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Final Report of Research
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Analysis of Time Dependent Phenomena Observed with the LPSP OSO-8 Instrument

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For the George C. Marshall Space Flight Center

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I) Introduction

This program studied the dynamics of the solar photosphere and chromosphere. Observations obtained by the Laboratoire de Physique Stellaire et Planètaire's ultra-violet spectrometer onboard the OSO-8 spacecraft were analysized, two reviews of the theory of solar atmospheric motions were presented, and dynamical models of the chromosphere and the emitted resonance line spectrum were calculated.

The next section discusses some of the unpublished data analysis and theoretical modeling which are being prepared for publication.

Attachment A consists of a discussion of the state of the theory of velocity fields in the solar atmosphere, prepared under this contract, which follows from a more detailed mathematical presentation at the E. Majorana School of Physics held at Erice (Sicily). Attachment B is an invited review presented at the OSO-8 Workshop on the topic of oscillatory motions in the quiet Sun. Attachments C, D and E contain the results of the OSO-8 data analysis prepared in close collaboration with LPSP scientists. Attachment F is the initial presentation of material being prepared for two articles, which will be completed with the support of contract number NASw-3053.

II) Discussion

Repeated spectral scans of strong, optically thick resonance lines formed in the solar chromosphere were analyzed for indications of oscillatory velocities and intensities. Figure 1 displays Lyman alpha data obtained during one orbit, which has had data losses replaced by interpolation. These spectra were taken away from active regions, near the center of the disk, with a spatial resolution of 4 x 10 arcseconds. They show only the central absorption reversal and one of the adjacent emission peaks, and succeeding scans are displaced vertically for viewing "clarity". One can see the geocoronal Lyman alpha absorption near grating position 898 and the blue peak near 928 (wavelength increases to the left). A slow displacement of the profile to the left can also be seen. Figure 2 shows the average profile for this orbit, after the correction for the wavelength drift has been applied.

Among other indicators of velocity which were studied, the blue peak is reasonably well defined, and the position of a parabola fitted by the method of least squares was used to define it. Figure 3 shows a series of spectra and the fitted parabolae, and Figure 4 shows the resulting variation of the peak's position. A sine wave, whose period equals the satellite's orbital period, has been drawn through the measurements, and the positions of data losses indicated by arrows. The residuals are shown on Figure 5, and (apart from the measurement at 560 seconds where the data was fit by a parabola with a minimum, rather than a maximum) one sees the indication of a variation with a period near one thousand seconds. All of the Lyman alpha data had this same characteristic oscillatory behaviour. Figure 6 presents the variation of the intensity of the blue peak and the curvature of the peak.

After the first flush of excitement over the discovery of this "900 second" oscillation - for that was its mean period - had passed and references to other observations of chromospheric oscillations with similar periods were dredged out of the literature, the real discovery was made that the observed periods corresponded precisely to the beat period between the repetition rate of the spectra (10.24 seconds) and the rotation rate of the spacecraft (10 seconds on the average, with slow drifts of several seconds). The amplitude of the intensity fluctuation is too large to be accounted for by displacements of the pointing axis, and it appears that it results from a modulation of the transmission with the period of the spacecraft rotation. Extensive additional observations and analysis by the P.I. team have demonstrated that the effect does not manifest itself in the other channels of the spectrometer, and the intermittency of the effect and its lack of correlation with the operational mode of the LPSP instrument suggests that it arises from another component of the spacecraft. Efforts to identify and correct for the modulation have been unsuccessful to date.

More positive results using statistical methods are contained in attachments C, D and E.

A major effort of this program was devoted to the dynamical modeling of the solar chromosphere with the dual goals of improving our understanding of 1) the dynamical processes themselves and 2) spectral line formation in the dynamic chromosphere. As these lines provide the principal diagnostic tool for chromspheric measurements, the calculation of the diagnostics combined with the complete knowledge of the physical conditions giving rise to these diagnostics gives us a means of evaluating the efficacy (and veracity) of the measurement techniques. The combination of hydrodynamics and radiative transfer in this way offers some exciting new insights into the behaviour of the Sun as we see briefly below. The results of this work will be published in two papers in collaboration with R.F. Stein of Michigan State University and P. Gouttebroze of LPSP.

A one dimensional, non-linear dynamical model of the solar atmosphere from 1.6 megameters below the visible surface to 3 megameters above was excited from below by pulses or oscillations in a series of calculations performed at LPSP. Figure 7 shows the velocity (solid lines) and pressure (dotted lines) at a number of different altitudes as a function of time for a typical calculation. The important points to note are the standing wave (pressure and velocity 90° out of phase) formed in the lower atmosphere (the zero of altitude corresponds to the visible surface) and the less regular, shorter period, standing wave formed in the chromosphere (1200 to 2000 kilometers). The photospheric oscillation is the well known "300 second" oscillation, and the chromospheric oscillation is the - slightly less - well known "200 second" oscillation. Variation of the structure of the chromosphere and the amplitude of the motions has shown that the chromospheric oscillation results from a trapped, interfering wave - much as the 300 second oscillation does - rather than from a ringing at the cut-off for propagating acoustic waves, as had been previously thought.

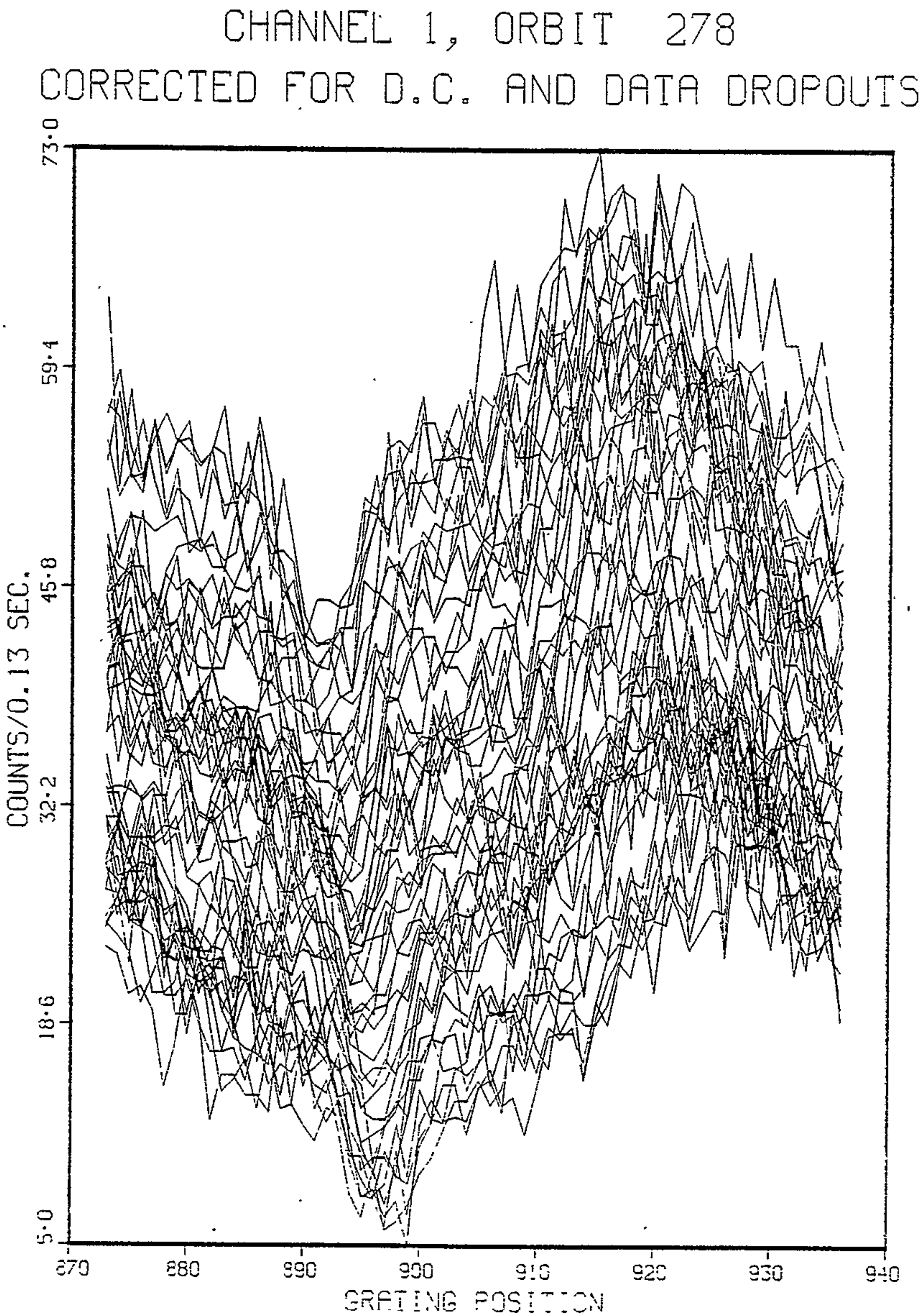
Figure 8 shows a series of magnesium resonance line profiles calculated for a dynamical model similar to those in Figure 7. A rather low amplitude motion was studied so that differences from the better understood, static line profiles would not be too great for an initial study. Displacements and intensity fluctuations of the emission peaks as well as of the central absorption reversal are evident. Figure 9 shows the variation of intensity at different wavelengths as a function of time. The photospheric 300 second oscillation dominates further than 0.5 Angstroms from line center, while closer to the center the 200 second oscillation dominates. The intensity variations of the emission peaks as well as the displacements of the central absorption stand out clearly. The intensity fluctuation at each wavelength has been expressed as a fractional change about the mean at that wavelength, and the fluctuation at each wavelength has been normalised to unity. The fractional fluctuation at each wavelength is indicated at the right. In the blue peak, the intensity varies by over a factor of two, even for this model with its relatively low chromospheric velocities.

Figures 10 and 11 show the results of fitting parabolae to the maxima and minima of the profiles. The central absorption is referred to as K3 and the emission peaks as K2 (violet and red). Because of the standing wave character of the dynamics, the perturbations remain in phase through a large range of heights in the chromosphere, and thus the two emission peaks are of equal intensity nearly simultaneously with the maximum of K3, and the zero crossing of the velocity. The very high vertical phase velocities result in diagnosed velocities which are remarkably close to those at the heights of formation of the spectral features. Perceptible differences in the phase of the three diagnosed velocities are nonetheless apparent.

The contribution to the emergent intensity as a function of altitude is shown in Figure 12, as a function of time, for a wavelength justly slightly to the blue of line center, within the central absorption feature. The variation in altitude of the emitting region results primarily from the motion of the matter up and down during the oscillation. Figure 13 plots the same contribution functions against the average height of the matter, so that the abscissa is just the mass depth transformed to read in kilometers. The emission arises from essentially the same material independently of the time. One should note that only a very, very small range of altitudes contributes. The behaviour at the blue emission peak is slightly more surprising (Figure 14). Reasonably large variations of the altitude of the emitting material occur, which results from the doppler shifts of the absorption profile with very rapid wavelength dependence. Figure 15 shows another projection of the same information. The depth above which 0.1, 0.2, 0.3 ... 0.9 of the emission arises is plotted for the same wavelength as Figure 12, as a function of time. The variations of the thickness as well as the altitude of the emitting region are striking.

Finally, Figure 16 shows the contribution functions on the flanks of the emission peak where a dramatic alternation of the emitting material by over 1000 kilometers occurs. This is but the beginning of the understanding of this great wealth of information which promises to not only increase our knowledge of the formation of spectral lines and their use as diagnostics, but also to enable us to make testable predictions on the bases of various hypotheses concerning stellar atomspheric dynamics.

This work would not have been possible without the generous collaboration of the staff of the Laboratoire de Physique Stellaire et Planètaire. Access to the data, even after it had been taken, was possible only as a result of a tremendous effort on their part. The non-linear, hydrodynamic calculations and the radiative transfer calculations were carried out on the CDC 7600 computer of the Centre National d'Etudes Spatiale. The data analysis and analysis of the results of the dynamical and transfer calculations were carried out within the Space Astronomy Group of LMSC and profited greatly from their expertise. Finally, I wish to thank NASA for its support of this research program.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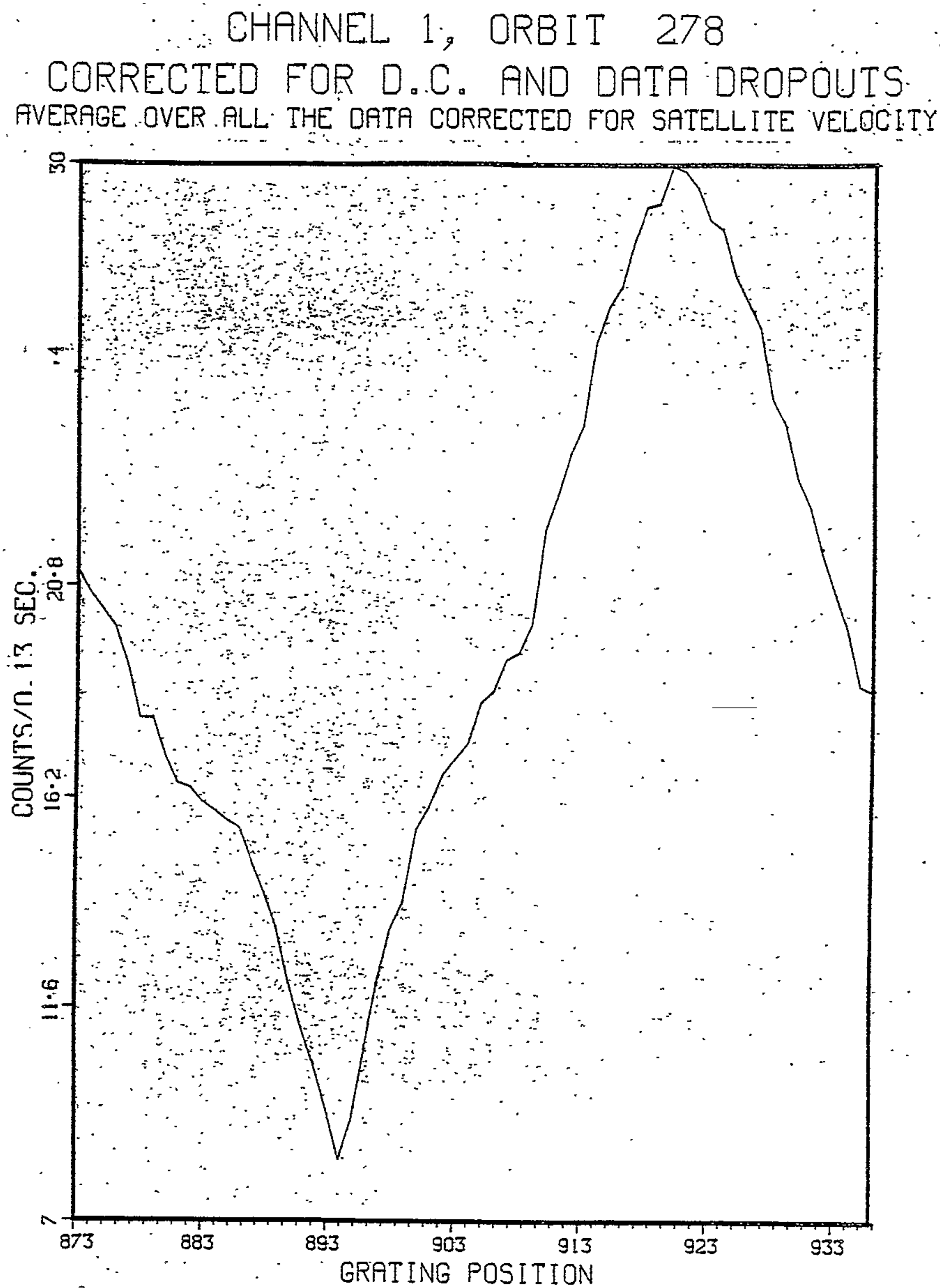
CORRECTED FOR D.C. AND DATA DROPOUTS
COUNTS/0.13 SEC.
73.0
59.4
45.8
32.2
18.6
5.0
870
880
890
900
910
920
930
940
GRATING POSITION

Figure 1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AVERAGE OVER ALL THE DATA CORRECTED FOR SATELLITE VELOCITY
COUNTS/0.13 SEC.
30
20·8
16·2
11·6
7
873
883
893
903
913
923
933
GRATING POSITION

Figure 2

LY α, ORBIT 278

PARABOLIC FIT TO 17 POINTS STARTING AT 919

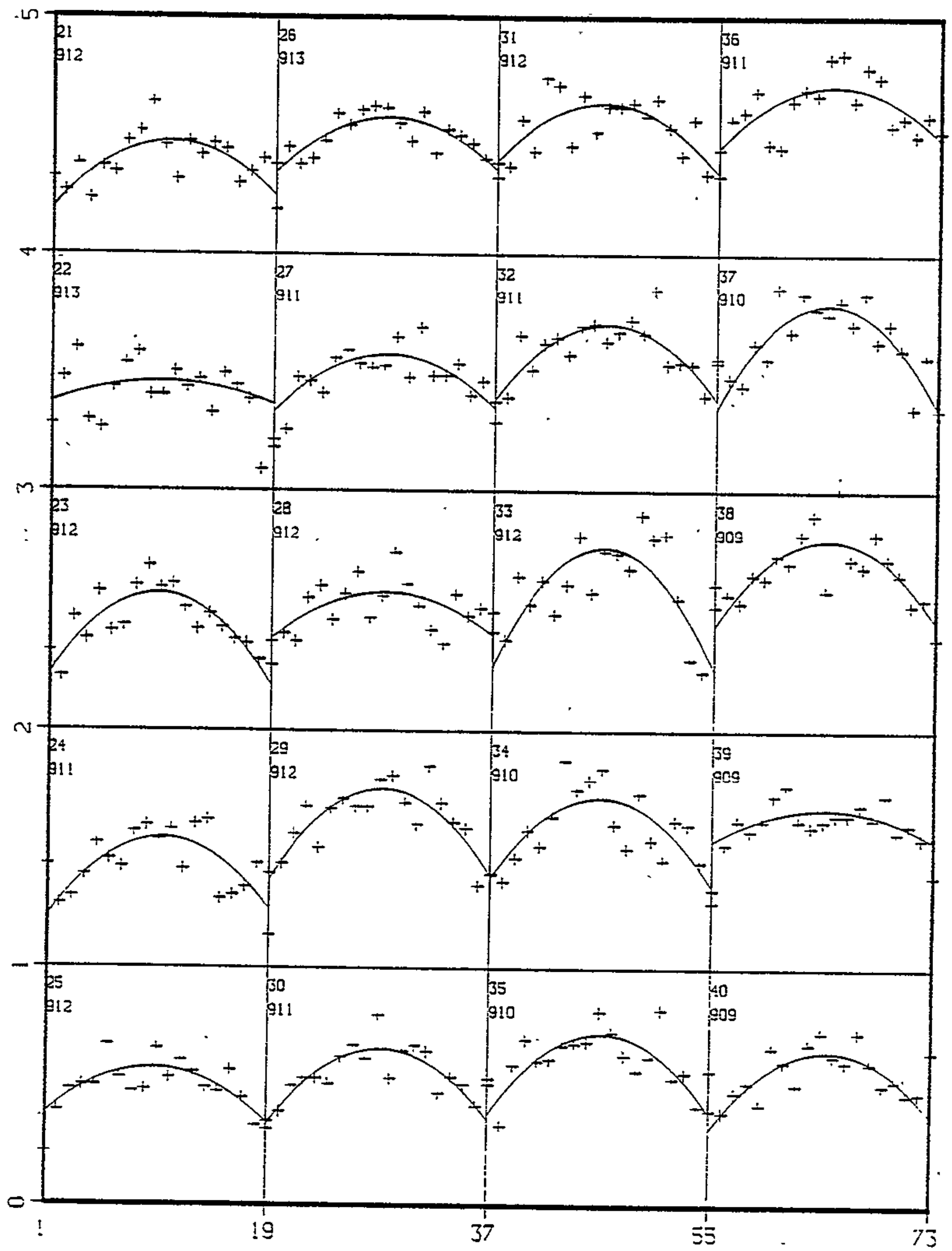


Figure 3

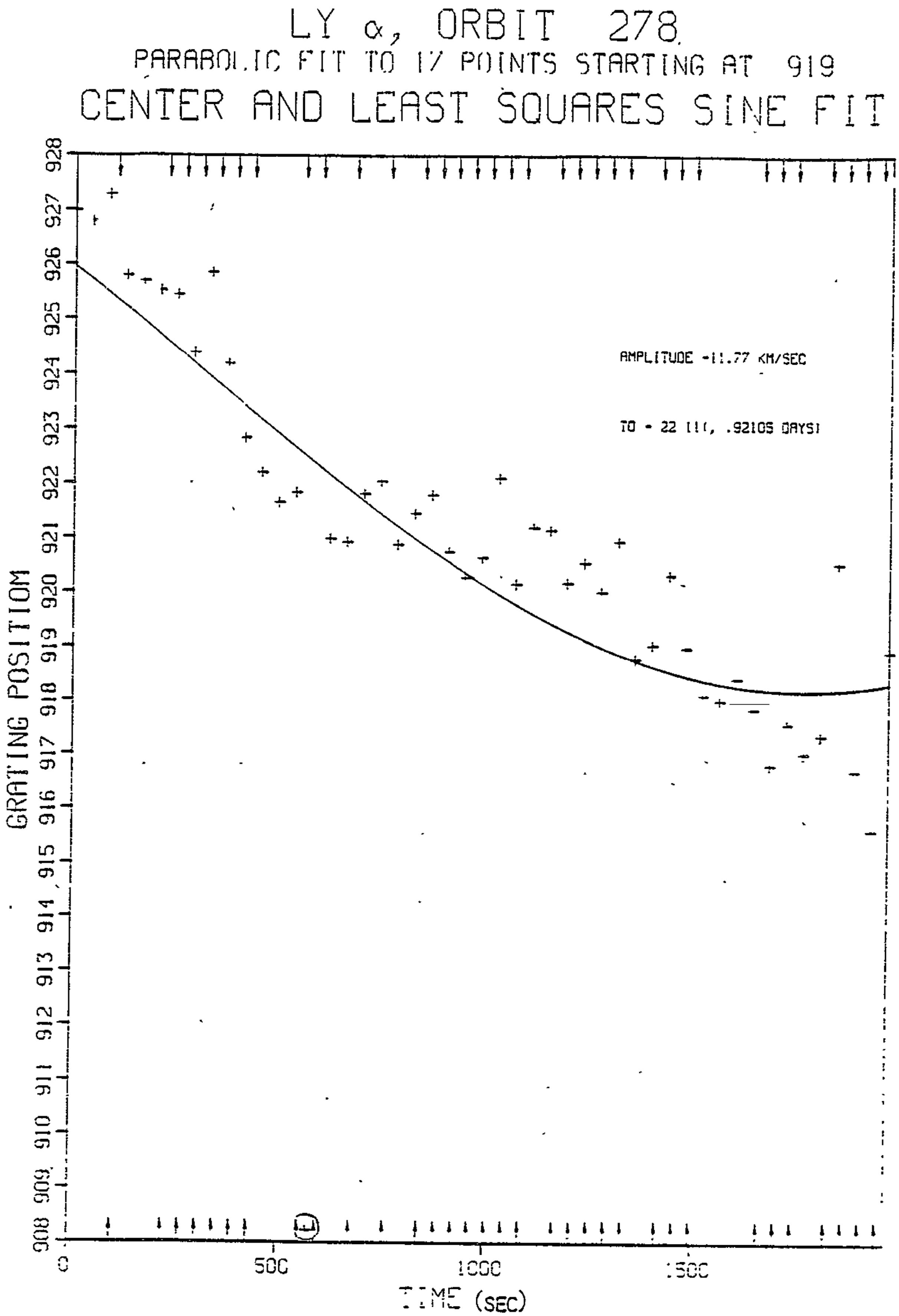

LY α, ORBIT 278
PARABOLIC FIT TO 17 POINTS STARTING AT 919
CENTER AND LEAST SQUARES SINE FIT
AMPLITUDE -11.77 KM/SEC
TO - 22 11(, .92105 DAYS)
GRATING POSITION
TIME (SEC)
0
500
1000
1500

Figure 4

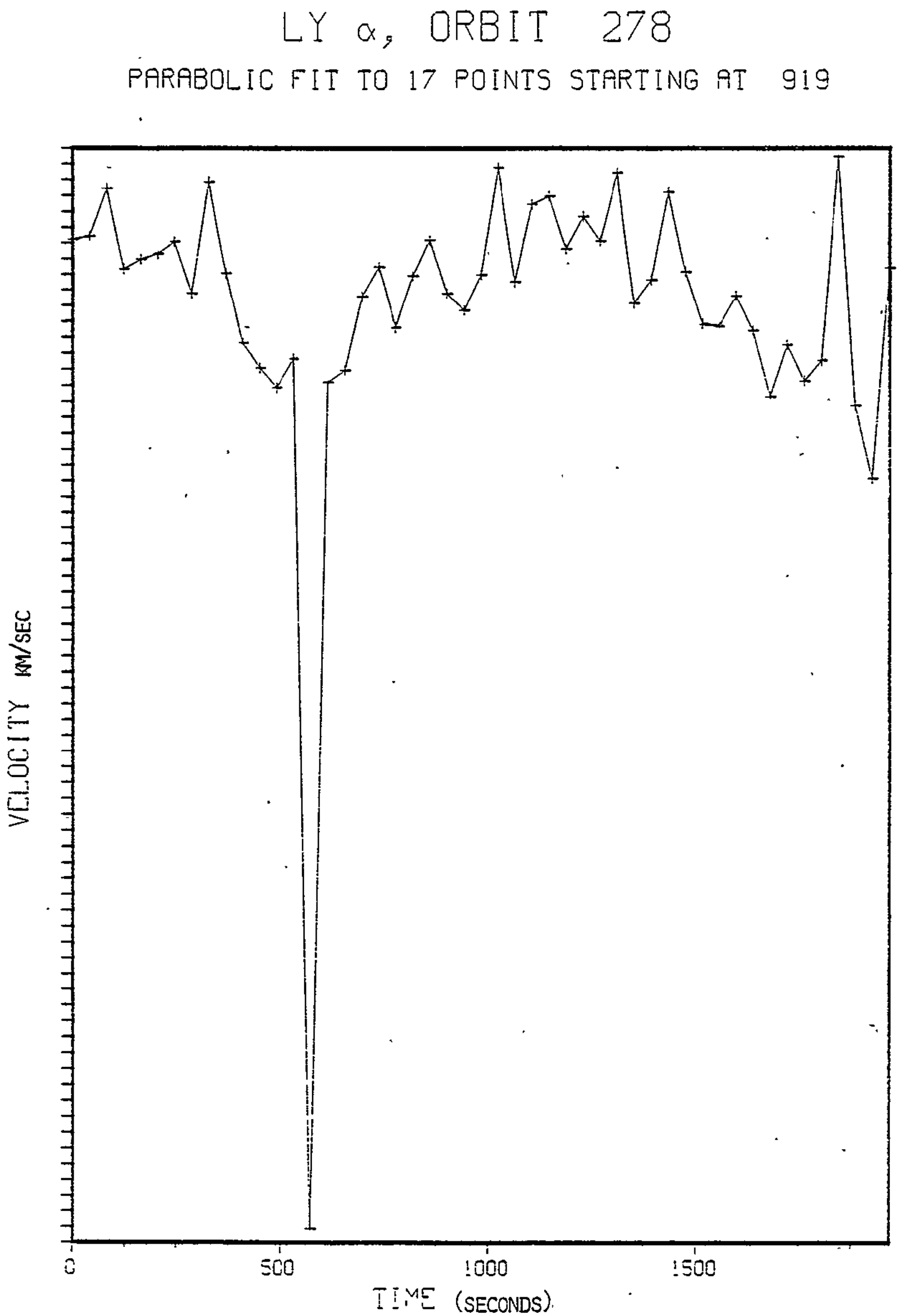
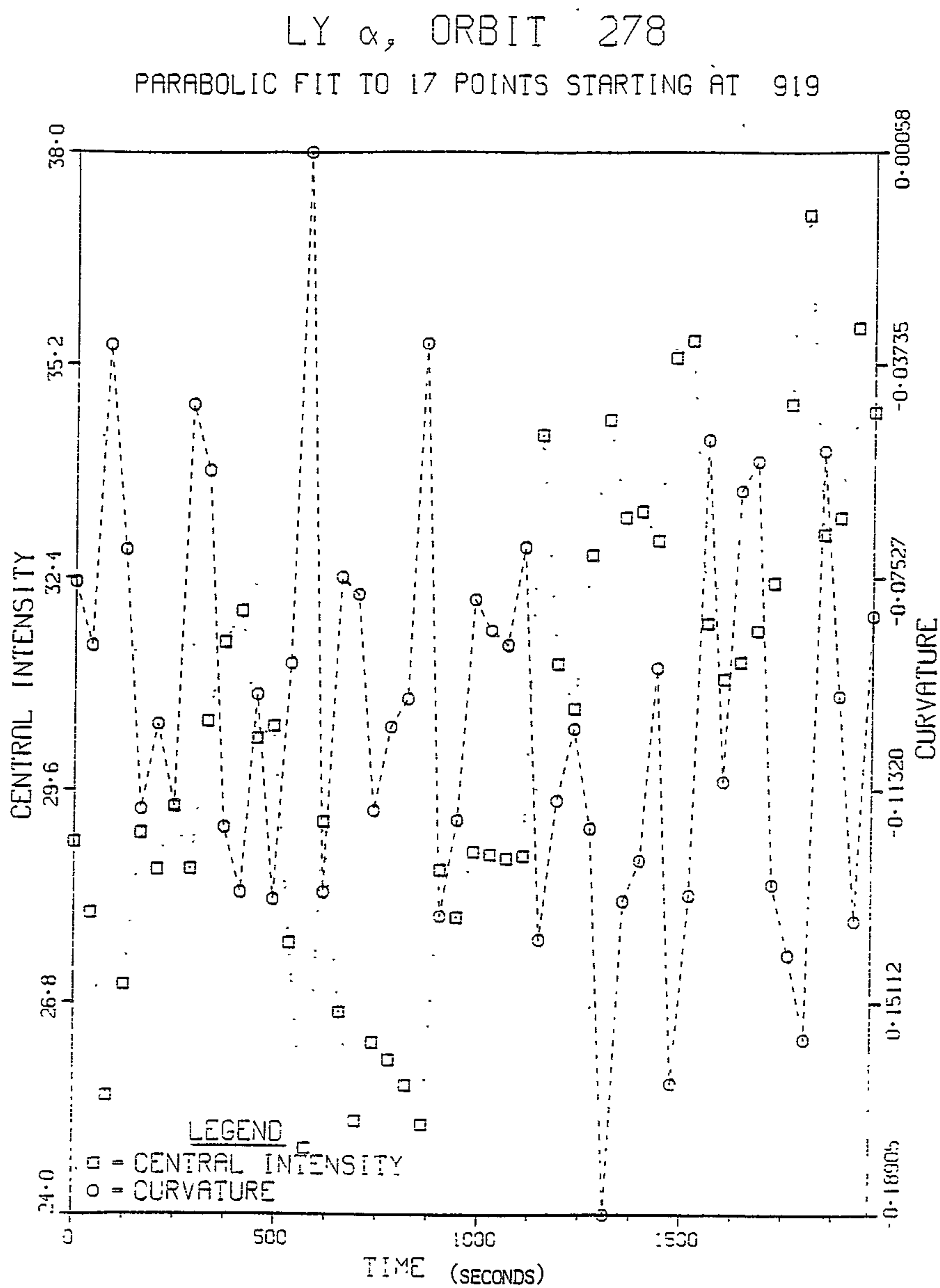

LY α, ORBIT 278
PARABOLIC FIT TO 17 POINTS STARTING AT 919
VELOCITY KM/SEC
0
500
1000
1500
TIME (SECONDS)

Figure 5



LY α, ORBIT 278
PARABOLIC FIT TO 17 POINTS STARTING AT 919
CENTRAL INTENSITY
CURVATURE
TIME (SECONDS)
38.0
35.2
32.4
29.6
26.8
24.0
0.00058
-0.03735
-0.07527
-0.11320
-0.15112
-0.18905
0
500
1000
1500
LEGEND
□ = CENTRAL INTENSITY
○ = CURVATURE

Figure 6

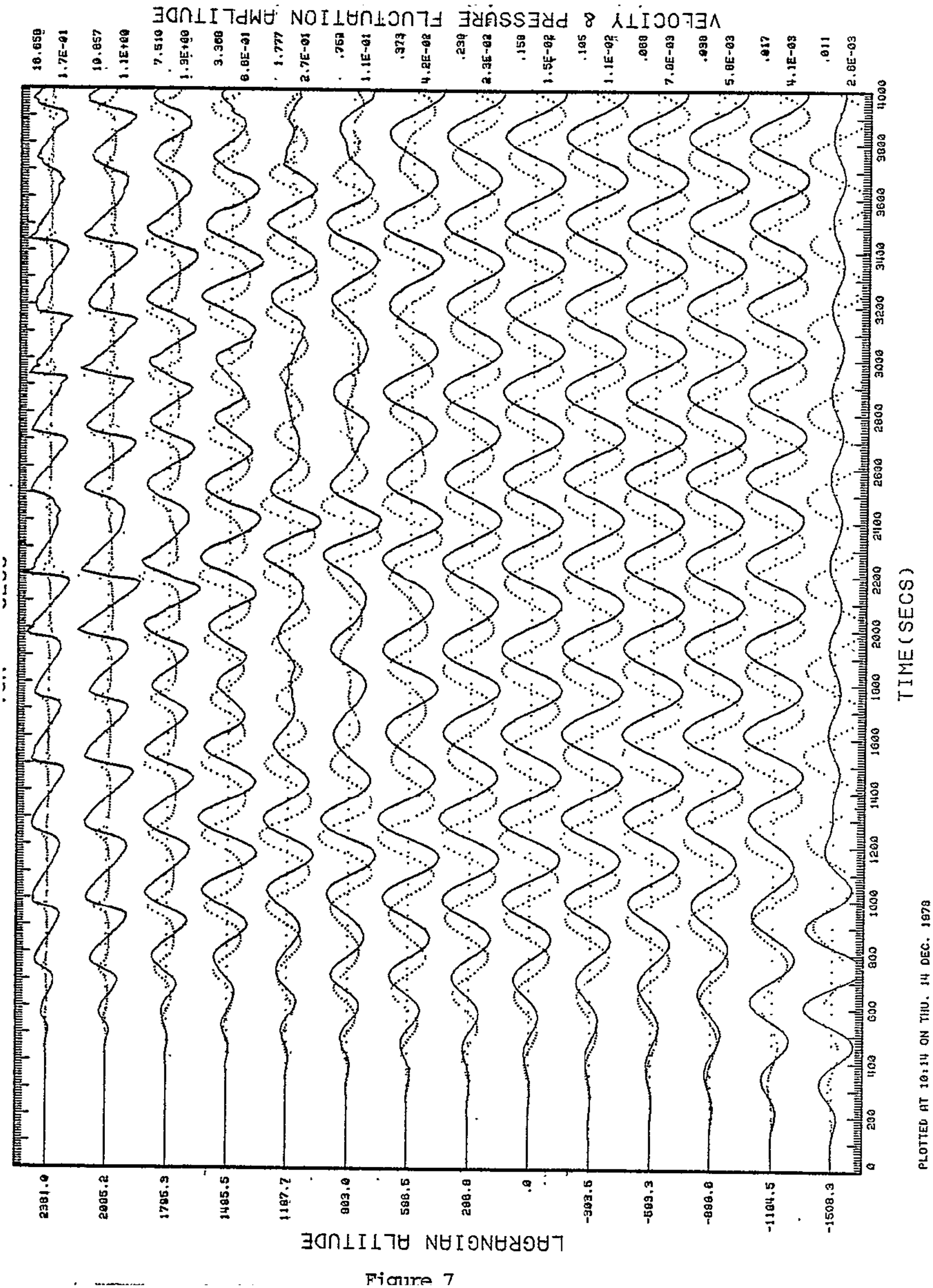

VELOCITY & PRESSURE FLUCTUATION AMPLITUDE
LAGRANGIAN ALTITUDE
TIME (SECS)
PLOTTED AT 10:14 ON THU. 14 DEC. 1978

Figure 7

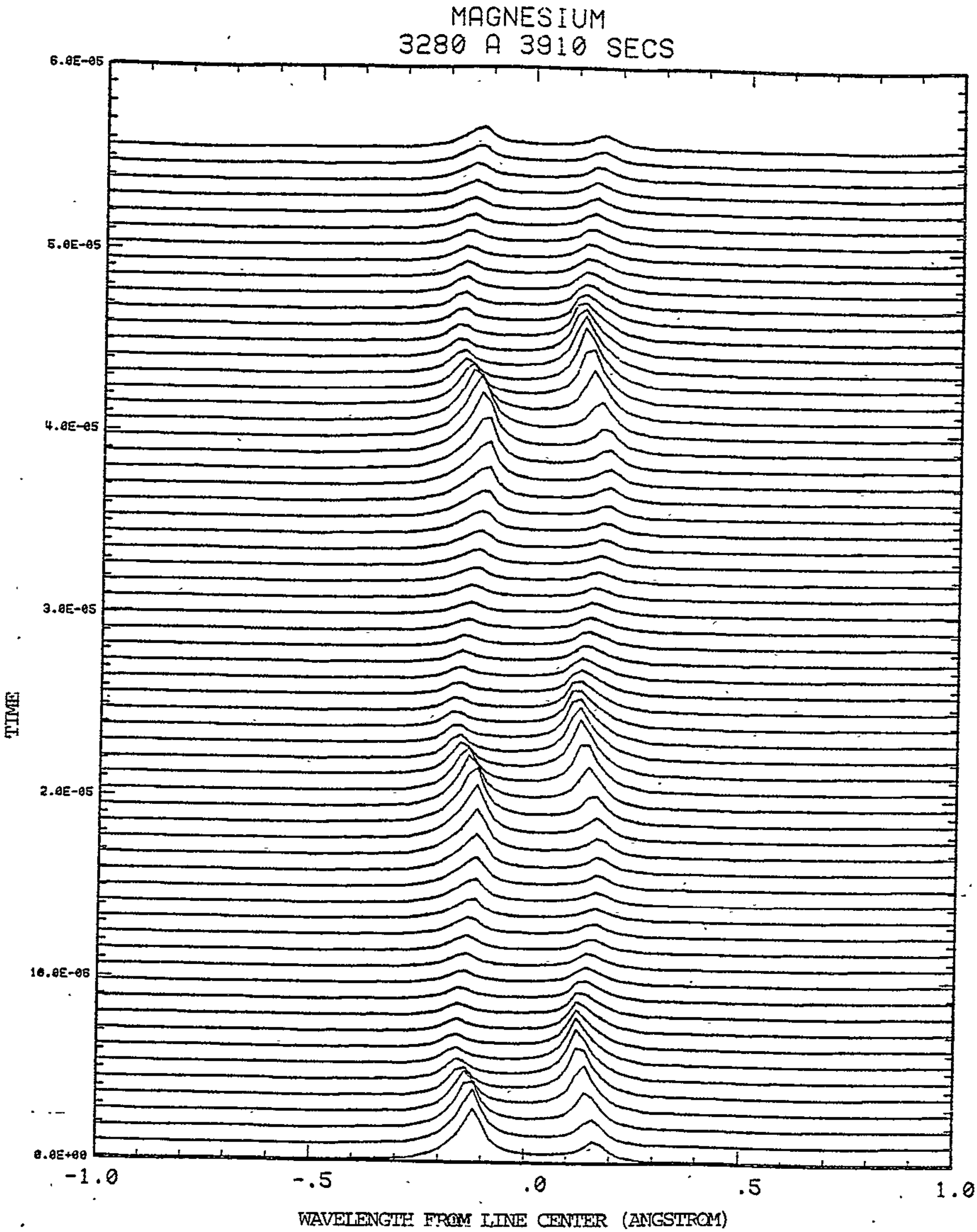


FIGURE 8

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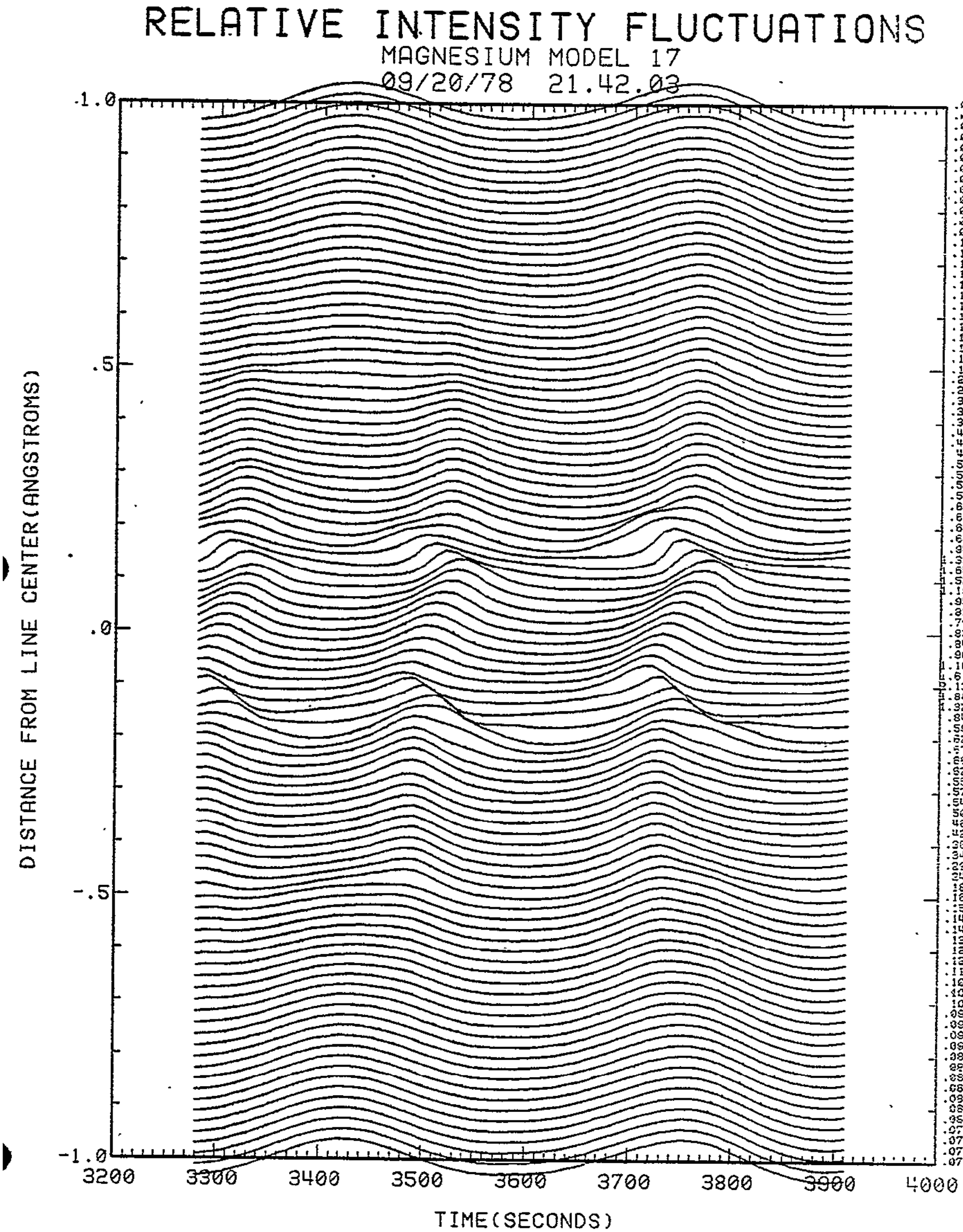
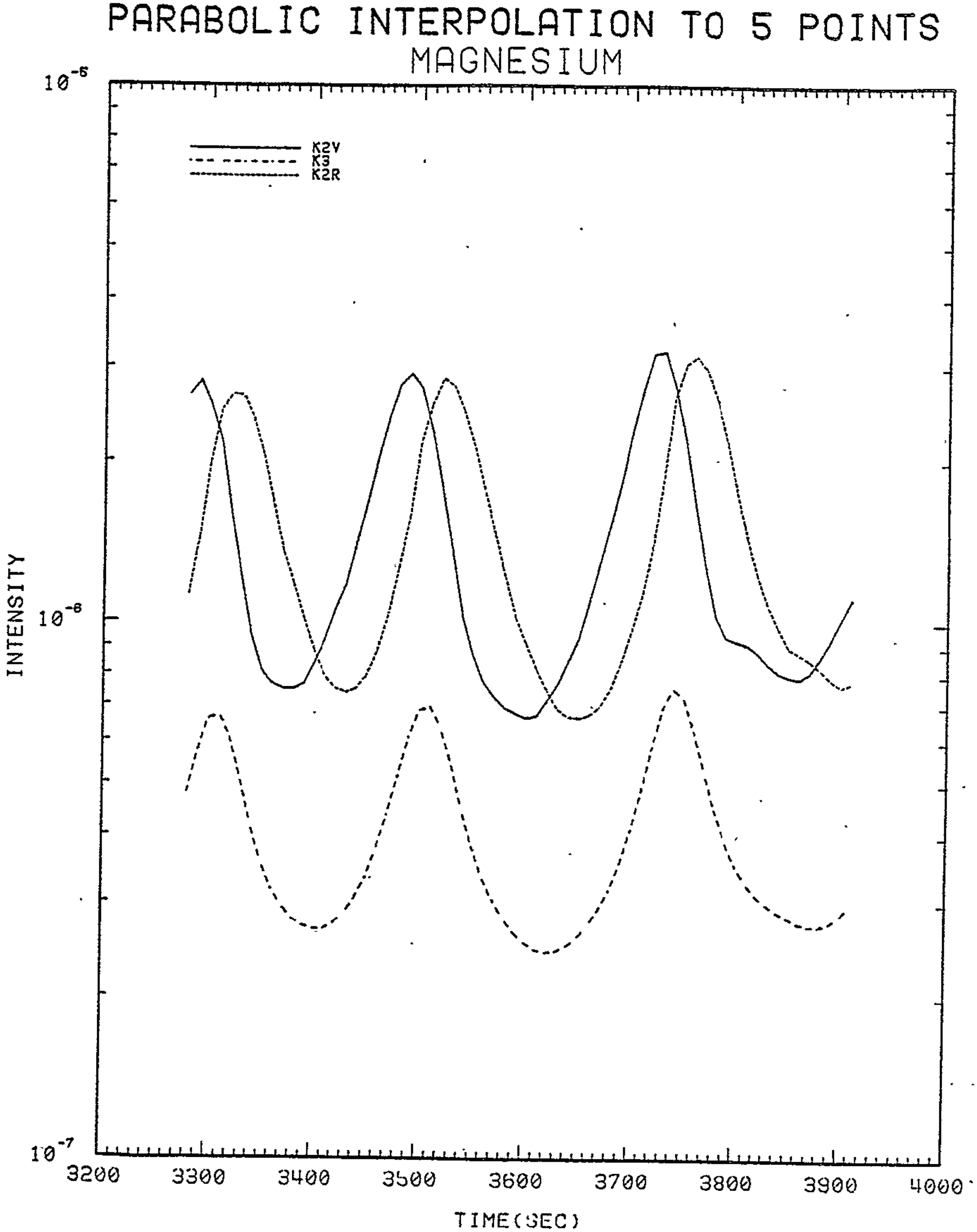


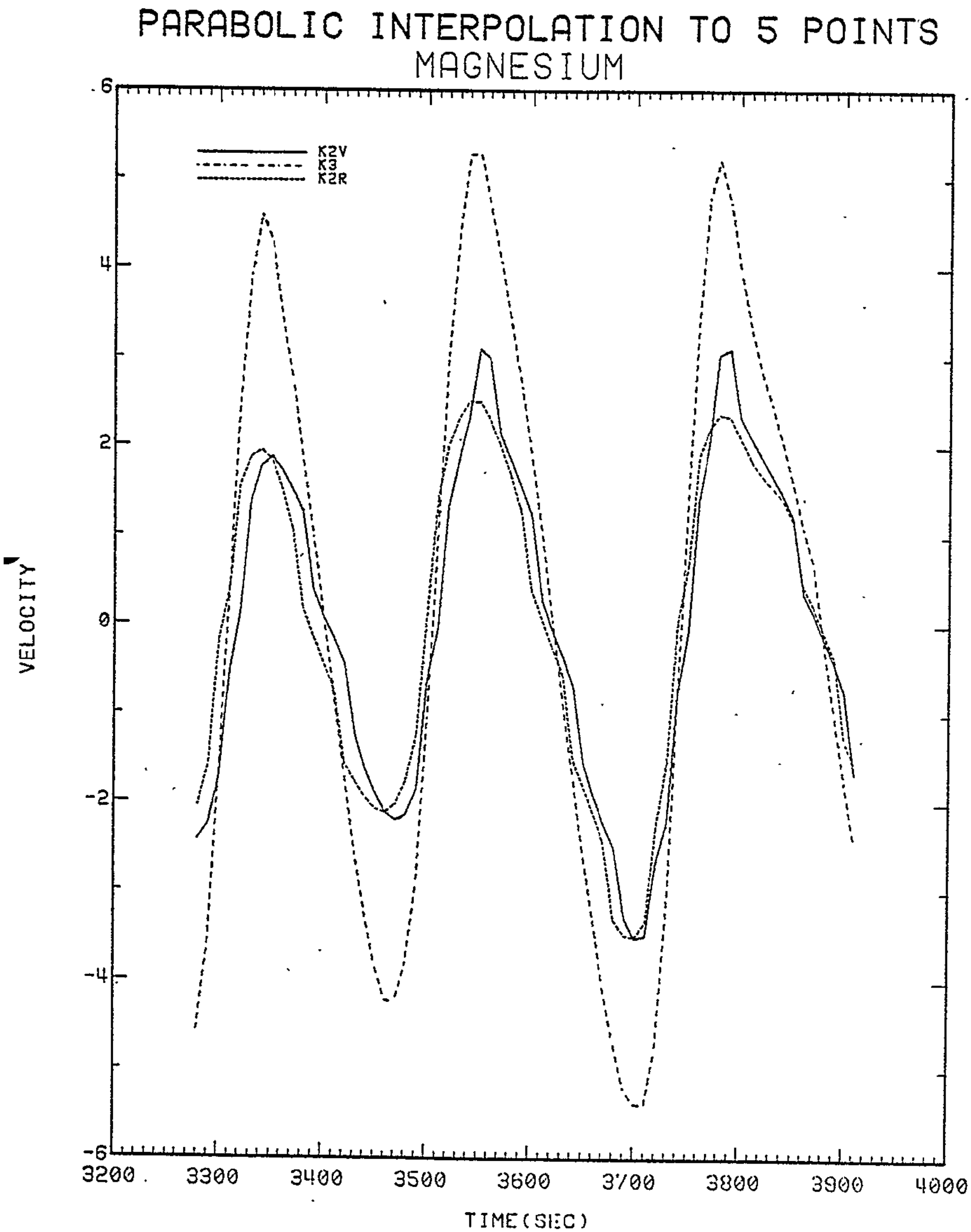
Figure 9

PLOT NO. 1 DONE AT 23:41 ON THU, 4 JAN., 1979



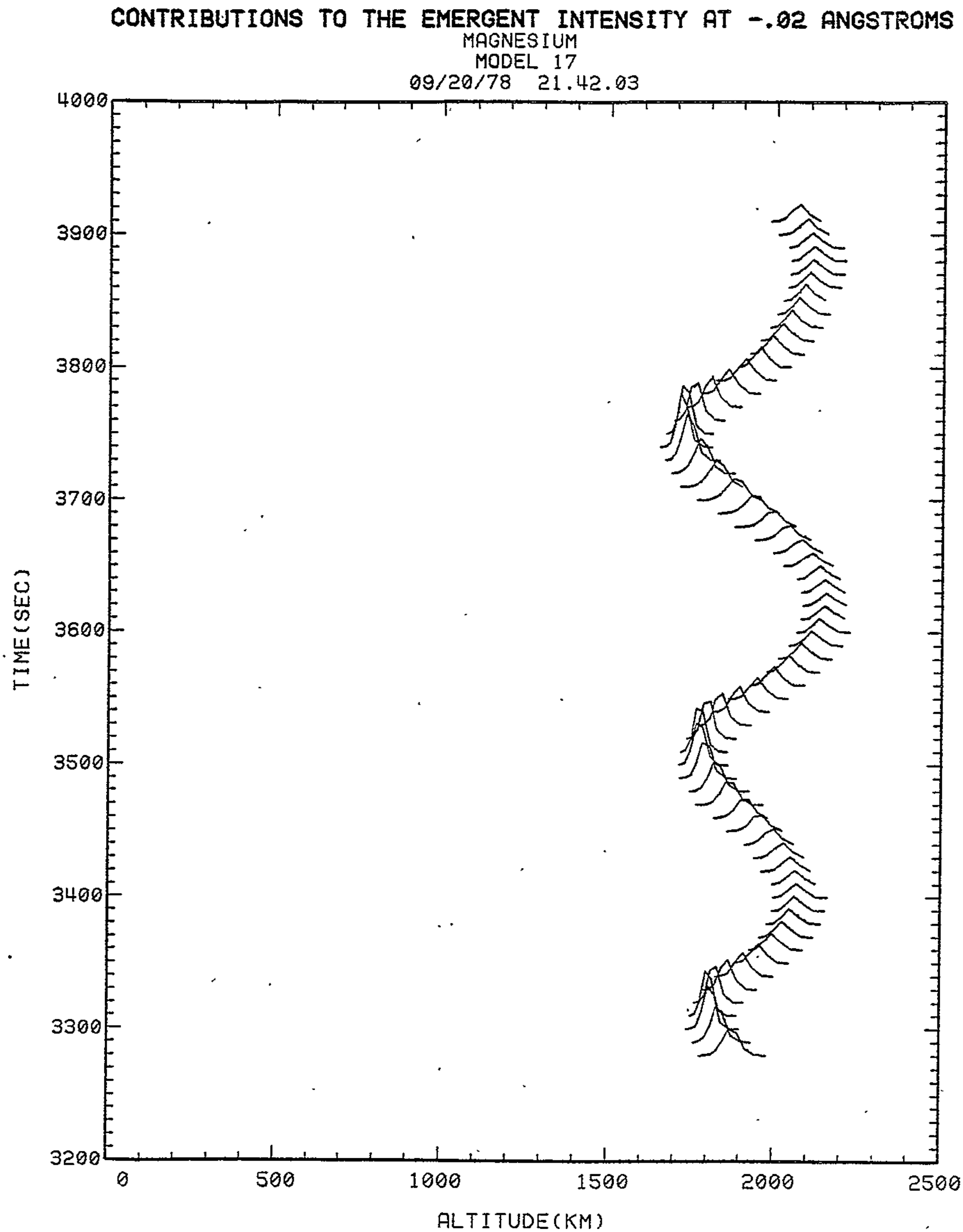
PLOT NO. # DONE AT 14:00 ON FRI, 3 NOV., 1978

FIGURE 10



PLOT NO. 1 DONE AT 14:08 ON FRI, 3 NOV., 1978

FIGURE 11



PLOT NO. 3 DONE AT 1:32 ON WED, 3 JAN., 1979

Figure 12

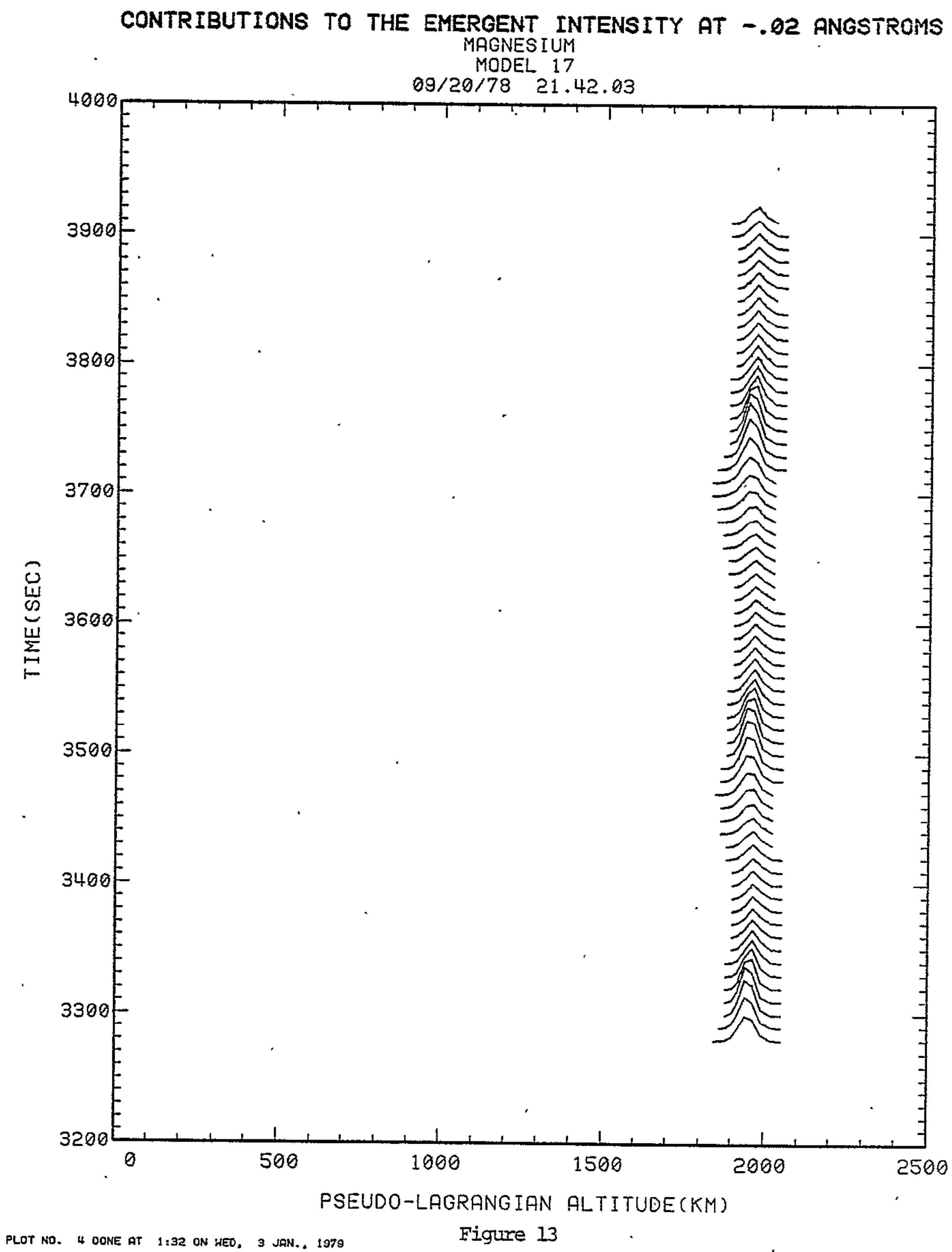
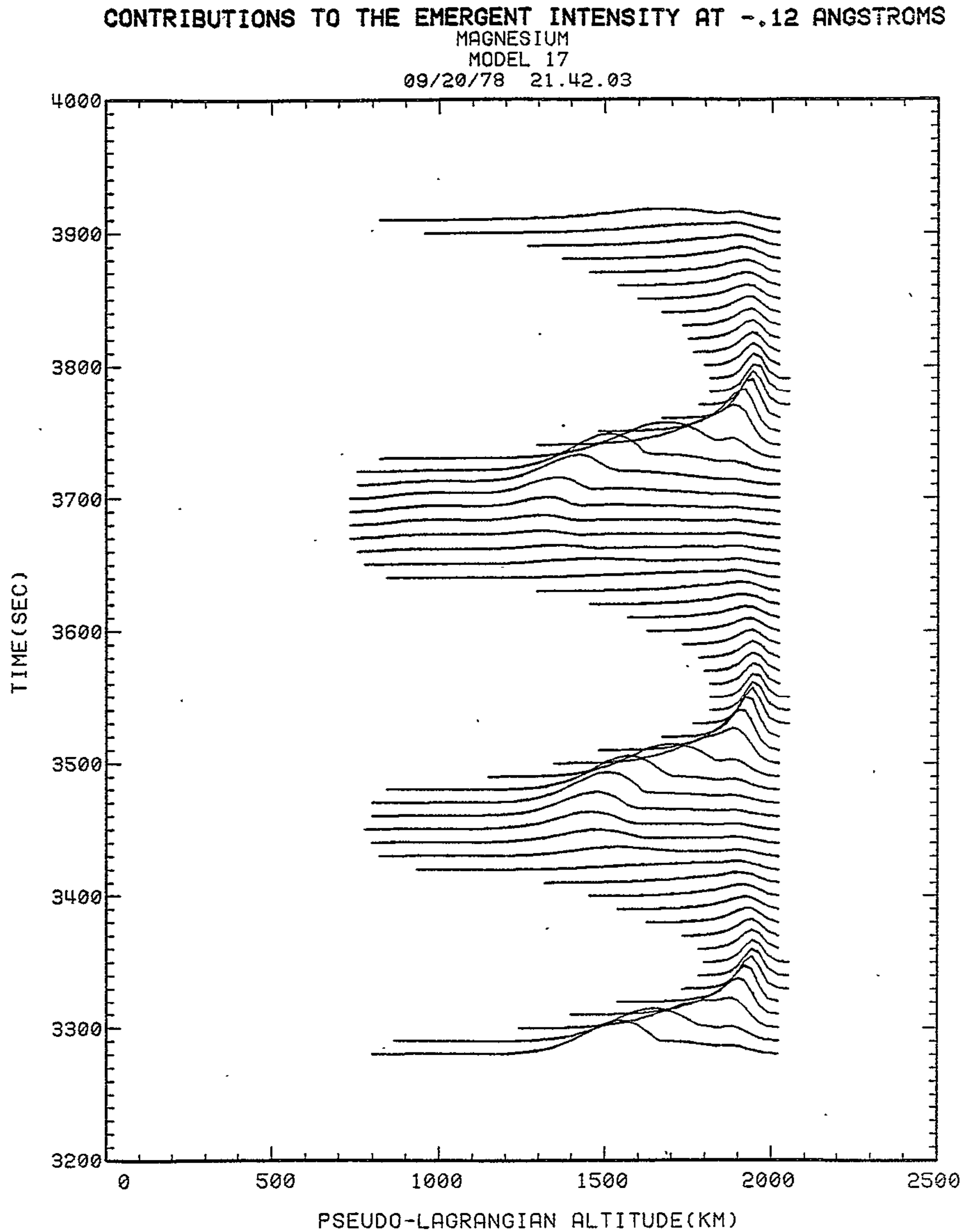
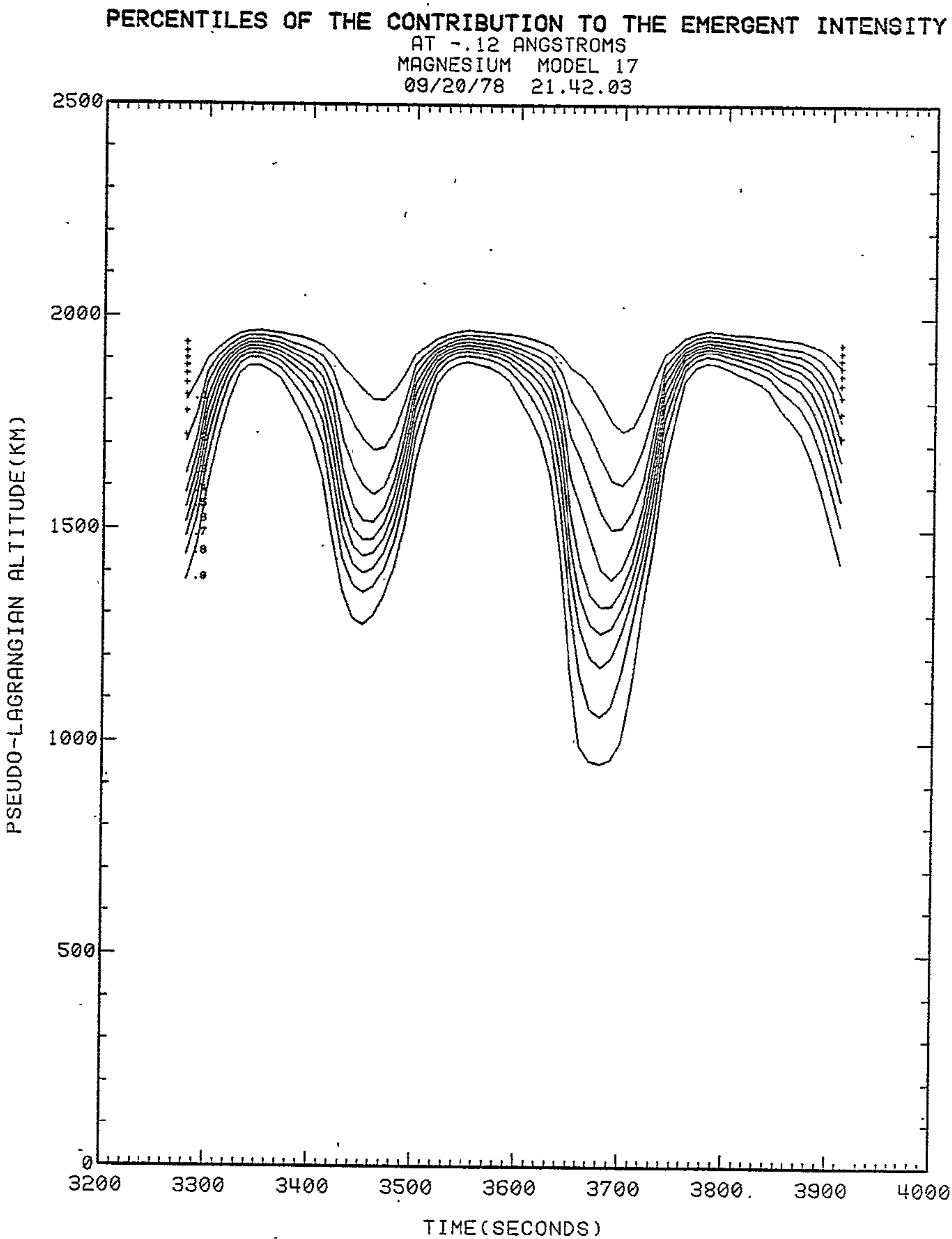

CONTRIBUTIONS TO THE EMERGENT INTENSITY AT -.02 ANGSTROMS
MAGNESIUM
MODEL 17
09/20/78 21.42.03
TIME(SEC)
4000
3900
3800
3700
3600
3500
3400
3300
3200
0
500
1000
1500
2000
2500
PSEUDO-LAGRANGIAN ALTITUDE(KM)
PLOT NO. 4 DONE AT 1:32 ON WED, 3 JAN., 1979

Figure 13



PLOT NO. 4 DONE AT 1: 9 ON WED, 3 JAN., 1979

Figure 14



NO. 4 DONE AT 2:51 ON WED, 3 JAN., 1979

Figure 15

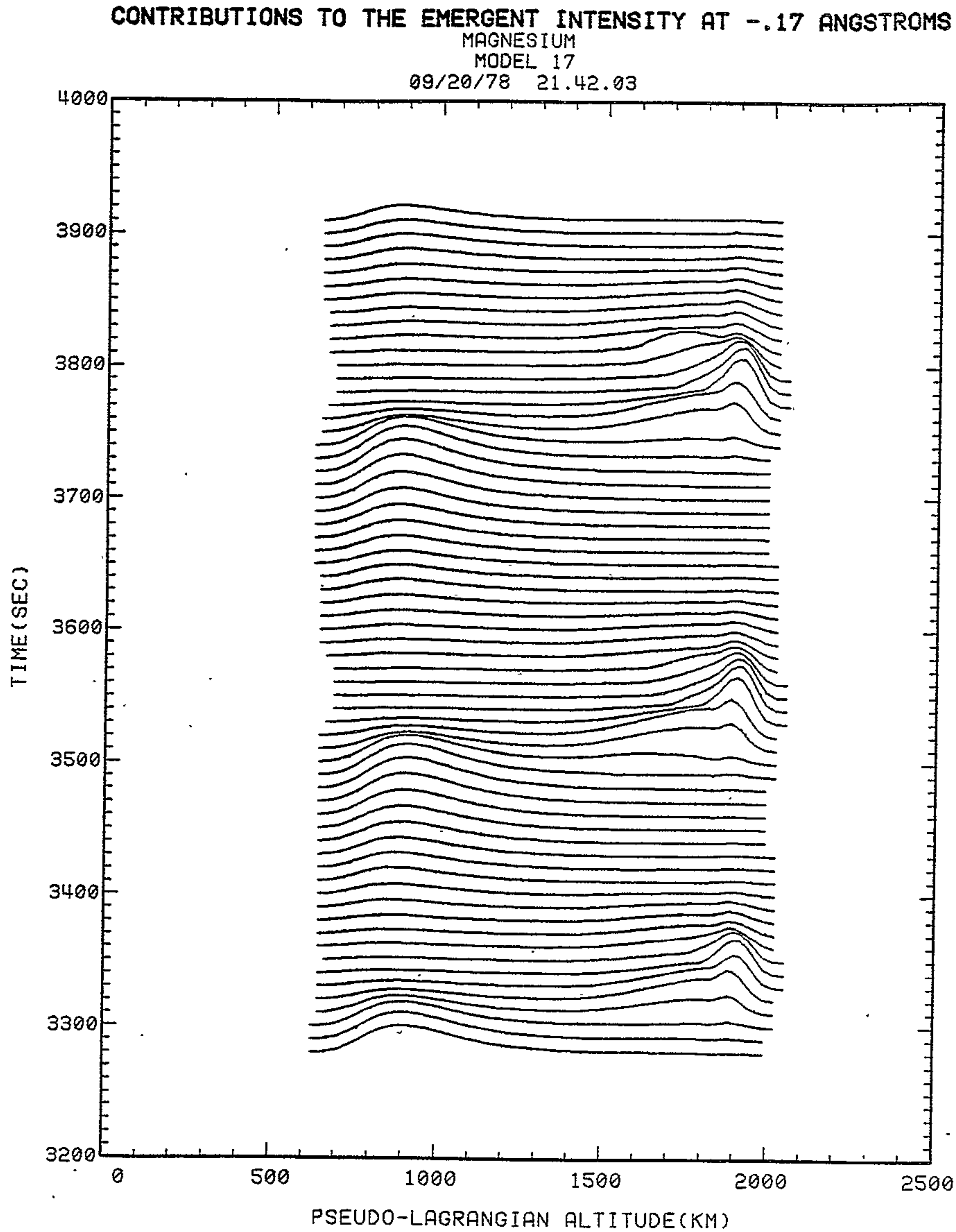


Figure 16

PLOT NO. 2 DONE AT 1: 8 ON WED, 3 JAN., 1978

Attachment A

A RECOLLECTION OF
LECTURES PRESENTED AT THE "ETTORE MAJORANA"
CENTRE FOR SCIENTIFIC CULTURE

Velocity Fields in the Solar Atmosphere: Theory

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INTRODUCTION

The distribution of topics for discussion at this School demonstrates conveniently the importance currently accorded to dynamical effects in determining the structure of the Sun -- on a global scale in determining the overall energy transfer and on a local scale through their interaction with the spectro scopic diagnostics upon which essentially all of our information is based.

In addition to providing glorious sunsets over the Aegadian Islands, and a source of fascinating astrophysical problems in its own right, the Sun provides us with a conveniently located setting in which to observe a wealth of processes; many of which may be associated with only minor perturbations of the gross solar structure but whose presence has awakened us to their possible importance which has then subsequently been identified in more interesting and bizarre objects. For example, the discovery of the "relatively inconsequential" solar wind, which carries but 10^{-14} solar masses per year and only a few percent of the solar energy flux, some twenty years ago, underlies our developing models for more massive stars, where the mass flux may exceed 10^{-3} solar masses per year, and for the more exotic X-ray producing close binaries. The complexity of the phenomena that astrophysicists undertake to describe -- although sometimes we may delude ourselves into thinking that we may actually be "explaining" -- has become sufficiently overwhelming that few, if any, theoreticians would seriously support the contention, attributed to Eddington, that a sufficiently well intellectually endowed astronomer, on the surface of a perpetually cloud covered planet should be able to "deduce" the properties of the Sun and other constituents of the firmament "from first principles." On the contrary, educated observational serendipity has indisputedly played a major role in advancing our appreciation of the physical conditions which exist in the universe, far from the limited horizons of our puny imaginations; e.g. the discovery of pulsars, or the "five-minute" oscillation.

In much the same way that observational and theoretical discoveries work together symbiotically to advance our appreciation of the Sun, or any other object, astrophysicists are beginning to realize that the Sun plays a seminal role in developing our understanding of other astronomical objects. (See for example, Pecker and Thomas, 1976.)

With this "relevance" of solar physics in mind, the organizers of this school encouraged the participants to open themselves to the more general problems of astronomy which we all have struggled to do, in spite of our unfortunate inclination as technicians to revel in the detail of the problem at hand. I should point out that the course was based almost entirely upon the information furnished by diagnostics in the visible spectrum, so that relations between solar and extra-solar astrophysics associated with "energetic" phenomena -- as seen in the radio or X-ray spectrum -- were essentially excluded. This is not to say that these relationships do not exist; and in fact it is difficult to imagine that the physics of magnetic field line reconnection, extensively studied in the earth's magnetosphere, and placed in an astronomical context in solar flares will not prove to be an important effect in other areas of astrophysics.

The present subject touches, and overlaps, with the material presented by Deubner and Ulmschneider. In some loose sense, the temperature minimum forms the dividing line between the atmosphere discussed by myself and by Ulmschneider. Thus, I did not consider the complicated velocity field observed in Hα for example -- about which there has been little hydrodynamic modeling. Furthermore, several hydrodynamic phenomena of major astrophysical importance which nonetheless are traditionally considered to be unrelated to the problems of maintaining a chromosphere and corona or accounting for the small scale (less than a tenth of the solar radius) dynamic properties were not included. For a recent discussion of differential solar rotation, the reader is directed to the reviews by Durney and Gilman. The recent resurgence of interest in the problem of the solar dynamo has been discussed by Stix (1974). These effects, which appear to play rather secondary roles in the Sun, are thought to be of major significance in early type stars and in evolved, rapidly rotating objects and once again we may anticipate that the lessons learned in the rather well behaved solar "laboratory" will help to unravel these more complicated problems.

Within this framework, I presented four lectures which encompassed convection, the generation and propagation of waves, and a discussion of models of the "five-minute" oscillation; all in the cursory nature that the number of topics per lecture suggests. This material has been presented elsewhere many times and in many forms, and my own selection reflected fairly faithfully my previous summaries in this domain: Leibacher (1973), Stein and Leibacher (1974), Leibacher and Stein (1975). There is little reason to supplement the already well documented introductory material with yet another reformulation of the basic equations; instead, I shall take this opportunity, after a brief discussion of what I consider "the problem" to be, to point out some of the more recent publications of interest and to enumerate some of the problems for theory and for observation that I consider exciting in terms of their importance yet rewarding in terms of their tractibility Finally, I shall indicate where one may find the "well documented introductory material."

WHAT IS THE QUESTION?

The existence of hot solar and stellar coronae and the restrictions imposed by the second law of thermodynamics upon the transfer of energy from a cooler to a warmer body have posed a sufficiently long standing problem in astrophysics that one begins to think of it as a "classical problem." As is worthy of a classical problem, there is a classical suggestion for a solution (although venerable might be a more appropriate word) advanced by Biermann (1946), Alfven (1947), and Schwarzschild (1948), that propagating disturbances generated within the hydrogen convection zone carry energy outwards to lower density regions where, upon dissipation, the temperature rises above that attainable in thermal equilibrium. Although there exists a large body of circumstantial evidence suggesting the veracity of this suggestion, and it is attractive on many grounds, there is little, or no, compeling reason, observation or motivation for accepting it. In fact, other possibilities exist. For example, our currently developing picture of the quiet sun being rather liberally sprinkled with bundles of magnetic field, whose energy density is comparable with that of the surrounding gas, should certainly give us cause to reflect that whatever gives rise to the enhanced heating in active regions -- another "classical problem" -- might well be occurring on a widespread, but microscopic, scale. This "suggestion" has the appealing aspect that it combines two "classical problems" (although it solves neither).

At the same time that Schatzman (1949) and Schirmer (1950), among others, were exploring the theoretical and practical ramifications of the "classical suggestion" and hydrodynamicists were -- for entirely unrelated reasons -- developing the theory for the generation of waves by turbulence -- "jet noise" --

Lighthill (1952), some brave souls were out looking to see if one could actuall observe these propagating disturbances (e.g. Richardson and Schwarzschild, 1950). Because the convective source of the motions was assumed to be turbulent, it was supposed that the disturbances would also be characterized by a noise spectrum -- an assumption which Leighton (1960) dramatically showed to be incorrect with his discovery of the so-called "five minute oscillation." (See Michalitsanos,1973a, for a discussion of the models.) So now in addition to the energy flux problem there was added this curious resonance of the solar atmosphere and the obvious question: were the two related? In some fundamental sense, the two problems are very different. The heating of the corona and chromosphere may be thought of as an effect in search of a cause.(We diagnose the corona to be hot. What makes it that way?) Whereas the "five minute" oscillation in addition to being an effect in search of a cause has spent the majority of its existence as a problem faced with the supplementary difficulty of our not knowing what it (the effect) was. The identification of the nature of the problem, once we recognized its peculiarity, was long in arriving: given the hypothesis that we were seeing a wave motion, was it an internal gravity wave or an acoustic wave?, was buoyancy or compressibility the dominant restoring force? , and for either of these possibilities was it a free or a driven oscillation? It may be presumptuous to think that we have succeeded today. Although it "seems" clear (observationally) that the "five minute" oscillation is associated with the quiet, non-magnetic Sun, there exist a host of other observed motions for which the preliminary, diagnostic problem is unresolved, whose relationship with magnetic fields is less clear: granulation (normal, penetrating, exploding, and abnormal), supergranulation, micro- and macro-turbulence, chromospheric bright points,... In addition there exists another whole class of problems of identification of motions "clearly"associated with magnetic fields: downflow over (in) plages, running penumbral waves (Zirin and Stein, 1972), umbral bright point oscillations (Phillis, 1975), spicules (Beckers, 1972)... The search for observational and theoretical models for these modes of motion is an exicting enterprise not only in its own right; but also for the implications that these modes may have for the overall energy balance of the Sun. In this regard, I want to draw attention again to the largely unexplored importance of magnetically associated velocity fields for heating stellar chromospheres and coronae. Although these modes may turn out to be energetically unimportant overall for the Sun, we already have indications that chromospheric activity in other stars is related to their magnetic field, through their rotation (Skumanich, 1972). Be that as it may, our purpose here is to discuss, if not promulgate, the conventional wisdom; so let us see what sort of model has emerged in the thirty years since Biermann's suggestion from this collective human enterprise we call "doing astrophysics."

A SCENARIO FOR THE QUIET SUN, WITH DIGRESSIONS TO ADDRESS THE QUESTION: WHAT QUESTIONS ARE PEOPLE ANSWERING?, AND STILL OTHERS TO ASK: WHAT QUESTIONS MIGHT WE POSE (WHICH WE MIGHT SOLVE), WHICH COULD SHED SOME LIGHT ON "THE QUESTION"?

I would like to present here an equationless description of one man's picture of the hydrodynamic state of the lower solar atmosphere, pointing out as we go those areas currently being analyzed in some depth, and some others which seem to be amenable to treatment in some small fraction of the human lifespan. I shall not pretend to attain completeness, and I council the less initiated reader to stop and read my two previous reviews -- Leibacher (1973) and Stein and Leibacher (1974) -- instead. I will try to limit myself here to the literature which has appeared since those were published. Let us start in the convection zone -- which I have even fewer pretentions of competence about discussion than I have for the regions above the visible surface, and which I include only at the request of the organizers for the sake of completeness -- and pan upwards.

First of all, as with "the question," the convection zone is of interest both insofar as it affects the gross thermal structure of the solar envelope (what is the resulting temperature-pressure profile?) and for the effects caused by its dynamical state (i.e. the fluctuating velocity and temperature fields which carry the convective flux). We have learned in this decade that the observable dynamic and thermal phenomena of the visible solar atmosphere (i.e. that part of the sun amenable to direct diagnostic techniques) are directly sensitive to the dynamic and thermal state of the convection zone, so that the optimistic among us have begun to imagine the day when we might use the photosphere to diagnose the subphotospheric layers, and the truly adventuresome have already started to do so (Ulrich and Rhodes, 1977)

Because of the high opacity, due primarily to the negative hydrogen ion for temperatures near and above the temperature of the visible surface, a very steep temperature gradient is necessary to transport energy efficiently by radiation -- compared to a more transparent atmosphere at the same temperature. (Crudely we might imagine the radiative transfer of energy as requiring a certain temperature difference per photon mean free path, independent of the geometrical scale.) If the outward decrease of temperature exceeds the decrease in temperature of a parcel displaced outward slightly by an arbitrary little demon, then the parcel will be hotter than its surroundings, hence less dense, hence buoyancy will accelerate it outwards and transport energy: we say that the temperature structure is convectively unstable. The rate of decrease of temperature of our displaced parcel as it moves outwards is determined by its specific heat (at constant pressure), and this also undergoes a dramatic increase just below the visible surface. When an abundant atomic constituent of a gas -- such as hydrogen or helium -- is undergoing ionization, i.e. it is ~ one-half ionized, the change in internal energy required by an adiabatic change in volume is primarily achieved by a change in the ionized fraction, rather than by a temperature change as is the case for a neutral or completely ionized gas. Ionization changes are much more effective than temperature changes, because the energy liberated (or absorbed) in a recombination (or ionization) is many times the thermal energy, when the gas is half ionized. (For densities characteristic of the solar hydrogen ionization zone, the thermal energy is only one-tenth of the ionization potential.) Thus, the outward decrease in temperature experienced by the demon's little parcel may be an order of magnitude less than it would have been, had the atmosphere not been half ionized, and hence a correspondingly smaller temperature gradient will be convectively unstable. These two effects conspire to make convective motions the dominant source of energy transport within the outer third of the sun. Because of the high efficiency of convective energy transport as we understand it today, i.e. the phenomenological, mixing-length formulation, the actual velocities of the convective "blobs " required to transport the solar flux are very small compared with other characteristic velocities of gas, such as the velocity of sound waves, throughout all but the upper most several scale heights -- where the velocities become rather large. So large that we should exercise more caution than is frequently done in applying the results of these calculations. This cautioned is even more called for, and even more callously ignored, in other stars where obviously fallacious supersonic convective velocities are calculated, and occasionally even "used."

The mixing length approach and the majority of other discussions of convection are based upon the Boussinesq approximation that the flow is essentially incompressible except insofar as the buoyancy force is concerned (see Spiegel and Veronis, 1960). This requires, essentially, that the vertical scale of the motion be infinitesimally small compared with the scale height of the atmosphere. (However, in its application, the mixing length formation sets these two equal to one another!) The result is a completely locally specified "diffusive" process so that this mechanical transport can never become uncoupled from the local thermal structure, which it in turn controls, until some other competing mechanism takes over part of the energy transport. Non-local mixing length theories have been created (e.g. Ulrich, 1970a), but some uncharitable commentators have likened this approach to adding new epicycles to the Ptolemaic model.

The Boussinesq approximation is around for a good reason -- convection is "difficult," and the "problem of compressible convection" is probably not going to disappear in the next decade. Nevertheless, certain aspects amenable to treatment by the "anelastic" approximation (which essentially filters out sound waves -- Latour et al., 1976) probably are. In addition, the dynamical effects of convection in stars earlier than spectral type F5, where convection is no longer significant energetically, are probably amenable to discussion now. Furthermore, with the relaxation of the purely local description we may find a natural explanation for the bimodal distribution of horizontal scales (granulation and super-granulation). The effect of a magnetic field upon granulation, long a subject of interest only for sunspots, has assumed a much broader importance with the discovery of filigree (Dunn and Žirker, 1973) and the correlation with the fuzzy "abnormal" granulation (Ramsey, Schoolman and Title, 1977).

Because of the non-zero momentum with which convective elements reach the limit of the convectively unstable region, they will penetrate into the stable region. This appears to occur on the Sun where granulation is observed several scale heights above the level of neutral convective stability. At first thought, the absence of driving might make this seem like a simple problem until one considers the difficulties encountered by meteorologists in discussing thunder cloud penetration into the tropopause, despite the enormously simplified diagnostic problem that confronts them -- they can actually wander around inside the thing which they are trying to understand and sample it!

The description of convection bears directly upon several aspects of the problem of the generation of propagating disturbances. However, before discussing the problem of the generation of waves, it will be useful to recall some of the elementary properties of the oscillatory atmospheric modes of motion bearing in mind my earlier eschewing of completeness and defaulting to earlier reviews. Perhaps the simplest type of motion of an atmosphere occurs when locally a compression occurs (for example, when the boundary moves). Since work has been done on the gas, its internal energy increases; that is to say, its temperature increases. The equation of state for the gas then tells us that a temperature increase is accompanied by a pressure increase -- unless it has an extraordinarily strange equation of state. This pressure increase will result in a pressure differential with respect to the overlying gas so that our compressed gas will move into its neighbor, compressing it and starting off the whole cycle again. Nature can trip through these equations very, very rapidly and the result is known as a sound wave. The speed with which this compressing wave (or rarefraction wave, since the whole process works just as well backwards) moves through the gas is just the root mean square thermal speed of the atoms, to within a constant factor of order unity. The macroscopic motions of the gas are in the direction of propagation, so we say that this is a longitudinal wave. To really get a wave out, however, we have to wiggle our source back and forth; unless we consider that Fourier taught us that a more or less arbitrary disturbance can be considered to be a superposition of sine waves. Since all of the disturbances travel with the same sound speed, the wavelength of a wave is just the speed of sound times its period. As the force which drives this motion - "compressibility" or pressure - does not really care about gravity, the principal effect of introducing a sound wave into a gravitating atmosphere is through the wave's interaction with the density stratification (we could achieve the same thing with a gradient of the mean molecular weight). Roughly speaking, when the wavelength of the wave becomes comparable with the density scale height of the atmosphere, the atmosphere responds with an exponentially decreasing wave, rather than sinusoidally as was the case for the short wavelength waves. Alternatively, in the time domain, as the driving frequency decreases, the atmosphere is eventually capable of responding by rising and falling in phase with the driving. A zero frequency wave is just a compressionless displacement of the atmosphere. Thus, high frequency sound waves propagate ripples (and energy), and low frequency waves do not. The cut-off frequency is very nearly 200 seconds throughout the major part of the photosphere and low chromosphere, and it decreases as the temperature increases -- inversely as the square root of the temperature.

While this describes pretty much the whole story if we push the atmosphere up and down; if we introduce horizontal differences in the gas, buoyancy forces will arise and these too can propagate disturbances. In a convectively stable atmosphere, the parcel perturbed by a little demon would decelerate, return to its initial position and continue to execute an oscillation about the equilibrium. Whereas for sound waves we found a characteristic velocity, for these buoyancy waves the only characteristic quantity is the gravitational acceleration, so the motion has a characteristic frequency. These waves exist in their pure form in incompressible media; where, since there is no compression, the particle motions must be orthogonal to the wave motion, so the wave is purely transverse. If you looked at a wave propagating towards you, you would see no line of sight velocities. Buoyancy also drives waves at the interface between two fluids of different densities -- the familiar water waves which made us all ill on the way to Levanzo -- which are called "surface gravity waves," so to distinguish these waves which occur within a fluid, they are called "internal gravity waves." Since in a convectively unstable atmosphere the little test parcel would not return to equilibrium, internal gravity waves cannot exist there. While the oscillation frequency of the parcel is determined for a vertical displacement, if we constrain it to move at an angle to the vertical it will oscillate more slowly; although if we move it sideways it won't oscillate at all. So internal gravity waves are possible at and below a critical frequency -- referred to as the Brunt-Väisälä cut-off.

If we now "turn-off" the force of gravity and that due to pressure gradients, but consider instead a magnetic field permeating the atmosphere we have another wave mode. If we think of the magnetic field in terms of its lines of force, then these have an equivalent magnetic tension which causes the field line to behave just as a string under tension: it supports transverse oscillations which propagate along the field line at a velocity proportional to the tension and inversely proportional to the density. In a compressible gas, in addition to this compressionless Alfven wave, two other wave modes exist: one which looks very much like a normal compression, or sound wave, the other which looks somewhat like an Alfven wave. Since the propagation characteristics depend upon the angle which the wave makes to the magnetic field, the situation becomes very complicated when one introduces another directional force (gravity). (cf. Schwartz and Stein, 1975.)

Other modes of motion exist; in fact, one for every restoring force which is present. However, none of the others seem to play an important role for the phenomena we are describing. For example, solar rotation introduces a Coriolis force, but the characteristic frequencies are far below those observed.

Every specialty seems to have a favorite diagram, upon which to talk shop and confound the novice, and solar hydrodynamics is no exception: the diagram plots temporal frequency (ω) against horizontal wavelength (k_x) and is called the "diagnostic diagram." As part of the figure, which I discuss later on, note the dashed lines which are the boundaries between regions of propagating waves and non-propagating (or evanescent) waves. The high frequency - low horizontal wavenumber (i.e. short period - long wavelength) region of propagation is due to compressibility - these are sound waves, modified somewhat by gravity. The low frequency - large horizontal wavenumber region arises because of buoyancy -- these are internal gravity waves. Energy is not propagated vertically, by single waves, between the two regions. Part of the utility of this diagram is in the comparison of the regions of propagation for isothermal atmospheres of different temperatures and the discussion of refraction and trapping in regions of varying temperature. (Although there has been some muttered criticism of this procedure recently in astronomical circles, Pierce (1966) has established the equivalence between a series of isothermal slabs and a continuously varying temperature when the interfaces between the slabs are treated correctly.)

Having identified these propagating disturbances, let us return to the problem of their generation in the sub-surface convection zone. The original "suggestion for a solution" of "the problem" was based upon the generation of sound waves by the turbulent convective velocity field (the "Lighthill mechanism") -- an intrinsically inefficient process since the (essentially) incompressible convection couples only weakly (through the quadrupole moment) to sound waves. (See for example Morse and Ingaard.) As a result, the total emitted power is a high power (the seventh) of the Mach number of the flow. In addition, Stein (1968) has shown how extremely sensitive the emitted acoustic flux is to the turbulent spectrum of the source. Limits on the variation of this spectrum would be very important in evaluating the importance of aerodynamically generated sound waves, which appear to be particularly important in heating the chromosphere. Although it makes no sense to speak of an internal gravity wave in a convectively unstable region -- since convection is just the unstable version of internal gravity waves (see Defouw, 1970b, for a nice discussion) -- in a convectively stable region the generation of internal gravity waves by turbulence appears to be much more efficient than the generation of sound waves, because the characteristic velocity of the source is much more nearly commensurate with the phase velocity of the wave. Above the temperature minimum this may be a very important effect, although it does not appear to have been studied in any detail. However, it may turn out to be a difficult problem because of its importance; that is to say that because the gravity wave flux may provide a substantial sink for the driving turbulent field, the Lighthill approach of treating the sources as a priori knowns which are unaffected by the waves, may no longer be valid.

There is a somewhat related, apparently much simpler, problem that has always seemed to be nicely defined and which might give some insight into the previous situation. Consider the motion in an atmosphere consisting of a convectively unstable region bounded by a stable one (or ones) for modes (ω, k_x) which correspond to internal gravity waves in the stable atmosphere, and which would be normal convective motions in the unstable region. Depending upon the thickness of the two regions and the boundary conditions, one would imagine the "eigen-oscillations" to be vibrationally unstable -- sinusoidally varying with an exponentially increasing amplitude -- or simply unstable -- a small displacement would grow exponentially. The driven oscillations in the former case might in fact occur on the Sun.

But, of course, the principal effect of the convective instability is to maintain the temperature gradient just slightly in excess of the adiabatic value throughout the convection zone, with the exception of the ends where a strongly super-adiabatic temperature gradient obtains. Having started with a solar model in radiative equilibrium which turned out to be convectively unstable, and which hence resulted in a model in radiative equilibrium for two ranges of radius separated by a region in convective equilibrium, one might well ask if the resulting configuration is stable; although this appears not to have been asked until quite recently. It appears that sound waves may, in fact, be thermally unstable in the solar convective zones, so that a small amplitude compression wave would be capable of extracting energy from the convectively maintained thermal structure and growing in amplitude, until some other process limited its amplitude. We say that the wave is vibrationally unstable, or overstable.

This somewhat hypothetical possibility has been investigated recently following the suggestion by Ulrich (1970) and Leibacher (1971) that oscillatory instabilities of the kind thought to be responsible for variable star pulsations - the "K", or Eddington value mechanism, as well as the interaction of a sound wave with a superadiabatic temperature gradient in the presence of radiative dissipation (the "Cowling mechanism") - might well be the source of energy to drive the "five-minute" oscillation, once the model of a resonating sub-photospheric cavity had been considered (Leibacher and Stein, 1971). Ando and Osaki (1975) have considered the problem in detail and Graff (1976) has performed an aesthetic analysis of the underlying physics. (It is worth recalling that Moore and Spiegel, 1964, had signaled this possibility over a decade ago, but that the idea lay dormant. Another sad testimony of the "non-linearity" of the process of making progress in astrophysics!) They find that waves in the region of the diagnostic diagram occupied by the "five minute" oscillation do grow in amplitude by extracting heat from the convectively maintained thermal structure in phase with the temperature fluctuation of the wave.* However, the growth rates for the oscillations are very small -- of the order of 500 periods for a factor of e increase - and there exists some serious concern that other processes may stabilize the waves at very small - smaller than observed - amplitudes. In particular, Goldreich and Keeley (1977) have considered a model wave interaction with convection and find that it may quench ths oscillation. (This area of research is of much wider application, for the redward limit of the band of cepheid instability in the H-R diagram may also be caused by the pulsation - convection interaction.) This unfortunate (in the sense that it would be a heavy blow against a personally attractive hypothesis) possibility aside, the "current wisdom" is that the oscillations would grow in amplitude until the mechanical flux, which leaked through the non-propagating region

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* We recall from elementary thermodynamics that heat added when a cyclical fluctuation is warmer than average will increase the energy of the process -- locally reverse the second law of thermodynamics, if you will -- while heat added while the fluctuation is cooler than average will dissipate the fluctuation.

around the temperature minimum, was dissipated in the chromosphere and corona at just the rate that energy was added to the wave in the convection zone. But of course, additional non-linear effects (and it is crucial that the dissipation depend non-linearly upon the amplitude, or else it would just grow at the same rate as the amplitude and never be able to stop the further growth) may turn out to be important, such as saturation of the driving mechanism. This would arise if the amplitude of the fluctuations in the driving region become so large that over part of the wave period the driving became damping (i.e. adding heat during the cold part of the cycle and vice-versa) until finally the amplitude stabilizes at a level such that there was equal driving and damping during a period, and any increase in amplitude would cause a further increase in the damping.

Of course this new source of propagating disturbances will provide chromospheric-coronal heating in addition to that provided by the Lighthill mechanism, and one wonders whether we may not have now provided too much heating. Unfortunately, at least for the high frequency waves generated by the Lighthill mechanism, we may never know if we restrict the discussion to the question of the energy budget, for a very large fraction of the mechanical flux carried by these waves is dissipated by thermal radiative damping as the waves propagate outward through the photosphere. Thus, the mechanical flux available for heating is the difference of two large numbers, neither of which we should expect to estimate to better than "astrophysical accuracy." The high frequency waves (periods of the order of ten to sixty seconds) have the additional characteristic of being essentially invisible -- which even a disinterested bystander would probably admit is a real nuisance. This arises because their wavelength (just the sound speed - 7 km/sec - times the period, for these high frequencies) is small compared to the thickness of the region contributing to the formation of the spectral line profiles which provide our diagnostics. We are then left to infer the existence of these high frequency waves only by the thermal energy they deposit when they become non-linear and dissipate through the formation of shock waves. Deubner in a companion lecture to this one presents a (not universally) accepted interpretation of data that may in fact give us a statistical measure of these waves. Another possible manifestation of these waves is the "fudge factor" from spectral line calculations: "microturbulence." This broadening of absorption coefficients is in fact quite probably nothing more than a random acoustic field. Because of the pressure-velocity correlations of acoustic waves as opposed to convection or internal gravity waves, these different possibilities should be readily distinguishable.

The two different heating mechanisms may also be distinguished by their differing dependence on stellar structure. The vibrational instability mechanisms depends upon the thermal structure of the stellar envelope -- which happens (only extraneously) to be governed by convective energy transport in the solar case -- while the Lighthill mechanism depends upon the turbulent spectrum of the convective velocities. Thus, in stars earlier than spectral type F5 for whom the Lighthill mechanism is expected to yield only a very small acoustic flux because significant convective velocities occur only in regions of low density. A large flux may nonetheless arise from the vibrational instability mechanisms.

Moving upward, the convectively controlled temperature decreases and the opacity with it until the optical depth in the energy carrying part of the spectrum reaches unity, and the atmosphere becomes "visible." At very nearly the same height, in the Sun, convection ceases to be able to carry the thermal flux with a temperature gradient only slightly in excess of the adiabatic value so that the temperature gradient increases markedly and the convective velocity becomes very large (a substantial fraction of the sound speed, according to the mixing length). Because of the decreased opacity, radiation is able to take over the energy transport at this point and as a result the temperature gradient decreases, and the atmosphere becomes convectively stable.

The fundamental dynamic phenomenon of the photosphere appears to be the "five-minute" oscillation, which has received considerable theoretical attention in the past two years primarily related to its suggested capability of converting disorganized thermal energy into propagating mechanical energy, as discussed above.

Personally, the most exciting result has been Deubner's observation of the predicted modal structure in the diagnostic diagram (Deubner, 1975) which has been confirmed by Rhodes, Simon and Ulrich (1977); thus, lending enormous support, if not credence, to the sub-photospheric trapping model. The figure shows these modes in the diagnostic diagram, for a particularly simple analytical model of the solar temperature minimum. The solid curves show the variation with horizontal wavenumber of the frequency of the fundamental and the lowest vertical harmonics, and it is this behavior -- the resolution of the "five-minute" oscillatory power into bands which increase in frequency with increasing horizontal wavenumber -- that has been observed. The observations correspond, almost disconcertingly well, to the more detailed calculations of Ando and

Osaki (1975). The figure shows that the oscillations are non-propagating, exponentially varying, evanescent waves in the temperature minimum and an examination of the eigenfunctions shows that the fundamental consists essentially of one quarter cycle in the underlying high temperature region which reaches a maximum at the base of the isothermal region from which point it decays exponentially upwards.

While the efforts have addressed primarily the question of the excitation of the "five minute" oscillation, the results inevitably bear upon some of the lingering problems of their behavior in the photosphere. In particular, the coherence tim (packet length) of 23 minutes, which just translates into the width of the power spe trum in the Fourier transform domain, has a very straightforward interpretation if the "lifetimes" of the individual frequency components are as long as the vibrational instability growth rates indicate. Then the observed lifetimes would be interpreted directly as the consequence of the combined frequency response of the sub-photospheric cavity and the instability. The horizontal coherence length should emerge similarly, although it has posed a less annoying problem because of its much poorer observational definition, which results - under the current interpretation - from a broad horizontal wavelength response of the cavity and instability.

Although research on magnetohydrodynamic modes has been motivated almost exclusively by phenomena associated with sunspots in the past, as I have tried to emphasize earlier the localized magnetic fields, equal in energy density to that of the adjacent plasma, now observed throughout what was thought of as the "quiet sun" have rekindled interest in the long neglected suggestion for heating of the chromosphere and corona by MHD waves (Alfven, 1947; Piddington, 1973 and earlier references therein). Cowling (1976) has recently presented a very useful critique of the work of Parker (1974b) on the cooling of sunspots by an Alfven wave flux, which applies also to Uchida and Sakurai (1975), that provides a good introduction to the debate in this area. It is interesting to note that in sunspots we may well have a laboratory for testing our description of MHD propagation in the more difficult to observe, isolated flux tubes, i.e. different field morpholigies, strengths, histories, etc.... At the risk of insisting too strongly upon the obvious, this heating mechanism would provide an entirely different dependence of coronal heating on position in the H-R diagram than do the Lighthill or vibrational overstability mechanisms. I would like to suggest this area to the beginning researcher as a "hot one" in which we may expect to see significant progress in the delineation of the basic mechanisms in the next several years.

IS THERE AN ANSWER?

"Of course not!"

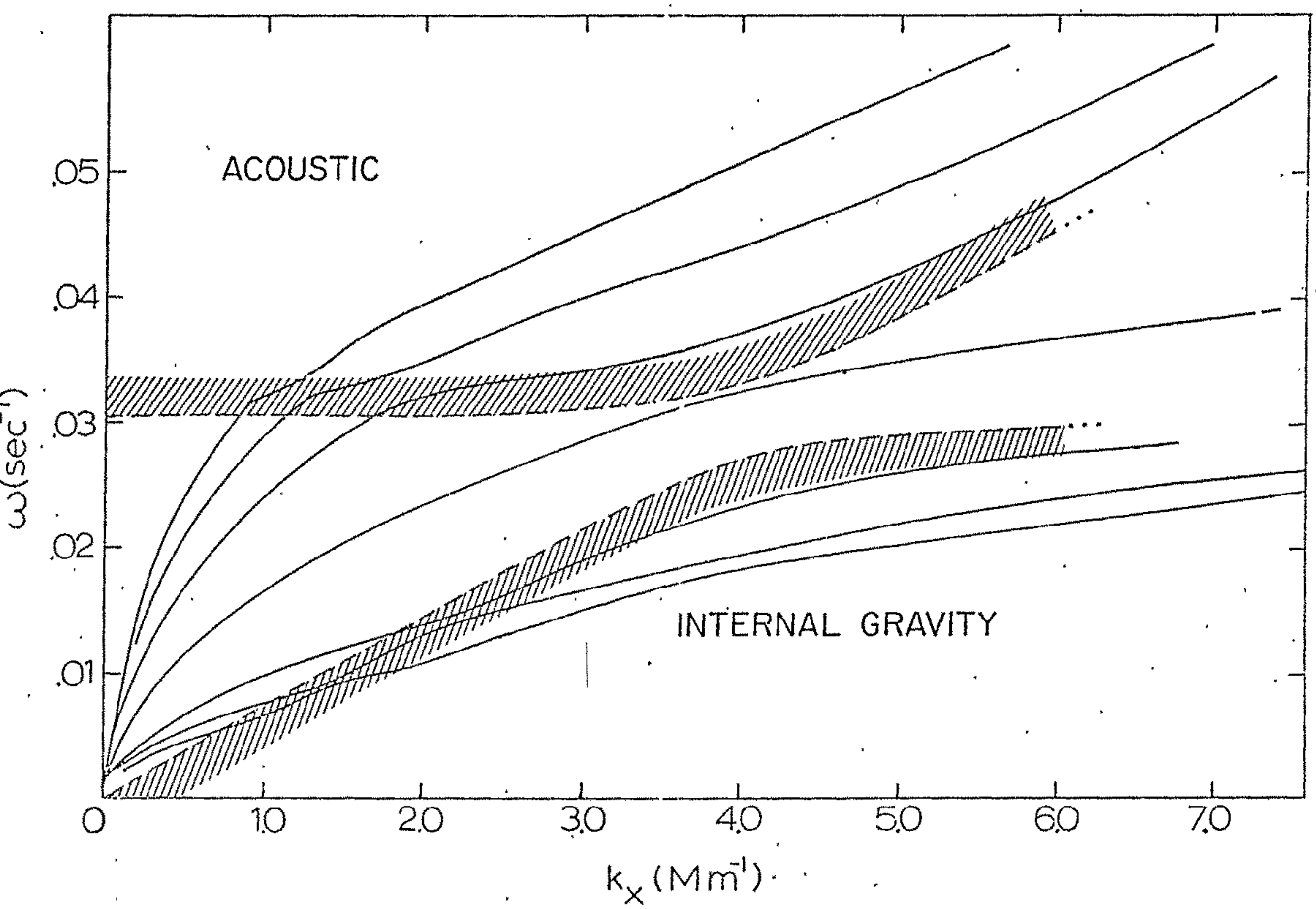
It would be tempting to stop there, if not from the philosophical resignation that we can never "understand" nature but only "describe" what we have measured about it, then out of the pessimism that "old theories never die, their proponents just fade away," and hence we rarely anticipate a consensus on any point of major disagreement within the lifetime of the combattants. Nonetheless, astrophysics has become a sufficiently large human undertaking that this attitude seems distinctly outdated. One should recall that at the same time that the "classical suggestion for a solution" was being made such eminent men as Bondi, Hoyle and Lyttleton were suggesting that the corona was heated by infalling interplanetary material (a backwards solar wind); an idea which seemed eminently possible at the time but which has nevertheless been put to rest as surely as one can imagine.

Well then, what sort of answers can we hope to achieve? We should, I think, be able to imagine identifying the mechanisms which give rise to significant fractions of the mechanical energy. We should be able to exclude others which are demonstrably unlikely. I don't think that we should expect to do the dynamical equivalent of determining the solar gold or silver abundance, if one can imagine that. Nor does it seem reasonable that we should try to play the game with the radiative transfer folks of specifying temperatures to one percent.

Rather, I think we should content outselves with the aspiration of maintaining parity with firstly the solar observers by predicting as many observable that they hadn't thought to look for as they find phenomena that we hadn't imagined might exist, and secondly with the extra-solar community by utilizing our mundane but resolvable Sun to disentangle the constituents of their complex phenomena as often as their bizarre objects point out a new process that had heretofore escaped the wildest flights of our imagination.

FIGURE CAPTION

The first several linear modes of oscillation of an atmosphere consisting of an isothermal temperature minimum bounded above and below by semi-infinite regions of linearly increasing temperature. The dashed lines indicate the limits of the regions of propagation at the temperature minimum. (After Leibacher, 1971.) The isothermal temperature minimum at 4000K is 1.5 mm thick. The temperature rises at 10K/km towards the interior and 100 K/km towards the exterior. At low horizontal wavenumbers, the modes descend asymptotically as parabolae to zero frequency. At high horizontal wavenumbers the modes approach the curves for constant vertical wavenumber in the isothermal temperature minimum.



ACOUSTIC
INTERNAL GRAVITY
.05
.04
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$k_x\,(Mm^{-1})$

WHERE DOES ONE "LEARN" THE BASIC PHYSICS AND MATHEMATICAL MANIPULATIONS TO ATTACK THE QUESTION?

The researcher who has bothered to read to this point is (among other things) most likely well versed in the fundamentals of astrophysics, and to a lesser extent those of atomic physics and applied mathematics. But it is unlikely that (s)he has more than a "common sense" background in fluid dynamics, magnetohydrodynamics, or plasma physics. If I were forced to suggest a single work for such a person to take with them into seclusion to familiarize themselves with the aspects of fluid dynamics of interest here, I would stretch the point and suggest the two volumes of Zeldovich and Raizer: The Physics of Shock Waves and High Temperature Hydrodynamic Phenomena. In spite of the rather imposing title, they start off with a very readable discussion of the basic equations of motion. Landau and Lifshitz cover a much more extensive list of topics in their usual magnificent style; but I personally find their textbooks more useful once one already has some acquaintance with a subject and one really wants to "understand" it. Liepmann and Roshko's textbook was a standard introduction for many years, but those wishing a more recent presentation might prefer the general introduction by Batchelor. No listing of references in fluid dynamics would be complete without Lamb's Hydrodynamics. The astrophysical literature of the last ten years contains more than one rediscovery of results published by Lamb nearly seventy years ago.

My acquaintance with the study of convection being rather more passing, I can only refer the reader to Turner's Physics of Buoyant Flows as a text in this area. Cox and Guili's discussion of the astrophysical application of the mixing length approach is sufficiently well written and detailed to be capable of standing alone. Spiegel's review articles in the Annual Reviews of Astronomy and Astrophysics will reward the diligent reader, and Roger's more recent review is worthwhile for its discussion of progress in non-astronomical context.

Ffowcs-Williams articles in the Annual Reviews of Fluid Mechanics should be consulted for the aerodynamic generation of sound. Fay's article in the same series discusses isolated buoyant structures, which may provide an appropriate description of granules penetrating into the convectively stable photosphere. Souffrin's lecture notes (Souffrin, 1971) discuss the overstable generation of waves in the convection zone.

Eckart's Hydrodynamics of Oceans and Atmospheres remains the fundamental discussion of the linearized equations of motion and the various wave modes that may arise in atmospheres. His use of entropy, rather than temperature, as basic variable conforms to the meteorological community's conventions, and may prove to be a source of some confusion initially. The papers by Tolstoy (1963) and Uchida (1965) contain useful presentations of the basic equations, derivations of the wave equation, and identification of the modes. Vincenti and Krueger devote a surprisingly readable textbook to the interaction of microscopic reactions of the gas with the macroscopic flow.

In addition to the general texts cited initially, one should not overlook Courant and Friedrich's classic work on shock waves. These can be usefully supplemented by the monograph of Harlow and Amsden on more up-to-date numerical methods and results. A more complete bibliography and a discussion of progress made in other areas of astrophysics is given by Leibacher and Stein (1975).

As I have mentioned earlier, the conventional wisdom and these lectures, concentrate on the non-magnetic aspects of the hydrodynamics of the quiet sun. One might mention the lecture notes "Plasma Astrophysics" edited by Sturrock and the monograph by Kaplan, Pikelner, and Tsytovich to assuage, to some extent, this incompleteness.

Finally, one must pay tribute to the outstanding series of conference proceedings: Fourth Symposium of Cosmical Gas Dynamics (Varenna, 1960) edited by Thomas, Aerodynamic Phenomena in Stellar Atmospheres (Nice, 1966) also edited by Thomas, and Physique des mouvements dans les atmospheres stellaires (Nice, 1975) edited by Cayrel and Steinberg.

THE END:

It is a pleasure to thank the organizers of this School for their hospitality and the students for their indulgence. I wish to apologize to the other lecturers for any delay in this joint publication created by my tardy submission and to the reader for the somewhat flip style and rather preliminary state of these notes brought about by the loss of the entirety of my original manuscript and notes. Support by NASA contracts NAS5-22411 and NAS8-32356, as well as that of the Laboratoire de Physique Stellaire et Planetaire, is gratefully acknowledged.

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I have not always faithfully followed the astronomical convention of placing the date of publication after the author's name in these notes where no ambiguity resulted. In the spirit of these "lecture notes" I have also taken the liberty of including a much more complete bibliography than the references in the text require; with the thought that the accompanying titles may provide the reader with a resource of some value. My apologies to my colleagues for the inevitable oversights.

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Attachment B

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Theoretical Aspects of the 300 Second and Related Oscillations of the Solar Atmosphere

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I. Introduction

It seems to me that only extremely rarely does our knowledge of the behaviour of the Sun, and astronomical objects in general, advance in a nice, clear fashion at all similar to The Scientific Method, whose virtues were extolled back in high school physics courses. Only infrequently do real, testable predictions emerge from hypotheses formulated to describe known, but unexplained phenomena. Even less frequently is the physics sufficiently simple that one effect dominates and the predictions are unambiguously confirmed. Nonetheless, this has occurred recently in the interpretation of what for a long time was known as "wiggly line spectra" - the spatially and temporally resolved velocity field of the solar photosphere. It is thus with nostalgic pleasure that I undertake a description of the denouement of nearly twenty years of research into the nature of the "five-minute" oscillation of the solar atmosphere.

After briefly recalling what the problem was, I shall review the model of the "five-minute" oscillation which has demonstrated this predictive success - first, the atmospheric properties which determine the resonant frequencies, the variation of these frequencies with horizontal scale and the vertical structure of the resonant motions; and second, the mechanisms which have been proposed to drive these motions. While the detailed, numerical agreement between theoretical predictions of the resonant frequencies and observation has not only confirmed the model but allowed its application as a diagnostic of sub-surface conditions ("solar seismology"), our ideas about the excitation and damping mechanisms are in a much more preliminary state.

Then, I shall discuss the chromospheric concomitants of the observed photospheric motions. (Given the input of the photospheric oscillations, what do we expect to see in the chromosphere as a result ?) Although the mechanism for the decrease in energy of the "five minute oscillation" and the increase in energy of the "three minute oscillation" appears to be understood, attempts to model the temporal variation of optically thick lines have been largely unsuccessful. Although it is possible that our dynamical description is in error, it seems clear that the proper combination of hydrodynamic models and line formation diagnostics has not yet been used to derive appropriate predictions for comparison with observation. Finally, we are forced to conclude that the most naive expectations of shock wave heating of the solar chromosphere and corona have not been fulfilled, and that while the observational quest must continue - guided by more realistic theoretical predictions - alternative heating mechanisms should be actively investigated.

II. Oscillatory Motions of the Solar Photosphere

Although the oscillatory motions of gravitationally stratified, compressible fluids - atmospheres - have been "well understood" since the work of Lamb at the beginning of the century, in the absence of specific problems posed by observation, astronomers seem not to have considered the consequences of the existence of such hypothetical motions. While Biermann and Schwarzschild had conjectured that running waves generated in the convection zone could transport the energy required to account for departures from radiative equilibrium in the outer layers of the solar atmosphere, it was assumed that these waves would span a broad spectrum of temporal and spatial scales commensurate with the "turbulent" convective motions thought to be responsible for generating them. When Leighton actually measured the time variation of the velocity at a point on the Sun, he found much to everyone's apparent surprise that instead of being a more or less random function, the velocity oscillated quite regularly with a period near five minutes. What is so special about five minutes? How does the Sun go about selecting just this one narrow range of periods?

It turns out, embarrassingly enough, that there are a lot of ways to do it - none so much as suspected before Leighton's observations directed attention to the problem - and within a decade half a dozen distinctly different, but "credible" models for the five minute oscillation emerged. (The interested reader is referred to reviews by Michalitsanos(1973) and Stein and Leibacher(1974)). Within the last two years observations have been obtained (Deubner, 1975) and corroborated (Rhodes, Ulrich and Simon, 1977) which confirm predictions made on the basis of one of these models, and thus in the current order of things this model has been elevated to the status of "astrophysical truth" - not to be confused with "astrophysical accuracy." Let me qualitatively describe the important aspects of this model.

The "truth" is that acoustic waves with periods greater than 200 seconds will be trapped within a limited region, some tens of megameters thick, just below the visible surface of the Sun where they couple to the thermal and dynamic state maintained by the outward convective transport of the solar flux. These trapped waves drive non-propagating, evanescent waves seen in the visible atmosphere. To describe this phenomenon, it behooves us to think a little about acoustic waves.

A change in the density of a gas, brought about by pushing on one end of it for example, generally causes a change in the pressure through the conservation of energy. Since the pressure is just the internal energy density, compressing the gas increases the pressure. Since the pressure has not increased everywhere, only on the side where we pushed, a pressure gradient now exists which will in turn accelerate the gas towards the low pressure. This acceleration compresses the low pressure gas and we've gone around the loop and start once again: a density increase (via the conservation of energy) causes a pressure increase, a pressure gradient (via the conservation of momentum) causes an acceleration, an acceleration (via kinematics) causes a displacement, a differential displacement (via conservation of mass) causes a density increase. This compressional disturbance is propagated by the internal random, thermal motions of the particles at a speed $\sim\sqrt{kT/m}$, which is referred to as the speed of sound.

In fact, in an infinite,isothermal, homogeneous gas, the sound speed represents the only characteristic dimensional quantity, and it is just the signal propagation speed for small disturbances. If we look at a plane parallel sound wave, the wave crests move at the sound speed along the direction of propagation, and hence they must move faster than the sound speed along any other direction. (It's worth drawing a little sketch.) For example on a plane nearly perpendicular to the direction of propagation, the crests will move sideways at "nearly infinite" speed. The propagation speed of the crest (or trough, or node) is often referred to as the phase velocity. Interesting things occur at the interface between two regions of differing sound speed (i.e. different temperature). Waves which are propaging towards the region of higher sound speed with an arbitrary period and wavelength (just the product of the period and the sound speed) will maintain their period and wavelength along the interface (that is, the phase velocity along the interface is the same on both sides of the interface). But in the region of higher sound speed, the wavelength corresponding to a given period must increase and hence the wavelength perpendicular to the interface must increase (since the wavelength parallel to the interface is fixed by continuity). This is just the same as saying that the direction of propagation changes, in the sense that the wave propagates more nearly parallel to the interface. Which is all just equivalent to Snell's law in optics - waves propagating into a region of decreasing index of refraction (increasing speed of light) are refracted away from the normal. The "interesting things" happens when the temperature increases so that the sound speed in the higher temperature region equals, or exceeds, the horizontal phase velocity of the incident wave. The wave can no longer propagate perpendicular to the interface in the hot region, and it is reflected ("total internal reflection"). In general, the wave doesn't stop abruptly at the interface, but it's energy falls off exponentially into the hot region. This "evanescent wave" is curious in that although at any point the velocity varies sinusoidally in time, there is no phase propagation away from the interface. The velocity reaches a maximum (or minimum) everywhere simultaneously, so it might be more appropriate to think of the phase velocity perpendicular to the interface as béing infinite. Furthermore, in contrast to the propagating waves where the pressure and velocity fluctuate in phase - which is just what is required for a net amount of work to be done around one cycle - the pressure and velocity are ninety degrees out of phase, so that no energy is transmitted.

A wave propagating at some angle to the temperature stratification in the direction of increasing temperature will eventually get to a region (temperature) where the sound speed equals the horizontal phase velocity and the wave will be turned around. It is worth noting that if we look at waves of the same frequency but varying angle of propagation with respect to the temperature stratification, or equivalently varying horizontal wavelength if we think of a "vertical" temperature stratification, the more nearly horizontally propagating waves will be reflected first (at the lowest temperature) and the sound speed to which the waves can propagate is just proportional to the horizontal wavelength; or inversely proportional to the sine of the angle to the vertical. Thus waves propagating "straight in", that is waves with infinite horizontal wavelength, will never be reflected. The existence of such reflections is of interest in that it can exclude waves from the high temperature region (the deep interior of the sun) and, more significantly in the present context, in that two reflections will form a cavity, or duct (an organ pipe or cello string) in which interference will occur and certain frequencies will be selected from a broad band excitation. For example, one of the first models for the "five minute oscillation" - proposed by F.D. Kahn but later shown to be unacceptable on several points - was based upon the trapping of sound waves near the temperature minimum by the higher temperatures above and below.

Other "interesting things" happen to sound waves when they propagate in a region of changing density - such as occurs in the presence of a gravitational field, but which would also occur if the mean molecular weight were stratified for example. If this "atmosphere" were displaced upwards or downwards "slowly", then sound waves would run back and forth, and after they damp out and the atmosphere would return to its stratified equilibrium. That is all well and good, but what is "slowly"? Whereas the isothermal gas we considered above had only a characteristic velocity associated with it, the density stratification introduces a characteristic length - the scale height. If we move the atmosphere periodically up and down with a period sufficiently long so that a small density fluctuation would travel many ("many" turns out to equal 4π) scale heights in one period, then the atmosphere more or less stays together and moves up and down in phase. However, if we jiggle the atmosphere up and down very rapidly - more rapidly than the atmosphere can respond - then waves zip on up at the sound speed. Since the sound speed remains constant, these waves propagate without reflection. However, since the atmospheric density varies, the velocity amplitude must vary inversely to maintain the constant flux of energy ($\rho v^2 c$, where c is the velocity of sound). Thus waves propagating upwards, into less dense gas will increase in amplitude as $\rho^{-\frac{1}{2}}$. As the period increases to that at which the atmosphere can respond in phase - the cut-off period for propagation - the energy propagation velocity decreases to zero and the wavelength increases to infinity. For periods slightly longer than the cut-off, the atmospheric fluctuations vary exponentially rather than sinusoidally with height, and these waves are again referred to as "evanescent."

If the gas is stratified gravitationally, the scale height is inversely proportional to the temperature, so the time for a density disturbance to propagate a scale height is just proportional to $T/\sqrt{T}$ or $\sqrt{T}$. Once again, the propagation characteristics change with a change in temperature so that when a wave propagates into a cooler part of the atmosphere - with a smaller scale height - waves of sufficiently long period will no longer propagate, that is they will be reflected. Thus a sound wave propagating into a region of continuingly decreasing temperature will eventually reach a region where its period times the sound speed equals 4π times the density scale height, at which point energy will be propagated no further. If sound waves covering a range of periods propagate into a region of decreasing temperature, the longest period waves will be reflected first and the short period high frequency waves will propagate down to low temperatures (small scale height). Combining this behaviour with the reflection that occurs at high temperature (when the sound speed equals the horizontal phase speed) we see (I hope) that in an atmosphere there exists a range of temperatures within which a given acoustic mode (specified pair of period and horizontal wavelength) may propagate. Whereas we have already seen how a cavity capable of trapping acoustic waves is formed at the temperature minimum, we now have discovered that there exist additional cavities in the rising temperature regions above and below the temperature minimum. In fact, the second model for the "five minute oscillations" - proposed by Bahng and Schwarzschild but alas, also shown to be unacceptable on several points - suggested that waves trapped in the chromosheric temperature rise could account for the observations.

There followed many other descriptions; some using running acoustic waves, others buoyancy waves trapped in the temperature minimum; before the importance of acoustic waves trapped in the temperature rise towards the solar interior was pointed out by R. Ulrich and independently by Bob Stein and myself. As simple as this description now seems, it took an embarrassingly long time to arrive at it. In my own case, I was considering a very different aspect of the problem and was extremely annoyed that the model developed beautiful five minute oscillations long before it had a chance to develop what I wanted to study. After a lot of hard work trying to make the oscillations go away, I conceded defeat and accepted what the model was trying to tell us. Ulrich recounts a similar serendipitous experience, having originally thought that the "overstability", or growing amplitude of the oscillations was a numerical difficulty of his computer program. But I am getting ahead of the story. Let us consider in a little more detail the properties of the sub-photospheric cavity, before discussing how these trapped waves are excited.

For any given wave mode (period and horizontal wavelength), in a propagating region, there exists two waves corresponding to upward and downward propagation. If a reflection exists somewhere, then the wave propagating away from the reflection is just the wave propagating towards it, but turned around. Of course, the wave experiences a phase change at the reflection. This would be the situation in a semi-infinite uniform gas with a wall at one end, for example. If we introduce a second reflection the situation becomes much more intersting. Consider an excitation operating within the cavity; a diaphragm moving up and down for example. For an arbitrary periodic excitation, the waves reflected back to the excitation will arrive somewhat out of phase with it and will impéde the excitor. Thus the gas may be moving upward at the diaphragm while the diaphragm is trying to push the gas back down. Not a very efficient way to transfer energy, I hope we all can agree. For certain periods of excitation, however, the reflected wave will arrive back at the driving exactly in phase with it and the excitor can put more energy into the gas and the wave will grow in amplitude. That is, the gas would be moving with the diaphragm. A slightly more concrete analogy, would be trying to push a child on a swing. If you don't push in phase with his swinging, it doesn't work very well. These resonant modes, often referred to as "normal modes", are of interest to us here just because of their resonant response to broad band excitation. That is, while waves spanning a broad range of periods and horizontal wavenumbers will be trapped in the sub-photospheric cavity, these resonant modes should be preferentially excited to large amplitudes.

In general, a cavity formed by two reflections will have many resonant modes, that is many wavelengths that can satisfy the requirement that after two reflections they arrive back at the "starting point" in phase. For example, the cello string has as resonant modes all of those sine waves which go to zero at both ends. Thus the longest wavelength, resonant mode consists of a half cycle of a sine wave, but 1, 1½, 2, 2½,..... cycles will also resonate. Thus each successively higher order resonant mode has an additional zero crossing along its length. Since the reflections at the end are indpendent of the wavelength (ideally), this cavity possesses an infinite number of resonant modes. In addition, for this simple system, the wavelength and the period of a wave motion are linearly related so that these resonances have a simple harmonic relationship between the periods. Such systems, for which waves of all periods propagate at the same speed are said to be "dispersionless", a packet of energy consisting of a range of wavelengths does not disperse as it propagates. As we have seen above, the propagation speed and reflection of acoustic waves in the solar atmosphere depend both upon the period and the horizontal wavelength. Hence they are dispersive. Thus while vertically propagating waves with periods of 300 and 400 seconds will be reflected downward just below the visible surface because the scale height gets too short, 200 second waves will just propagate into the visible atmosphere and 100 second waves will propagate right past the temperature minimum and on up into the chromosphere. So in fact, the cavity does not exist for these short period waves. Purely vertically propagating waves will go all the way in to the center of the sun without being reflected, so the cavity will be extremely thick for them, while waves propagating very obliquely will be reflected back upwards before they have penetrated very deeply.

At a fixed horizontal wavelength, the longest vertical wavelength which resonates has the longest period, and higher harmonics have shorter periods. Since the downward reflection no longer exists for sufficiently short period waves, only a finite number of resonant modes exist below the solar surface - in contrast to the situation for the cello string. In addition, while for the nice, uniform cello string all of the higher order resonant modes had the wave energy distributed more or less uniformly along the string which, of course, has the same length for all of the harmonics, in the subphotospheric cavity the lower order resonant modes propagate more nearly horizontally than the higher order ones and thus they propagate in a more limited range of depths in the solar convection zone than the higher order (shorter vertical wavelength, shorter period) resonant modes. Of course the resonance will exist for other horizontal wavelengths, for which - because of the dependence of the vertical wavelength on the horizontal wavelength and the period - the resonant period will be different. The ensemble of resonant modes with the same number of vertical wavelengths trapped in the cavity is often referred to as a "vertical mode" and the number of zero crossing of the pressure fluctuation - for example - used as an index. The longest vertical wavelength mode - which has no zero crossings - is called the "fundamental". For a given vertical mode, longer horizontal wavelengths penetrate deeper in the solar convection zone to higher temperatures; thus the cavity is more extended, the vertical wavelength longer and hence the period longer. The precise functional dependence of the period upon the horizontal wavelength results from the detailed mathematical formulation, however the qualitative relationship can be arrived at quite simply. At any temperature in the atmosphere, the characteristic period - the acoustic cut-off period - is just proportional to the square root of the temperature, while the characteristic length - the scale height - is proportional to the temperature. Thus in an atmosphere with a more or less smoothly varying temperature, by keeping the ratio of the period to the characteristic period and horizontal wavelength to the characteristic length constant, that is since

$$P \sim \sqrt{T}$$

and

$$\lambda \sim T,$$

then

$$P \sim \sqrt{\lambda},$$

the resonant modes with the same number of vertical modes all "look the same", with the longer period, long horizontal wavelength ones just being shifted to higher temperatures - deeper in the convection zone. This square root dependence is, in fact, precisely the analytic result for an atmosphere consisting of a linear temperature increase, and it obtains as the large horizontal wavelength limit for the more complicated temperature distribution in the solar sub-photospheric cavity.

Figure 1 displays the low order resonant modes calculated analytically for a model solar atmosphere consisting of an isothermal temperature minimum of 4000°K, 1.5 Mm thick, between a linear rise of 100°/ km into the "corona" and a rise of 10° / km into the interior. (It is generally more convenient for theory and analysis to proceed using the Fourier transforms of the real variables, so reciprocal periods (frequencies) and reciprocal wavelengths (wavenumbers) are most commonly used.) Acoustic waves can propagate above the shaded band. The fundamental mode is evanescent everywhere, and it lies very close to the compressionless waves for which the divergence of the velocity vanishes. "Internal gravity" waves - corresponding to the buoyancy restoring force - exist in the lower shaded region, and the first three internal gravity wave modes are shown. Note the square root dependence of the frequency on the horizontal wavenumber for small wavenumbers. The observed oscillations correspond to horizontal wavenumbers of the order of several tenths of a Mm^{-1}, and the higher horizontal wavenumber behaviour - where the modal curves are open upward, rather than downward - which corresponds to a constant number of vertical wavelengths in the temperature minimum-region-has not been observed. The S - shaped bends in the higher harmonics occur as the mode crosses a line corresponding to the same number of vertical wavelengths in the isothermal temperature minimum as a lower order mode. The detailed vertical variation of the energy density in the resonant modes is unfortunately not so amenable to a simple qualitative discussion. But it is interesting to note that while for horizontal wavelengths greater than 4π times the scale height at the temperature minimum the oscillatory energy of the fundamental mode is concentrated in the sub-photospheric cavity, for smaller horizontal wavelengths the energy concentrates in the chromospheric cavity - as suggested by Bahng and Schwarzschild. Furthermore, the maximum amplitude of the higher order modes alternates from the convection zone to the chromosphere from mode to mode.

Numerical calculations with temperature and density distributions given by realistic solar models have been carried out by Ando and Osaki (1975, 1977) and Ulrich and Rhodes (1977). Both groups draw attention to modes which are trapped in the chromosphere with a period near 240 seconds. As mentioned above, analytic studies predict a whole series of such chromospheric modes. Deubner has found some observational evidence suggesting the possible existence of power at this frequency. However, quite frankly, it would be somewhat surprising were this mode to exist because of the large amplitude of the motion at chromospheric heights. That is, the wave will significantly distort the resonating cavity. The least that one might expect is that the modes with different horizontal wavelengths, instead of being completely independent, would have their phases locked together. As we shall see below, the currently discussed excitation mechanisms all operate below the visible surface and hence the excitation of the chromospheric mode is not expected to be favored. However, it should be pointed out that for comparable amplitudes near the visible solar surface, the chromospheric mode should be much more visible in the chromosphere than the normal modes with their maximum in the sub-photospheric cavity. While the astounding coincidence with observations served to establish the sub-photospheric cavity model, more recently small remaining differences between observation and theory have been exploited as diagnostics of the thermal structure of the hydrogen convection zone. It may be that no plausible choice of a mixing length would be capable of precisely matching the observations, thereby vitiating the mixing length treatment of convection. The different depth distribution of the energy in the different modes appears to be capable of providing a diagnostic of the variation of the solar rotation rate with depth (Deubner, Ulrich and Rhodes, in preparation).

While in what has been said up to now, any horizontal wavelength was as good as another; along a model curve, for every wavelength there corresponded a period. If , however, the oscillations last for a very "long" time, where now "long" is understood to be of the order of the time for the phase to propagate around the circumference of the Sun; then even though there are no reflections, the wave can interfere with itself after going all of the way around and once again only those modes with wavelengths which end up in phase with themselves will resonate. The necessary observational resolution to resolve the horizontal modes is not impossible to imagine, and the existence or non-existence of this secondary modal structure should be an exciting diagnostic of the lifetime of the modes. In any case, there are several hundred thousand modes which contribute to the observed "five-minute" oscillation!

While the fact that the observed structure of the "five minute" oscillations coincides so impressively with the normal modes of the sub-photospheric cavity gives us confidence in the appropriateness of the model, I haven't given the reader any reason to suppose that there is any means of putting energy into these modes; or in the lingo of the trade, to "excite" them. (Just because unicorns could exist, one is not compelled to assume that they do.) As often seems to be the case, there exist a plethora of mechanisms available and the problem seems to be more choosing amongst them. The different mechanisms differ not only in their dependence upon the period and horizontal wavelength of the mode, but also in their dependence on the structure of the atmosphere. Thus for other stellar types the relative importance of the different mechanisms will almost certainly change.

Two fundamentally different ways of putting energy into a wave, or oscillatory motion exist: internally or externally, via the energy equation or via the momentum equation. By pushing on the gas in a cavity - mechanically through a diaphragm, as discussed above, or via some other motion in the atmosphere - at one of its resonant frequencies, the gas will be excited to an oscillation at the amplitude specified by the pushing ("driving" is the more commonly used lingo). The sound wave could exist at any amplitude in this formulation, the non-linearities having been neglected. Thus if a resonant mode was oscillating away at some amplitude and the driving was turned on at a lower amplitude, the driving would reduce the oscillation amplitude and thus would really be dissipation. Lighthill has formulated this approach in connection with the generation of sound waves by the turbulence in the exhaust from jet engines, and it has been used in astrophysics - primarily by Stein - to evaluate the flux of sound waves emitted by the "turbulent" flow in the hydrogen convection zone. "Turbulent flow" is the buzz word used to describe the velocities responsible for carrying the convective flux of energy - as specified by the mixing length treatment of convection. Given a characteristic velocity, which depends upon an assumed numerical and functional form for the mixing length, a turbulent spectrum of temporal and spatial scales is assumed. Unfortunately, the emitted flux is very sensitive to all of these assumptions. This flux is primarily at very short periods (less than 100 seconds) which are not trapped. Although these high frequency waves do not contribute to the "five-minute" oscillation, they may well be important in the heating of the lower solar chromosphere. Recently Goldreich and Keeley (1977) and Keeley (1977) have considered the same mechanism for the longer period, resonant modes and they find that although the turbulence acts primarily to dissipate the radial modes, it is capable of exciting the non-radial modes to amplitudes comparable with observation. This mechanism arises primarily in the upper parts of the convection zone where the convective velocities and the associated dynamical effects rise rapidly before falling to zero in the convectively stable photosphere. While this pushing acts on the wave through sources which appear in the momentum equation, periodic addition of internal energy has also been suggested as a means of exciting the resonant modes.

As the temperature and density of the gas vary throughout the oscillation, the interaction of the gas with the mean atmosphere will also vary. Depending upon the phase between the energy transfer and the temperature fluctuation, the effect will increase or decrease the amplitude of the wave. For example, if heat is lost when the gas is hot and gained when the gas is cold, the oscillation will be damped. By reducing the energy density when it is high we reduce the restoring force of the compresibility and hence the energy of the wave has been reduced. If on the other hand, the gas could be made to absorb more energy when it was hot and less energy when it was cool, the amplitude of the wave would increase. This occurs quite generally for any thermodynamic cycle: heat absorbed during the hot part of the cycle adds to the energy of the oscillator, heat added during the cool part of the cycle reduces the energy. When the energy added is proportional to the amplitude - often called a "linear instability" - the amplitude will grow exponentially in time. An oscillator whose amplitude increases exponentially in time is said to be "overstable" or "vibrationally unstable". The amplitude will continue to increase until some process whose importance depends non-linearly on the amplitude grows to dominate - a parabola, or higher order polynomial, starts rising from zero more slowly than any straight line but eventually will exceed it. These non-linearities may occur in the excitation or in the dissipation process. If the amplitude of the wave in the driving region becomes large, over part of the cycle the excitation may change to dissipation. Thus any further increase in the amplitude would increase the dissipation more rapidly than it increased the excitation and thus the growth of the oscillation would cease. This limitation is often referred to as a "saturation" of the excitation. Leakage from the cavity may also limit the amplitude. The sound waves penetrate slightly through the temperature minimum region and will be dissipated at greater heights. This dissipation increases rapidly in its efficiency with increasing amplitude; so that were nothing else occuring, the wave amplitude would increase until the energy dissipated above the temperature minimum just equaled the energy put into the wave by the overstability.

Such overstabilities have been invoked for years to account for the Cepheid pulsation phenomenon. Although several effects are intimately combined, the increasing opacity with increasing temperature (at constant density) which prevails in the hydrogen and helium ionization zones of stellar envelopes takes energy from the outward thermal flux and transforms it to acoustic waves. Rather than controlling the deposition of energy into the wave, the opacity mechanism regulates the escape of energy through the wave; and, following Eddington, this distinction between periodic injection and periodic damming up of a continuous flux is referred to as the "Eddington Value". This fluctuating opacity mechanism is often referred to as the "κ mechanism" in distinction to the contribution made by the fluctuation in the internal energy brought about by the fluctuating ratio of specific heats - the "γ mechanism". At temperatures above the maximum of ionization, further into the interior, the situation reverses and increasing temperature leads to a decreasing opacity, and thus fluctuations deep in the stellar interior are damped. Since the driving "changes sign" at high temperatures, as the temperature fluctuation in an oscillation grows with amplitude, eventually the driving will saturate and the amplitude will be limited. Resonant modes with large amplitudes in the damping region will not be excited, while those with large amplitudes in the outer regions, where hydrogen and helium are ionizing, will be excited. Thus, along a modal curve for-say-the first harmonic, since longer horizontal wavelength modes will resonate deeper in the interior they will grow less rapidly in time than shorter horizontal wavelength modes; and very long horizontal wavelength modes will most probably not be overstable. However, Provost (1973) has cautioned against such "intuitive" reasoning. Ando and Osaki (1975, 1977) have done extensive calculations of the variation of the growth rate with horizontal wavenumber for the different modes.

While this overstability arises in the outer region of the solar convection zone, near the depths where the "Lighthill mechanism" is effective, the thermal rather than dynamical coupling to the mean atmosphere should uncouple the relative importance of these two mechanisms in other stars. Ando (1976) has calculated growth rates of the overstability in other stars.

Another physically distinct overstability, suggested long ago by Cowling, revived by Spiegel and discussed recently in detail by Graff (1976), derives energy from the super-adiabatic temperature gradient maintained by convection. Because the mean atmospheric temperature gradient is greater than that of the displaced gas in the sound wave, any dissipative mechanism - such as radiative transfer - will add heat when the fluctuation is displaced towards the interior; that is, compressed and heated; and remove it during the other half cycle. (This type of mechanism has also been suggested to generate MHD waves, particularly in connection with the problem of cooling sunspots. A recent article by Cowling (1977) is of interest here.) It appears that for the Sun, the κ mechanism contributes much more than this "Cowling - Spiegel" to the overstability of acoustic modes in the sub-photospheric cavity. Because of the tremendous efficiency of convection in the Sun, the actual temperature gradient exceeds the adiabatic gradient by less than a part in a thousand throughout almost the entire convection zone. It is only in the outer scale height or two that substantially super-adiabatic gradients exist, and thus only a relatively small mass is available to participate in the driving. However, in other stars where convection may be less efficient and extended super-adiabatic zones present, this mechanism may contribute.

In concluding this section, let me repeat that the theoretical "action" in the near future appears to focus on the generation of these resonant modes whose existence has been established. To evaluate the amplitudes attained by the overstabilities for comparison with observation and to evaluate the energy loss by dissipation, a much more difficult non-linear problem must be attacked. In addition, having established a new paradigm, new observations must continue to test it. In particular, the interaction of a magnetic field, be it in a sunspot, an active region, or in the quiet sun network, with the resonant modes is of great interest. The observations reported on at this meeting by Livingston (see also Giovanelli, Livingston and Harvey, 1978) provide an excellent stimulus for this undertaking.

II. Chromospheric Dynamics

One of the principal programs of the pointed instruments onboard OSO-8 has been the observation of velocity and intensity fluctuation fields throughout the solar chromosphere and the transition to the solar corona. These fluctuating fields are of interest not only as phenomena in their own right but also because of their relation to the mechanical energy transport which has been speculated to be responsible for the heating of the chromosphere and corona. Because spatial inhomogeneities are known to be much greater in the chromosphere than in the photosphere and the effect of magnetic fields more important, we may anticipate that several processes may simultaneously contribute to the chromospheric dynamics and that the isolation and identification of the phenomenon may prove more difficult. Thus humbled, it behooves us to examine the apparent consequences for the chromosphere of the model of resonant modes trapped in the sub-photospheric cavity. We shall show that the frequencies which cannot propagate near the temperature minimum and are trapped in the convection zone, propagate once again in the higher temperature chromosphere. In addition, waves at the cut-off period are generated near the temperature minimum and these play an important role in the chromosphere. Finally, even for resonant oscillations with amplitudes smaller than those observed near the visible surface, the chromospheric amplitudes are sufficiently large that non-linear effects become important. These effects will be illustrated by the results of numerical calculations of the one dimensional response of the chromosphere.

The resonant modes trapped in the sub-photospheric cavity occur because waves of the frequencies of these modes cannot propagate at the temperature minimum where the scale height becomes too small. An evanescent, exponentially varying wave extends into the photosphere and the energy density decreases upwards towards the chromosphere. Although the energy density decreases, the velocity amplitude actually increases upwards, just not rapidly enough to overcome the effect of the rapidly decreasing density. Although the velocity becomes large, it is very difficult for these evanescent waves, with pressure and velocity out of phase, to dissipate, and they certainly will not form shock waves in the normal sense of the term. At large amplitude, they presumably couple to higher frequency waves which can propagate and dissipate. If the low temperature region extended to infinty, the reflection would be perfect. However, after approximately seventeen pressure scale heights, the temperature rises and the resonant mode frequencies can once again propagate. If the amplitudes were very small; a resonant cavity similar to that in the hydrogen convection zone would exist - as discussed above - and the two cavities would be coupled by the evansecent waves in between. As we shall see below, the waves are sufficiently strong to distort the high temperature reflection region of the chromospheric cavity and the chromospheric resonance is destroyed. Thus somewhat higher than 2 megameters above the visible surface the five minute oscillation will start propagating once again, but the amplitude of these modes is now quite large and as soon as they can propagate, they start to dissipate their energy.

Another process, whose existence might not have been anticipated from the modal analysis, seems to be of greater importance however. Lamb - who I indicated earlier discovered practically all of the basic physics of atmospheres over fity years ago - showed that when an isothermal atmosphere is subjected to a pulse of energy, a wake remains after the pulse,oscillating at the acoustic cut-off period. This is about 200 seconds for the solar temperature minimum region. Like the evansecent waves, this cut-off period wave transmits very little energy, and the pressure and velocity fluctuations are nearly ninety degrees out of phase. In contrast with the evanescent wave, the energy density does not decrease with altitude in the atmosphere. This wave appears to be excited by the 300 second evanescent wave in the solar photosphere, with which it enjoys a resonance - in that after two 300 second periods, three 200 second periods have elapsed. This is illustrated in Figure 2 where the non-linear response of a plane parallel solar atmosphere to a pulse started 1.6 megameters below the visible surface has been followed for 1400 seconds. A rigid lower boundary was raised about a kilometer in 50 seconds, so that the maximum upward velocity of the impulse was 0.05 km/sec. The resulting 300 second oscillation is rather weak only 0.1 km/sec at the surface. In contrast to the 300 second oscillation at negative altitudes, above the temperature minimum (550 km) a very regular 200 second oscillation has been established. Above 1000 kilometers the velocity oscillations become significantly asymmetric in time, and the pressure pulses narrow so that by 2400 kilometers the pulse is only about twenty percent of the period. High in the chromosphere, the pressure more than doubles in these short pulses, so that the atmosphere is blasted upwards and then nearly free falls back down until the descent is arrested by the next upward blast. As low down in the chromosphere as 1800 km, the particle excursions are of the order of 600 km, that is to say several scale heights. Thus even for this relatively low amplitude sub-photospheric, resonant mode, there remains no semblance of a mean, equilibrium chromosphere. Another resonant mode, of infinitesimal amplitude, could no longer interact with an equilibrium atmosphere, but rather it would see drastic time changes.

Attempts have been made to understand the temporal evolution of strong chromospheric lines such as the calcium K resonance line (Heasley (1975), Cram (1976)) and the hydrogen Lyman α line (Kneer and Nakagawa, 1976) by calculating line profiles from the chromosphere as a pulse, like the one which initiates the motions in Figure 2, propagates upwards. Durrant, Grossman-Doerth and Kneer (1976) have argued that such an isolated pulse with pressure and velocity in phase, is not capable of reproducing the observed profile changes. In fact, one sees that the situation following the initial pulse is distinctly different, in that the pressure and velocity fluctuations are significantly out of phase - nearly ninety degrees. Thus in a real, dynamical atmosphere the 200 second pulses are always moving into an atmosphere far removed from equilibrium by the passage of the previous pulse. Of course, there may exist other sources of pulses with no special phase with respect to the 200 second oscillation - those generated by exploding granules for example. But these too will move into an atmosphere whose time averaged properties bear little resemblence to the equilibrium, static atmosphere - there is no way that a micro-turbulent pressure is going to model even the mean state of an atmosphere with motions greater than the scale height. Furthermore, because of the substantial motions of the atmosphere, the velocity at constant mass depth - that is, measured in a Lagrangian coordinate - which bears a closer relation to what a spectral line will "see" than the velocity at a constant geometrical depth, contains striking differences for the upper chromosphere. Figure 3 displays the Lagrangian fluctuations for the same calculation presented in Figure 2. The phase velocities are reduced high in the chromosphere because of the outward impulses. The pulses also tend to form pairs, which is seen most clearly in the pressure fluctuation - the first pulse slows down the existing infall and the second re-accelerates the material outward. The resulting outward motion moves this mass depth away from the next outwardly moving pressure pulse, which as a result takes an increased length of time to catch up.

Although the most striking aspect of chromospheric dynamics - the decrease of the period of oscillation from 300 to 200 seconds - is easily accounted for within our present understanding of sub-photospheric resonant modes and propagation in the photosphere and chromosphere, the detailed evolution of optically thick spectral lines, which (presumably) provide us with much improved height resolution and a better constrained diagnostic, has not been satisfactorily described. While those who expected OSO-8 to observe beautiful N wave shock profiles to confirm the shock wave heating hypothesis (and deliver them their science on a silver platter) must feel somewhat disappointed, it certainly appears at this point that the ball has merely been placed back in the theoretician's court: it is incumbent on "us" to provide a meaningful expectation of the observable consequences of the "astrophysical truth" of the photosphere.

III. Chromospheric and Coronal Heating

The lack of unambiguous success in identifying propagating and dissipating shock waves in the chromosphere has certainly impeded the solution of the problem of chromospheric and coronal heating; but in addition to the diagnostic problem cited above, other theoretical aspects of a self-contained shock wave heating model remain to be resolved: total flux generated, distribution of the flux with period and horizontal wavelength, height distribution of the dissipation again as functions of the period and horizontal wavelength, effect of changes in the mean atmosphere on the generation and dissipation; to list but a few. It has been argued that the Sun is the ideal stimulus for attacking these questions not only because of the spatial and temporal resolution which its propinquity affords, but also because of the relative weakness of the chromosphere/corona phenomenon. Because only a very small fraction of the total flux appears to be required to heat the outer atmosphere above its radiative equilibrium temperature, only very small modifications to the conditions in the convection zone - or wherever else the generation of a propagating mechanical energy flux from a thermal flux may occur - would seem necessary. That is, the structure in the generation region may be calculated neglecting the mechanical flux, which is then just calculated as a perturbation - it exerts no effect back on the local, thermally controlled structure, such as might exist if very efficient wave generation refrigerated the atmosphere. However, because of the weakness of the pheonomenon it may well turn out that no one effect dominates and we may advance our understanding by studying the outer atmospheres of stars with more significant dynamical effects: cepheids or stars with more vigorous convection zones. Currently the situation is embarrassingly reversed; stellar astronomers seem to be taking unfounded solar hypothesis seriously and are applying them out of context. (See Linsky and Ayres (1977) for a critique).

These hypothesis have not changed significantly in recent years. Let me just outline them for the sake of completeness. Short period (less than 100 seconds) non-resonant waves generated by turbulence in the convection zone dissipate their energy by non-linear processes after propagating a shorter distance than the longer period, nearly resonant waves essentially because the short period waves have shorter wavelengths. Quite simply, they don't have to go so far in order to break. In addition to the horrible uncertainty in the power generated by this mechanism mentioned earlier, the short wavelengths - comparable to the region over which a spectral line is formed - have posed problems to the direct observation of these waves. Deubner (1977) has recently interpreted waviness in the temporal power spectra of photospheric oscillation at these periods as an indication of the existence of these short wavelengths. Ulmschneider and Kalkofen (1977) argue strongly in favor of the importance of this short wavelength heating, while Proderie and Thomas (1976) contest the treatment of radiative losses, Jordon (1976) supports Ulmschneider's position and Cram (1977) questions the whole edifice. These short wavelength waves would be primarily of importance in heating the low chromosphere, where they dissipate the remaining small fraction of their energy not lost by radiative damping as they propagate through the photosphere. Essentially none of their energy remains to heat the corona.

The model of heating by dissipation of sub-photospheric resonant modes in the corona has also suffered the difficulty of fundamental uncertainties in the energy generation rate. However, this appears to be in the process of being resolved. These modes have the advantage of being directly measured in the photosphere so that an observational normalisation is available. The direct calculation of the amplitude achieved by the overstability of non-vertically propagating modes is a challenging problem, which unfortunately has not been challenged. Since the amplitudes in the driving region are very small (less than one thousandth the sound speed), the oscillations will find it difficult to saturate the excitation mechanism. Calculation of the limitation of the amplitude growth by shock wave dissipation requires the coupled treatment of the overstability and of two dimensional shocks. While progress may be made using existing one dimensional shock wave computer programs, the determination of the importance of two dimensional effects must await development of the appropriate programs. According to Bob Stein, several groups are attacking this problem via different techniques.

Several authors have calculated the thermal structure to be expected from a balance between shock wave heating, radiative losses and thermal conduction using analytical expressions for the dissipation of the mechanical flux. Because the wavelengths are long compared to the scale height, approximate treatment of the propagation and dissipation of these waves by methods which assume the medium to be uniform are not valid. Nonetheless, a great deal of work and even more publications are based upon this invalid treatment. Stein and Schwartz (1972) have demonstrated the inappropriateness of applications of the "weak shock theory", which makes additional assumptions essentially equivalent to assuming that the shock doesn't exist, by comparing results with the full non-linear treatment.

In closing, it is appropriate to point out that while there remain many theoretical aspects of the hypothesis of shock wave heating of the outer solar atmosphere which require development before the hypothesis can be accepted or rejected, alternative hypotheses exist which may in time prove to be more successful in describing stellar chromospheres and coronae. In particular, very strong (greater than 1000 gauss), very small (less than an arc-second) magnetic fields are known to exist in the super-granulation network boundaries all across the "quiet sun", and these will support magnetic wave modes with generation, propagation and dissipation properites quite distinct from the purely acoustic modes described here. The work of Defouw (1976), Piddington (1973), Uchida and Kaburaki (1974), Wentzel (1974) should be consulted. In addition, one can imagine that these fields are capable of dissipating their energy in either very small flare-like, "catastrophic" events, or more uniformly in time - to give plasma physicists an easy problem for a change. In any case, I hope that it is clear that theoreticians have before them a wide range of exciting, relatively well defined problems and they may take heart from the recent success in the prediction of the modal structure of the five minute oscillation - some problems actually do manage to get themselves solved!

It is a pleasure to thank Robert Stein and Pierre Gouttebroze for many useful discussions and Lise Ouvrard for correcting the grammar. The non-linear calculations were performed on the CDC 7600 of the Centre National de Etudes Spatiales. This work was supported in part by NASA contracts NASW-3053 and NAS8-32356, and the Lockheed Independent Research Program.

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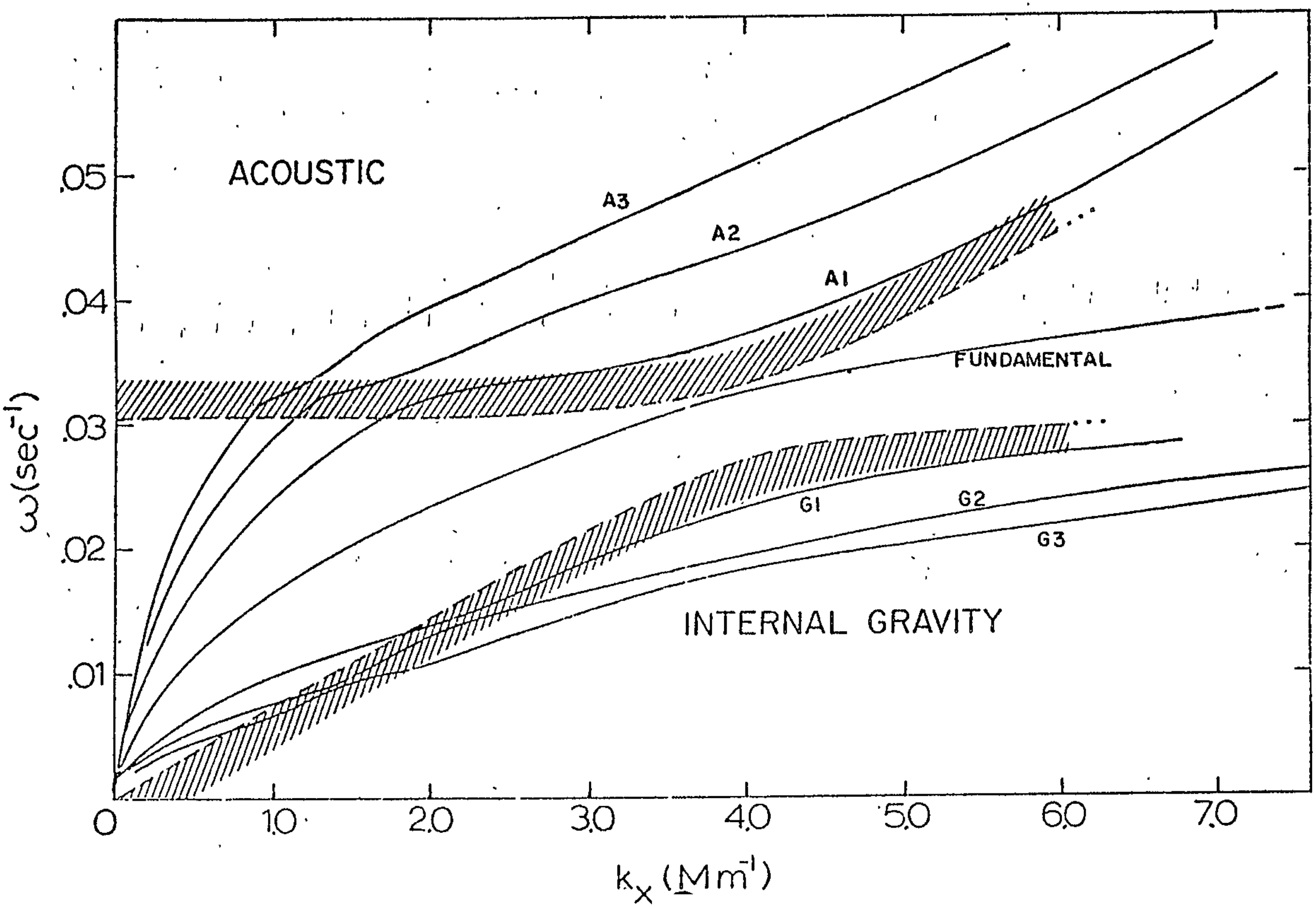
FIGURE CAPTIONS

Figure 1: Resonant modes for a plane parallel atmosphere with a 1.5 megameter thick temperature minimum at 4000°K, a 100°/km temperature gradient above and a 10°/km gradient below. Limits for propagating acoustic and internal gravity waves in the temperature minimum region are shaded. The fundamental and first three acoustic and internal gravity resonant modes are shown.

Figure 2: Velocity (solid lines) and relative pressure (dotted lines) fluctuations as a function of time at various altitudes in a model solar atmosphere. Altitude (in kilometers) is measured from a zero at $\tau_{5000} = 1$ in the initial atmosphere. The energy equation is adiabatic with a constant $\gamma = 1.4$. The velocity and pressure normalisation at each altitude was chosen to exhibit the fluctuations after the atmosphere had recovered from the initial pulse, and points out of range have not been plotted.

Figure 3: Same as Figure 2, except the fluctuations are measured at constant mass depths, corresponding (approximately) to the altitudes displayed in Figure 2 for the initial atmosphere.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A2
A1
FUNDAMENTAL
G1
G2
G3
INTERNAL GRAVITY
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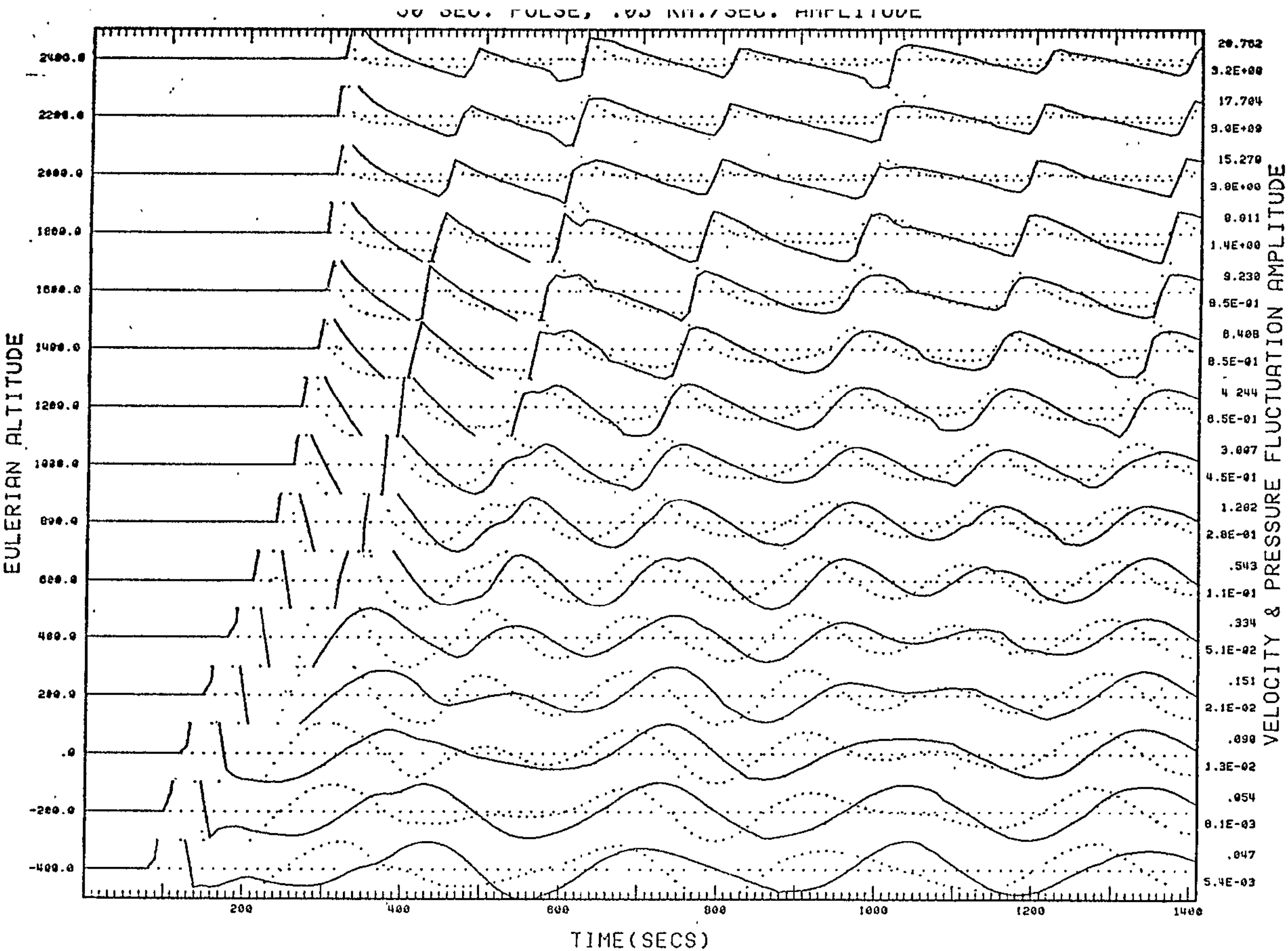
.04
.03
.02
.01
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
k_x (Mm⁻¹)

Figure 1

C-2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1800.0
1600.0
1400.0
1200.0
1000.0
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600.0
400.0
200.0
.0
-200.0
-400.0
TIME(SECS)
200
400
600
800
1000
1200
1400
VELOCITY & PRESSURE FLUCTUATION AMPLITUDE
20.762
3.2E+00
17.704
9.0E+00
15.270
3.9E+00
9.011
1.4E+00
9.230
8.5E-01
8.408
8.5E-01
4.244
6.5E-01
3.007
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.334
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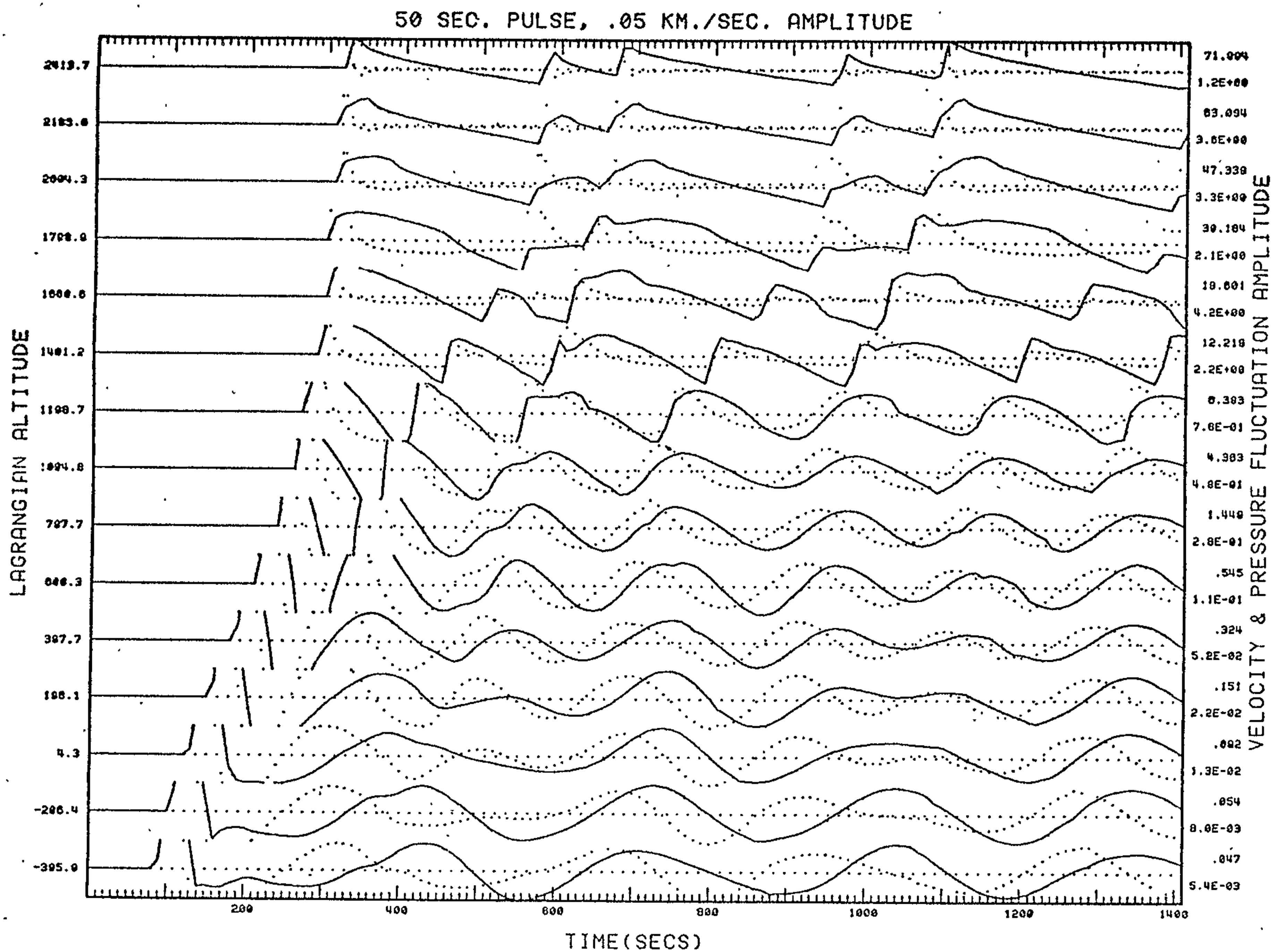
Figure 2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4.3
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VELOCITY & PRESSURE FLUCTUATION AMPLITUDE
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1.2E+00
63.094
3.6E+00
47.339
3.3E+00
30.184
2.1E+00
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5.2E-02
.151
2.2E-02
.092
1.3E-02
.054
8.0E-03
.047
5.4E-03
200
400
600
800
1000
1200
1400
TIME(SECS)

Figure 3

Attachment C

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Observations of oscillations of th. solar CaK, Mgk 2795 Å and H-Lyman α lines from OSO-8

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We have observed simultaneously the solar CaK (3933 Å), CaH (3969 Å), Mgk (2796 Å), Mgh (2803 Å), and H-Lyα 1216 Å solar lines with spatial, temporal and spectral resolutions of 1" x 10", 10 seconds and 0.02 Å, over time sequences ranging from 40 to 60 minutes.

When plotting as a function of time the integrated intensity of the Mgk line (over 1.09 Å), a clear quasi-periodic oscillation is visible on 48 out of 50 time-sequences ; 16 of the 48 measured periods are shorter than 197 seconds, 16 between 197 and 238 seconds, 16 greater than 238 seconds.

Within the 10 seconds resolution, the temporal evolutions of the intensity of the blue emission peak of the CaK and Mgk lines are correlated without phase shift.

A study of thepower spectrum of the temporal evolution of the intensity of the blue emission peak of the CaK and Mgk lines, for 12 time sequences, indicates that strong, short period oscillations (< 200 seconds) occur over quiet areas of the sun, such as the center of the supergranulation cells, whereas weak, long period (>250 seconds) oscillations occur over areas with active CaK profiles.

For 7 time sequences we have computed the average Lyman-α profile corresponding to the "blue" and "red" phases of the solar oscillations (i.e., for a time sequence of 300 spectra, we add the 100 Lyα profiles measured simultaneously with the 100 Mgk profiles with the strongest blue peak, and repeat one other Lyα average corresponding to the 100 Mgk profiles with the weakest blue peak). The resulting "blue" and "red" Lyman-α profiles have the same total intensity, the same intensity at the emission peaks, whereas the corresponding CaK and Mgk profiles are strongly different. The central reversal of the average "blue" Lyα profile is shifted to the red with respect to the average "red" profile, indicating that the part of the solar atmosphere where this central reversal comes from oscillates somehow in phase with the lower chromosphere where the Mgk lines originates.

Attachment D

THE ASTROPHYSICAL JOURNAL, 221:1032-1061, 1978 May 1

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THE LPSP INSTRUMENT ON *OSO 8*. II. IN-FLIGHT PERFORMANCE AND PRELIMINARY RESULTS

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ABSTRACT

The in-flight performance for the first 18 months of operation of the French, pointed instrument on board *OSO 8* are described. The angular and spectral resolution, the scattered light level, and various other instrumental parameters are evaluated from the observed data and shown to correspond mostly to nominal design values. The properties of the instrument are discussed, together with their evolution with time. The distribution of the first 8363 orbits between various observing programs is given. Preliminary results are also described. They include studies of the chromospheric network, sunspots and active regions, prominences, oscillations in the chromosphere, chromosphere-corona transition lines, and aeronomy.

Subject headings: instruments — Sun: chromosphere — Sun: prominences — Sun: spectra — Sun: sunspots — ultraviolet: spectra

I. INTRODUCTION

One of the major goals of solar physics is to understand the nature, origin, and evolution of the various features present in the solar atmosphere. Some, like the granulation, represent dynamical responses to the convection zone. Others, like spots or the more dispersed magnetic flux tubes (e.g., network fragments), represent symptoms of a magnetic process. Any advance in our understanding of such interior processes must come from high angular and spectral resolution observations of the line profiles of such features.

The NASA orbiting solar satellite *OSO 8*, launched on 1975 June 21, carried in its pointed section two instruments designed for the highest angular and spectral resolution achieved by spacecraft to date. One of these instruments was the responsibility of the Laboratory for Atmospheric and Space Physics (LASP) of the University of Colorado, the other was that of the Laboratoire de Physique Stellaire et Planétaire (LPSP) of the Centre National de la Recherche Scientifique (France).

In this paper, we describe the performance achieved in orbit and outline the main results obtained with the LPSP instrument after 18 months of successful operation. Most of these results are in a preliminary state. A complete description of the instrumentation has been given in Artzner *et al.* (1977), hereafter referred to as Paper I.

II. SUMMARY OF THE INSTRUMENT CAPABILITIES

Because of the limitations imposed by the size of the spacecraft (although considerably larger than the previous *OSO*s), the LPSP telescope was a Cassegrainian with a diameter of 16 cm. Consequently we limited our observations to the most intense chromospheric lines. Because the chromosphere is of limited depth, the spectrometer was designed so as to simultaneously observe six lines:

Ca II H (396.9 nm) and K (393.4 nm);

Mg II *h* (280.3 nm) and *k* (279.6 nm);

H I Lα (121.6 nm) and Lβ (102.5 nm).

A very rapid and versatile spectral scanner made it possible to also study the lines of O VI (103.2 nm) and Si III (120.6 nm) nearly simultaneously with those listed above and enabled us to study propagation effects and to obtain height resolution from the upper-photosphere to the lower corona. Table 1 summarizes the main characteristics of the spectrometer, which operates with two different spectral resolutions.

Two methods were available to make spectroheliograms. One was by means of spacecraft rasters: two image sizes were available, $44' \times 40'$ and $2'.75 \times 2'.3$ (nominal). The reader is referred to Paper I (Table 2) for more details on these rasters. In addition, the LPSP telescope had an articulated secondary mirror which was moved by a two-axis stepping mechanism. Accordingly the solar image could be moved step by step. Each step was 1" on the solar surface while the maximum area covered was $64'' \times 64''$.

A slit wheel mechanism, at the focus of the telescope, was used to select various slit sizes ranging

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TABLE 1

DESIGN CHARACTERISTICS OF THE *OSO 8* LPSP SIX-CHANNEL HIGH-RESOLUTION SPECTROMETER

		Spectral Resolution (nominal)				
		Low Mode	High Mode			
Central Line	(nm)	(nm)	(nm)	km s⁻¹	Maximum Spectral Range (nm)	Spectral Increment per Grating Step (nominal) (nm)
Ca II H.......	396.9	0.1	0.0020	1.51	395.164–398.244	0.00149
Ca II K.......	393.4	0.02	0.0020	1.52	391.444–394.942	0.00169
Mg II *h*.......	280.3	0.1	0.0025	2.67	277.739–282.264	0.00219
Mg II *k*.......	279.6	0.02	0.0025	2.68	277.005–281.551	0.00220
H I Lα.......	121.6	0.02	0.0020	4.93	120.569–122.291	0.00083
H I Lβ.......	102.5	0.1	0.0060	17.65	101.686–103.229	0.00074

NOTE.—Wavelength units are nanometers (nm).

from 1″ × 1″ to 1″ × 40″ as well as one corresponding to 6″ × 2′.

III. IN-FLIGHT PERFORMANCE

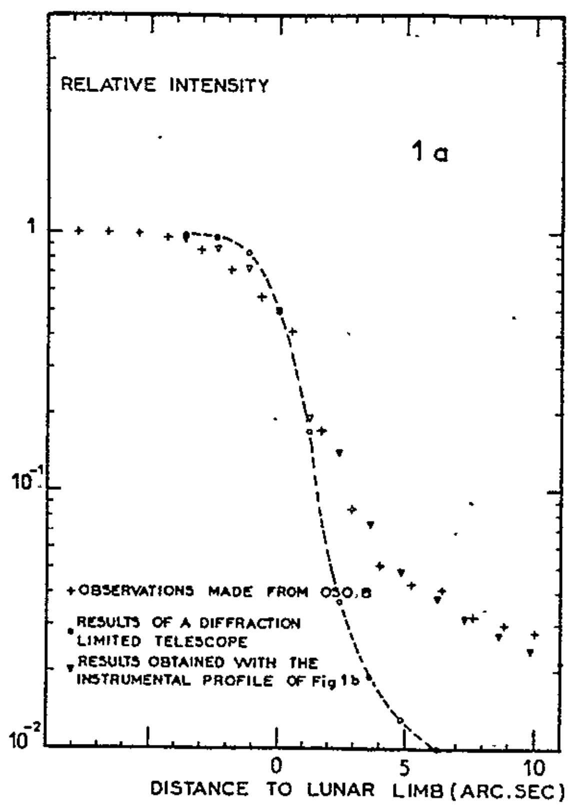
Prior to launch, the instrument was submitted to numerous tests and calibrations, the results of which are given in Paper I. Here we present the actual performance measured in flight.

a) Angular Resolution

The ground tests of the telescope led us to expect an instrumental profile with a full width at half-maximum (FWHM) of 2″. Two methods have been used to estimate the angular resolution in orbit:

i) *Images of Limb Shape*

Repeated scans of the solar limb, as observed with a 1″ × 1″ aperture using the internal raster mode in the



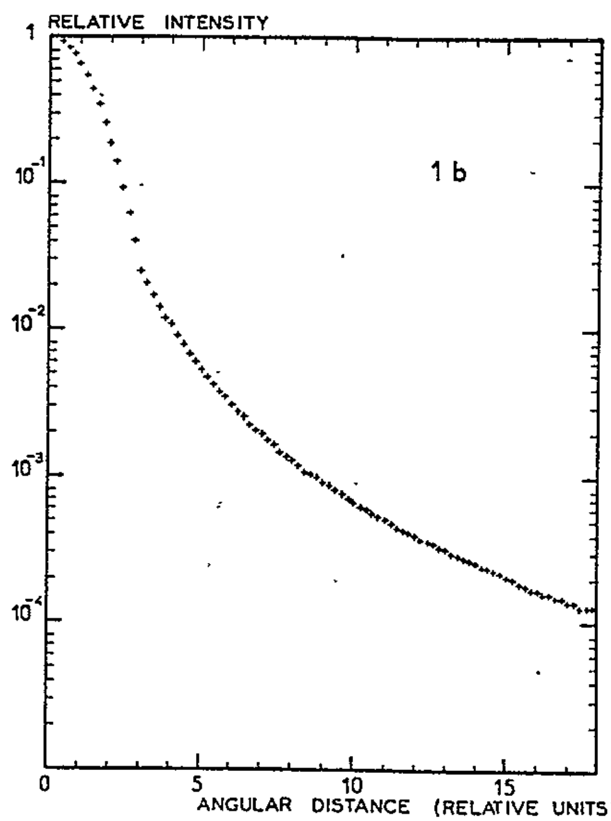


FIG. 1.- (*a*) Internal raster scans across the lunar limb in Ca K. The dots show the results one would obtain assuming the telescope to be diffraction limited. The triangles show the results one obtains assuming the instrumental profile to be that represented on (*b*), the telescope instrumental profile.

far wings of the Ca II line, show a limb darkening with a 50% decrease over an angular distance of 2″.

However, this method does not separate the resolution of the telescope from the jitter of the pointing system. Rapid, one-dimensional scan of the solar limb as well as other methods allowed us to estimate the amplitude of the rms jitter as 0″.5.

ii) *Partial Solar Eclipses*

On 1976 April 29 and October 23, two partial eclipses of the Sun were visible from *OSO 8*. Figure 1*a* represents spatial scans laterally across the lunar limb measured in relative intensity units. The actual observations are compared with the results of a computation assuming the 16 cm Cassegrainian telescope to be diffraction limited, and to have an instrumental profile as given in Figure 1*b*. The fit using the profile of Figure 1*b* represents a good approximation. We therefore conclude that the instrumental profile has a FWHM of 2″.5 ± 0″.5.

b) Spectral Resolution

i) *Lα and Lβ Channels*

For these we take advantage of the narrow absorption line due to geocoronal hydrogen. By applying a method developed for the study of interstellar absorption lines (Vidal-Madjar *et al.* 1977), we obtain a spectral resolution in flight of 0.002 ± 0.0005 nm at Lα, and 0.006 ± 0.001 nm at Lβ.

ii) *Calcium and Magnesium Channels*

We compare the solar spectra obtained by our instrument with ground based (Ca II channels) and balloon- or rocket-borne observations (Mg II channels).

In Figure 2 we show the full range Ca II K and Mg II *k* spectra from *OSO 8*. The variation with wavelength of the sensitivity of the instrument has been corrected for, and the spectra are deconvoluted from the instrumental profile. The comparison with the spectrum of the Kitt Peak Preliminary Solar Atlas (Brault and Testerman 1972), which has a spectral resolution of 0.0024 nm, shows that our resolution in orbit is better than this value. In the case of the Mg II channels, comparison with the spectra of Lemaire and Skumanich (1973) and Kohl and Parkinson (1976) yields a resolution of 0.0025 ± 0.00025 nm. This value is equal to the nominal design value (cf. Table 1).

c) Dispersion and Grating Mechanism (Spectral Scanner) Stability

The dispersion law of the spectrometer was determined in orbit by measuring the position, in units of a grating step, of 11 solar absorption lines of known wavelengths in the Ca II and Mg II channels. For the Lβ channel we used the O I lines at 130.48 and 130.6 nm and N I at 119.9 nm (which appear in the 11th and 12th orders of diffraction).

Because of the lack of lines in the Lα channel, we deduce the dispersion law from that at Lβ. The absorption line of geocoronal hydrogen provides an absolute reference. This proved to be valuable due to the appearance of positioning uncertainties (±1 grating step) in the movable Lα, Lβ exit slit mechanism. The dispersion law was measured repeatedly to check for long-term variations. Over 1 year we found that the correspondence between absolute wavelength and grating step number varied by no more than ±3 grating steps (cf. last column of Table 1).

To check the mechanism stability over one orbit, we measured the position of the photospheric line 391.52 nm in the wings of Ca II K. Any departure from the orbital Doppler effect could be attributed to photospheric Doppler shifts and/or changes in the spectrometer. The result is shown on Figure 3. One can easily recognize the 300 s photospheric Doppler oscillations after removal of the orbital Doppler shift, measured for the first time from space. The amplitude of the residual noise on this curve amounts to ± 30 m s^{-1}. The stability of the mechanism over a full orbit day is better than one grating step and exceeds our design expectations. We are able to easily and accurately measure Doppler shifts of photospheric and chromospheric lines (see § V*c* below).

d) Scattered Light Background and Dark Current

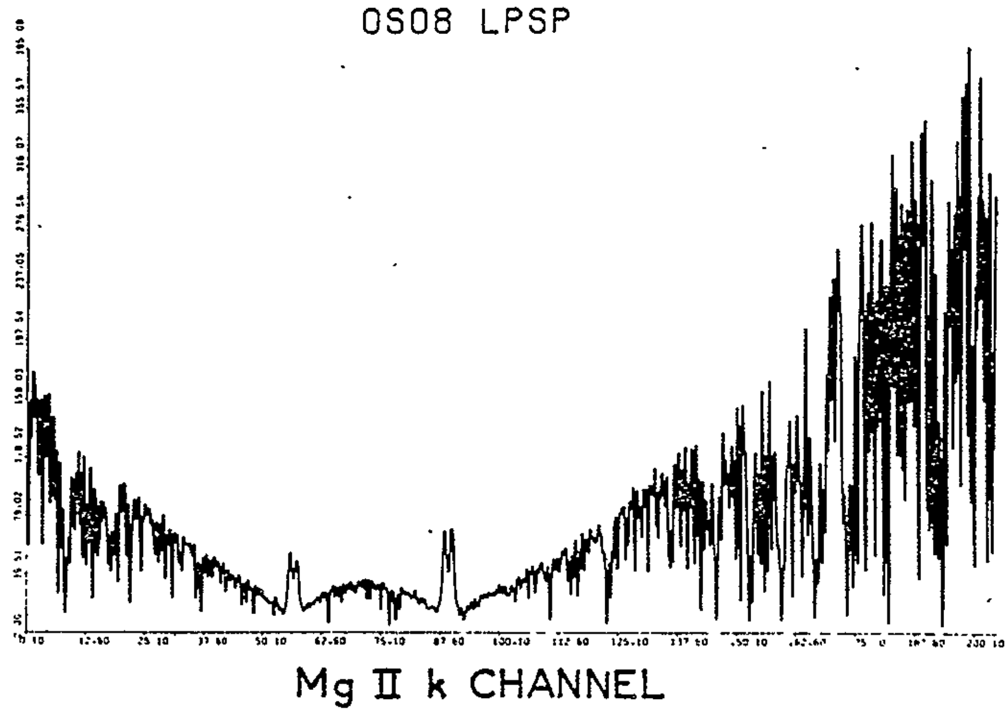
The level of scattered light in the telescope plus spectrometer was determined from partial eclipses of the Sun. From Figure 1 we see that at 11″ from the lunar limb this level amounts to 2% of the intensity of the disk in the calcium channels. For Mg II it is 4%. For Lα and Lβ these figures become 10% and 20%, respectively, which indicates that the scattered light level may vary with wavelength, roughly as $1/\lambda^2$.

No simple and unambiguous method was available to measure separately and give an absolute value for the amount of scattered light in the spectrometer due to wavelengths well away and near the wavelength of interest.

In the case of the Ca II and Mg II channels, we could compare the performance of our spectrometer with those of other ground-based or rocket-borne instruments. The result of this comparison appears in Table 2, where we give the ratio of intensities at Ca II H_1 and K_1, Mg II h_1 and k_1, relative to those of the Ca II and Mg II line wings. We notice that our performance is excellent for the Ca II channels, for which these ratios are smaller than those deduced from the Utrecht (Minnaert, Mulders, and Houtgast 1940) and the Air Force (Beckers, Bridges, and Gilliam 1976) atlases. We also compare our values with those of Linsky (1970) and of White and Suemoto (1968) who used particularly good optical systems. The Utrecht Atlas was used to evaluate the ratio of the H_3 and K_3 intensities relative to that of the continuum at 400.0 nm. The results are:

$$\frac{I_{H_3}}{I_{100.0}} = 0.053\,, \quad \frac{I_{K_3}}{I_{400.0}}\text{E} = 0.065\,, \quad \text{for } OSO\ 8\,,$$

while White and Suemoto (1968) find 0.071 ± 0.0015 and 0.061 ± 0.001, respectively, and Linsky (1970)



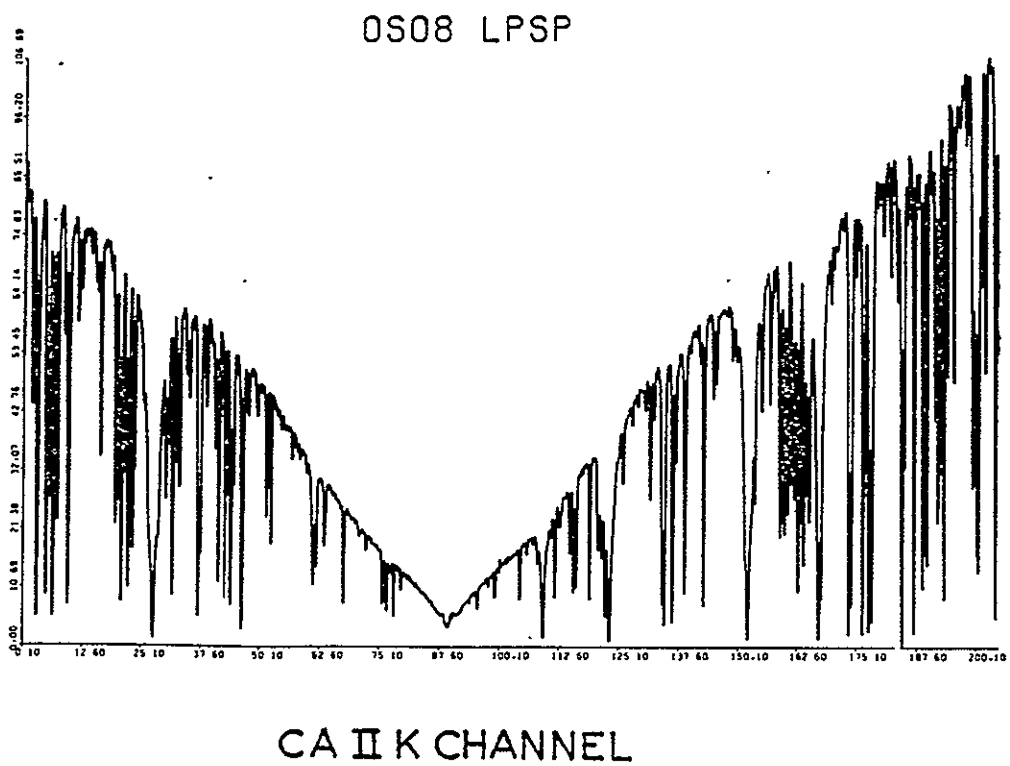


FIG. 2.—Full range spectral scans in the Ca II K and Mg II k channels using a 1" × 3" entrance slit. The ordinates are counts per gate. Instrumental sensitivity variations over the wavelength range have been corrected for. Notice the reversed asymmetries in the Mg II h and k lines. It takes approximately 50 s to go from Mg II k to h, and the asymmetries reflect time variations in the line profiles over 50 s.

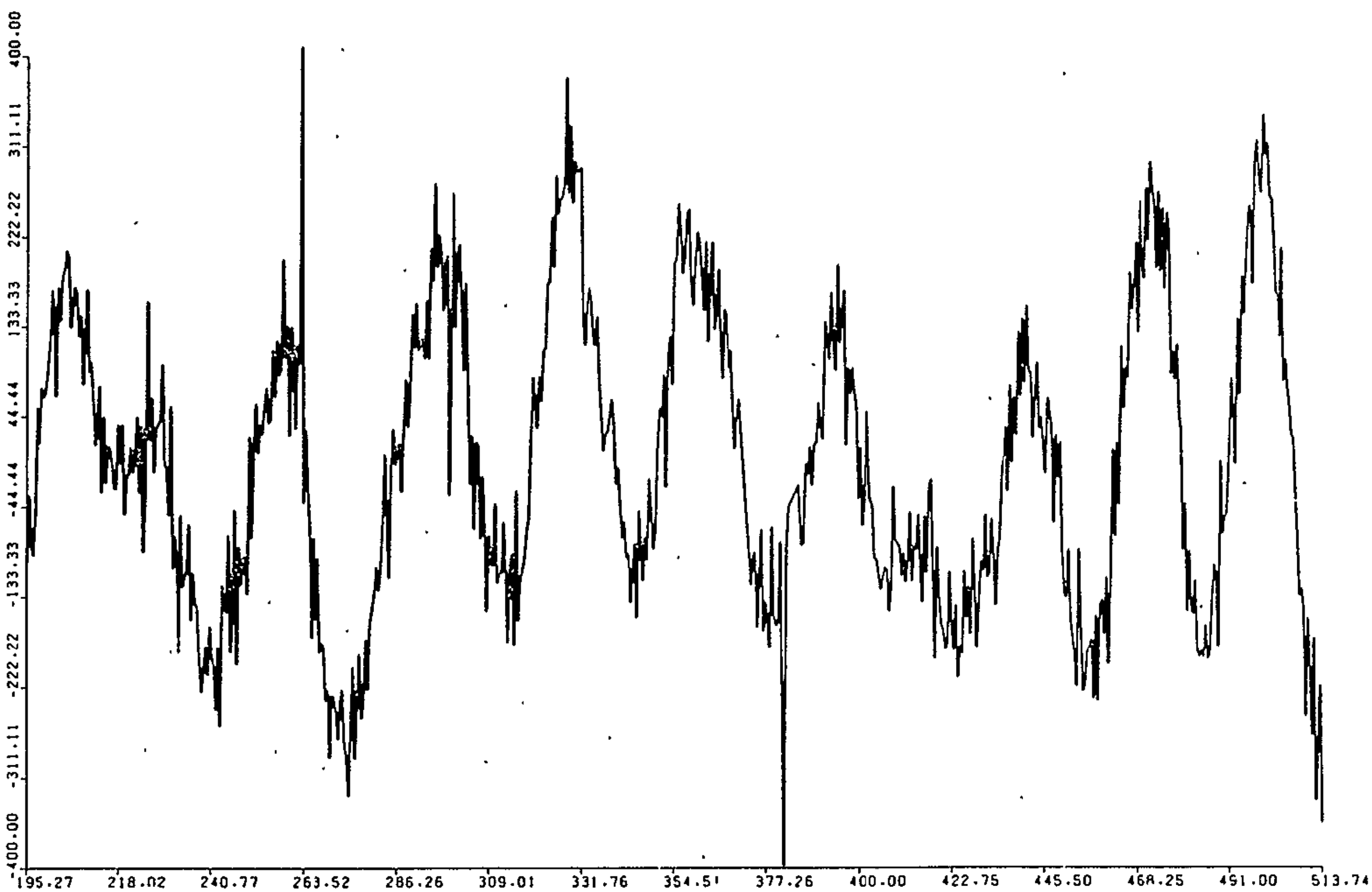


FIG. 3.—Relative velocity of the 391.52 nm photospheric line observed in the Ca II K channel. The 300 s oscillation is easily evidenced. The spacecraft Doppler shift has been removed. Spikes are identified as telemetry noise. The vertical scale is in m s^{-1}; the horizontal scale is in units of 10 s.

TABLE 2

RATIO OF INTENSITIES AT THE λ POSITIONS K_1, H_1, k_1, AND h_1 TO INTENSITIES MEASURED IN THE WINGS OF Ca II AND Mg II LINES IN THE *OSO 8* CHANNELS

Channel	Ratio	*OSO 8*	Utrecht Atlas (Minnaert *et al.* 1940)	Air Force Atlas (Beckers *et al.* 1976)	Kohl and Parkinson (1976)*
Ca II H.......	$I(395.18)/I(H_1)$	0.084	0.085	...	...
	$I(398.13)/I(H_1)$	0.077	0.090	...	...
Ca II K.......	$I(391.47)/I(K_1)$	0.078	0.088	0.087	...
	$I(394.85)/I(K_1)$	0.083	0.096	0.095	...
Mg II *h*.......	$I(k_1r)/I(277.73)$	0.079	...	...	0.048
	$I(k_1r)/I(282.01)$	0.063	...	...	0.045
	$I(h_1v)/I(277.73)$	0.046	...	...	0.028†
	$I(h_1v)/I(282.01)$	0.037	...	...	0.025†
Mg II *k*.......	$I(k_1r)/I(277.73)$	0.048	...	...	0.048
	$I(h_1v)/I(277.73)$	0.03	...	...	0.028†

NOTE.—The results are compared with the same ratios evaluated from Solar Atlases or available published data. *r* and *v* referred to the red and the blue part of the lines.

* We are indebted to Dr. J. Kohl for providing original records of his spectra.

† These values are probably uncertain due to the difficulty of measuring the solar intensity at k_{1_v}.

0.0409 ± 0.0022 and 0.0434 ± 0.0011 for the same ratios. Our results are intermediate between these two, confirming the very good performance of the Ca II channels.

For Mg II we have used the spectrum of Kohl and Parkinson for comparison. Excellent agreement is obtained in the *k* channel, our spectra indicating nearly exactly the same amount of scattered light as in the comparison spectrum. The agreement is, however, poor in the case of the *h* channel. Both the *h* and *k* lines can be observed in this channel together with the reference wavelength at 277.73 nm, allowing direct comparison between the two channels. As a result, we notice that the *h* channel has a much higher level of scattered light. This might be the result of degraded spectral resolution, due to a defective adjustment of the common coma and astigmatism corrector used in the Mg II channels whose delicate adjustment was optimized for the *k* channel.

For the Lα and Lβ channels we have made computations using the instrumental profiles, determined by ray tracing techniques, and the expected properties of the baffling inside the instrument; and we find that the level of scattered light is approximately 3% of the maximum flux in both channels.

Dark-current measurements were performed systematically each orbit during the first year and every 2 or 3 days in the second year. The dark current was found to be stable, with nearly no change during 18 months. The values are respectively 1.3, 1.1, and 0.1 counts s^{-1} for Mg II, Lα, and Lβ, respectively.

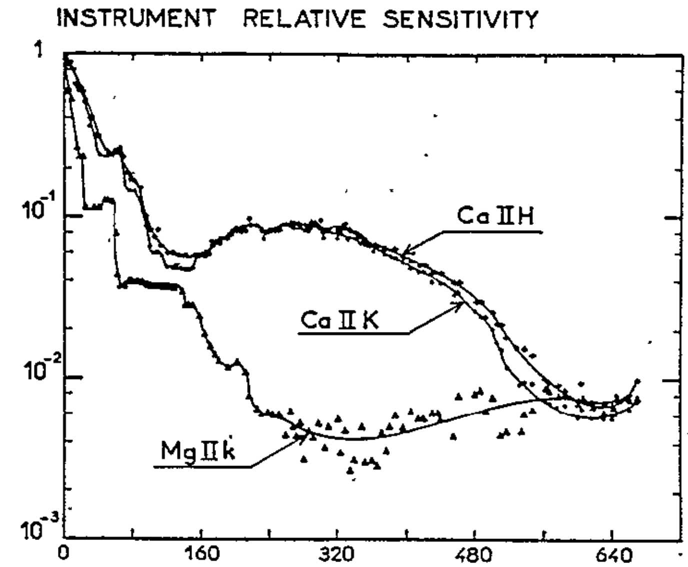
The calcium channel dark current was typically 200 counts s^{-1}. This comparatively bad performance is due to a leak in the enclosure system (skin).

e) Photometric Standardization

Photometric sensitivities have been measured regularly in orbit relatively to their values at launch. Such measurements are made every day or two with the 1″ × 10″ entrance slit at disk center quiet Sun, in the high spectral resolution mode for Ca II and Mg II and low resolution mode for Lα and Lβ. The number of counts at certain standard wavelengths (see below) measures the relative efficiency, whose variation as a function of time is shown in Figure 4.

The interpretation of these curves may be of interest to those who plan to utilize similar instruments in space. The telescope mirrors, the collimator, the grating, and all surfaces in the Lα, Lβ, and Mg II channels were coated at the Goddard Space Flight Center, with Al + LiF (Bradford *et al.* 1969). Elaborate precautions were taken in the storing and handling of optics throughout the mounting and calibration of the instrument. In fact, a special 300 square meter facility was built with air cleanliness and with temperature carefully controlled and humidity always kept below 30% (Salvetat 1975). A loss of sensitivity such as the one reported here is very unlikely due to a contamination in the instrument before the launch and should rather be regarded as caused by the outgassing of the spacecraft and the instrument once placed in the space vacuum. In that case, the greater the number of reflections, the larger the degradation. The presence of steps which appear at nearly the same time on all the curves of Figure 4 is probably the signature of sudden outgassing periods. The significant differences noticeable between the individual curves, however, are indicative of causes of degradation proper to each channel, affecting either the mirrors, the filters, or the detectors.

The two Lyman channels show nearly the same behavior, with the larger loss at Lα attributed to the larger number of reflections in this channel (seven at Lα versus five at Lβ). At day 540, i.e., 18 months after launch, the sensitivity at Lα and Lβ was 10^{-3} and 5.10^{-3}, respectively, of the value at launch. Assuming that each reflection is affected equally by the contamination (which is certainly a crude approximation), these numbers indicate that each reflection has reached 35% at Lα and 37% at Lβ of its value at



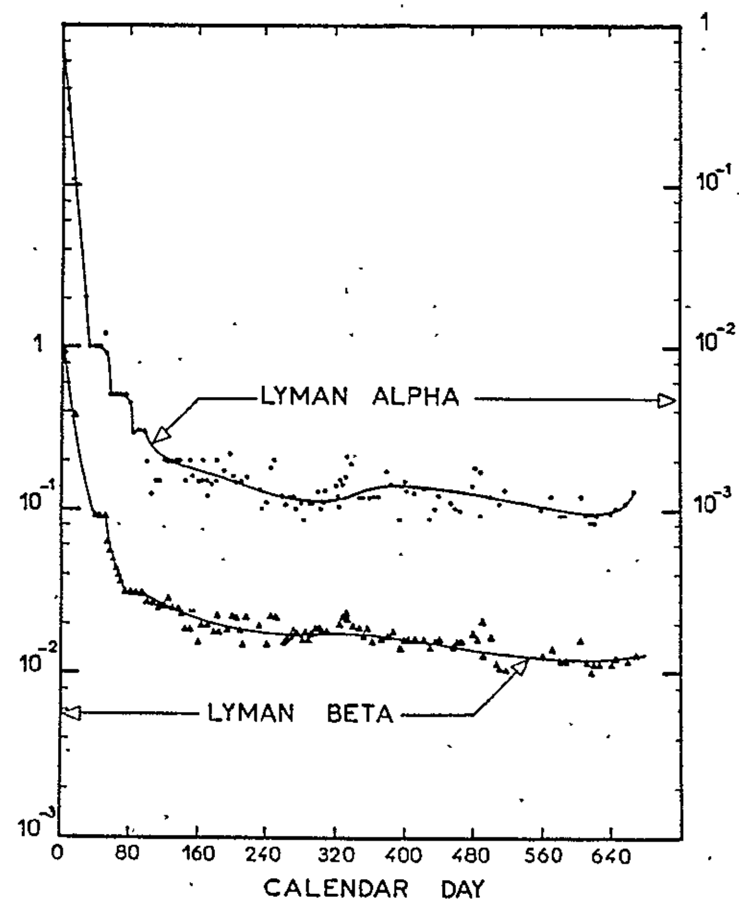


FIG. 4.— Variations of the instrument sensitivity relative to its value at launch. Time is in days after launch.

day zero. Such results are not particularly dramatic when compared with the photometric behavior of other solar space instruments (Huber *et al.* 1973).

However, the combined effect of outgassing and the baking of the secondary mirror surface by a flux of more than 18 "solar constants" is likely to be responsible in a large proportion for the sensitivity loss. A simulation made a few weeks prior to launch at NASA on Al+LiF coated samples illuminated by 17 "solar constants" and placed in a normally outgassing environment showed a decay in efficiency from 63% to 58% and from 67% to 35% at Lα and Lβ, respectively, only 52 hours after pumpdown.

Obvious solutions, such as closing a shutter in front of the telescope during the first orbits when outgassing is high, were unfortunately not possible and would have delayed the launch several months.

Assuming, arbitrarily, that the secondary mirror is responsible for a loss of a factor 10 at both Lα and Lβ, each surface would have reached an efficiency of 46% of its value at launch, which is more or less normal.

Totally unexpected and more striking is the behavior of the Mg and Ca channels. Although of yet unknown origin, outgassing might also be responsible for the degradation observed in these channels, at least until day 160 when the sensitivity reaches 1/40 and 1/20, respectively, of the value at launch. This corresponds to an average loss per reflection of 48% and 55%. After day 160 the sensitivity in the two Ca channels rises again. At the same time a faster decay is observed in the Mg channels. This peculiar behavior is attributed to interference phenomena, probably complementary, in Ca and Mg within thin films of contaminant(s) deposited on any one of the optical surfaces. Deteriorations of the interference filters which are used in all these channels may also contribute. In the case of the Mg channel it is also very likely that the detector itself is responsible for the loss of sensitivity. This is apparently not the case for the two Ca channels since their sensitivity follows nearly the same variation with time, which more likely reflects a variation in the optics used in common.

The overall loss of sensitivity compromised certain aspects of the observing program. However, the versatility of the instrument made it possible to obtain scientific data of high quality and value throughout the mission.

f) *Absolute Calibration*

The calcium channels were calibrated by comparison with the data of Linsky (1970) and Livingston and White (1978) which represent average quiet Sun conditions. The absolute intensity at our standard wavelengths H_{1_v} and K_{2_v} were taken as 0.0751 and 0.0687, respectively, in units of the continuum intensity at 400 nm.

For the magnesium channels we attempted to improve Bonnet's 1967 results (Bonnet 1968) and designed a high spectral resolution instrument calibrated against a blackbody constructed by R. Peyturaux at the Institut d'Astrophysique de Paris. This instrument was launched twice on the LASP rockets number 21029 on 1975 July 28, and 21030 on 1976 February 18, but because of malfunctions in the electronics it did not give reliable results. We prefer therefore to rely on other recent measurements—e.g., those of Kohl and Parkinson (1976). The absolute intensity at the standard wavelengths h_{1_v} and k_{2_v} were taken as 8 and 6×10^{-12} ergs cm^{-2} s^{-1} sr^{-1} cm^{-1}, respectively.

For the Lyman channels we also used the above rocket program to carry packages consisting of $\frac{1}{8}$ m Ebert-Fastie spectrometers, measuring the integrated solar disk to calibrate the LASP and LPSP instruments separately. Only the second flight yielded good calibration data. The results are given in Table 3 and are compared there with other measurements. The LPSP values are somewhat high; however, they are in the direction suggested by geophysicists (Levasseur *et al.* 1976). To use these integrated intensities in Lα and *L*β, we use quiet Sun average profiles computed for the whole disk (Fig. 5). We have taken into account the center-to-limb variation in an approximate way that will ultimately be improved upon by means of entire Sun raster-generated profiles (i.e., profiles constructed from spectroheliograms), when these become available from the data tapes. The absolute flux at the standard wavelength (core of the line) used to monitor the Lα relative sensitivity was taken to be 3×10^{10} photons cm^{-2} s^{-1} nm^{-1}.

IV. REAL TIME OPERATION AND PROBLEMS

The various modes of operation of the instrument have been described in Paper I. Here we discuss the "real-time" operation mode which allowed one, for

TABLE 3

INTEGRATED SOLAR FLUX MEASUREMENTS OBTAINED WITH CALIBRATION ROCKETS AT Lα AND Lβ

CALIBRATED FLUX	CALIBRATION ROCKETS				
	1975 July 28 LASP*	1976 Feb. 18 LPSP	1976 Feb. 18 LASP*	*OSO 5*† 1975 Aug. 8	AE/C‡ 1975 Apr. 11
F(10.7 cm) (10^{-22} W m^{-2} Hz^{-1}).....	75.5	70.1	70.1	70	
F(Lα) (ergs cm^{-2} s^{-1}).............	4.02	5.46 ± 20%	4.05 ± 20%	4.25	none
F(Lβ) (ergs cm^{-2} s^{-1}).............	none	0.078 ± 20%	none	none	0.050

* Rottman 1977.

† Vidal-Madjar 1977.

‡ Hinteregger 1976.

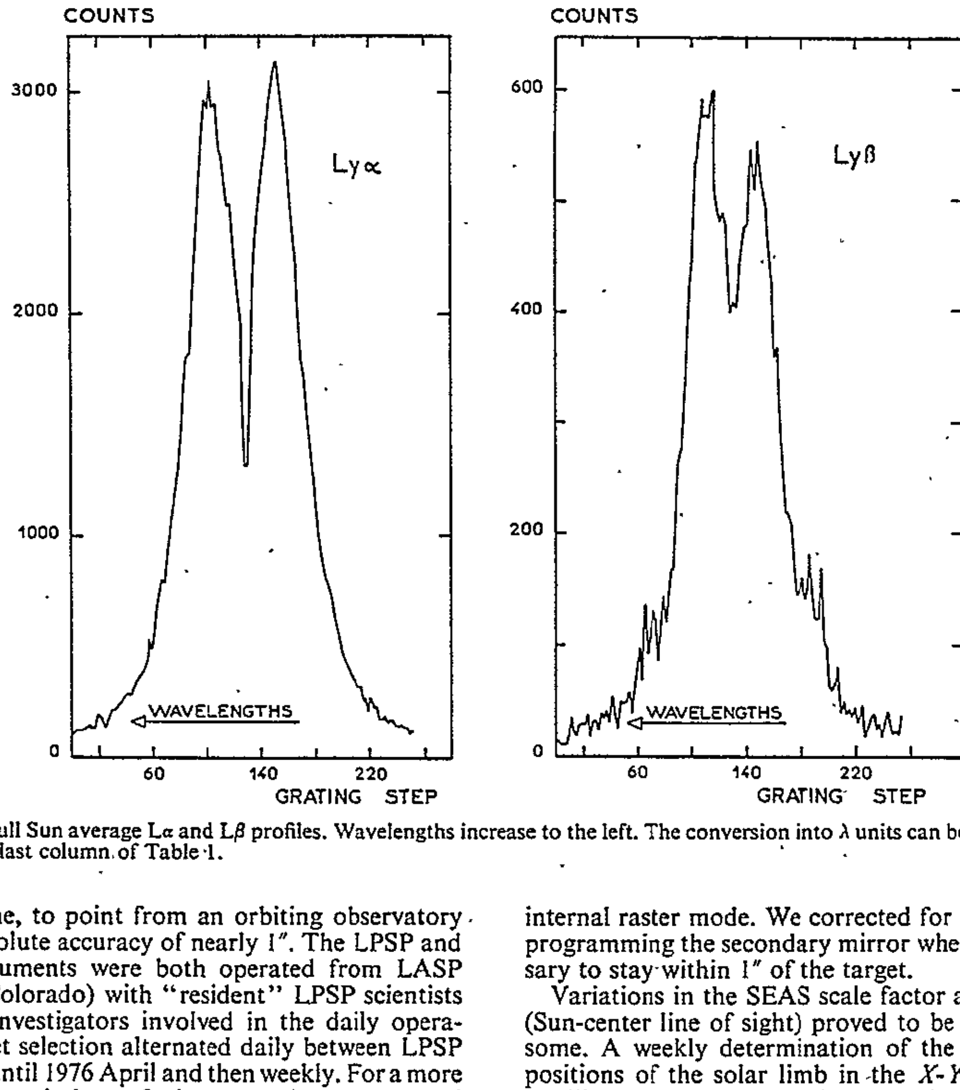


FIG. 5.—Full Sun average Lα and Lβ profiles. Wavelengths increase to the left. The conversion into λ units can be made using the values of the last column of Table 1.

the first time, to point from an orbiting observatory with an absolute accuracy of nearly 1″. The LPSP and LASP instruments were both operated from LASP (Boulder, Colorado) with "resident" LPSP scientists and guest investigators involved in the daily operations. Target selection alternated daily between LPSP and LASP until 1976 April and then weekly. For a more complete description of the operations command generation and quick-look facilities, see Jouchoux and Hansen (1978).

a) Pointing System Problems

The pointing system of the "sail" section of *OSO 8* uses either one of two Sun sensors (SEAS), designed by Hughes Aircraft Company, mounted on each instrument. These devices coalign the SEAS pointing axis with the optical axis of the associated telescope. This corrects for drifts of the optical axis with respect to the mechanical structure of the instruments.

Because of an electronic problem, the SEAS on the LPSP instrument failed after 56 days in orbit and all subsequent operations made use of the other SEAS. Consequently thermal and other drifts between the LPSP axis and the LASP axis had to be known. To determine these, we measure relative positions ($\pm X$, $\pm Y$) of the solar limb (in the X-Y frame of the satellite) during one orbit using images from the internal raster mode. We corrected for these drifts by programming the secondary mirror when it was necessary to stay within 1″ of the target.

Variations in the SEAS scale factor and zero point (Sun-center line of sight) proved to be more troublesome. A weekly determination of the absolute four positions of the solar limb in the X-Y frame of the satellite was necessary. Using such data, from spacecraft and internal rasters, an extrapolated scale and zero point could be found for the particular day of observation. This proved to be successful, and we were able to position targets at the very center of our field of view, often without the need for corrections. Finally, the repeatability of the pointing system at the limb was found to be within 1″ or 2″, but with occasional jumps of 5″.

b) Target Acquisition

Nearly 80% of the orbits under LPSP control were dedicated to studies of selected targets, often as small as a few seconds of arc. This mode of observation from an unmanned observatory involves a fairly complex procedure which requires considerable care and dispatch from the observer. We illustrate this in Figure 6 and describe the acquisition of the core of a sunspot.

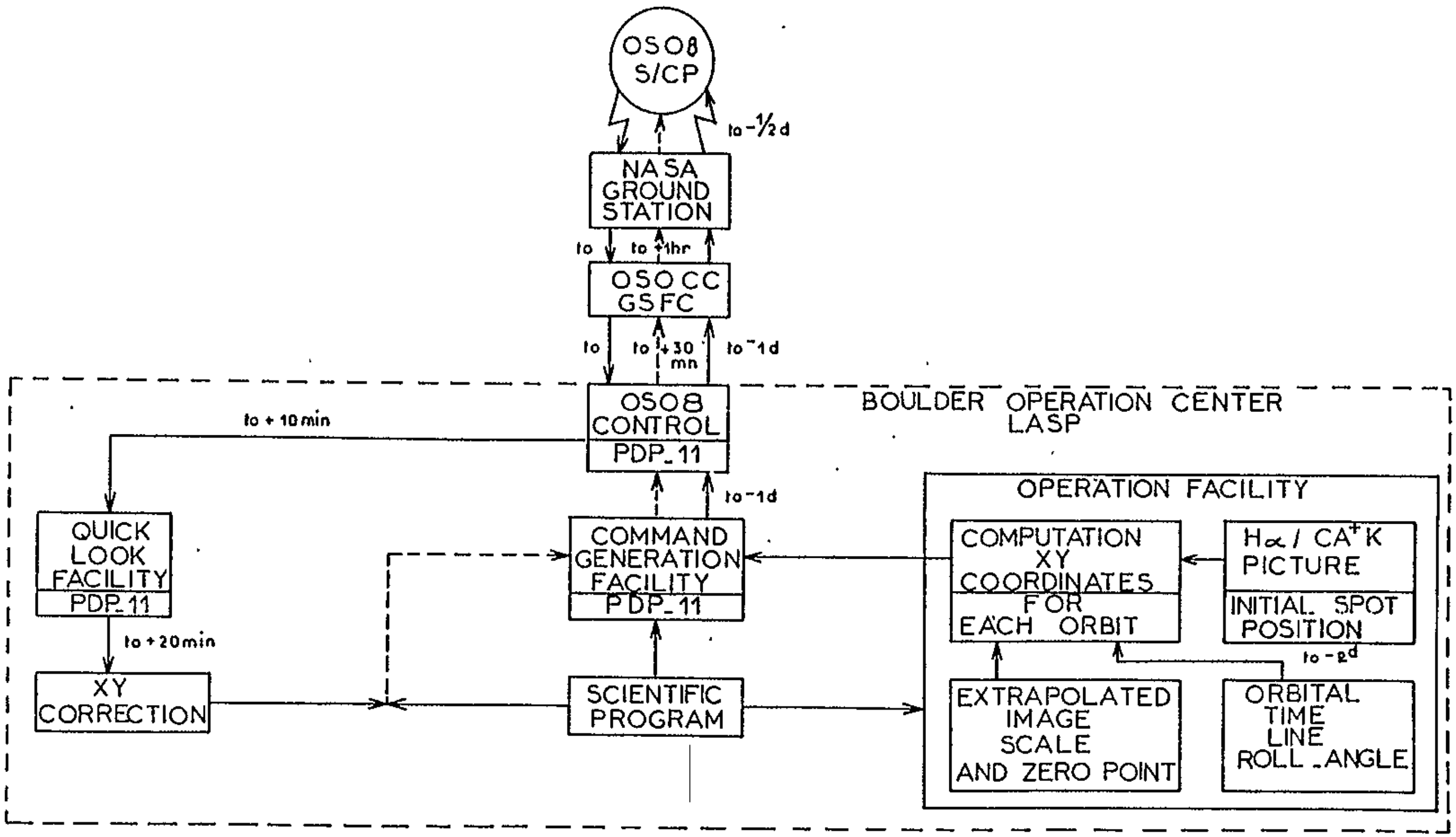


FIG. 6.—Block diagram showing the circuitry of telemetry and telecommand data between Boulder and NASA and illustrating "real-time" acquisition of a solar target (t_0 is the execution time).

As soon as a spot is visible on either a Hα picture (taken daily by NOAA/NBS in Boulder) or the Ca II K picture transmitted by telephone from Sacramento Peak Observatory, we determine its Stonyhurst coordinates for the time of the photograph. These coordinates are then transformed and oriented into the satellite spin frame of reference for the projected time of observation. Finally the scale distortion of the pointing system is corrected for. The instrument commands and associated pointing commands are generated and sent to NASA on the day before the date of observation. During the day of observation an internal image of the spot, 64″ × 64″, is executed in the far wings of Ca II or Mg II during a real-time pass of the satellite over a ground station. These real-time data are received by telephone via GSFC on the PDP 11 computer at Boulder, where they are subsequently decoded and displayed as an image. Any corrections to the position of the spot are determined from the image and are sent by telephone to NASA who uplink the corrections to the spacecraft. The time delay between the real-time pass and execution of pointing corrections can be as short as the time interval between two successive ground station passes, namely, $1\frac{1}{2}$ hours. This apparently straightforward operation is made more difficult because of the need to extrapolate the scale distortion parameters and to correct for the drifts of the line of sight already mentioned.

c) Lα *Modulation*

The Lα signal was discovered to be occasionally modulated with an amplitude which may reach 10% of the signal at precisely the rotation period of the spacecraft wheel except during the first 2 minutes after sunrise when sometimes a period distinctly shorter than the wheel period was found.

All attempts made to detect a similar phenomenon in the other channels have failed, suggesting that it is not caused by a pointing problem. Indeed we have sometimes observed oscillations in the pointing axis with periods equal to that of the wheel rotation and an amplitude of 0″5, but these affect all channels at the same time.

The phenomenon has to be taken into account when analyzing time series and profiles of the Lα line. As described in Paper I, the duration of every individual measurement is the product of 0.16 s gate time by a power of 2, and the most commonly used values are 10.24 s (64 grating steps) and 20.48 s (128 grating steps). The period of rotation of the wheel of the spacecraft varies from 10.7 to 9.5 s and for spectral scans with a time base equal to or larger than 10.24 s, the modulation induces a "beat" of period ranging from infinity to 131 s.

Figure 7 plots the raw data for the first moment of the wavelength of the line versus time. A strong 800 s period is evident. If the individual data points are corrected for the modulation with a period equal to that of the wheel and the first moment is recomputed, then the circles in Figure 7 show that the 800 s oscillation is suppressed.

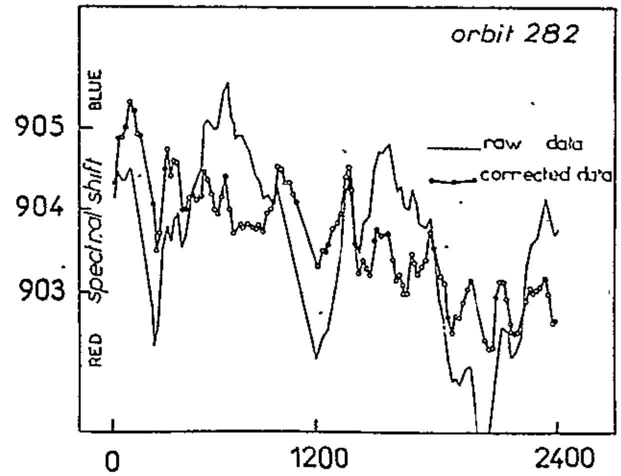


FIG. 7.—Variation with time of the position of the first moment of Lα. The solid line variation shows a strong oscillation of ~800 s period. Circles represent the same data after correcting the Lα profiles for the instrumental modulation: the 800 s oscillations have vanished. Abscissa is time (in seconds); ordinate is grating step number.

This proves without ambiguity that the phenomenon is purely instrumental and that the possibility of its solar origin, should be definitely disregarded.

V. PRELIMINARY RESULTS

Spacecraft (playback) data are sent by NASA to Boulder by telephone line and recorded there on magnetic tapes. Mass production tapes of this data are prepared by NASA and mailed to the Centre National d'Etudes Spatiales (CNES) (Toulouse, France), which is in charge of the processing and distribution of the final data tapes to the LPSP investigators and guest investigators. The results presented below have been obtained mostly from playback data at Boulder.

a) Observational Program

Table 4 presents a summary of the various types of observations that were programmed during the first 8363 orbits. No distinction is made in the table with regard to pointing control. Orbits with problems in either the instrument, the spacecraft, or the command system represent only 2% of the total.

The column headings in the table describe the modes of operation of the instrument while the rows indicate the scientific question or the solar feature under study.

Orbits labeled "Line Profiles" usually correspond to spectral scans ranging from 64 to 512 grating steps centered at either the six chromospheric lines or the O VI line at 103.2 nm. The "Others" columns indicate studies in either the wings of the Ca II and Mg II lines or the O V and Si III lines at 121.8 nm, 120.6 nm, respectively. Other lines such as O I, N I, etc., were observed in the Lβ channel by making use of the different grating orders. During these orbits the satellite was in the pointed mode.

TABLE 4

SCIENTIFIC PROGRAM OF THE FIRST 8363 ORBITS

Parameter	Line Profiles			Spectroheliograms			Velocity Fields and Oscillations	Transients	Large λ Scans	Guest Observer Orbits
	6 Lines	O VI 103.2	Others	6 Lines	O VI 103.2	Others				
Quiet Sun:										
Chromospheric network.......	554	194	...	465	80		310	257	254	463
Limb studies................	483	180	25	208	126	95				
Active regions..............	583	175	31	276	209	7	132	138	30	249
Sunspots....................	455	107	8	120	184	1	20	56	2	117
Coronal holes...............	42	87	14	25	40	11	...	...	4	5
Prominences.................	63	23	3	33	20	1	...	...	...	25
Filaments...................	55	23	...	26	35	...	...	...	...	...
Full Sun images:										
R 128s	High resolution (20″)			73	87	16	...	...	...	...
R 128f				13	2	3	...	...	...	...
R 64........................	Low resolution (40″)			135	1	...	...	...	...	...
Photometric and pointing calibration..................	360	...	...	...	123	...	...	...	...	...
Instrumental tests and miscellaneous...............	...	...	...	...	421	...	...	...	...	...

NOTE.—Numbers represent full day orbits.

Under "Spectroheliograms" we classify orbits for which most of the time is spent rastering, using either the internal or the satellite raster mode. Morphology and long-term variability studies of solar features were of interest here.

During orbits labeled "Velocity Fields and Oscillations" we spent most of the time in the pointed mode studying rather small areas of the disk, not more than 64" × 1". Here, special spectral scans were made. For example, short-period waves ($T < 40$ s) were searched for by scanning rapidly through the line profiles using wavelength position separated by 16 grating steps.

Under "Transients" are grouped orbits observed with the fast, low-resolution satellite rasters. The short time constant of such modes allows one to observe rapidly propagating shocks and any other rapid phenomena.

"Large λ Scans" represent the full scanning capability of the grating and were performed either to study lines in the low orders of the Lβ channel or to standardize the Mg II and Ca II line cores with respect to their far wings.

For most orbits, sunset and sunrise experiments were performed in order to measure atmospheric extinction at various wavelengths of interest (see § Vg below).

"Chromospheric Network Studies" include not only morphology and time evolution but also line profiles for center-to-limb and cell-network comparisons. "Limb Studies" include orbits dedicated to the shape of the limb, spicules, and the vertical extension of the solar atmosphere in various lines.

"Photometric Calibration" has already been described in § III; for these orbits the satellite is pointed at disk center in a quiet region.

The last five rows of Table 4 include scientific as well as instrument or satellite calibration orbits. Also included are orbits devoted to eclipse observations, to studies of the geocoronal hydrogen line, and to the search for lines such as Fe XIII 121.64 nm and He II 102.5 nm.

b) Quiet Sun and Chromospheric Studies

Figure 8 (Plate 21) represents an example of our study of the network and the quiet Sun. Such internal raster images along with associated profiles will permit an intercomparison of cell and network properties.

Figure 9 compares profiles obtained at the center of a cell and in a network fragment. One can notice the strong variation in intensity, particularly in Mg II *k* and Lα, between the two regions. This is due partly to a decreasing line background contribution as well as differential temperature sensitivity. The asymmetry of Lα is always much less pronounced than in the case of Mg II *h* and *k*, presumably because of smaller velocity gradients at the Lα height of formation.

Figure 10 shows average quiet Sun profiles of Lα and Lβ taken with a 6" × 2' slit at disk center and near the limb ($\mu = 0.14$). Notice the two lines of O I at 130.48 and 130.59 nm in the wings of Lβ (observed in the 11th order). By the insertion into the light beam of a MgF_2 filter one can block out all photons below 115 nm and observe only the two O I lines. Differencing permits one to reconstruct the Lβ profile. The result of this procedure is shown on Figure 11. The remaining slight anomaly at grating step 180, might be due to the Hβ line of He II (102.53 nm). Center-to-limb measurements at the corresponding wavelength show appreciable limb brightening. Investigations are under way to confirm this observation.

The variation of the distance between peaks of the Lα and Lβ lines from center to limb is apparent together with the variation of the ratio of the peak to core intensities (see Table 5). The values in Table 5 at $\mu = 0.14$ are close to those calculated by Vernazza (1972).

One noticeable feature is the reversed intensity asymmetry between the Lα and Lβ shortward and longward peaks at the disk center. In Lα the shortward peak is generally higher than the longward peak while the reverse holds in Lβ. At the limb, both Lα and Lβ profiles become symmetrical. It is possible that this effect may not be intrinsic but is either an instrumental effect or the effect of unresolved lines at Lβ. The matter is under study.

To study the morphology of network fragments and their evolution in time, monochromatic images have been obtained simultaneously in the six lines alternately with broad-band images in O VI (103.2 nm) for a number of observing sequences (Fig. 12). Preliminary analysis of a 20 hr sequence shows that significant evolutionary changes can occur over a 12 hr period. The larger size K_{2_v} fragments are easily identified in the Lα+Lβ (=H Lyman) and O VI images where they do not appear as extended as indicated by the ATM data (Reeves 1976). This is supported by an analysis of the Lα brightness distribution. Applying the method of Skumanich, Smythe, and Frazier (1975) to both the present *OSO 8* sequence and ATM data, one finds a fractional Lα network area of 37% and 41%, respectively. The ratio of mean network to mean cell brightness proved to be 1.9 and 2.1, respectively. For comparison the *OSO 8* Ca II distribution yielded a fractional area of 27% and brightness ratio of 1.3.

c) Quiet Chromospheric Oscillation and Transients

We have already mentioned in § IIIc (cf. Fig. 3) our successful detection of the 300 s oscillation of photospheric lines in the wings of Ca II H and K.

TABLE 5

Center-to-Limb Comparisons of the Distance between the Blue and Red Peaks and of the Ratio between the Average Peak Intensity and the Core Intensity of the Lα and Lβ Lines

	Separation of Peaks (nm)		I_{peak}/I_{core}	
Line	$\mu = 1.0$	$\mu = 0.14$	$\mu = 1.0$	$\mu = 0.14$
Lα........	0 043	0.05	1.3 ± 50%	2.2
Lβ........	0.027	0.031	1.4 ± 50%	1.5

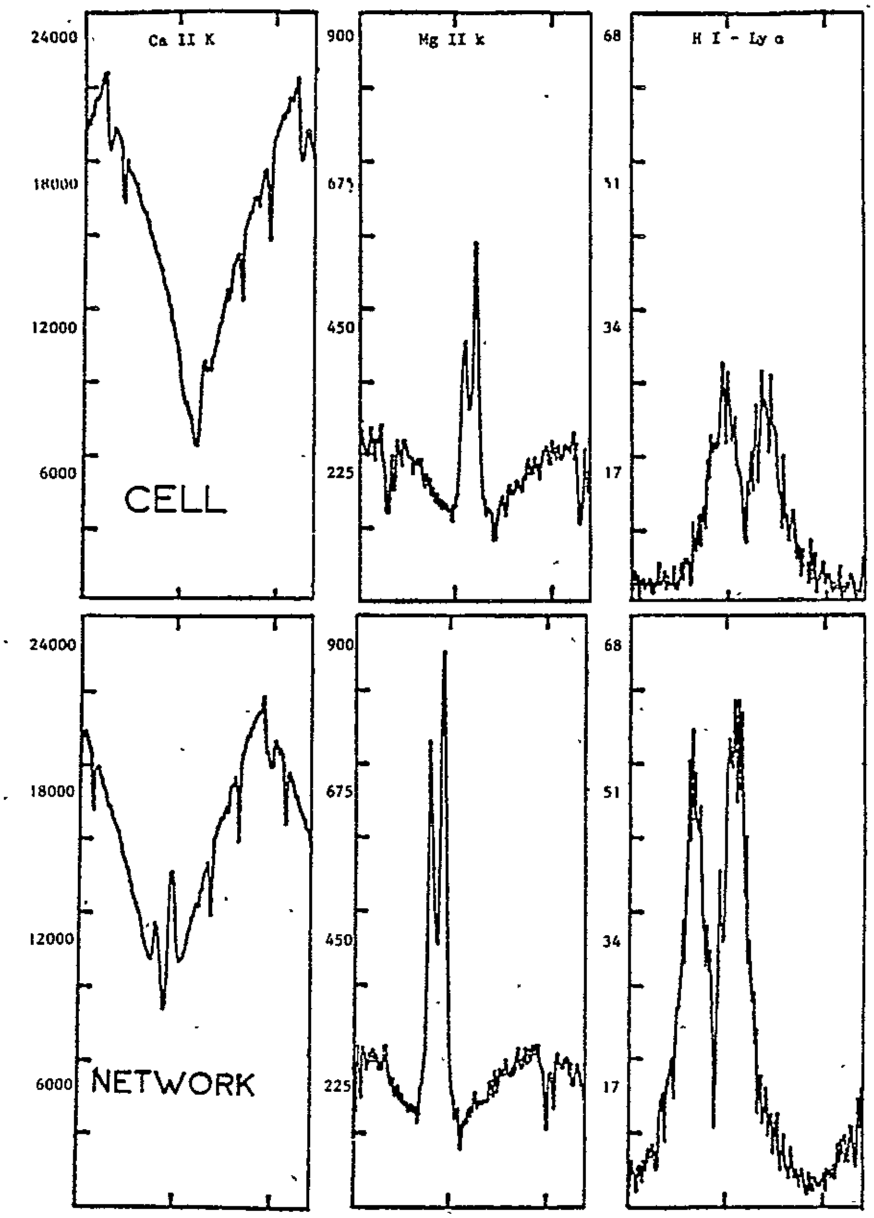


FIG. 9.—Comparison between simultaneous observations of Ca II K, Mg II k, and Lα profiles in the network and at the center of a supergranulation cell. The slit size is 1″ × 10″. Units are counts per counting gate.

The Mg II k and Ca II K lines (Fig. 13) show oscillations of $\sim$200 s period. We parametrize the profile of Mg II k as a difference of two Gaussians:

$$I(\lambda) = E_1 \exp\left(\frac{\lambda - E_2}{E_3}\right)^2\left[1 - A_1 \exp\left(\frac{-A_2}{A_3}\right)^2\right],$$

where E_1 and A_1 represent the intensities of the emission and absorption components of the profile, respectively, and E_2 and A_2 the average wavelength position (or "first moment of the wavelength") of the emission and absorption components. We should point out that no physical meaning is to be attached to this parametrization. The time behavior of these various parameters is shown on Figure 14.

The oscillation of the parameter E_2 or average emission position covers a range of $\pm$0.00186 nm or $\pm$2 km s^{-1}. For A_2 or average absorption position, this value is doubled. This clear difference might be interpreted as the amplification, with increasing height in the atmosphere, of a wave, if one assumes, as usual, that the core of Mg II k is formed at a higher altitude than the wings. The average "bluer" position of E_2 (emission) compared to A_2 (absorption) reflects the

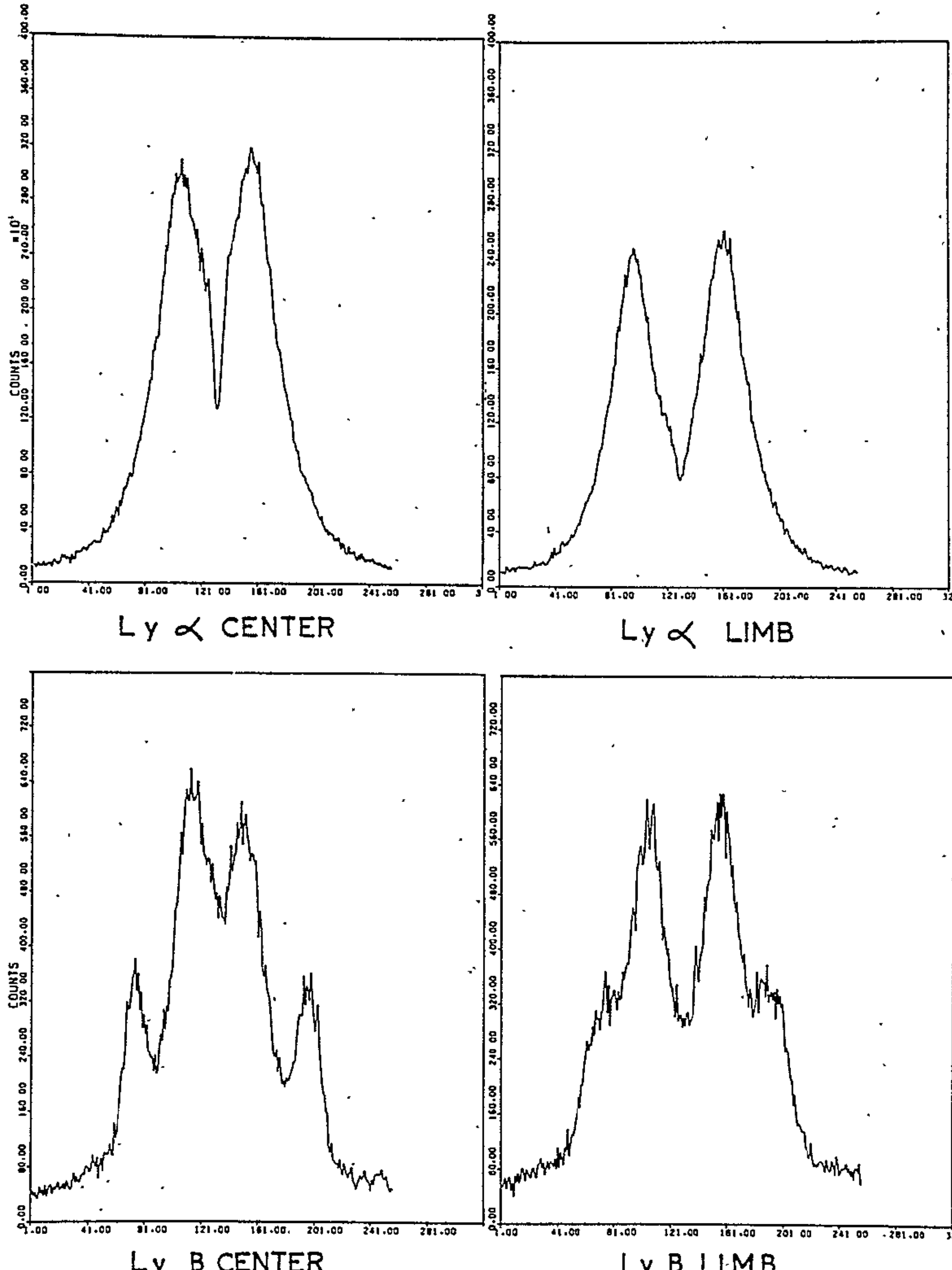
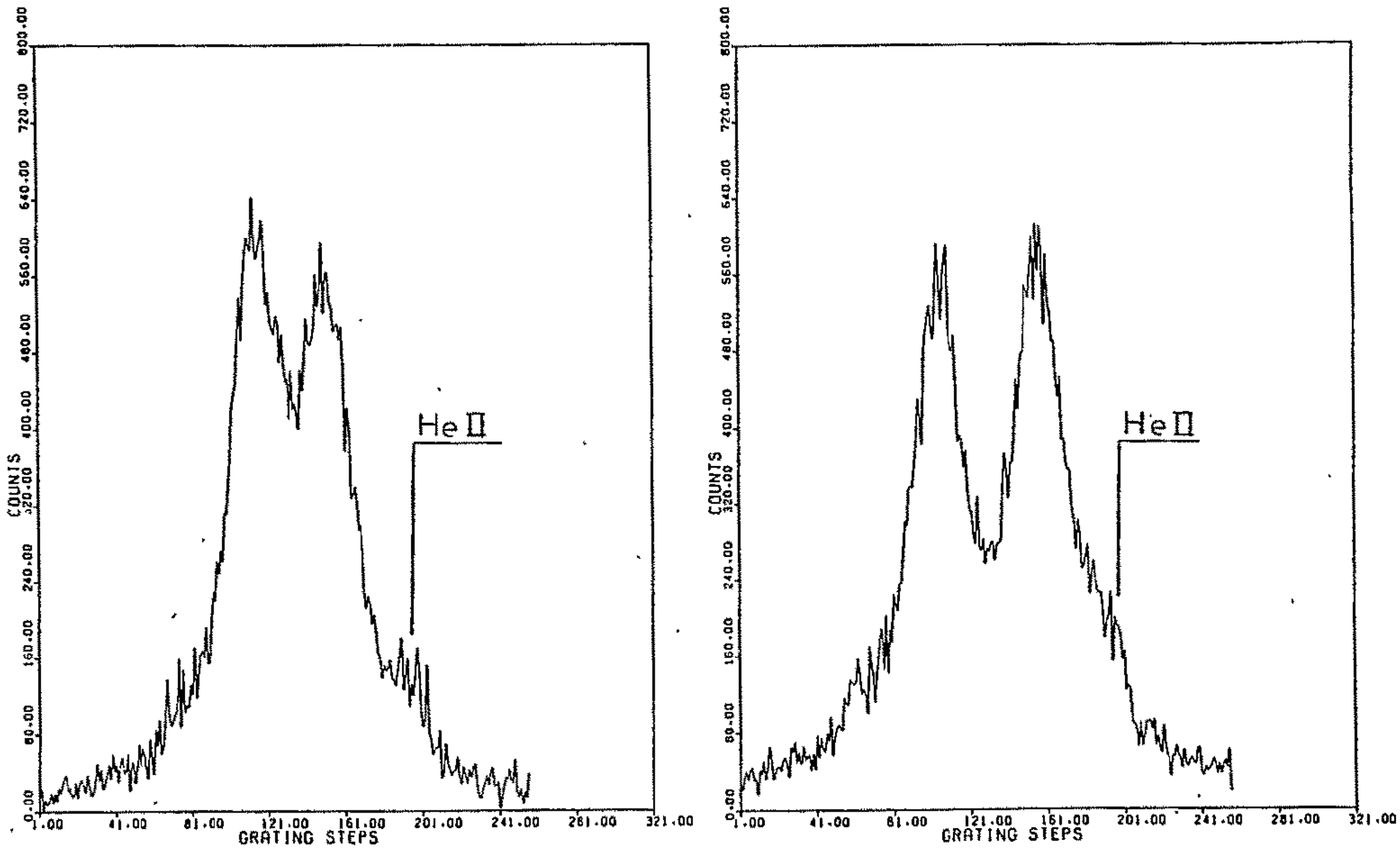


FIG. 10.—Lα and Lβ profiles at the center and at the limb of the Sun obtained with a 6″ × 2″ resolution. The two lines in the wings of Lβ are O I 130.48 nm and 130.59 nm appearing in the 11th order of diffraction. Wavelengths increase to the left. The abscissae are grating step numbers. For conversion in λ units, see Table 1.



CENTER

LIMB

FIG. 11.—Lβ profiles after the subtraction of the O I lines made by inserting a Mg F_2 filter in the beam. Wavelengths increase to the left. For conversion into λ units, see Table 1.

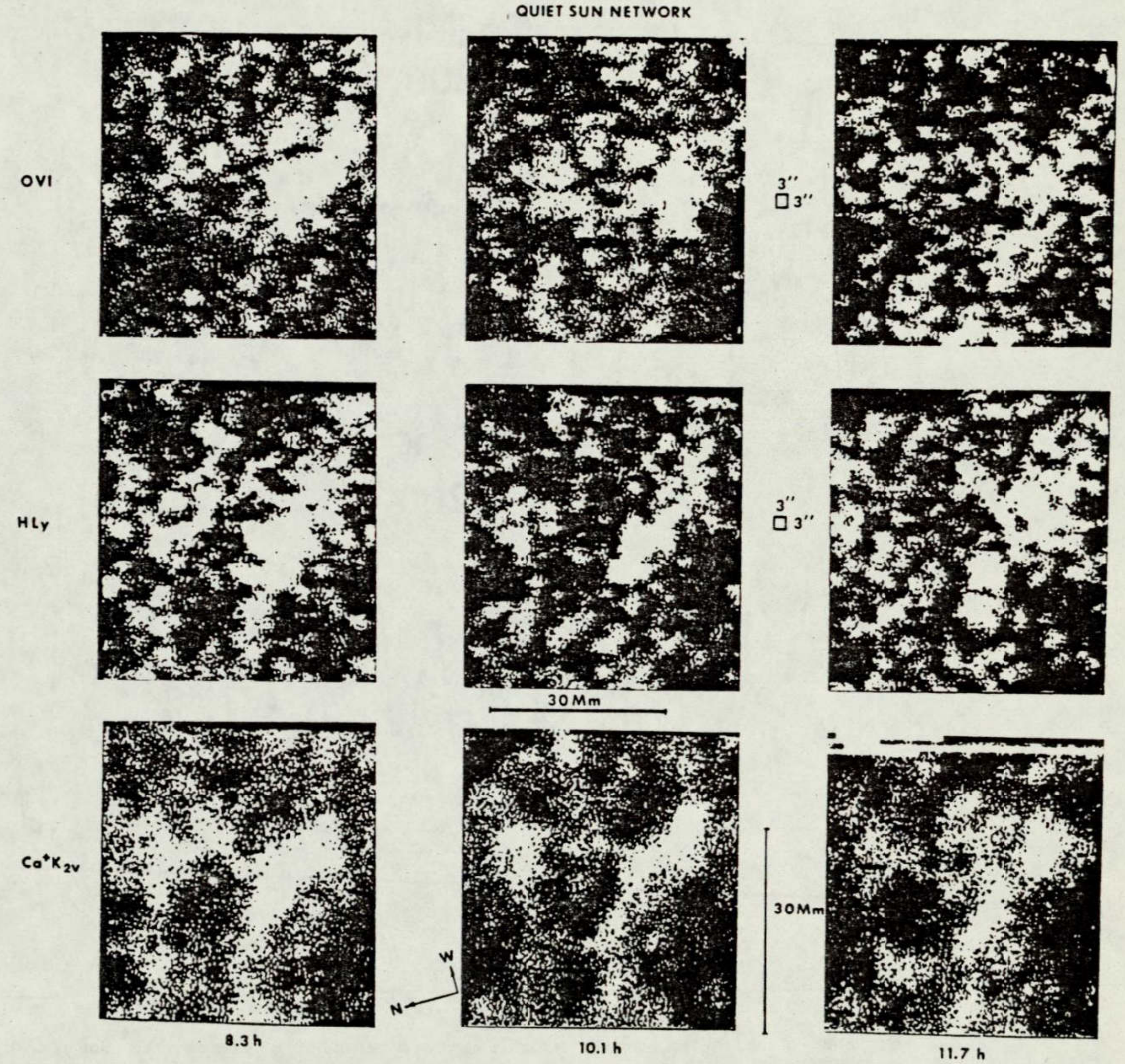


FIG. 12.—Evolution with time of network fragments, observed with 64″ × 64″ internal rasters in O VI, Lα, and Ca II lines

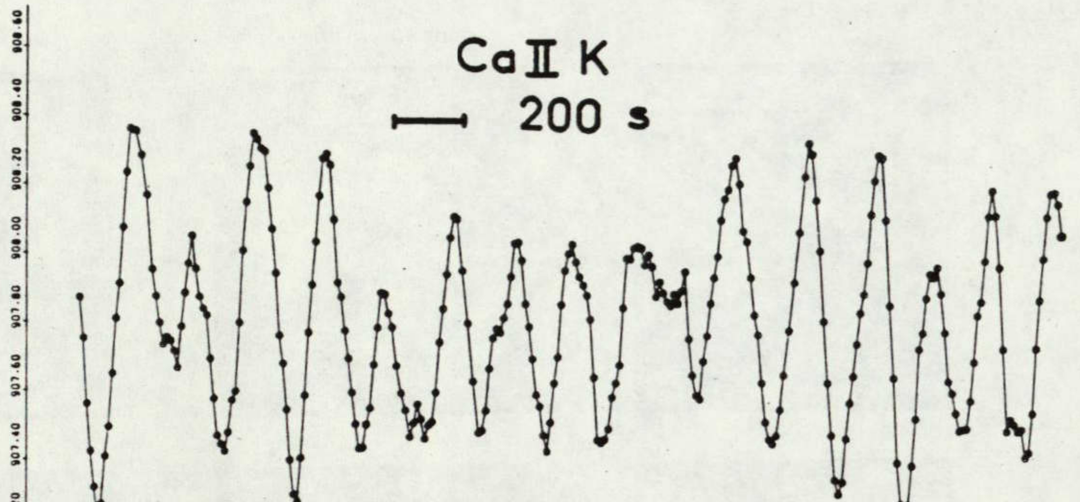


FIG. 13.—Oscillations of the center of symmetry of the Ca II (*upper curve*) and Mg II (*lower curve*) emission components. Horizontal units are multiples of 10 s.

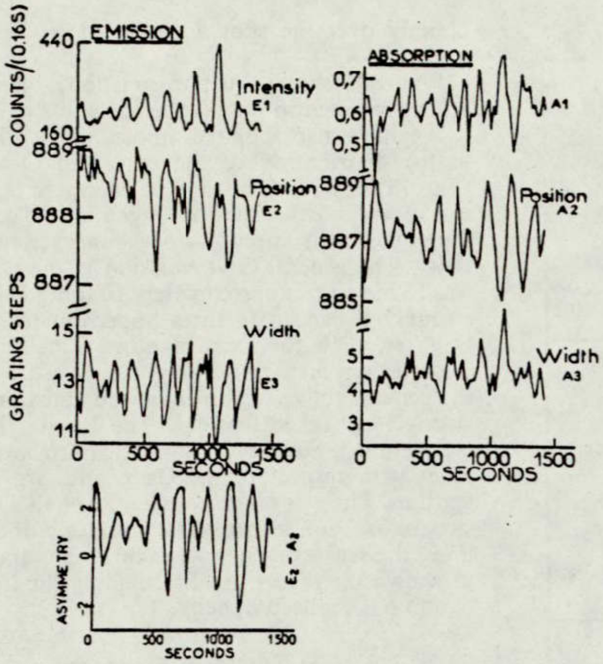


FIG. 14.—Time variations of the various parameters of the analytical function used to represent Mg II k. Observations are made at disk center.

fact that the average Mg II k profile in the Sun is asymmetric, with k_2v stronger than k_2r. This is illustrated also on Figure 15, where we see that the line shape varies from a strongly asymmetrical profile ($k_2v > k_2r$) to a nearly perfect symmetrical profile ($k_2v = k_2r$).

In Figure 16 we see the variation over 40 s of the Mg II and Ca II K profiles observed simultaneously.

The Mg II lines exhibit the same periods as the Ca II lines. We have a broad set of observations which contain wave trains lasting in general no longer than a few cycles with periods ranging from 250 s down to 130 s. A search for shorter periods was undertaken, in particular by guest observers, but no clear evidence has yet emerged from these investigations at this early stage of data analysis.

The good results obtained in Mg II encouraged us to search for a possible oscillation of Lα. The large contribution function of the line, which tends to smooth out the effects of any wave on the profile, together with the low photon count in this channel made this observation a particularly difficult one. We first tried to detect intensity fluctuations by integrating the number of photons over ± 0.025 nm from line center. We did not find any obvious evidence of variations, other than random, a result in accord with the previous attempts made from studies of *Skylab* results (Vernazza *et al.* 1975).

To overcome the low photon statistics problem, we tried to correlate the shape of Lα with that of Mg II k profiles. We definitely see evidence for a correlation, the bluer k profiles corresponding to redshifted Lα profiles. The amplitude of the shift is of the order of 2 grating steps (3 km s^{-1}). More work is under way, but we may state at this stage that the oscillations seen in Mg II k have an influence higher in the chromosphere, at the altitudes where Lα is formed (Artzner *et al.* 1978).

Several orbits were devoted to the study of oscillations in the O I, Si III, and O VI lines, but have not yet been analyzed. Transient and short time phenomena have been observed. Numerous tachograms dedicated

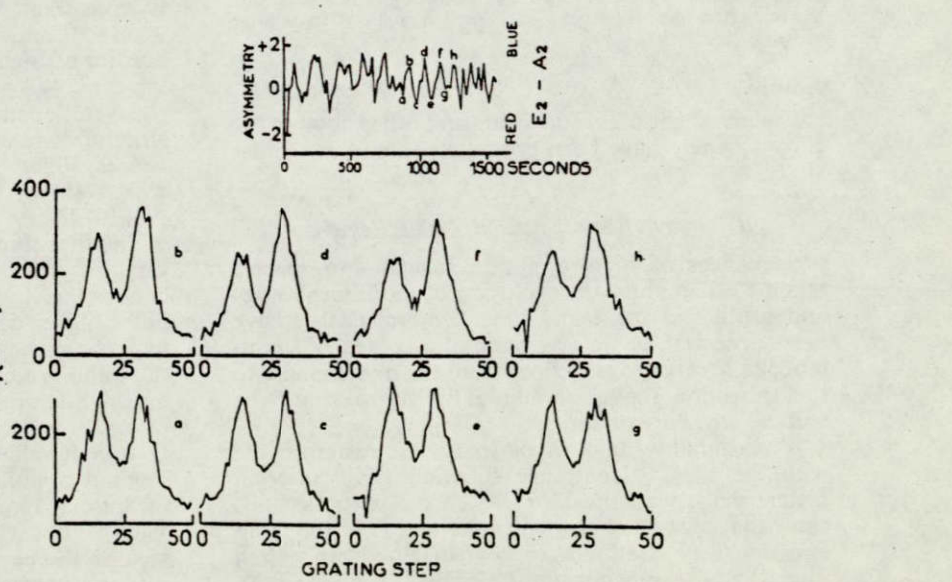


FIG. 15.—Mg II k profiles observed at the maxima and minima of the oscillations of the line center of gravity, showing obvious occurrence of asymmetrical blue peaked profiles at maxima and symmetrical or slightly asymmetrical red peaked profiles at minima. Wavelengths increase to the left.

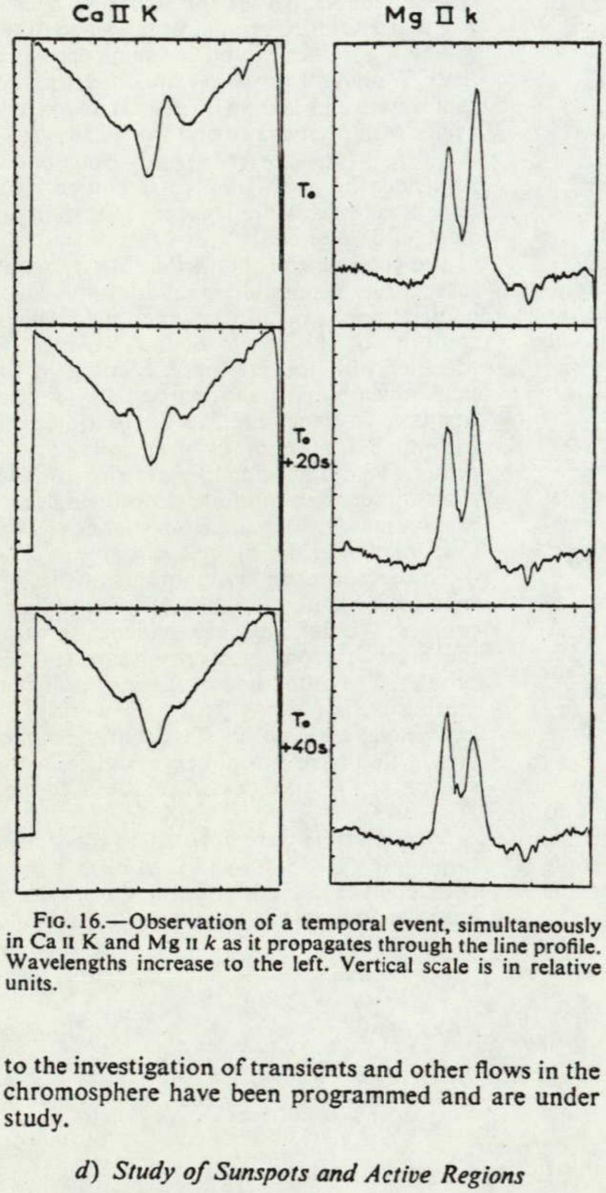


FIG. 16.—Observation of a temporal event, simultaneously in Ca II K and Mg II *k* as it propagates through the line profile. Wavelengths increase to the left. Vertical scale is in relative units.

to the investigation of transients and other flows in the chromosphere have been programmed and are under study.

d) Study of Sunspots and Active Regions

Sequences of high-resolution images and spectra taken 1″ apart show the evolution of spot morphology and profiles in space and time. Umbral flashes have been observed as well as oscillations. Nearly simultaneous observations of lines from the photosphere to the transition region should allow us to study the vertical structure of spots.

A preliminary analysis of spacecraft rasters made with the 1″ × 10″ entrance slit, and LPSP internal rasters made with the 1″ × 1″, 1″ × 3″ entrance slit, show that regions of strongly enhanced O VI 103.2 nm emission very often tend to be distributed other than directly above sunspot umbrae. This is the case both for some unipolar single spots as well as multipolar spot groups. However, we do find circumstances when single spots show the transition region "plume" directly over the spot as reported by Foukal *et al.* (1974).

Figure 17 shows this phenomenon, where isophotes are represented in photospheric light, Lα, and O VI.

We have also found examples of steplike changes in the distribution of the enhanced O VI emission (Fig. 18). If we assume that the enhanced O VI emission is associated with a specific magnetic field connectivity, then our results imply "step" changes in field connectivity. The general O VI emission in the active region was found to be approximately 10 times brighter, with strongly enhanced features approximately 100 times brighter, than the average quiet Sun. Simultaneous observations in Lα, Lβ, Mg II, and Ca II also show the general active-region enhanced emission as well as strongly enhanced features. The Lα and Lβ features are identical, but show systematic horizontal displacement with respect to the Ca II and Mg II emission features. Little or no correlation is found with the O VI structures. With regard to the profiles of the resonance lines, the self-reversal is weak or absent above regions as shown on Figure 19. Presumably the line-forming region has reduced opacity.

e) Studies of Prominences

Temporal evolution of, and velocity field in, prominences were studied with consecutive monochromatic spacecraft rasters. Figure 20 shows, at the top, Ca II images at wavelengths ranging from -0.012 nm to $+0.03$ nm from line center. The main loop is clearly visible only at line center; this is confirmed by spectra constructed from the different monochromatic images of the prominence which show a single emission peak with a FWHM of 0.020 nm which is typical of quiescent prominences (Engvold and Livingston 1971). This is consistent with a mean turbulent velocity of 9 km s^{-1} and a temperature $T_e = 8500$ K. At the bottom of Figure 20 are two simultaneous Lα and Lβ images.

Several observations were made to study the thermal structure and evolution of active and eruptive prominences. Figure 21 shows an internal raster performed with a slit of 1″ × 1″ above active region McMath No. 14127.

The first three simultaneous images in Lα, Lβ, and Ca II K$_2$v show a loop system with a rather faint contrast in K$_2$v as compared to the plage at the limb, but a higher contrast in Lα (and Lβ). The next three images are separated by 11 minutes (raster repetition rate) and are made in O VI 103.2 nm. They trace out the high-temperature evolution of the region (O VI being formed at approximately 350,000 K). The first O VI image shows a faint high loop, the second some residual brightness around the foot of the loop, and the third an important enhancement at this same point. Then within 20 min the loop disappeared, as can be seen on the next three images in Lα, Lβ, and Ca II K.

Many images and spectra have been obtained that will allow the study of temperature, density, and velocity variations during loop evolution (Vial *et al.* 1978).

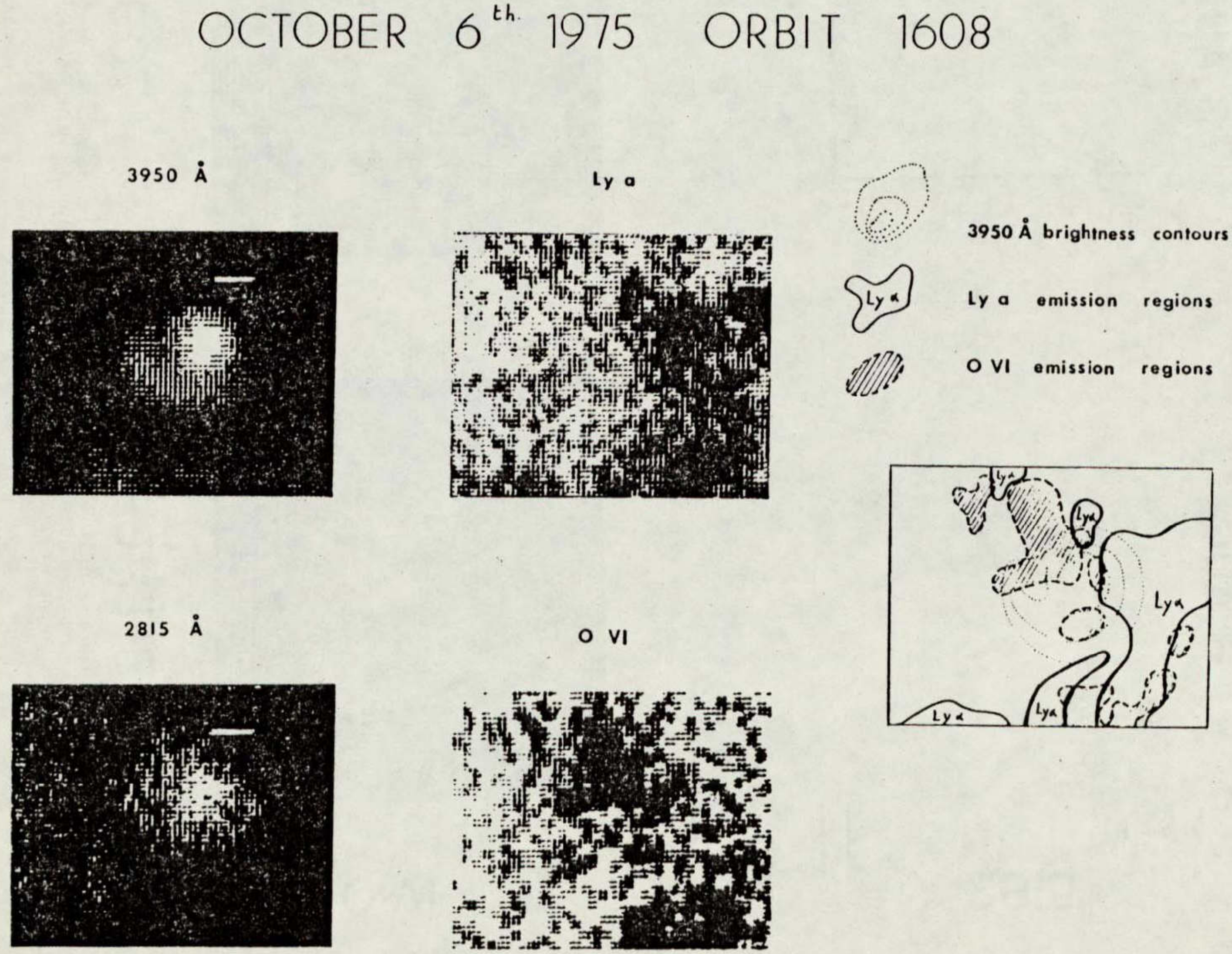


FIG. 17.—The variation with wavelength in the shape of a spot; the superposition of O VI, Lα and "White light" isophots evidence a deformation with height in the solar atmosphere.

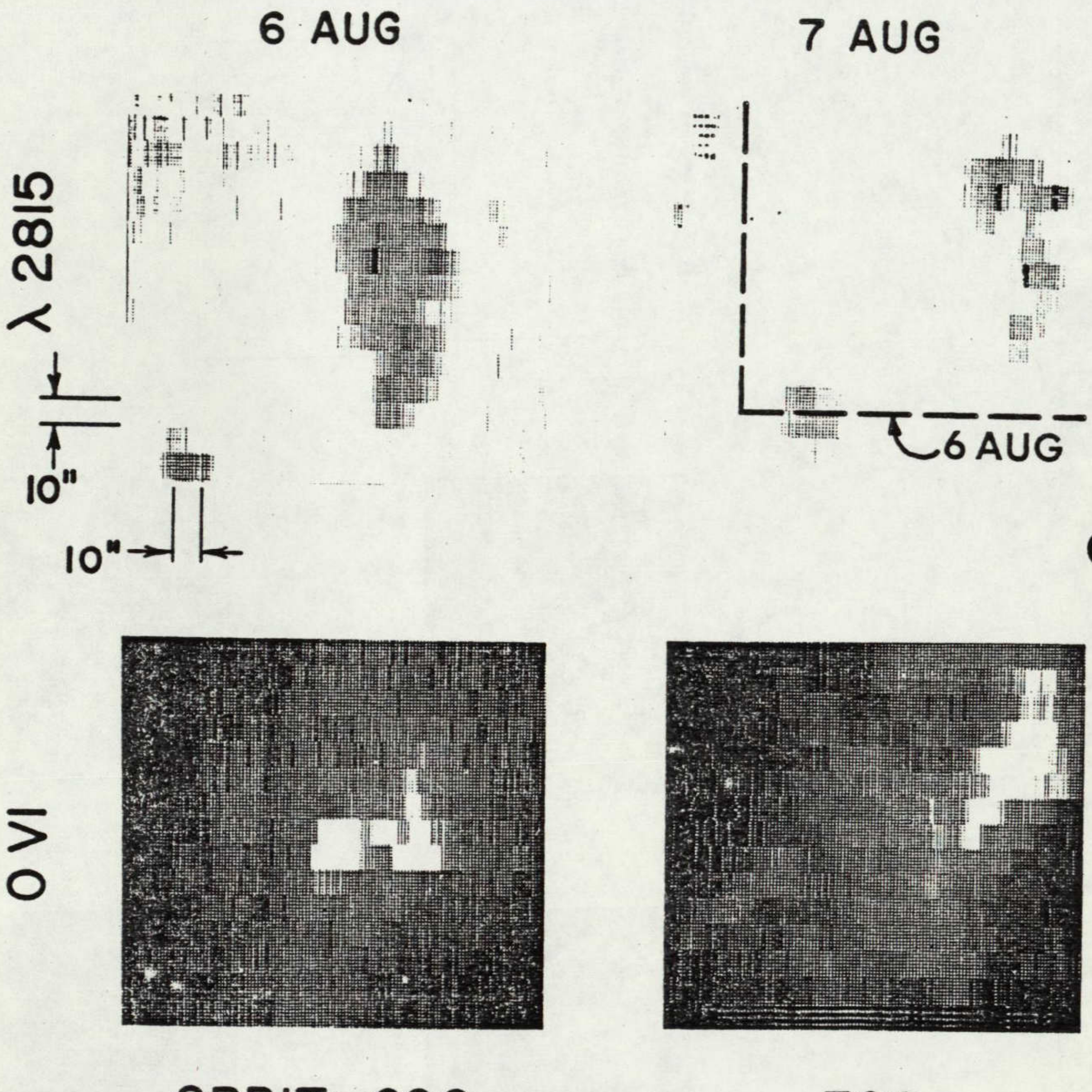


FIG. 18.—Illustration of step changes in field connectivity of spot evolution. The two upper pictures are satellite rasters made in the wings of Mg II *k*. The two lower pictures are taken simultaneously in O VI. The evolution of the sunspot group is continuous when observed in white light and discontinuous in O VI.

Figure 22 represents observations of an active region at the limb on 1975 July 7. The slit was parallel to the limb and probably intersected it slightly, as indicated by the presence of scattered light in the wings of the Ca II profiles. On the left portion of Figure 22, full and dotted lines correspond to profiles taken at positions separated by only 1″. The emission maxima in Ca II and Mg II are displaced shortward with an amplitude corresponding to about 20 and 15 km s^{-1}, respectively. These maxima may in fact correspond to K_2v and k_2v, while K_2r and k_2r are barely visible and show up only as asymmetries in the line profile. Lα is not displaced and shows the geocoronal reversal with no apparent self-reversal. The distance between its emission peaks is only 0.022 nm, leading to an optical depth of only 500 at line center. On the right panel of Figure 22, solid and dotted lines show temporal variations for a 22 min interval. Orbital Doppler effects have not been corrected for on the figure; but if they are corrected for, a shift to the longward is still found for Ca II and Mg II with an amplitude of 5 km s^{-1}. Moreover, Ca II and Mg II lines have essentially the same intensity while Lα has increased by a factor of 2.

f) Chromosphere-Corona Transition Lines

The two lines Si III 120.65 nm ($3s\,^1S$–$3p\,^1P^o$) and O VI 103.19 nm ($2s\,^2P$–$2p\,^2P^o$) are formed in the chromosphere-corona transition region at 40,000 K and 350,000 K, respectively (Jordan 1969). They are observed with the LPSP instrument with a spectral resolution of 0.002 and 0.006 nm, respectively.

The shape of transition-region line profiles may indicate whether there is any propagation of either acoustic or magnetohydrodynamic waves (McWhirter 1977). The presence of such waves may be symptomatic of coronal heating mechanisms.

Figure 23 shows an average (single orbit) Si III profile at the center of the disk (quiet Sun) observed with a resolution of 1″ × 40″. The FWHM is 0.015 nm and, if we assume that the line is optically thin, the rms (line-of-sight) nonthermal velocity is 22 km s^{-1}. This value is 4 km s^{-1} higher than the values obtained by Nicolas *et al.* (1976) for the Si III lines at 128.9 and 189.2 nm.

Quiet and active Sun profiles of the O VI line at the center of the disk are given on Figures 24*a* and 24*b*. This line is optically thin, and the FWHM is 0.021 nm nearly identical for both quiet and active Sun; the rms line-of-sight nonthermal velocity is 30 km s^{-1}. A departure from a purely Gaussian profile can be noticed in both profiles. The line appears asymmetric and may indicate the effect of a velocity structure in the region of formation of the line.

Figure 24*c* shows a quiet limb O VI profile, averaged over several positions above the limb (+2″ + 6″). The FWHM is now 0.026 nm, equivalent to a rms line-of-sight nonthermal velocity of 38 km s^{-1}. This is larger by 11 km s^{-1} than the value previously quoted by Moe and Nicolas (1977).

The chromosphere and transition region height distribution is shown on Figure 25 as derived from internal raster scans simultaneously in the wing of Mg II *h*, Mg II h_3, O V 121.8 nm, and N I 119.95 nm.

As is apparent from the figure, the h_3 chromosphere appears to have an additional contribution, which may likely be due to spicules that appear to peak at about the same height as the O VI component. Separate measurements of O VI (and for the far wing of Mg II *h*) show a similar behavior as O V. These results would argue for an inhomogeneous transition between chromosphere and corona (cf. Doschek, Feldman, and Tousey 1975).

TABLE 6

CHARACTERISTICS OF SPECIES IN THE EARTH'S ATMOSPHERE OBSERVED WITH THE LPSP INSTRUMENT

OSO 8 Channel	Component	Wavelength (nm)	Range of Altitudes in the Earth Atmosphere (km)
Mg II	O3	277.7–282.3	60–80
Mg II	OH	281.6	> 75
Lα	O2	120.6–122.3	90–110
Lα	H	121.6	> 500
Lβ	O2	101.7–103.2	150–200
Lβ	H	102.5	> 500

g) Aeronomy Investigations

At orbital sunsets and sunrises, the solar UV light is absorbed by successively denser layers of the Earth's atmosphere. Vertical distribution of number densities of several components may be studied by this technique as indicated in Table 6. The light in the Ca channels is not attenuated and provides a pointing reference.

The measurement of the width and depth of the hydrogen geocoronal absorption was undertaken during several orbit days. This is a new and very promising observational technique to measure simultaneously the exospheric temperature at each point of the orbit and the atomic hydrogen density at the exobase, which may solve the question of what mechanism(s) control(s) the hydrogen distribution at the exobase. The preliminary results of aeronomy investigation have been published in Vidal-Madjar *et al.* (1976).

VI. CONCLUSION

We have described here the actual performance of one of the most complex solar physics instruments launched into space and the main results obtained with the first high-resolution multichannel UV and visible spectrometer placed in orbit by *OSO 8*. For the first time, an absolute pointing accuracy of nearly 1″ could be achieved in orbit with real time operations. It undoubtedly represents the largest and most complex experiment of the French space program in solar physics. Although the bulk of the data has not yet

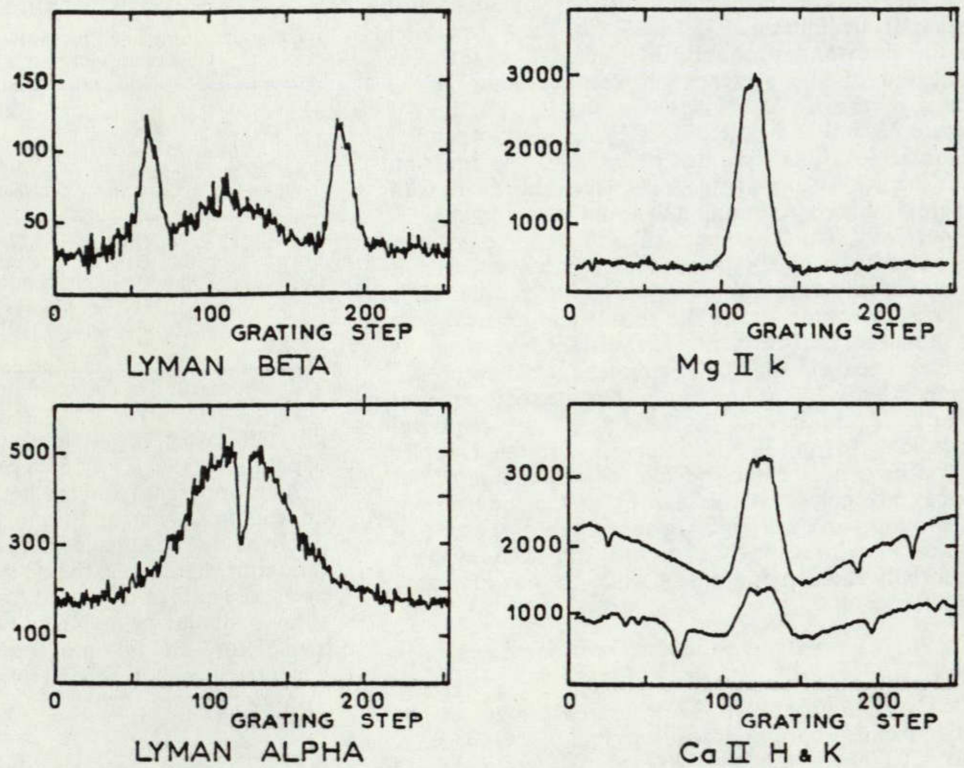


FIG. 19.—Profiles of Ca II K, Mg II k, Lα, and Lβ observed simultaneously over an active region. All lines are free from the central self-reversal usually observed over quiet Sun areas. The two peaks in the Lβ profile are the two O I lines. For conversion into λ units, see Table 1. Wavelengths increase to the left.

been examined in detail, preliminary analyses show that the performance of the instrument was nominal and at times beyond nominal expectations. The results presented here are only isolated samples of what has been obtained in the first 18 months. The instrument continues to perform nominally and has begun its third year of operation. This will allow us to obtain more data on active regions and particularly on flares which were very rare during the first 18 months. Indeed, only one flare, that of 1977 April 19, has been observed so far (Jouchoux *et al.* 1977).

The operation of the instrument has been very exhausting, and we have benefited from the assistance of many people. Our experience with regard to the remote management of an entirely automated complex instrument is, we feel, of great value for similar experiments in the future.

The accomplishment of this experiment would not have been possible without the support of CNES and particularly of Dr. A. Lebeau, former Director of Programs and Plans, and Professor M. Levy, former President. We would like to thank collectively the NASA and CNES engineers who have contributed to this experiment.

The operations of the instrument from Boulder would not have been possible without the kind hospitality of LASP, in particular of its Director, Professor C. Barth. We also thank the LASP *OSO 8* staff for their contributions. We are indebted to NASA and LASP for access to space on the American calibration rockets. The excellent spirit of cooperation and the dedicated service of the *OSO 8* Control Center at the Goddard Space Flight Center was certainly a key to the success of real time acquisition and of the daily programming of observations in general. The observations of sunspots, active regions, and flaring regions could not have been done without the generous assistance of NOAA, Big Bear Solar Observatory, Meudon Observatory, Sacramento Peak Observatory, and Lockheed Research Laboratory. We wish to express our warmest acknowledgements to these numerous and often anonymous people who played such an important although thankless role in the daily work required by the continuous observation of the Sun during several years. Highly appreciated were the contribution of Drs. P. Bruston and M. Malinovsky of LPSP in the preparation and checkout of observing programs. Invaluable and continuous support in the daily operations was provided by M. Bruston (Mrs.) and N. Dionnau of LPSP. We also thank J. Borsenberger (Institut d'Astrophysique de Paris) and B. Phissamay (LPSP) for their important contribution.

Last but not the least, all of the Guest Investigators who have assisted our team in the operation and

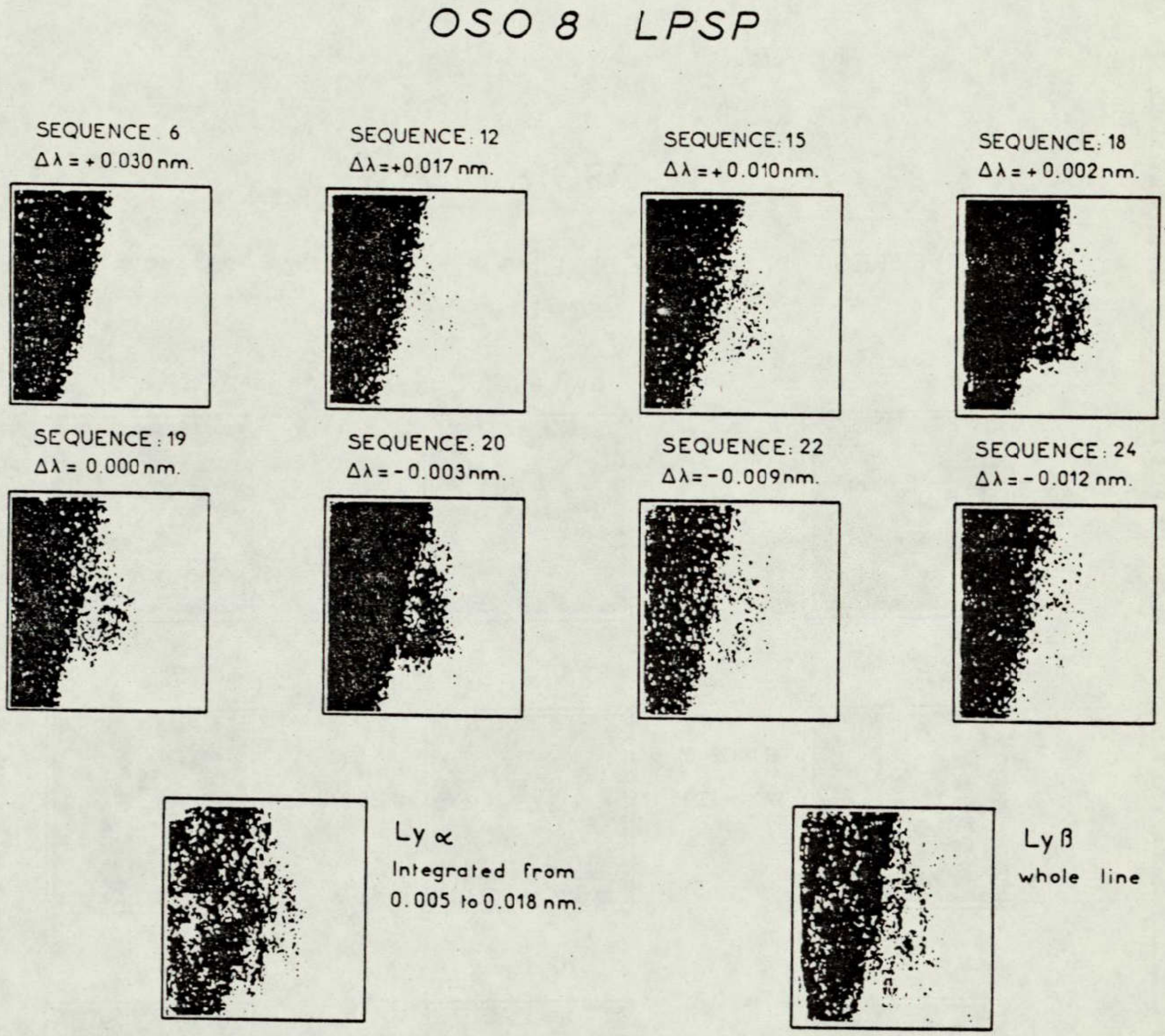


FIG. 20.—Series of satellite raster negative images, taken at different positions in the Ca K line ranging from −0.012 nm to +0.03 nm from line center. At the bottom are two simultaneous images of the loop prominence in Lα and Lβ. Image size is $2'.3 \times 2'.7$, repetition rate 82 s, resolution $10'' \times 10''$.

planning should be acknowledged here. They are: D. Dravins, S. Dumont, E. Frazier, K. Fredga, U. Grossman-Doerth, M. Hersé, S. Jordan, H. P. Jones, F. Kneer, P. McWhirter, W. Mattig, D. J. Mullan, J. C. Noens, J. Pasachoff, J. C. Pecker, G. Sharmer, G. Simon, J. O. Stenflo, M. von Uexuel, and A. Wyller.

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Additional acknowledgement must go to G. Sharmer for his extensive and supportive contributions which far exceeded his role as Guest Investigator.

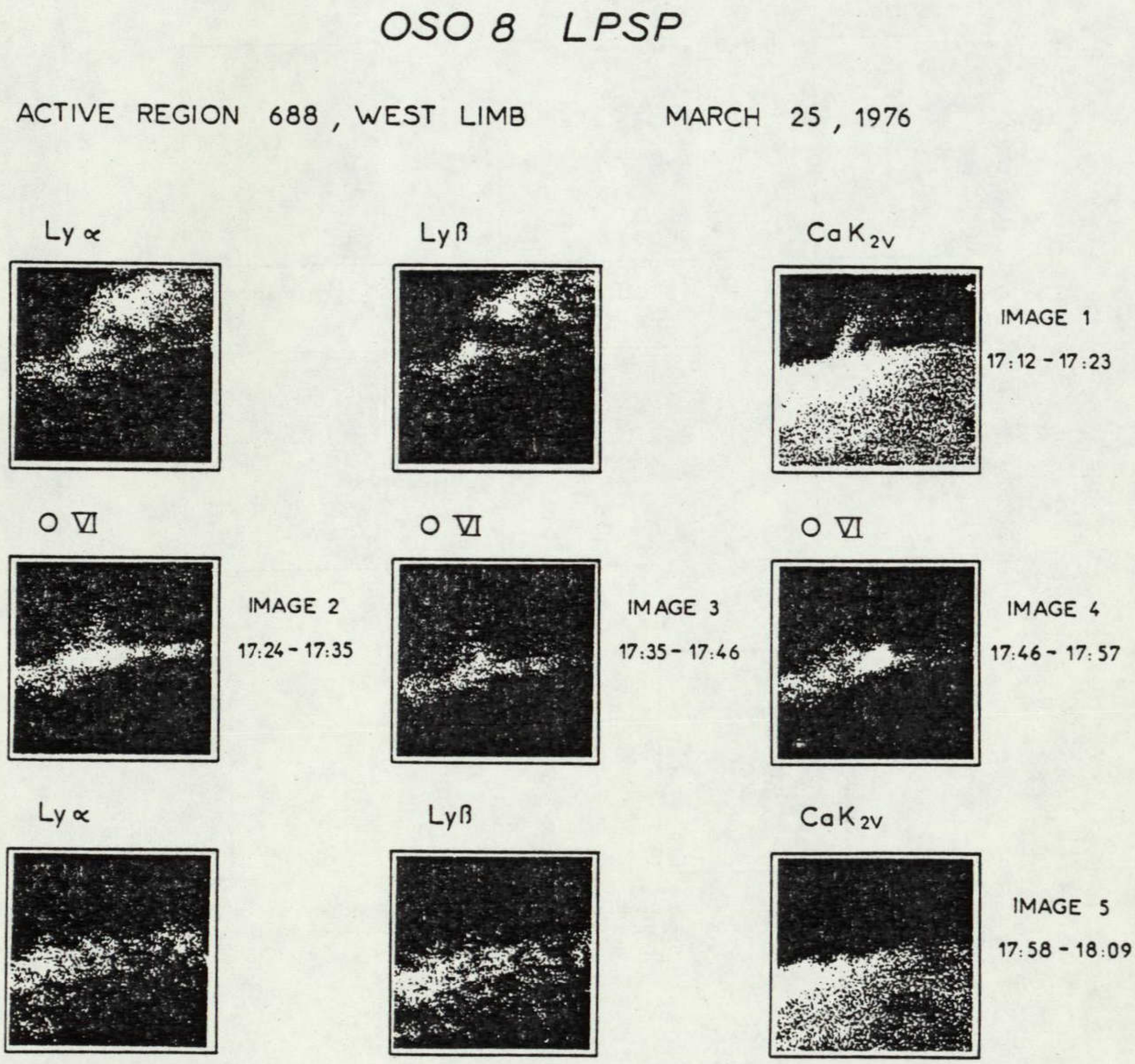

FIG. 21.—Development and evolution of an eruptive prominence associated with Active Region 14127 (McMath number) when it crossed the west limb.

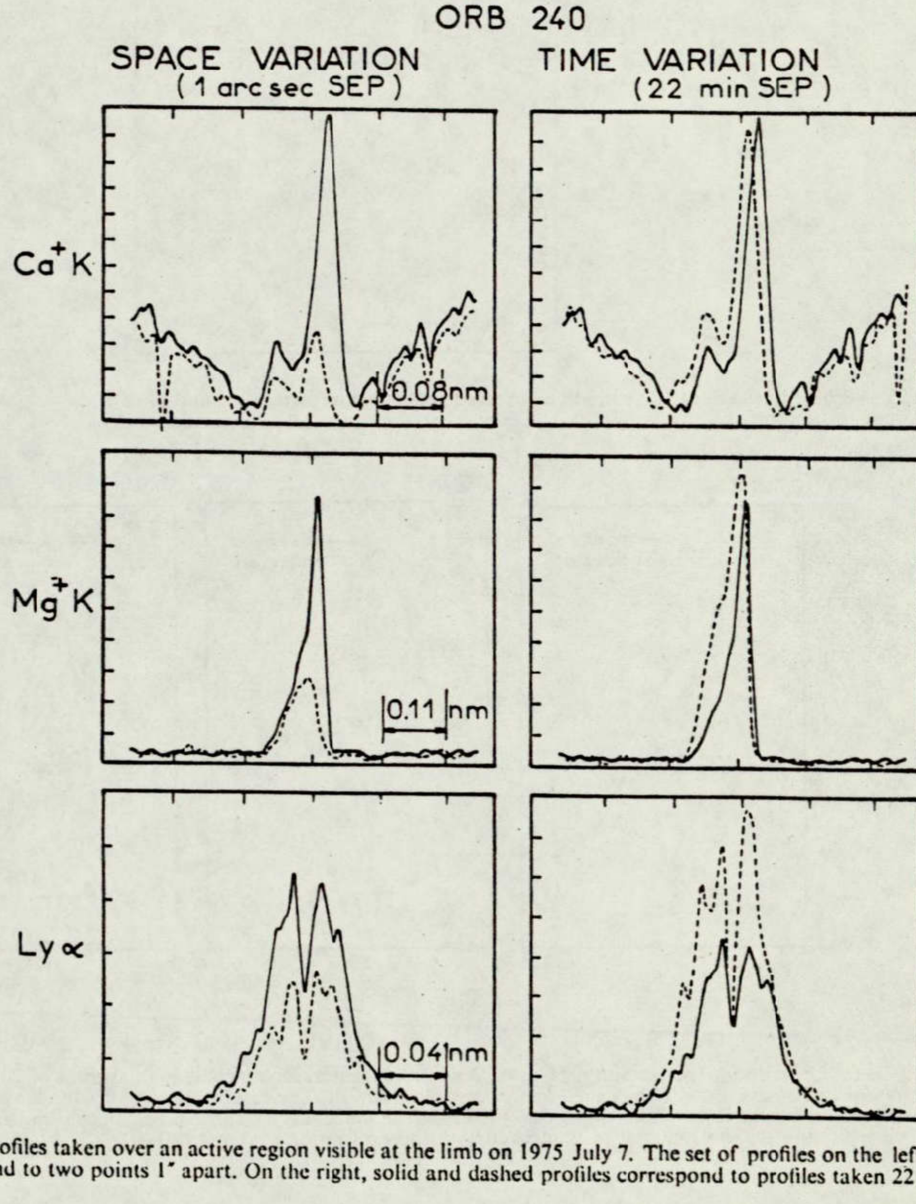

FIG. 22.—Profiles taken over an active region visible at the limb on 1975 July 7. The set of profiles on the left (*solid* and *dashed lines*) correspond to two points 1" apart. On the right, solid and dashed profiles correspond to profiles taken 22 min apart, in time.

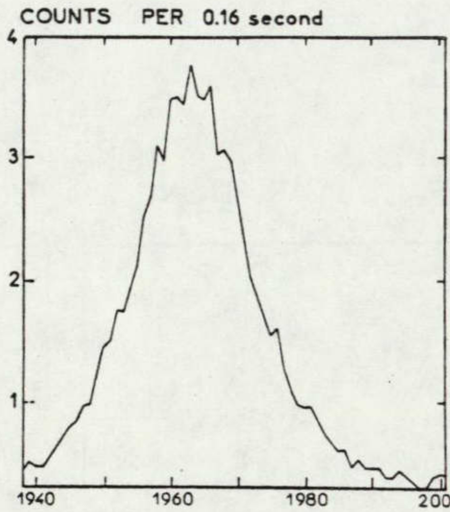

FIG. 23.—Profile of the Si III 120.6 nm line observed at Sun center with a resolution of 1″ × 40″. Wavelengths increase to the left. For conversion into λ units, see Table 1. Counts represent an average over one orbit.

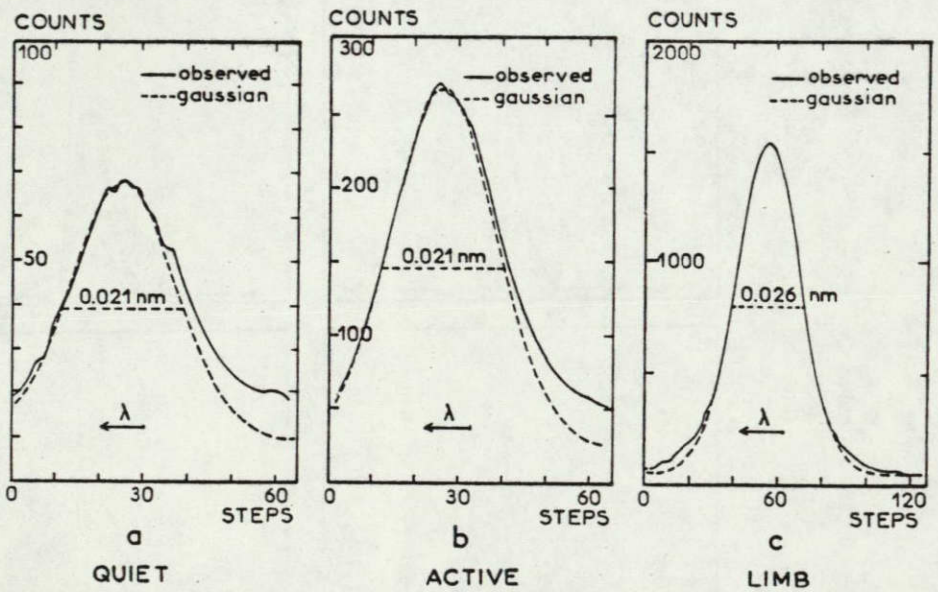

FIG. 24.—(*a*) Quiet and (*b*) active Sun profiles of O VI at Sun center. Each profile is an average of 20 individual profiles. The full lines represent the observations; the dashed line, a best Gaussian fit. The resolution is 1″ × 40″. Wavelengths increase to the left. For conversion into λ units, see Table 1. Profile (*c*) refers to the limb; it is also an average, but the individual profiles were observed at another orbit, and the units cannot be compared with those of profiles (*a*) and (*b*).

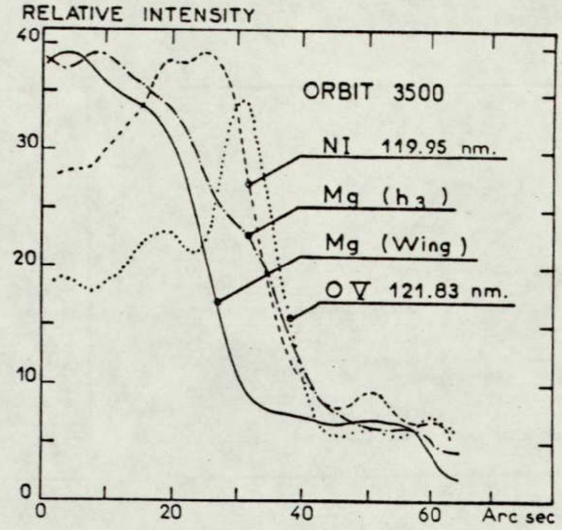

FIG. 25.—Limb "darkening" profiles, in Mg II *h*3, the far wing of Mg II *k*, N I 119.95 nm, and O V 121.83 nm. Distance is measured in arcsec (arbitrary origin).

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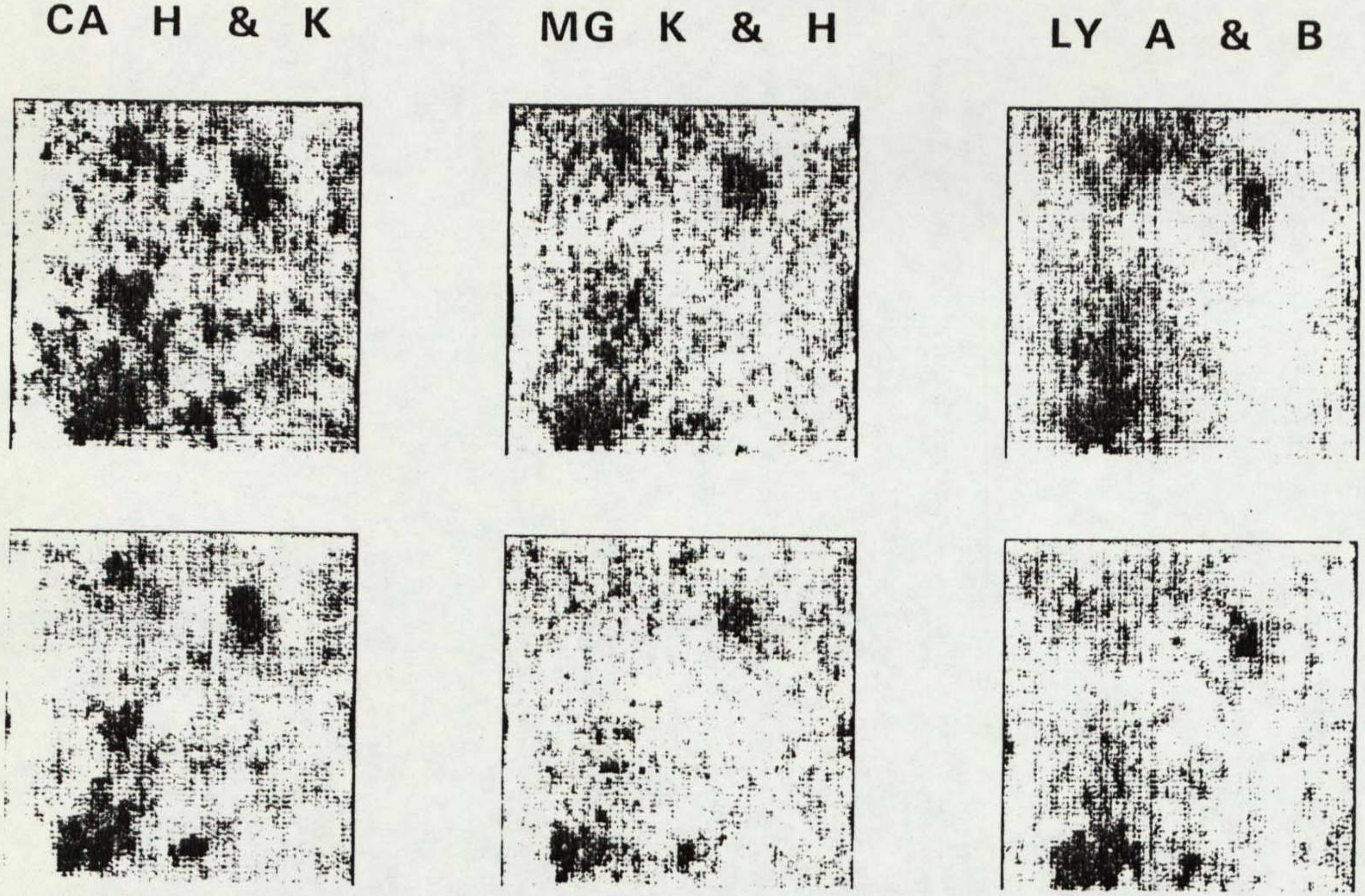

FIG. 8.—Internal raster images of the quiet Sun chromospheric network in Ca II K and H, Mg II *h* and *k*, Lα, and Lβ. The field is $64'' \times 64''$, the slit size $1'' \times 1''$.

BONNET *et al.* (*see* page 1044)

Attachment E

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SIMULTANEOUS TIME-RESOLVED OBSERVATIONS OF THE H Lα, Mg *k* 2795 Å, AND Ca K SOLAR LINES

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ABSTRACT

Observations indicate that the temporal variations of wavelength of the reversal of the solar H Lα and Mg *k* lines are correlated.

Subject headings: Sun: atmospheric motions — Sun: chromosphere — Sun: spectra

I. INTRODUCTION

The solar photospheric and chromospheric lines exhibit ubiquitous quasi-periodic oscillations of intensity and wavelength. The presence or absence of periodic fluctuations higher in the solar atmosphere has been investigated by measuring the intensity variations of spectral lines formed between 10^4 K and 1.5×10^6 K (Vernazza *et al.* 1975), the microwave emission of the Sun around 10^4 K (Avery 1976), the intensity and position of the C II 1336 Å line formed around 20,000 K (Chipman 1977), the intensity and position of the C IV 1550 Å line formed around 100,000 K (Bruner 1977), and the line profile of the Fe XIV λ5303 coronal line (Tsubaki 1977).

We report here the first observations of the solar HLα 1216 Å line formed near 25,000 K with temporal, spectral, and spatial resolution adequate for the study of solar velocity fields.

II. OBSERVATIONS

The LPSP instrument on board *OSO 8* is described by Artzner *et al.* (1977). The observations reported here, mostly at disk center, had a $1'' \times 3''$, $1'' \times 10''$, or $1'' \times 20''$ spatial resolution, a spectral scanning increment of, respectively, 2.4, 2.3 and 1.6 km s^{-1} for the Lα, Mg *k*, and Ca K lines, and a time resolution of from 10 to 40 s. A sequence of observations consists of 100 to 180 successive spectra scanning the Lα line over ± 0.53 Å, the Mg *k* line over ± 1.4 Å, and the Ca K line over ± 1.1 Å.

In order to discriminate between actual solar oscillations and pointing variations, we have measured the pointing stability by three different methods (Bonnet *et al.* 1978). As a result, we estimate that the pointing drifts randomly at a rate smaller than 1″ per 3 minutes of time.

As a check of the instrumental stability over 1 hour and of the procedure to compensate for the Doppler-Fizeau component of the velocity of the spacecraft, we have averaged Lα spectra during three consecutive 20 minute intervals of the 60 minute daylight portion of an orbit. The constant position of the geocoronal line demonstrates that the wavelength drifts by less than 4 mÅ over one orbit. The observed spectral resolution does not vary, but the shape of the geocoronal absorption is wider during the third part of the orbit day than during the first part. This measured geophysical effect, most likely due to the heating of the terrestrial atmosphere between local sunrise and sunset, will be investigated elsewhere and gives us confidence in the ability of the instrument to detect minor changes in the shape and position of spectral lines during 1 hour.

The low measured dark current (1.1 counts s^{-1}) enables us to make use of data taken through orbit 380, when the sensitivity was 35 counts s^{-1} at the blue Lα peak with 0.01 Å and $1'' \times 10''$ resolution.

Note that the simultaneously measured counting rates may vary from 10 (Lα wing) to 100,000 (K2v peak of Ca K), because of the combined increase of solar flux and instrumental sensitivity from 1216 to 4000 Å.

III. DATA ANALYSIS

Any plot of the data exhibits quasi-periodic oscillations of the Ca K, Ca H, Mg *k* 2795, and Mg h 2803 Å lines. These are reported in Artzner *et al.* (1978). As indicated by Bonnet *et al.* (1978), the Lα signal for a constant solar input is modulated in phase with the rotation of the spacecraft wheel, with a period of the order of 10 s. Therefore a mathematical procedure (as used by Artzner *et al.* 1978) applied to the raw, noisy, uncorrected Lα data will fail to reveal the true time behavior of this line, because it will essentially reflect the "10 second modulation" of the signal. As the mean intensity of the Lα line, measured over 10.24 or 20.48 s, is much less sensitive to this modulation than the velocity measurements, we have integrated the Lα profiles over ± 0.41 Å and we have computed the average power spectrum (for 16 sequences) of the time variation of this quantity (Fig. 1). The result agrees with the observations of Vernazza *et al.* (1975). For each sequence we have measured the standard deviation of the values of the integrated intensity (Table 1). For the sequences with low average numbers of counts per profile, the intensity variation is found to be primarily due to statistical noise, but for the sequences with higher count rates, the standard deviation is considerably larger than photon statistics alone would imply.

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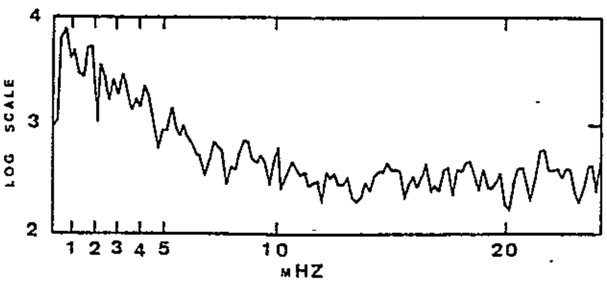

FIG. 1.—Temporal variations of the Lα intensity; bandwidth ±0.41 Å. Average of 16 power spectra.

TABLE 1

Lα 1216 Å LINE (bandpass ±0.41 Å)

Duration (minutes)	Average Number of Counts per Profile	Standard Deviation around Average
40........	200	23
49........	210	14
55...... .	230	16
42........	240	13
38........	270	16
28	290	14
37..	290	20
37........	300	21
39........	330	16
33........	340	20
40........	350	27
42........	370	28
56........	400	24
47........	450	62
53........	520	35
56........	520	29

As of now, we have analyzed 21 orbits of the Lα data. The analysis has been conducted in such a way as to be insensitive to the 10 s modulation: we classify into three classes the Mg k spectra according to the relative strength of the k_2 peaks and then compare average Lα spectra corresponding to each of the three classes. Class I has a high ratio of (Mg k_{2r} intensity/Mg k_{2r} intensity), while classes II and III have successively lower values of this ratio. This procedure reduces statistical noise and should reduce the effect of the "10 second" modulation, because the solar oscillations observed in Mg k and the spinning of the spacecraft should have a random relationship. As a result, after correcting for the Doppler component of the velocity of the spacecraft, average class I, II, and III profiles are computed, not only for the Mg k line but also for the simultaneously observed H Lα, Ca K, Ca H, and Mg h lines.

1. For the Mg k channel, the average class I profile actually has a strong (blue peak/red peak) ratio, as a verification of the procedure.

2. A very similar effect is seen for the Mg h, Ca H, and Ca K channels.

3. For the Lα line, the average class I and class III profiles are identical in the wing, but shifted in the central reversal. The integrated intensity of the average "class I" Lα profile is equal to the integrated intensity of the average "class III" Lα profile, whereas the integrated intensity of the average "class I" Mg k profile is stronger than for the average "class III" profile.

We have fitted to the Lα and Mg k line profiles a six-parameter formula, I, λe, We, A, λa, Wa,

$$I(\lambda) = I \exp\left[-\left(\frac{\lambda - \lambda e}{We}\right)^2\right] \times \left\{1 - A \exp\left[-\left(\frac{\lambda - \lambda a}{Wa}\right)^2\right]\right\}. \tag{1}$$

The parameters λe and We refer to the wings and the parameters λa and Wa to the position and width of the central reversal.

The data points within ±35 mÅ of the geocoronal line were excluded from this fit. The zero of the wavelength scale is, for the Lα observations, fixed by the geocoronal absorption (no correction for the solar rotation is needed, as the observations reported in Tables 2 and 3 are at disk center). The zero of the wavelength scale for the Mg k line, at the present stage of data reduction, may be affected by a systematic error of ±0.01 Å. For the sake of comparison, the wavelengths have been converted in meters per second. The numbers quoted do not imply that such velocities are present in the solar atmosphere; the derivation of actual solar velocities is beyond the scope of this *Letter*.

Table 2 shows the results of these fits for the three

TABLE 2

POSITION AND INTENSITY OF SPECTRAL FEATURES OF AVERAGE SPECTRA*

	High (Mg k_{2v}/Mg k_{2r}) Ratio Class I	Average Ratio Class II	Low (Mg k_{2v}/Mg k_{2r}) Ratio Class III
		Lα	
λa–H telluric (central reversal).....	+3800 m s^{-1}	+2300 m s^{-1}	+950 m s^{-1}
λe–He telluric (wings)......	+1100 m s^{-1}	+1100 m s^{-1}	+780 m s^{-1}
Ie............	8.9	8.9	9.0
		Mg *k*	
λa central......	+4150 m s^{-1}	+2950 m s^{-1}	+1720 m s^{-1}
λe emission.....	+330 m s^{-1}	+730 m s^{-1}	+1350 m s^{-1}
Arbitrary units *Ie* emission...	315	283	269
Faint Mn I photospheric line zero average......	+75 m s^{-1}	−25 m s^{-1}	+50 m s^{-1}
H geocoronal absorption (zero average)	−60 m s^{-1}	+120 m s^{-1}	−60 m s^{-1}

* Classified according to the K_{2v}/K_{2r} ratio; three equal classes for each time sequence.

classes of profiles defined above. From the same set of data, by averaging of faint and bright sequences, we have computed typical Lα and Mg k faint and bright profiles, and applied the same fit with a six-parameter formula (Table 3). From the comparison of Tables 2 and 3, it appears that, for the Lα and Mg k lines, if the position of the central reversal is related to the atmospheric velocity fields, the instantaneous, time-resolved velocity fluctuations are greater than the large-scale (chromospheric network) permanent velocity features.

We have also computed three average profiles by sorting out at random the observed profiles into three classes to derive an estimate of the statistical precision of our measurements. We find the Lα, photospheric line, and geocoronal line velocities are accurate to about ± 100 m s^{-1}, while the Mg k velocities are accurate to ± 25 m s^{-1}. The Lα intensity values are accurate to ± 0.1 in our units, and the Mg k intensities to ± 2.

TABLE 3

POSITION AND INTENSITY OF SPECTRAL FEATURES OF AVERAGE SPECTRA*

	Average of 5 Brightest Sequences out of 16	Average of 5 Faintest Sequences out of 16
	Lα	
λa–H telluric central reversal	+2600 m s^{-1}	+2100 m s^{-1}
λe–H telluric wings..	+900 m s^{-1}	+330 m s^{-1}
Ie....	12, 5	5, 4
	Mg k	
λa central reversal...	+3000 m s^{-1}	+3060 m s^{-1}
λe emission.........	+1300 m s^{-1}	+450 m sec
Ie	391	241

* Brightest sequence versus faintest sequence.

IV. CONCLUSION

At this stage of OSO *8* data reduction, we cannot yet present the power spectrum of the spatially resolved solar Lα line velocity fluctuations; nevertheless, we have demonstrated that the Lα central reversal does exhibit wavelength fluctuations positively correlated with the oscillations of the chromospheric Ca K and Mg k lines.

Temporal variations in the derived velocity of the central reversal feature of 2500 m s^{-1} in Mg k are accompanied by variations in the same sense of approximately 2800 m s^{-1} in the central reversal feature of Lα.

This *Letter* is the continuation of efforts of teams on the *OSO 8* project at Verrières-le-Buisson, Greenbelt, Los Angeles, and Boulder. Special acknowledgment goes to A. Jouchoux, who obtained special observing sequences for this program. The computations were carried out on the CDC 7600s of NCAR and CNES. The CNES funded the fabrication and operations of the instrument under contracts 70-220, 71-202, 72-202, 73-202, 74-202, 75-202, 76-202, and 77-202.

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Attachment F

Abstract of Paper presented at the 153rd Meeting of the American Astronomical Socity. Will appear in the Bulletin of the A.A.S., 1979.

A Dynamical Representation of the Solar Chromosphere, J.W. LEIBACHER, Lockheed and P. GOUTTEBROZE, Laboratoire De Physique Stellaire et Planetaire = We present investigations of the non-linear hydrodynamic state of a model solar atmosphere and the time dependent, ionized calcium and magnesium resonance line profiles emitted by the chromosphere. We calculated the one dimensional response to an excitation 1.6 Mm below the visible surface using a finite difference code, and the resulting motions exhibit the well known 300 second oscillation of the photosphere and 200 second oscillation of the chromosphere. Both oscillations have the chracter of standing waves. We shall discuss the formation of these oscillations and their dependence upon parameters of the calculation. Time sequences of resonance line profiles display asymmetry and intensity variations that result from both oscillations. This work was supported by NASA contracts NAS8-32356 and NASW-3053, the Lockheed Independent Research Program and the Centre National d'Etudes Spatialies.