiting the cancellation where ripples would arise is nonlinear. We are currently developing graphics to study the output from the calculations and a scheme to calculate the self-gravitational attraction of the fluid.

This 3D code will be tested on three problems.

(i) Spherical blast wave in uniform and decreasing density medium. Comparsion will be made with the Sedov similiarity solutions.

(ii) Accretion in a rotating disk about a point mass without self-gravity. This will test the viscosity and angular momentum transport in the code. Comparison will be made to the analytic solutions of Lyndon-Bell and Pringle (1974).

(iii) Spherical accretion problem. This will test the self gravity scheme. Comparison will be made to the similarity solutions of Larson (1969).

B. Waves in the Transition Region

Skylab observations have shown evidence of acoustic pulses in the transition region (final report on AF contract F19628-75-C-0013), but there is no evidence of the "five-minute" oscillation (Vernazza et. al. 1975). Also there is great doubt about whether acoustic waves supply sufficient energy to heat the upper chromosphere, transition region and corona (Jordan, 1977; Athay and White, 1978; Brunner and McWhirter, 1978). Dr. J. Vernazza and I continued our study of vertically propagating acoustic waves in the transition region in order to investigate these problems. Our original calculations assumed the waves were isothermal. More realistic calculations have now been performed.

We have used a one-dimensional Lagrangian fluid dynamic code. The energy equation includes electron conduction and optically thin radiative losses (Cox and Tucker, 1969). The initial structure of the transition region is determined primarily by the condition of constant conductive flux. For most part the transition region is very finely zoned to achieve high resolution. The one exception is the region between 4×10^4 °K and 3×10^5 °K which is covered by only one zone of thickness 150 km. This will produce some unreal numerical wave reflection, but the effect seems to be small. The waves were driven by a piston 1.5Mm below the top of the convection zone.

Results for 300s waves show:

(i) The velocity amplitude is nearly constant but decreases slightly from the middle to the top of the transition region (figure 1).

(ii) The density amplitude decreases by a factor of 3 between the top of the chromosphere and the transition region (figure 2).

Preliminary results on acoustic wave fluxes and velocity amplitudes confirm Jordan's results that acoustic waves can't supply sufficient energy to heat the corona. We have looked at wave trains with 75s, 150s and 300s periods. Waves, with velocity amplitudes less than ±1 km/s at the temperature minimum have energy fluxes less than 2×10^4 erg/cm^{2}s in the transition region. The energy flux is larger for 150s than either 75s or 300s waves. This flux is 2×10^4 erg/cm^{2}s, too small to supply the coronal energy needs of 3×10^5 erg/cm^{2}s. Another interesting result is that the velocity amplitude in the transition region is only about ± 20 km/s when it is ± 1 km/s at the temperature minimum. This transition region value is lower than inferred from line widths by Boland et al. (1975) even though the temperature minimum value is large (Canfield and Beckers 1977). Furthermore, the velocity amplitude in the transition region is very insensitive to the driving amplitude. It changed by less than 25% for a 300% change in the amplitude at the temperature minimum and the driving piston.

C. Minicomputer

A Nova 3/D minicomputer was purchased primarily with funds from NSF, but with a diskette unit purchased with funds from this contract. It was delivered toward the end of February 1978.

When operational it will greatly facilitate work under this contract: (a) Time dependent calculations will be run for very long times - until statistical steady state is reached. Such calculations are prohibitively expensive when one must pay by the hour for computer time (b) A high level editor will make program development easier. (c) A phone link to the CDC 7600 and Cray I computer at the National Center for Atmospheric Research in Boulder, CO will be implemented. This link will enable calculations to be performed with these super high speed large memory computers.

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Figure 1: Velocity vs. time at three different temperatures: Solid line is for 10^4 °K (below the transition region). Dashed line is for 3.5×10^5 °K (middle of the transition region). Dotted line is for 9×10^5 °K (above the transition region). Waves are driven by a piston 1500 km below the photosphere with a velocity amplitude 10^{-3} the local sound speed.

Figure 2: Density vs. time for the same cases as in figure 1.

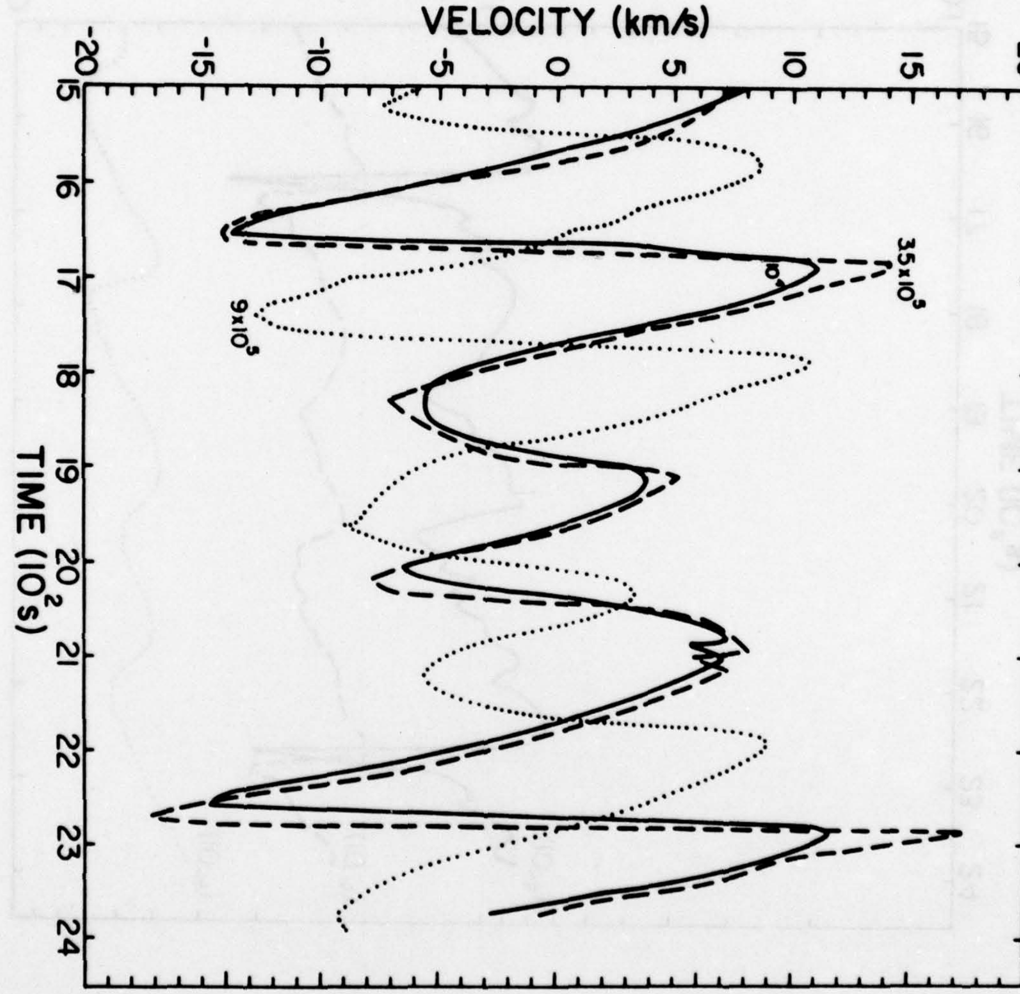

Figure 1

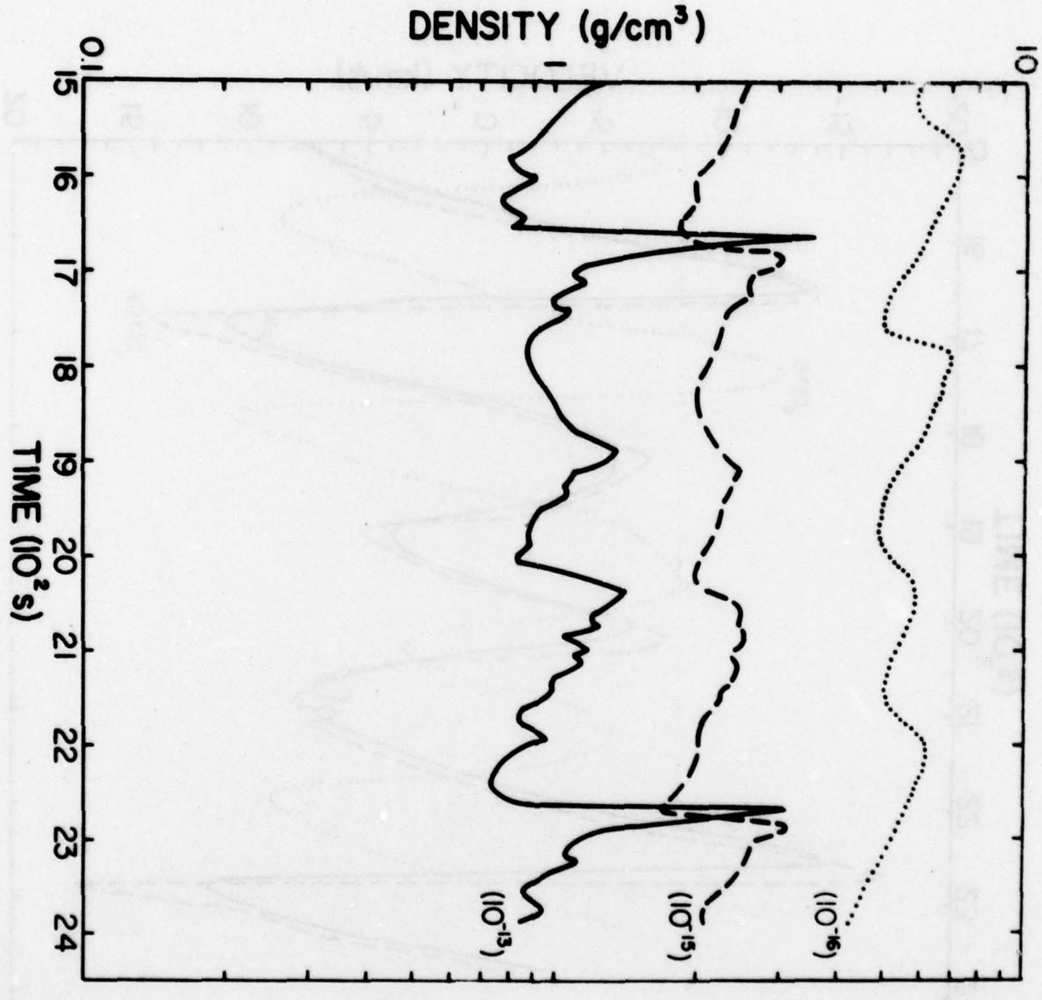
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Figure 2