

# FIVE-MINUTE OSCILLATION: OBSERVATIONS

Robert J. Rutten

<http://www.staff.science.uu.nl/~rutte101>

- *discovery*
  - (Plaskett 1954), Leighton et al. 1960
  - chromospheric 3-min: Noyes 1967
- *confusion*
  - restoring force: pressure, gravity, magnetic field?
  - nature: propagating, standing, evanescent?
  - periodicity: piston, cavity, filter?
  - origin: subsurface, surface, atmosphere?
- *enlightenment*
  - prediction: (Leibacher & Stein), Ulrich 1970
  - spherical sun: Wolff 1972, Ando & Osaki 1975
  - identification: (Ulrich & Rhodes), Deubner 1975
- *deployment*
  - helioseismology: low- $l$  networks, South Pole  $\Rightarrow$  GONG, SOHO/MDI, SDO
  - time-distance local helioseismology & far-side mapping
  - asteroseismology

## REVIEWS

- Jain et al.: *Fifty Years of Seismology of the Sun and Stars* [2013ASPC..478.....J](#)
- William (Bill) Chaplin (2006): *Music Of The Sun: The Story Of Helioseismology*
- Jack B. Zirker (2003): *Sunquakes: Probing the Interior of the Sun*
- Deubner & Gough: *Helioseismology: Oscillations as a Diagnostic of the Solar Interior* [1984ARA&A..22..593D](#)
- Stein & Leibacher: *Wave generation*, in “The Sun as star” (orange book) [1981NASSP.450..289S](#)
- Stein & Leibacher: *Waves in the solar atmosphere* [1974ARA&A..12..407S](#)
- Bray & Loughhead: *The Solar Chromosphere* [1974soch.book.....B](#)
- Leibacher: PhD thesis [1971PhDT.....1L] @ ADS?

## MOTIONS IN THE SUN AT THE PHOTOSPHERIC LEVEL

## V. VELOCITIES OF GRANULES AND OF OTHER LOCALIZED REGIONS

*H. H. Plaskett*

(Received 1954 May 5)

*Summary*

Velocities and surface brightness in three Oxford spectra, showing granulation, have been measured. The results are in good agreement with those earlier found by Richardson and Schwarzschild in a Mount Wilson spectrum. In two of the three Oxford spectra a significant correlation coefficient of  $r = -0.28$  has been found between the surface brightness and the sight-line component of the velocity, showing that the bright granular matter is moving vertically upwards. Assuming that the top of the granulation zone occurs at an optical depth of unity,  $0.75 \text{ km sec}^{-1}$  is a lower limit to the velocity of ascent of the bright granular matter. The smallness, or in one spectrum the absence, of any correlation between surface brightness and velocity suggests that the granular velocities are being partially or completely masked by some other perturbation of velocity. Removing from the observed velocities that part due to granulation, the perturbing velocities are found to originate in an oscillatory velocity field with an average period of  $5''$  of arc and an amplitude of the order of  $0.5 \text{ km sec}^{-1}$ .

# DISCOVERY

*Leighton, Noyes & Simon 1962ApJ...135..474L*

## VELOCITY FIELDS IN THE SOLAR ATMOSPHERE

### I. PRELIMINARY REPORT\*

ROBERT B. LEIGHTON, ROBERT W. NOYES, AND GEORGE W. SIMON

California Institute of Technology, Pasadena, California

*Received October 16, 1961*

#### ABSTRACT

Velocity fields in the solar atmosphere have been detected and measured by an adaptation of a technique previously used for measuring magnetic fields. Data obtained during the summers of 1960 and 1961 have been partially analyzed and yield the following principal results:

1. Large "cells" of horizontally moving material are distributed roughly uniformly over the entire solar surface. The motions within each cell suggest a (horizontal) outward flow from a source inside the cell. Typical diameters are  $1.6 \times 10^4$  km; spacings between centers,  $3 \times 10^4$  km ( $\sim 5 \times 10^3$  cells over the solar surface); r.m.s. velocities of outflow,  $0.5 \text{ km sec}^{-1}$ ; lifetimes,  $10^4$ – $10^5$  sec. There is a similarity in appearance to the  $\text{Ca}^+$  network. The appearance and properties of these cells suggest that they are a surface manifestation of a "supergranulation" pattern of convective currents which come from relatively great depths inside the sun.

2. A distinct correlation is observed between local brightness fluctuations and vertical velocities: bright elements tend to move upward, at the levels at which the lines  $\text{Fe } \lambda 6102$  and  $\text{Ca } \lambda 6103$  are formed. In the line  $\text{Ca } \lambda 6103$ , the correlation coefficient is  $\sim 0.5$ . This correlation appears to reverse in sign in the height range spanned by the Doppler wings of the  $\text{Na } D_1$  line and remains reversed at levels up to that of  $\text{Ca}^+ \lambda 8542$ . At the level of  $\text{Ca } \lambda 6103$ , an estimate of the mechanical energy transport yields the rather large value  $2 \text{ W cm}^{-2}$ .

3. The characteristic "cell size" of the vertical velocities appears to increase with height from  $\sim 1700$  km at the level of  $\text{Fe } \lambda 6102$  to  $\sim 3500$  km at that of  $\text{Na } \lambda 5896$ . The r.m.s. vertical velocity of  $\sim 0.4 \text{ km sec}^{-1}$  appears nearly constant over this height range.

4. The vertical velocities exhibit a striking repetitive time correlation, with a period  $T = 296 \pm 3$  sec. This quasi-sinusoidal motion has been followed for three full periods in the line  $\text{Ca } \lambda 6103$ , and is also clearly present in  $\text{Fe } \lambda 6102$ ,  $\text{Na } \lambda 5896$ , and other lines. The energy contained in this oscillatory motion is about  $160 \text{ J cm}^{-2}$ ; the "losses" can apparently be compensated for by the energy transport (2).

5. A similar repetitive time correlation, with nearly the same period, seems to be present in the

# SUPERGRANULATION

*Leighton, Noyes & Simon 1962ApJ...135..474L*

1. Large “cells” of horizontally moving material are distributed roughly uniformly over the entire solar surface. The motions within each cell suggest a (horizontal) outward flow from a source inside the cell. Typical diameters are  $1.6 \times 10^4$  km; spacings between centers,  $3 \times 10^4$  km ( $\sim 5 \times 10^3$  cells over the solar surface); r.m.s. velocities of outflow,  $0.5 \text{ km sec}^{-1}$ ; lifetimes,  $10^4$ – $10^5$  sec. There is a similarity in appearance to the  $\text{Ca}^+$  network. The appearance and properties of these cells suggest that they are a surface manifestation of a “supergranulation” pattern of convective currents which come from relatively great depths inside the sun.



MDI supergranulation movie

# SUPERGRANULATION MEASUREMENT

Noyes 1967IAUS...28..293N

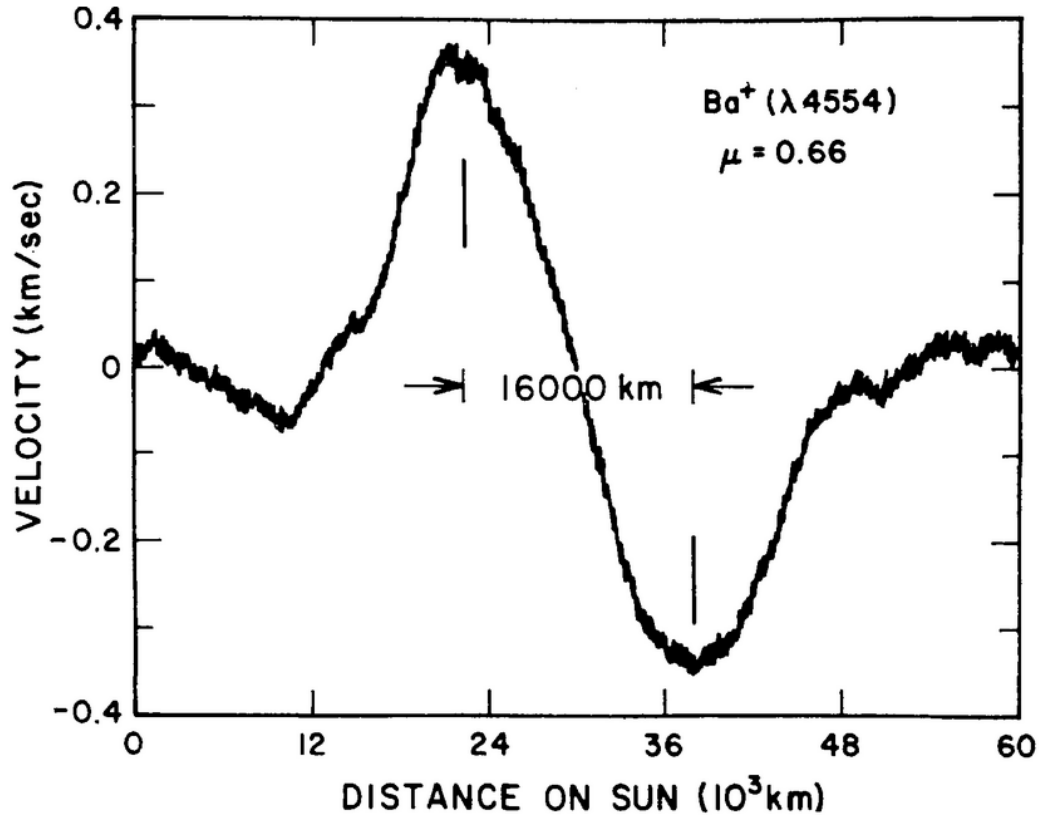
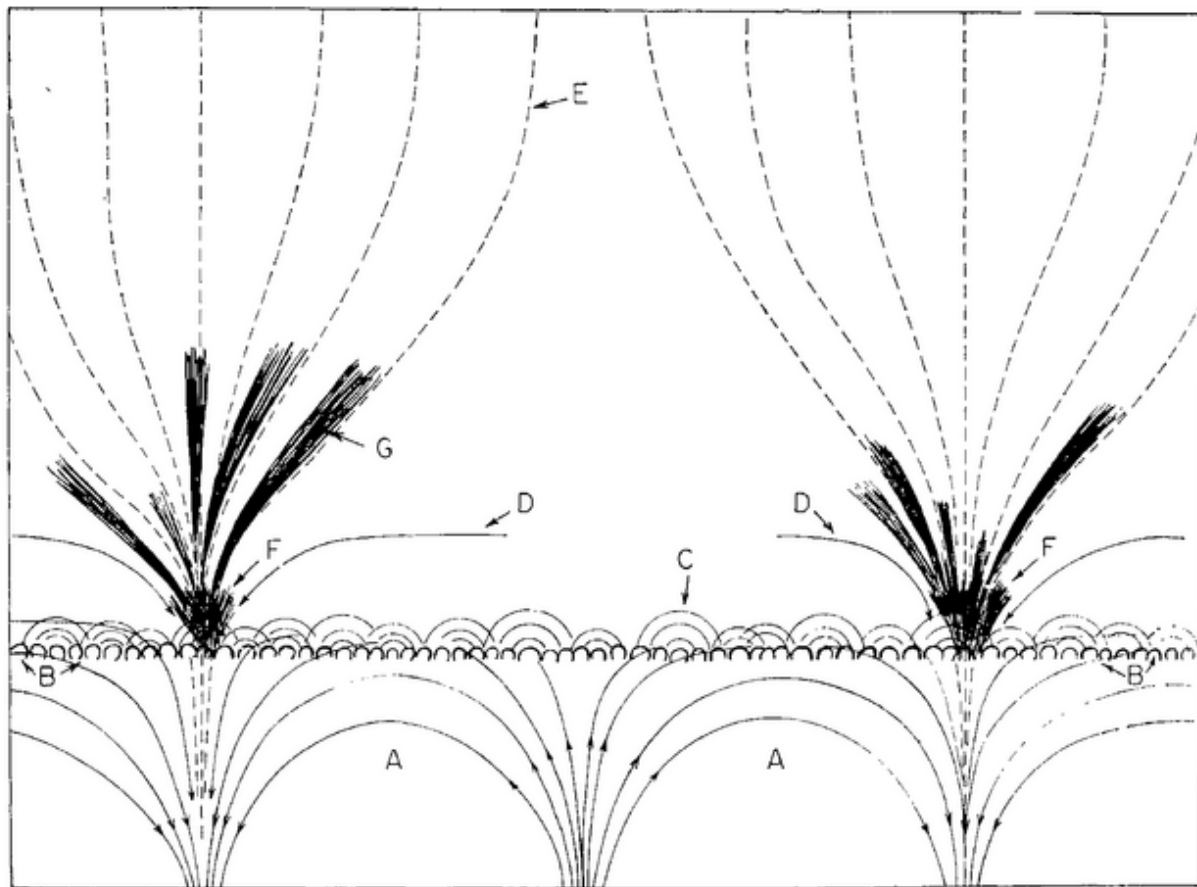


FIG. 8. Microphotometer tracing across an individual supergranulation cell, perpendicular to the solar limb (Simon and Leighton, 1964).

# SUPERGRANULATION CARTOON

Noyes 1967 *AUS...*28..293N



# REVERSED GRANULATION

*Leighton, Noyes & Simon 1962ApJ...135..474L*

2. A distinct correlation is observed between local brightness fluctuations and vertical velocities: bright elements tend to move upward, at the levels at which the lines Fe  $\lambda$  6102 and Ca  $\lambda$  6103 are formed. In the line Ca  $\lambda$  6103, the correlation coefficient is  $\sim 0.5$ . This correlation appears to reverse in sign in the height range spanned by the Doppler wings of the Na D<sub>1</sub> line and remains reversed at levels up to that of Ca<sup>+</sup>  $\lambda$  8542. At the level of Ca  $\lambda$  6103, an estimate of the mechanical energy transport yields the rather large value  $2 \text{ W cm}^{-2}$ .

- DOT movie 2002-12-08-QS-gb+ca-L7.mpg
- DOT comparison G-band - Ca II H intensities 2004A&A...416..333R
- KIS comparison G-band - Ca II H intensities 2005A&A...431..687L
- SST comparison Mg Ib2 and Na I D1 2011A&A...531A..17R
- Na I D1 seismology 2011A&A...531A..17R



# FIVE-MINUTE OSCILLATION

Leighton, Noyes & Simon 1962ApJ...135..474L

3. The characteristic “cell size” of the vertical velocities appears to increase with height from  $\sim 1700$  km at the level of Fe  $\lambda$  6102 to  $\sim 3500$  km at that of Na  $\lambda$  5896. The r.m.s. vertical velocity of  $\sim 0.4$  km  $\text{sec}^{-1}$  appears nearly constant over this height range.

4. The vertical velocities exhibit a striking repetitive time correlation, with a period  $T = 296 \pm 3$  sec. This quasi-sinusoidal motion has been followed for three full periods in the line Ca  $\lambda$  6103, and is also clearly present in Fe  $\lambda$  6102, Na  $\lambda$  5896, and other lines. The energy contained in this oscillatory motion is about  $160 \text{ J cm}^{-2}$ ; the “losses” can apparently be compensated for by the energy transport (2).

5. A similar repetitive time correlation, with nearly the same period, seems to be present in the *brightness fluctuations* observed on ordinary spectroheliograms taken at the center of the Na  $D_1$  line. We believe that we are observing the transformation of potential energy into wave energy through the brightness-velocity correlation in the photosphere, the upward propagation of this energy by waves of rather well-defined frequency, and its dissipation into heat in the lower chromosphere.

[MDI Doppler movie](#)

[DOT movie 2002-12-08-QS-gb-L7+H7+2xsmooth.mpg](#)

# CHROMOSPHERIC DYNAMICS

*Leighton, Noyes & Simon 1962ApJ...135..474L*

6. Doppler velocities have been observed at various heights in the upper chromosphere by means of the  $H\alpha$  line. At great heights one finds a granular structure with a mean size of about 3600 km, but at lower levels one finds predominantly *downward* motions, which are concentrated in “tunnels” which presumably follow magnetic lines of force and are geometrically related to the  $Ca^+$  network. The Doppler field changes its appearance *very rapidly* at higher levels, typical lifetimes being about 30 *seconds*.

DOT movie 2004-10-15-filament-gb+ca+haw+hac.avi: quiet area with filament

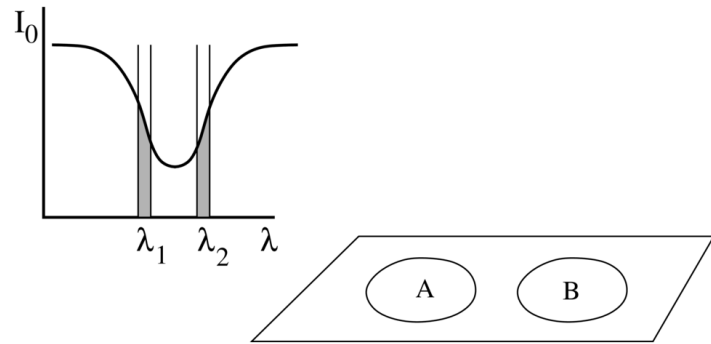
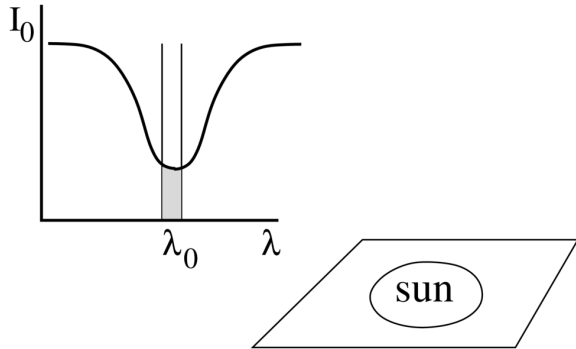
DOT movie 2005-07-13-AR10789-gb+caw+hac+had.mpg: quiet region with small spot

SST movie 2005-10-04: active region near limb

DOT movie 2006-04-24: very rapid stuff

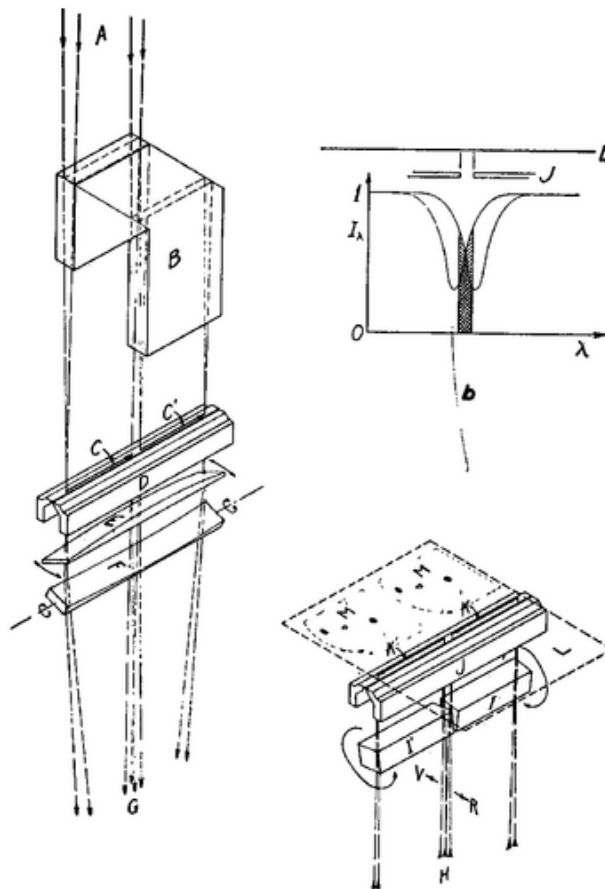
# SPECTROHELIOGRAPH TRICKS

Spectroheliograph and two-slit spectroheliograph:



# PHOTOGRAPHIC DOPPLER ANALYSIS

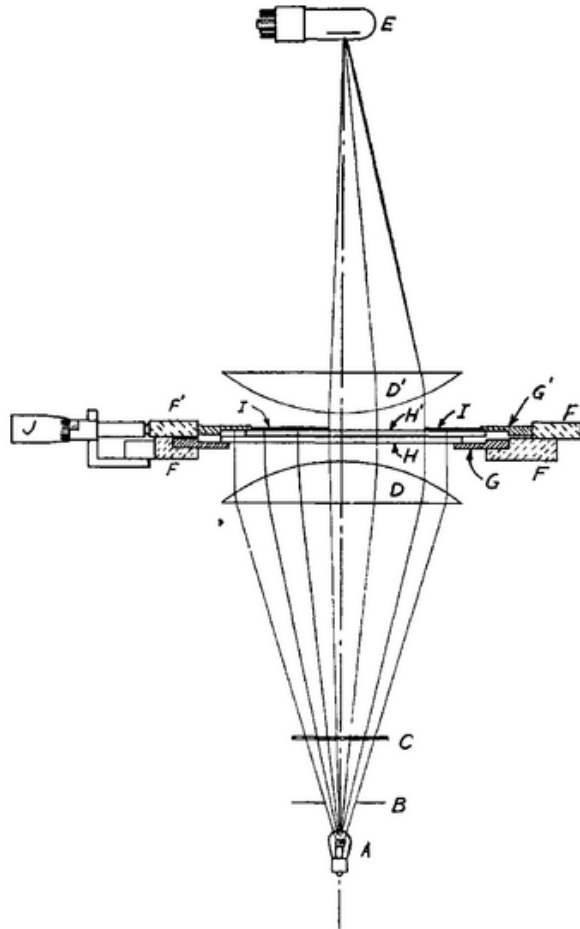
*Leighton, Noyes & Simon 1962ApJ...135..474L*



*a*

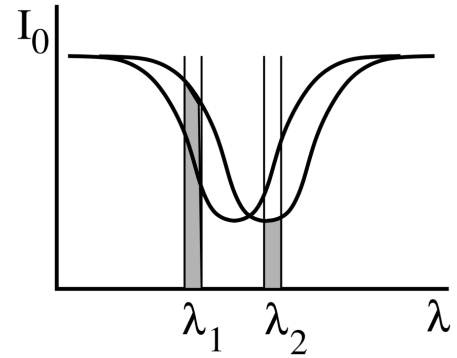
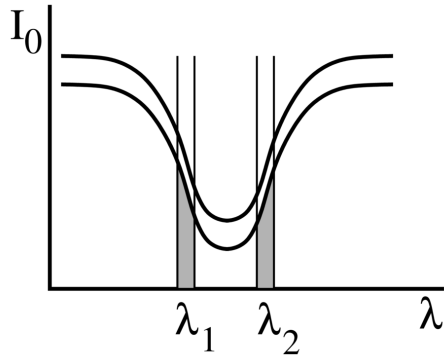
# PHOTOGRAPHIC CROSS-CORRELATION

*Leighton, Noyes & Simon 1962ApJ...135..474L*



# SPECTROHELIOGRAPH TRICKS

Difference and sum plates:



# SUPERGRANULATION

*Leighton, Noyes & Simon 1962ApJ...135..474L*

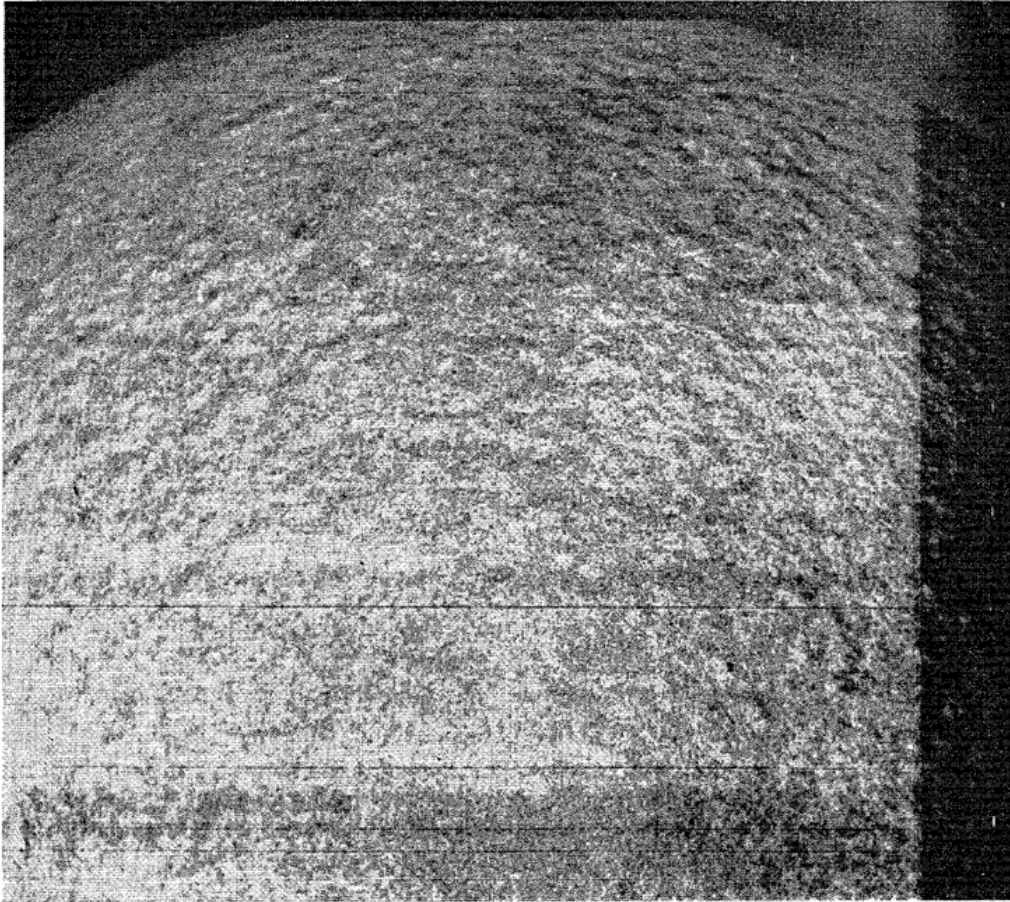
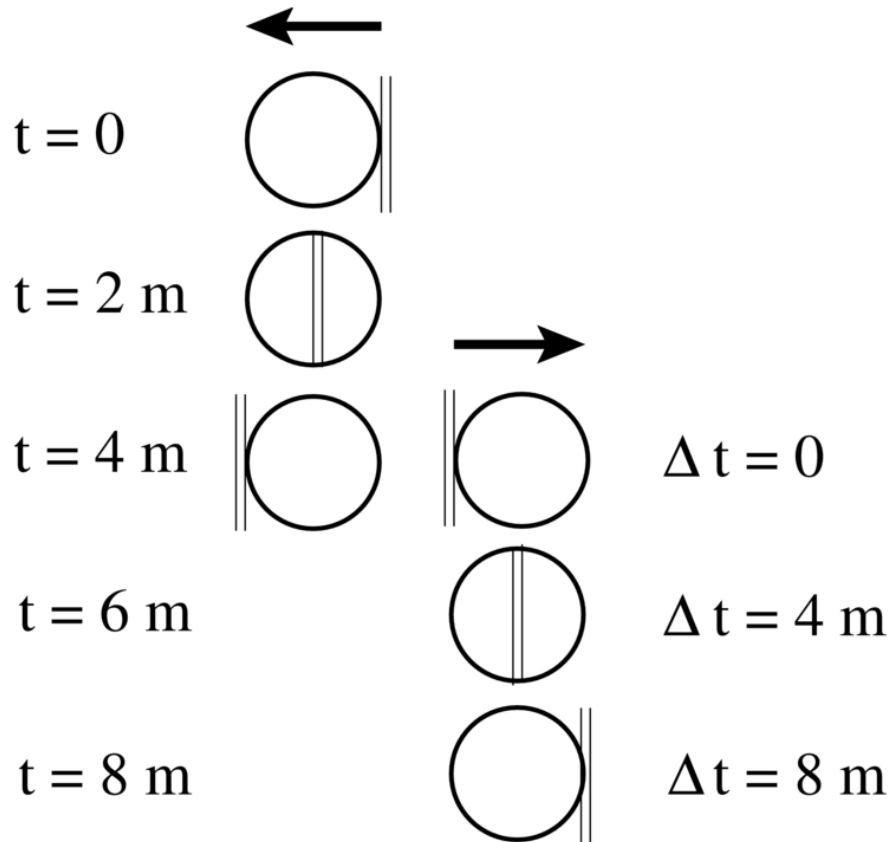


FIG. 4. Doppler-cum-plate of 17 cm solar image in the line Ca 6103, showing large- and small-scale

# SPECTROHELIOGRAM SCANNING





# FIVE-MINUTE OSCILLATION

*Leighton, Noyes & Simon 1962ApJ...135..474L*

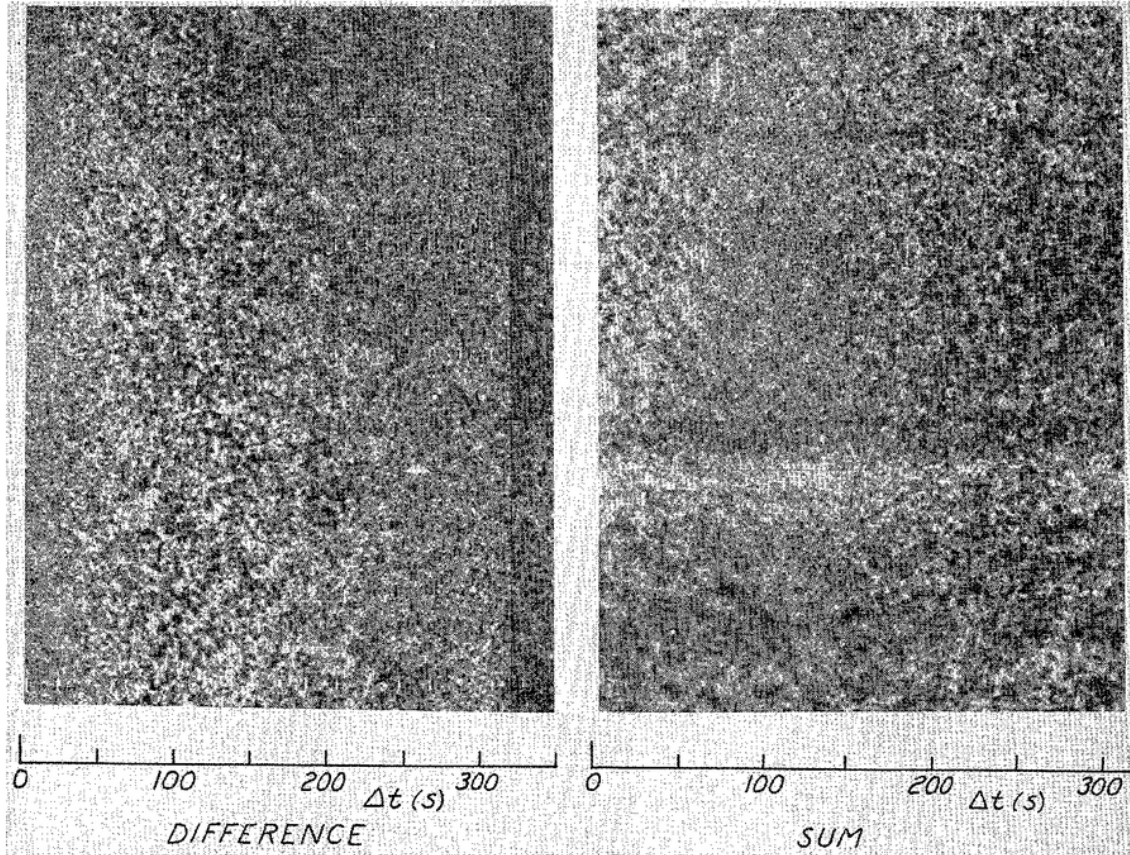
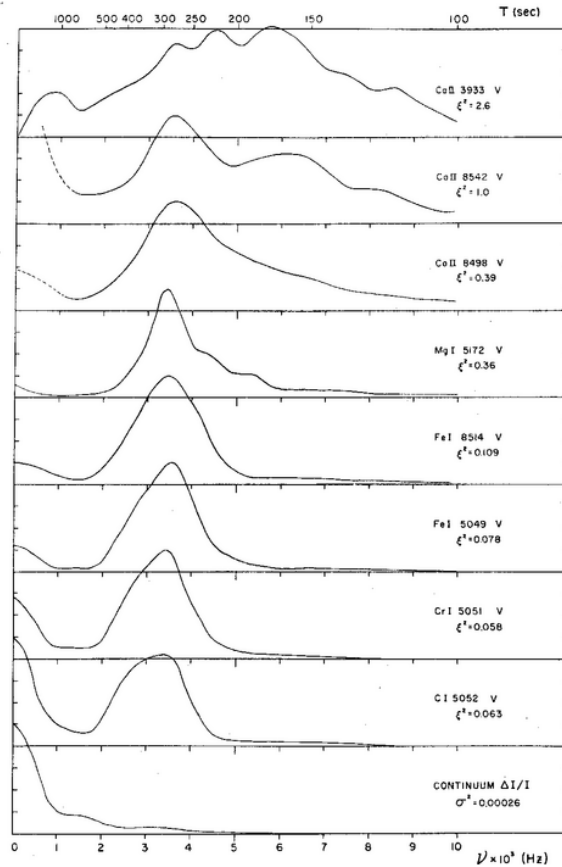


FIG. 17.—Doppler difference (*left*) and sum (*right*) plates, in the line  $\text{Ba}^+ 4554$ . July 1, 1961,  $13^{\text{h}}55^{\text{m}}$  U.T.

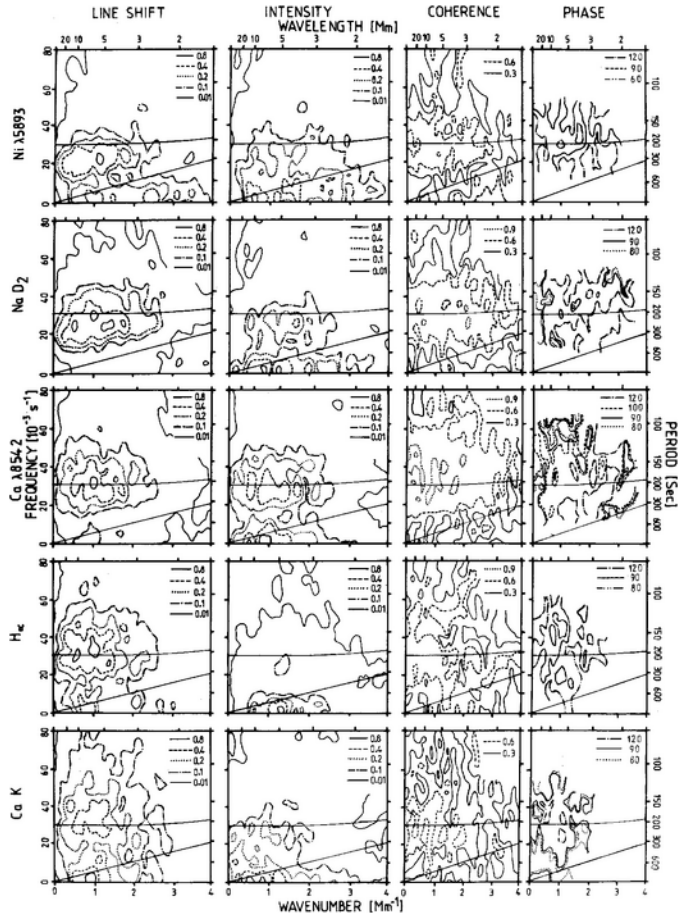
# OSCILLATION POWER WITH HEIGHT

Noyes 1967IAUS...28..293N



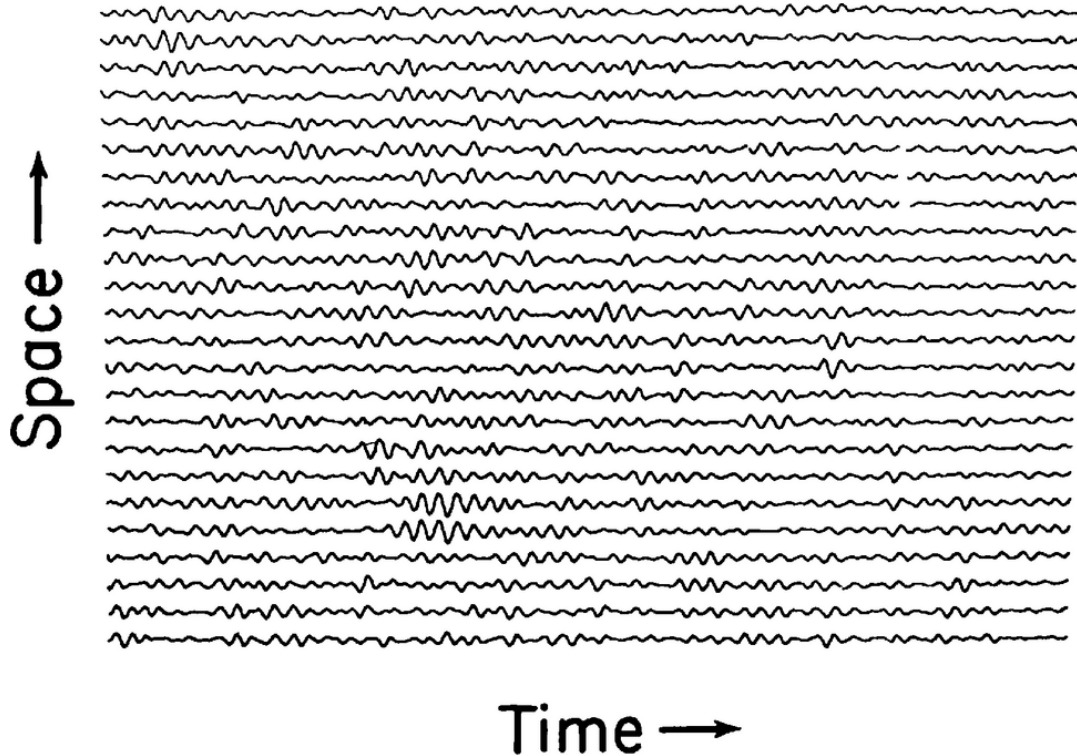
# CHROMOSPHERIC THREE-MINUTE OSCILLATION

Cram 1983ApJ...272..355C



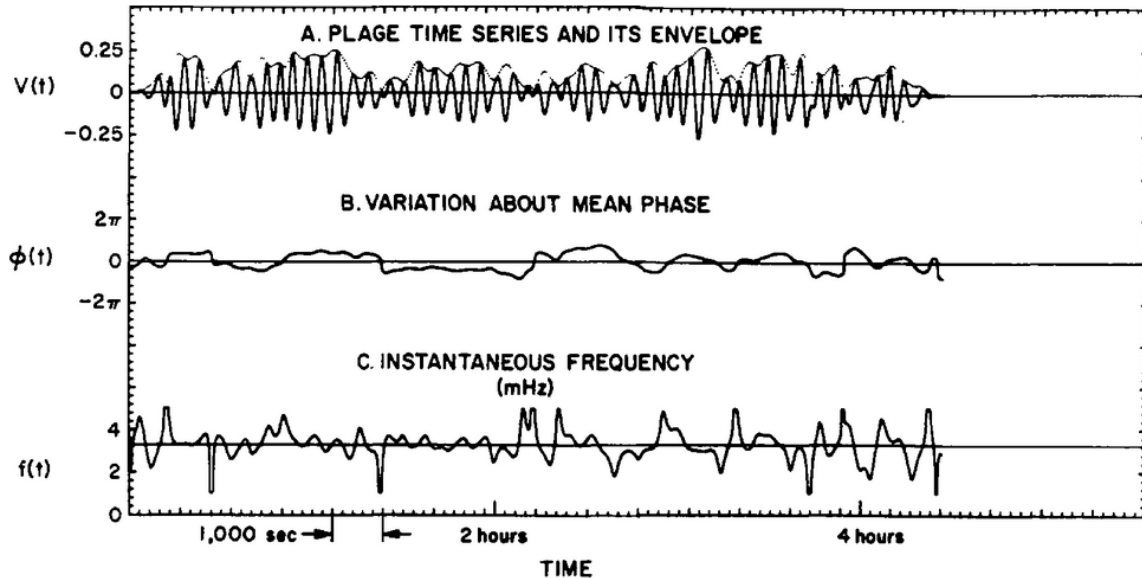
# FIVE MINUTE OSCILLATION WAVETRAINS

*Stein & Leibacher 1974ARA&A..12..407S*



# FIVE MINUTE OSCILLATION AS RANDOM PHENOMENON

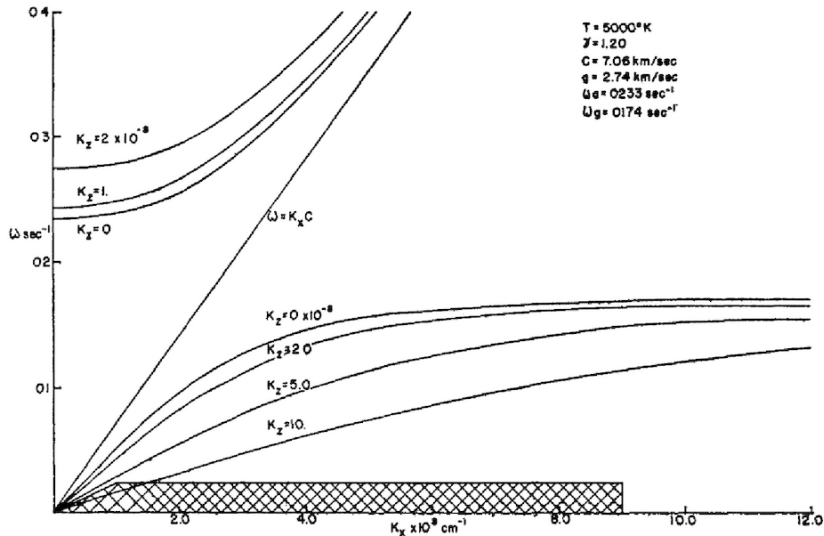
White & Cha 1973SoPh...31...23W 1973SoPh...31...55C



**Abstract.** Four Mt. Wilson measurements ( $T > 4$  h) of the photospheric motion at one point on the Sun are shown to have the characteristics of a narrow-band random process. The motion is shown to have a characteristic correlation time of 23 min and a mean power spectrum that is a smooth, single-peaked function centered at 3.4 mHz. In order to make this classification we use the *analytic signal* to estimate the amplitude, phase, and frequency as functions of time. The power spectrum analysis differs from the common approaches in that it uses the theoretical expression for the mean spectrum for a sequence of random pulses. Because of the random nature of the motion, we doubt the existence of more than one eigenfrequency characteristic of the photosphere as a whole. Likewise, any description of the observed motion in terms of simple deterministic functions will be inadequate for the data used here.

# DIAGNOSTIC DIAGRAM

Whitaker 1963ApJ...137..914W



- clear derivation of slanted gravity waves in stratified medium
- clear presentation of diagnostic diagram (“k–omega”, “FLD”?)
- explained corona and solar wind streamers....
- thanks to C.O. Hines 1960CaJPh..38.1441H and E.N. Parker

## DIAGNOSTIC DIAGRAM

Mein 1966AnAp...29..153M

*Le troisième chapitre comporte une étude statistique bidimensionnelle des séquences d'observation mentionnées plus haut. Les résultats sont traduits dans le diagramme diagnostique (fréquence — nombre d'onde sur le disque solaire). Les spectres de puissance obtenus permettent l'étude de l'évolution du champ de vitesses avec l'altitude, en comparaison avec la théorie des ondes. Des ondes évanescentes sont probablement responsables des oscillations de moyenne fréquence ( $T \sim 300$  s); le domaine des ondes acoustiques reste sans doute limité aux périodes inférieures à 240 s pour les altitudes envisagées; quant à la présence d'ondes de gravité, elle n'est pas incompatible avec les résultats obtenus pour les perturbations de basse fréquence, bien qu'il semble plus vraisemblable d'attribuer à ces perturbations un caractère convectif.*

*Section three consists of a two-dimensional statistical study of the above-mentioned observational sequences. The results are given in the diagnostic diagram (frequency — wave number on the solar disk). With the power spectra obtained, the evolution of the velocity field with height may be studied and compared with wave theory. Evanescent (stationary) waves are probably responsible for oscillations of moderate frequency ( $T \sim 300$  s); the region of acoustic waves is apparently limited to periods less than 240 s for the heights considered; as far as gravity waves are concerned, their presence is not incompatible with results obtained for low frequency perturbations, although it seems more realistic to treat these perturbations as convective in character.*

# DIAGNOSTIC DIAGRAM

Mein 1966AnAp...29..153M

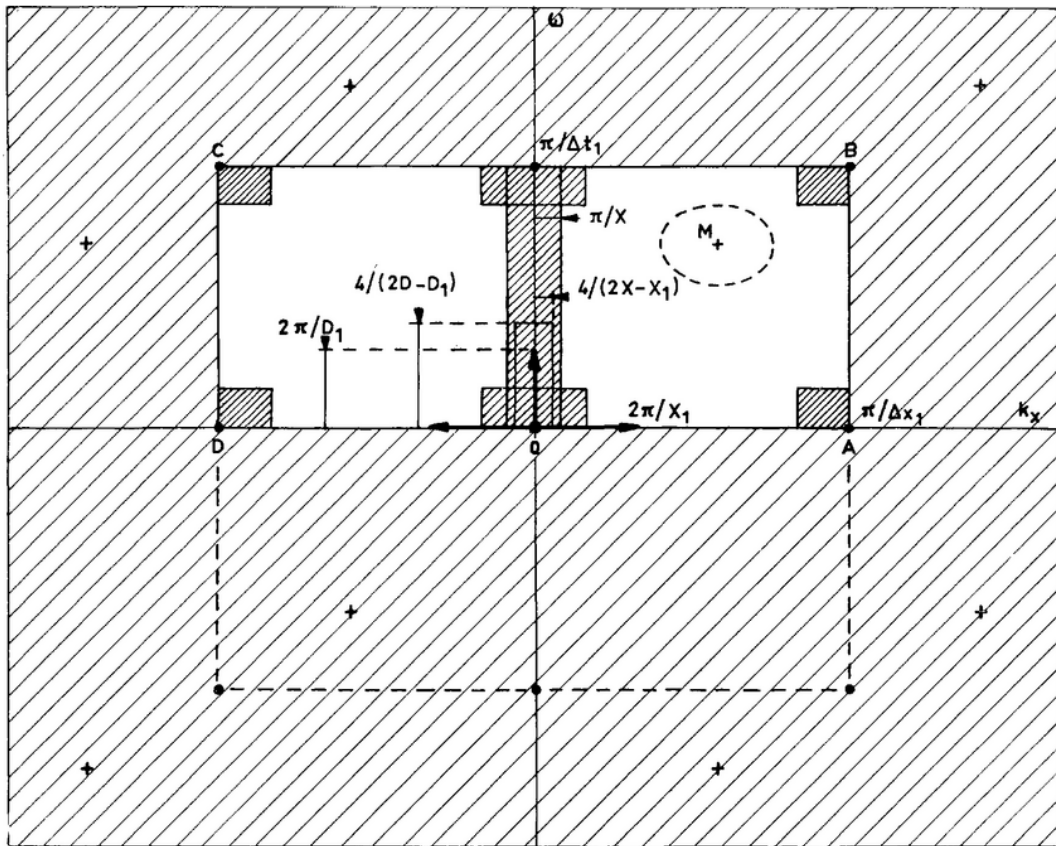


FIG. 6. — Domaines de définition du spectre  $F_1(k_x, \omega)$ . Le calcul est dépourvu de sens physique ou imprécis dans les zones hachurées ; les flèches représentent sensiblement les « éléments spectraux ».



# DIAGNOSTIC DIAGRAM

Mein 1966AnAp...29..153M

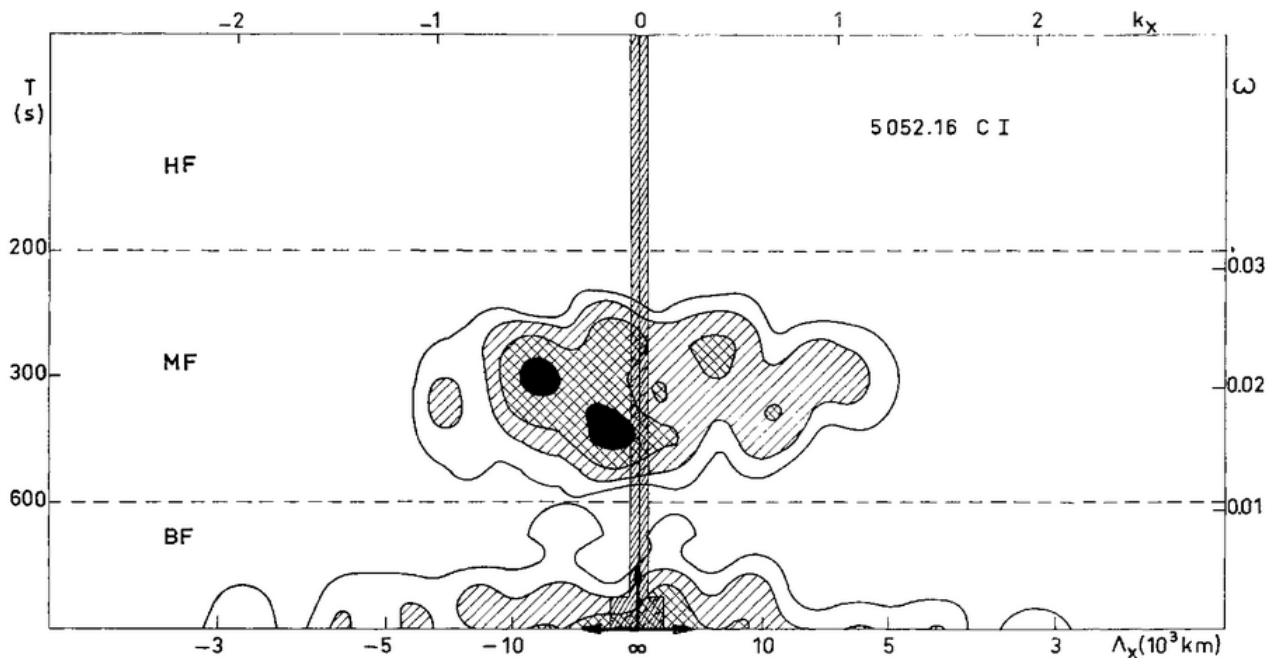


FIG. 7. — Spectre de puissance des vitesses (raie 5052 C I) dans le plan  $(k_x, \omega)$ . Les courbes de niveau correspondent aux produits de la valeur maximale par 0,1 ; 0,2 ; 0,4 ; 0,8. Les flèches représentent les éléments spectraux.

---

# DIAGNOSTIC DIAGRAM

Mein 1966AnAp...29..153M

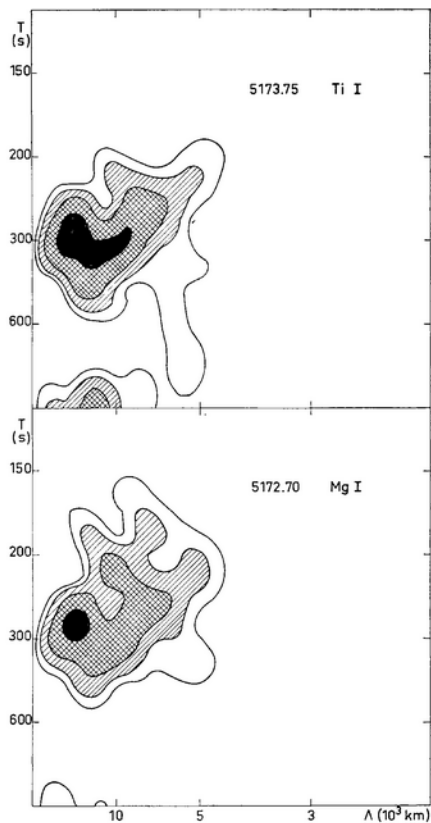


FIG. 9. — Spectres de puissance dans le plan  $(k, \omega)$  relatifs aux vitesses observées pour les 8 échantillons. Les axes sont gradués en longueurs d'onde horizontales et en périodes. Les courbes de niveau correspondent aux produits des valeurs maximales par 0,1 ; 0,2 ; 0,4 ; 0,8.

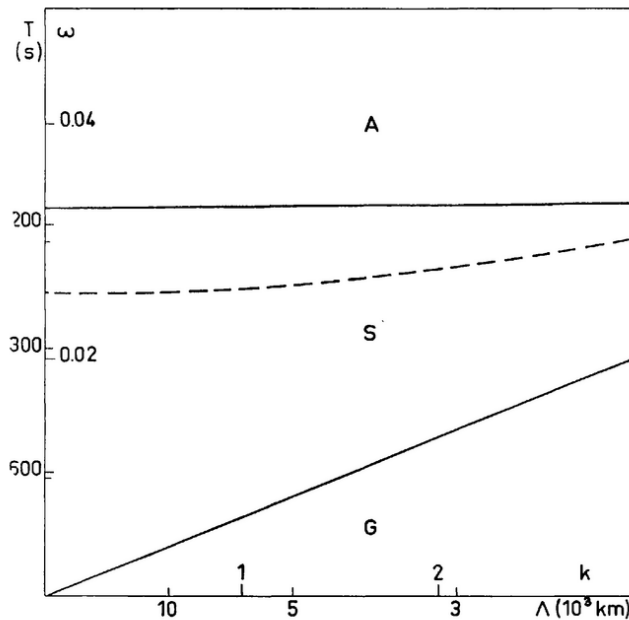


FIG. 11. — Diagramme diagnostique dans le cas solaire pour une température moyenne de 5000 °K. La portion de plan  $(k, \omega)$  représentée est la même que dans la figure 9.

# FIVE MINUTE OSCILLATION K-OMEGA

Frazier 1968ZA.....68..345F

Stein & Leibacher 1974ARA&A..12..407S

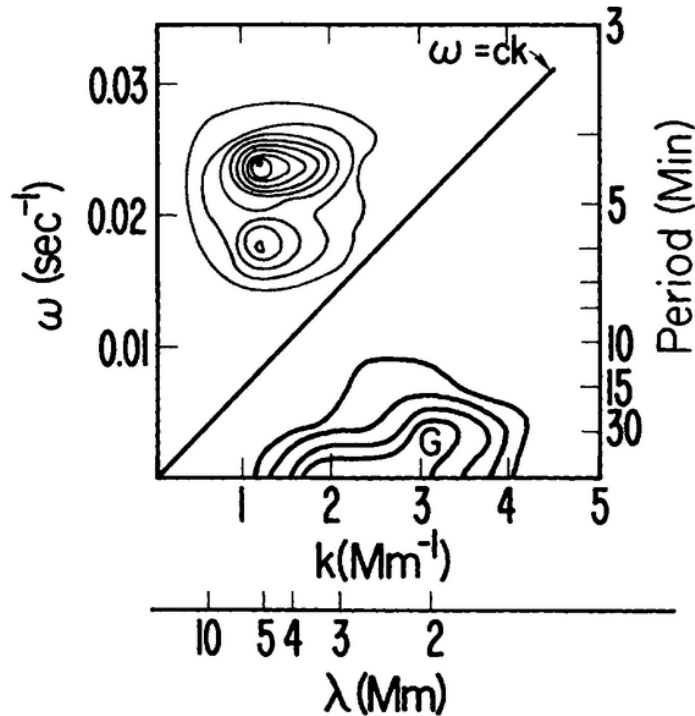


Figure 6 Observed velocity power spectrum in Fe I 6355. The cutoff at small  $k_x$  is caused by the size (7 Mm) of the region observed, and the cutoff at large  $k_x$  is caused by atmospheric seeing. The extension of low frequency power (G) resembles an internal-gravity modal curve. (Frazier 1968b, reprinted by permission from *Z. Ap.*)

## *p*-MODE CONFUSION

Deubner 1972SoPh...22..263D

(exam: whose Solar Physics volumes did ADS scan?)

The most interesting results are the following:

(1) The 5-min oscillations appear in our power spectra as smooth peaks, although the spectra would easily resolve e.g., a double peak structure like that in Frazier's spectra. The appearance of multiple peaks (in smaller samples) does not depend on high spatial resolution. On the other hand we have new arguments that even a  $10'' \times 10''$  area is not large enough a sample of the solar surface to provide statistical stability. We therefore conclude that only observations which cover the duration of several wavetrains at many physically independent positions – an area of  $100'' \times 100''$  observed for 2 hr might be appropriate – give us a consistent picture of the average dynamical properties of the solar photosphere. Nevertheless, it will be still interesting to study carefully the properties of isolated wave trains in order to learn more about their propagation and their possible sources. The low photospheric layers, where the oscillations are less ubiquitous, provide a suitable layer for such studies.

(2) Large wavelengths of  $30''$  to  $60''$  are found to be most prominent among the 5-min oscillations in the  $k-\omega$  power spectra. This agrees with earlier measurements from which a phase coherence length comparable to supergranular size had been derived. These wavelengths are compatible with a model which assumes an oscillatory field consisting of statistically independent elements with a  $10''$  to  $20''$  diameter. It is

# FIVE MINUTE OSCILLATION: FIRST LIGHT

*Ulrich 1970ApJ...162..993U*

## THE FIVE-MINUTE OSCILLATIONS ON THE SOLAR SURFACE\*

ROGER K. ULRICH

University of California, Los Angeles

*Received 1970 March 5; revised 1970 June 3*

### ABSTRACT

The acoustic properties of the subphotospheric layers are examined. It is shown that standing acoustic waves may be trapped in a layer below the photosphere. These standing waves may exist only along discrete lines in the diagnostic diagram of horizontal wavenumber versus frequency. The positions of these lines are derived from a modal analysis of the solar envelope. The lines for the fundamental mode and the first-overtone mode pass through the centers of the two peaks observed by Frazier. An examination of the energy balance of the oscillations shows that they are overstable. When they are assigned an amplitude of  $0.2 \text{ km sec}^{-1}$ , they generate about  $(5-7) \times 10^6 \text{ ergs cm}^{-2} \text{ sec}^{-1}$ . This power output suggests that the dissipation of the 5-minute oscillations above the temperature minimum is responsible for heating the chromosphere and corona.

1002

ROGER K. ULRICH

I would like to thank Dr. E. N. Frazier for suggesting that the 5-minute oscillations might be dependent on the subphotospheric layers. I am grateful to Professor R. F. Christy for suggesting that my unexpected result that the oscillations are self-exciting might be more than a numerical error. I wish to thank the Kellogg Laboratory at Caltech for their hospitality and support during the initial phases of this work.

# FIVE MINUTE OSCILLATION: FIRST LIGHT

Ulrich 1970ApJ...162..993U

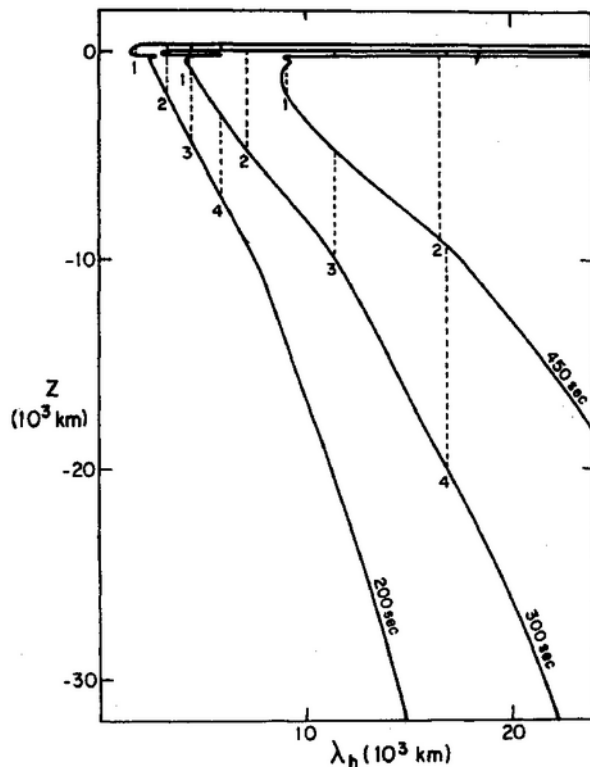
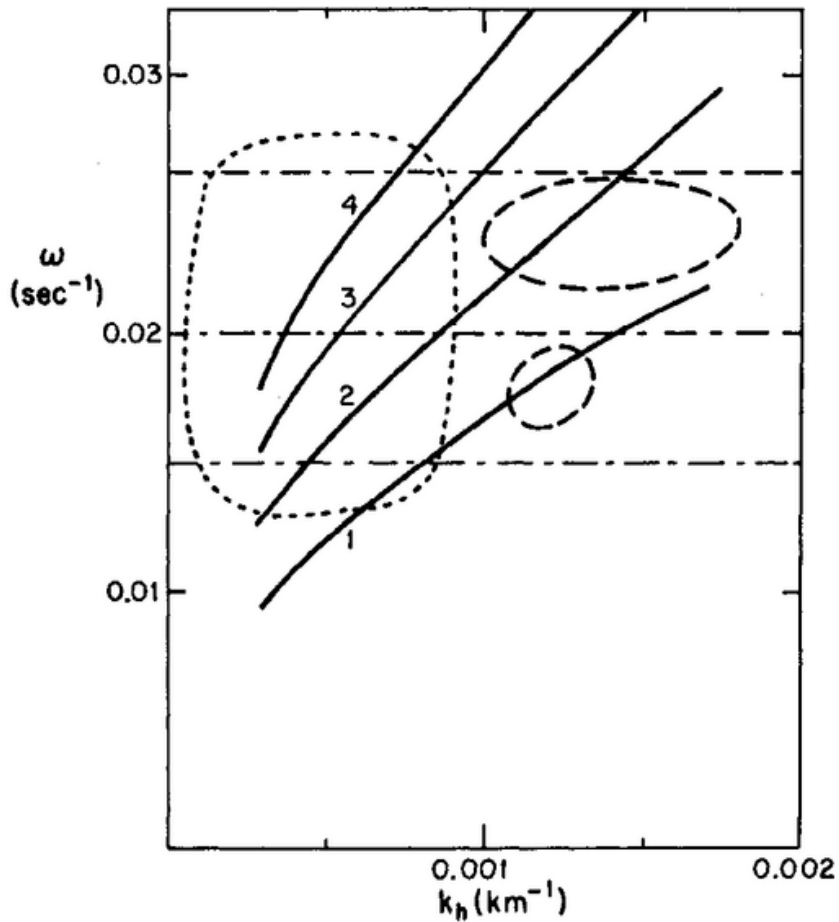


FIG. 1.—Altitude  $z$  of the reflecting layer versus horizontal wave length  $\lambda_h$  for three periods of oscillation. Permitted oscillations are found to the right of each line. Dashed lines indicate positions of the eigensolutions found in § III. These solutions are labeled by their modal numbers defined as the number of nodes between the reflecting layers plus one.

# FIVE MINUTE OSCILLATION: FIRST LIGHT

Ulrich 1970ApJ...162..993U



# THE SUN IS A SPHERE

*Wolff 1972ApJ...177L..87W*

## THE FIVE-MINUTE OSCILLATIONS AS NONRADIAL PULSATIONS OF THE ENTIRE SUN

CHARLES L. WOLFF

Laboratory for Solar Physics, NASA-Goddard Space Flight Center, Greenbelt, Maryland 20771

*Received 1972 June 23; revised 1972 August 14*

### ABSTRACT

Calculations of the stability coefficient show that the Sun should be pulsating as a unit in nonradial modes of high order. The pulsations are driven by the superadiabatic gradient of the low photosphere and by the same sensitive changes in opacity that are known to be important in variable stars. The existence of solar pulsations can explain many of the large scale features observed in the well known 5-minute oscillations of the solar atmosphere.

An obvious way to test this theory is to search for velocities distributed over the solar surface according to some spherical harmonic. Because of the long wavelengths involved, fairly large scanning elements  $\sim 10^2$  square seconds of arc can be used, and this would have the added advantage of diminishing the relative contribution of the solar granulation noise. But the data for the spatial analysis must be carefully restricted to narrow bands of acoustical frequencies; otherwise, one will average over many modes and obtain only the transient and complicated patterns which have been seen many times before. If solar pulsations can be monitored with enough precision, they will ultimately prove valuable probes of the solar interior structure and will place additional experimental limits on stellar convection theory.



# THE SUN IS A SPHERE

Wolff 1972ApJ...177L..87W

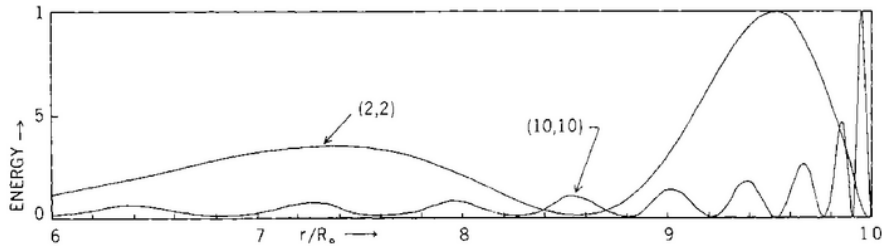
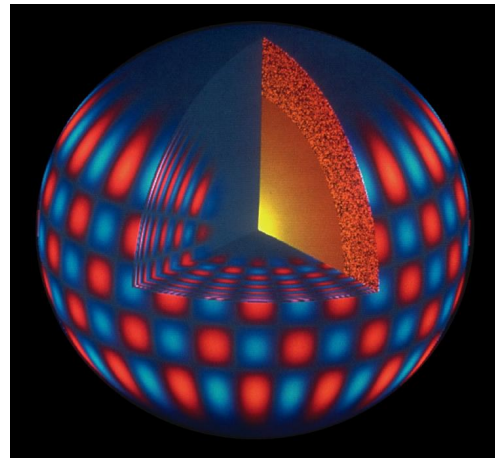
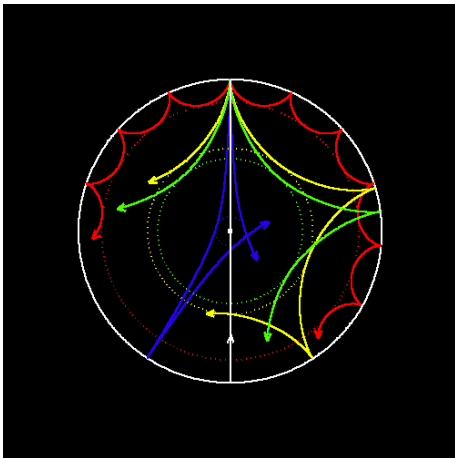


FIG. 1.—Radial distribution of kinetic energy (arbitrary units) in spherical shells of unit thickness for two nonradial  $p$ -modes of solar oscillation.



## NUMERICAL $p$ -MODE PREDICTION

*Ando & Osaki 1975PASJ...27..581A*

The stability of acoustic modes trapped in the solar convection zone is studied by solving the equations of linear nonadiabatic nonradial oscillations. The radiative transfer of perturbations is treated by the Eddington approximation which can be applied both for the optically thick and thin cases. The growth or damping rates of oscillations are determined from the imaginary part of eigenfrequency. The results are shown in the diagnostic  $(k_x, \sigma)$ -diagram, where  $k_x$  is the horizontal wave number and  $\sigma$  is the angular frequency of oscillations. It is found that many of the acoustic modes are overstable and that the most unstable modes occupy a long mountain-range-like region in the  $(k_x, \sigma)$ -diagram centered with a period of 300 s and with a wide range of horizontal wavelength, which is in good agreement with observations of the five-minute oscillation. It is shown that the driving of oscillations is mainly due to the  $\kappa$ -mechanism of the hydrogen ionization zone, while the radiation loss in the optically thin layers contributes appreciably to the damping.

# NUMERICAL $p$ -MODE PREDICTION

*Ando & Osaki 1975PASJ...27..581A*

## (a) *Basic Equations and Boundary Conditions*

The basic equations governing nonadiabatic radial pulsations in the radiative atmosphere were formulated by UNNO (1965), in which the radiative transfer was treated in the Eddington approximation. UNNO and SPIEGEL (1966) have demonstrated that the Eddington approximation in the radiative heat equation is very useful in three-dimensional time-dependent problems. We thus utilize this in the present paper. The basic equations governing nonadiabatic nonradial oscillations in the radiative atmosphere are then given as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)$$

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho} \nabla P - \mathbf{g}, \quad (2)$$

$$c_P \rho \left( \frac{dT}{dt} - \nabla_{\text{ad}} \frac{T}{P} \frac{dP}{dt} \right) = -\pi \nabla \cdot \mathbf{F}, \quad (3)$$

$$\mathbf{F} = -\frac{4}{3\kappa\rho} \nabla J, \quad (4)$$

and

$$J = \frac{ac}{4\pi} T^4 + \frac{c_P}{4\pi\kappa} \left( \frac{dT}{dt} - \nabla_{\text{ad}} \frac{T}{P} \frac{dP}{dt} \right), \quad (5)$$

# NUMERICAL $p$ -MODE PREDICTION

*Ando & Osaki 1975PASJ...27..581A*

We assume as usual that the small perturbation of a physical quantity  $f$  is written as

$$\left. \begin{array}{l} f'(r, \theta, \varphi, t) \\ \delta f(r, \theta, \varphi, t) \end{array} \right\} = \left. \begin{array}{l} f'(r) \\ \delta f(r) \end{array} \right\} Y_l^m(\theta, \varphi) e^{i\omega t}, \quad (6)$$

where  $(r, \theta, \varphi)$  is the spherical polar coordinates, the Eulerian and the Lagrangian perturbations are denoted by prime ( $'$ ) and  $\delta$ , and  $Y_l^m(\theta, \varphi)$  is the spherical harmonics. We introduce a nondimensional frequency  $\omega$  and five nondimensional variables  $x, p, \theta, j$ , and  $\lambda$  defined by

$$\left. \begin{array}{l} \omega^2 = (R^3/GM)\sigma^2, \\ x = \delta r/r, \quad p = P'/\rho g r, \quad \theta = \delta T/T, \\ j = \delta J/J, \quad \lambda = \delta L_r/L_s, \end{array} \right\} \quad (7)$$

where  $L_r = 4\pi^2 r^2 F$  is the luminosity at radius  $r$  and  $L_s$  is the luminosity at the surface. By linearizing equations (1)-(5), we then obtain four first-order linear differential equations and one auxiliary equation:

# NUMERICAL $p$ -MODE PREDICTION

Ando & Osaki 1975PASJ...27..581A

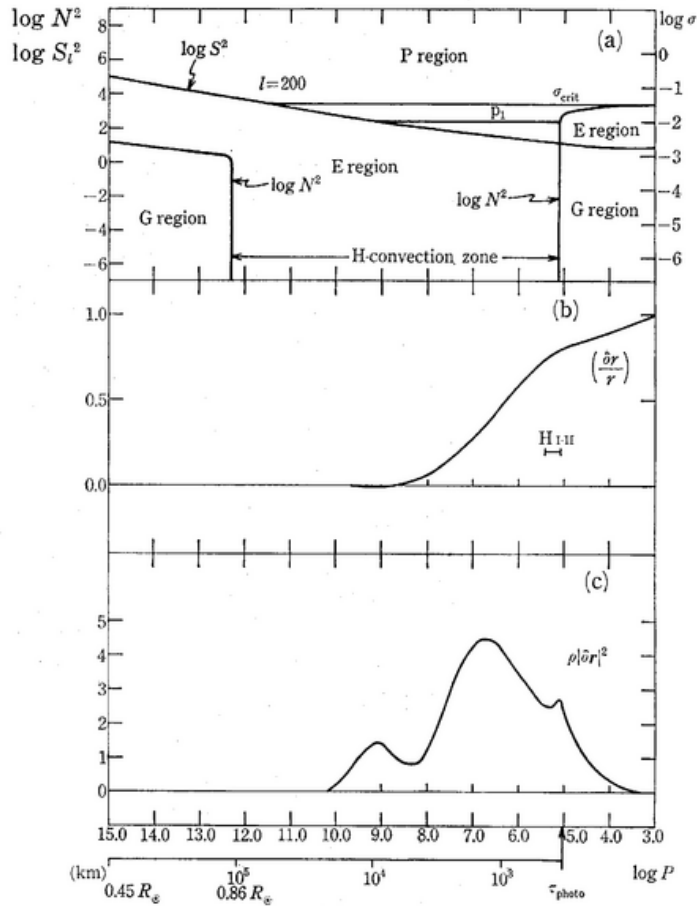
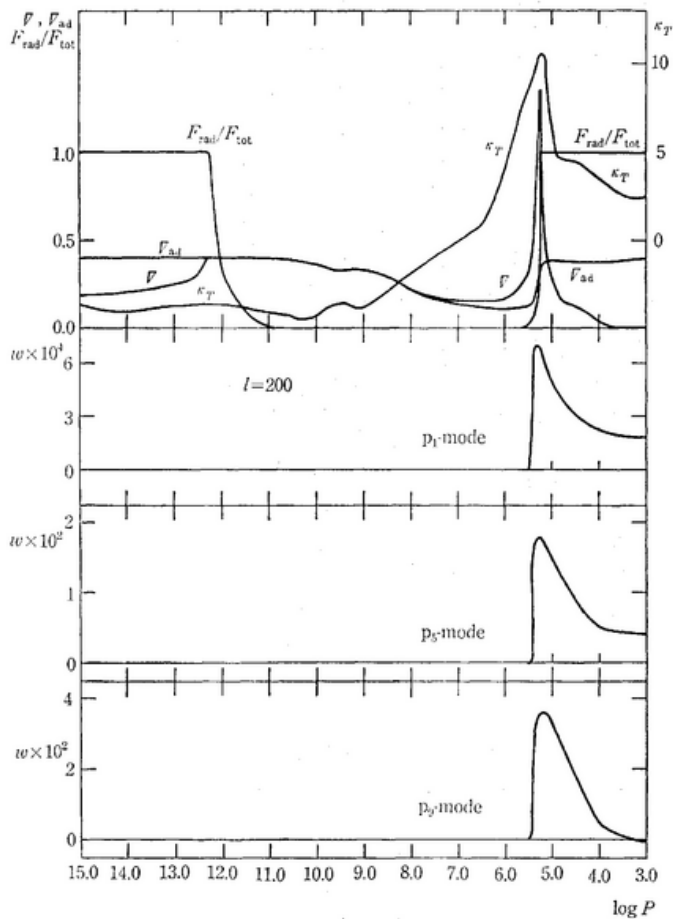


Fig. 1. (a) Dispersion diagram of the adiabatic exponent  $\sigma$  versus  $\log P$ .

# NUMERICAL $p$ -MODE PREDICTION

Ando & Osaki 1975PASJ...27..581A



# NUMERICAL $p$ -MODE PREDICTION

Ando & Osaki 1975PASJ...27..581A

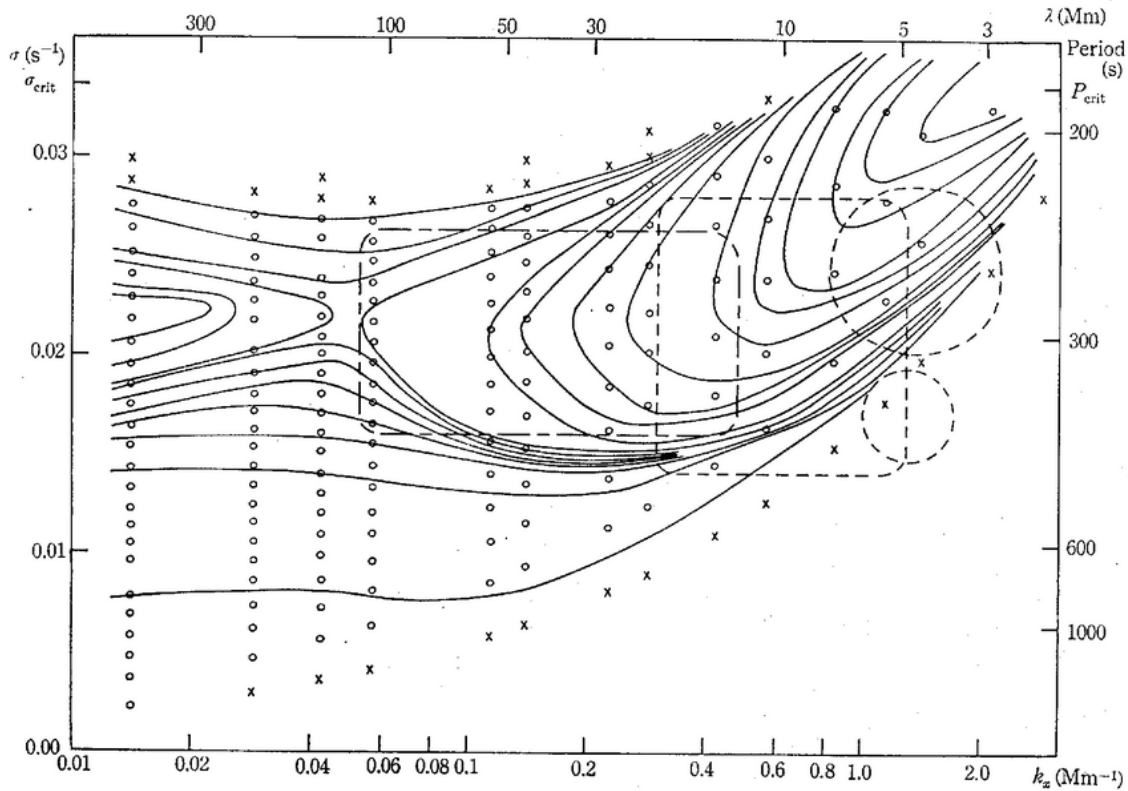


Fig. 7. The diagnostic  $(k_x, \sigma)$ -diagram showing unstable (○) and stable (×) modes. The solid curves show the contour map of equal growth rates  $\eta$ . The regions of observed power of oscillations are also indicated.

# Observations of Low Wavenumber Nonradial Eigenmodes of the Sun<sup>\*</sup>

Franz-Ludwig Deubner

Fraunhofer-Institut, Freiburg i. Br., Fed. Rep. Germany

Received April 10, 1975

**Summary.** New photoelectric observations of the photospheric velocity field with high resolution in horizontal wavenumber and frequency have been carried out in the CI 5380 line. Three or four discrete stable modes of the five-minute oscillations are resolved in the  $k, \omega$  diagram, which agree in many respects with the predicted fundamental modes of subphotospheric standing acoustic waves.

Some interesting aspects of the confirmation of a “global” excitation mechanism of the five-minute oscilla-

tions are pointed out. Several apparently discordant details of previous observations are rediscussed, and it is shown that they can be reconciled with the present results.

**Key words:** solar atmosphere — photospheric oscillations — nonradial eigenmodes



# *p*-MODE IDENTIFICATION

Deubner 1975A&A...44..371D

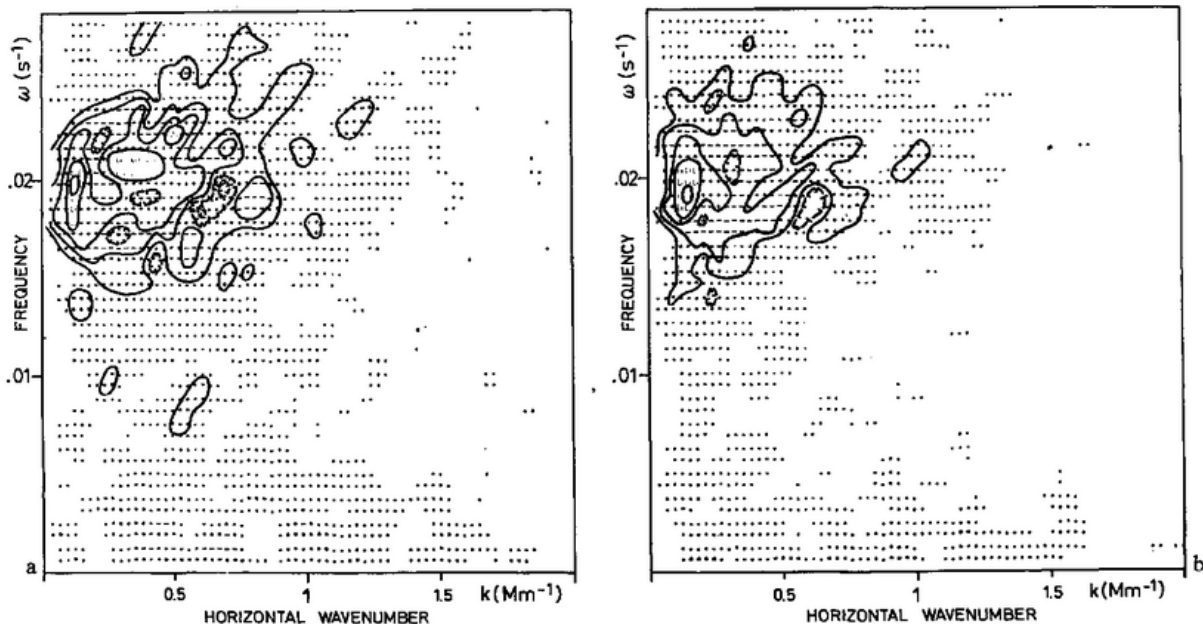


Fig. 1. (a) Diagnostic diagram of the photospheric velocity field computed from Doppler shifts of the CI 5380 line. Six different printer symbols bordered by solid contour lines indicate quadratically increasing levels of kinetic power per unit wavenumber, the lowest level printed (not outlined) being 2.8% of the maximum. Valleys are bordered by broken lines. (b) Same as 1a, obtained with different orientation of the scan line

# *p*-MODE IDENTIFICATION

Deubner 1975A&A...44..371D

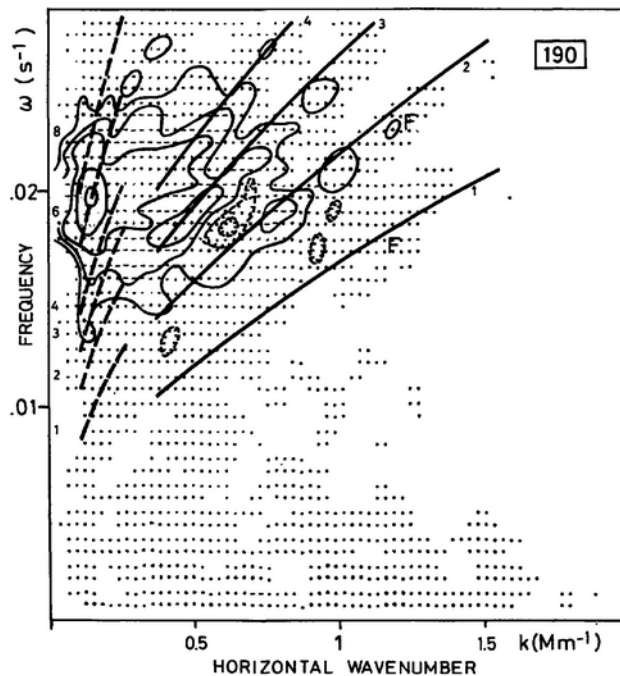
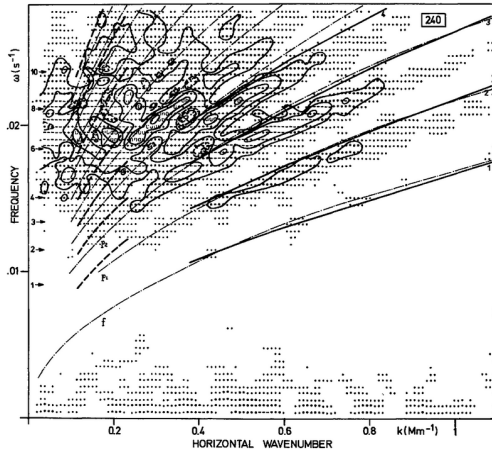


Fig. 2. Diagnostic diagram of the photospheric velocity field obtained by combining the statistically independent power spectra of Fig. 1a and 1b. The spectral resolution element with the number of "degrees of freedom" is given in the upper right corner. Predicted normal modes of trapped acoustic waves are drawn and their radial eigenvalues are given according to Ulrich (solid lines) and Wolff (dashed lines). The two power maxima observed by Frazier (1968) are indicated by a capital *F*

# *p*-MODE IDENTIFICATION

Deubner 1975A&A...44..371D



*Note:* Another set of four-hour recordings of the solar eigenmodes was obtained recently (June 1975) with a larger scan line extending across half the solar diameter. The average  $k, w$  diagram resulting from three such recordings is plotted in Fig. 3. Due to the high spectral resolution achieved, more than five modes may be traced down to wavenumbers as low as  $0 \text{ s Mm}^{-1}$ , and can be compared with the theoretical predictions.

We also included in this graph the new results of Ando and Osaki (1975, to be published) who solved the equations of linear *nonadiabatic* nonradial oscillations of the solar envelope. We note that with increasing modal index their solutions (as well as Ulrich's) tend to deviate progressively from the observed positions of the individual

Since the five-minute oscillations very likely contribute significantly to the heating of the upper chromosphere and corona (for a review of literature see Stein and Leibacher, 1974), it seems desirable that the production of this energy flux which has to be supplied continuously and over the whole surface of the sun, does not depend on localized events of a shallow surface layer. The observations provide sufficient evidence that this basic process of the solar envelope is indeed deeply and firmly rooted in the solar body.

## *p*-MODE ROTATION

*Deubner, Ulrich & Rhodes 1979A&A....72..177D*

**Summary.** We present new photoelectric observations of the solar *p*-modes with improved resolution in wave number and frequency. An analysis of the width of the strongest peaks in the  $k, \omega$  diagram suggests that the *p*-modes pervade the solar convection zone as a globally coherent phenomenon,  $Q$  being probably much larger than 100.

The nodal pattern of the *p*-modes can be regarded as being “frozen in” at well-defined levels within the convection zone, and therefore, as a tracer of large scale horizontal motions. Differences in the depth dependence of different eigenmodes permit the measurement of the solar rotation rate as a function of depth. The rotation rate is found to be non-uniform, layers at about 15,000 km below the photosphere rotating faster than the surface at about the rotation rate of sunspots.

### **Summary**

The identification of the 5-min oscillations as a global phenomenon which is highly phase coherent in space and time, has given us a tool to observe directly systematic large scale motions in the solar interior. Extension of the present work to solar latitudes other than the equator will eventually provide a quantitative three-dimensional picture of the large scale circulation pattern of the solar interior.

# *p*-MODE ROTATION

*Deubner, Ulrich & Rhodes 1979A&A....72..177D*

tance of 192" on the Sun. Three boxes of 32 diodes were placed on either side of the  $g=0$ , Fe I 5576.099 line.

A bandwidth of  $2 \times 76 \text{ m}\text{\AA}$  in the wings of the line is viewed by each pair of diodes, a band of  $76 \text{ m}\text{\AA}$  at the center of the average position of the line is blocked by a mask. The equivalent width of the spectrograph slit was 2".

The solar surface was scanned diametrically parallel to the equator from *W* to *E* once every 100 s. The starting position for the scan was continuously shifted westwards at a rate corresponding to the equatorial surface Doppler velocity of rotation. Each scan consists of 544 steps at  $1''.825$  ( $=20$  guider steps) intervals. The integration time at each position is 133 ms. Including the time for stepping the guider head ( $\sim 1000 \text{ steps s}^{-1}$ ) the total time for a complete scan is about 82 s (without flyback). Every third scan a Ca II  $K_2$  slitjaw filtergram was taken at the center of the flyback motion for reasons explained below. Each of the three observations consists of the tape records of 256 such scans, covering a total of 7.11 h.

Thus, our data reduction procedure comprises basically the following steps:

1. Update the "gaintable" (sensitivity of the 192 individual diodes) every 136 guider steps, as explained in Sect. 2, and correct the raw signals accordingly.
2. For each guider step, and position along the slit, calculate the ratio of the "right wing" to the "left wing" signal.
3. Convert this ratio into a relative velocity by means of the fitted calibration curve (see Sect. 2).
4. For each guider step, calculate the average relative velocity from all 96 pairs of diodes ("long slit").
5. Remove spectrograph drift by subtracting the position of the reference iodine line (Sect. 2) determined from a 9-point fitted parabola, after conversion into a velocity shift.

# *p*-MODE ROTATION

Deubner, Ulrich & Rhodes 1979A&A....72..177D

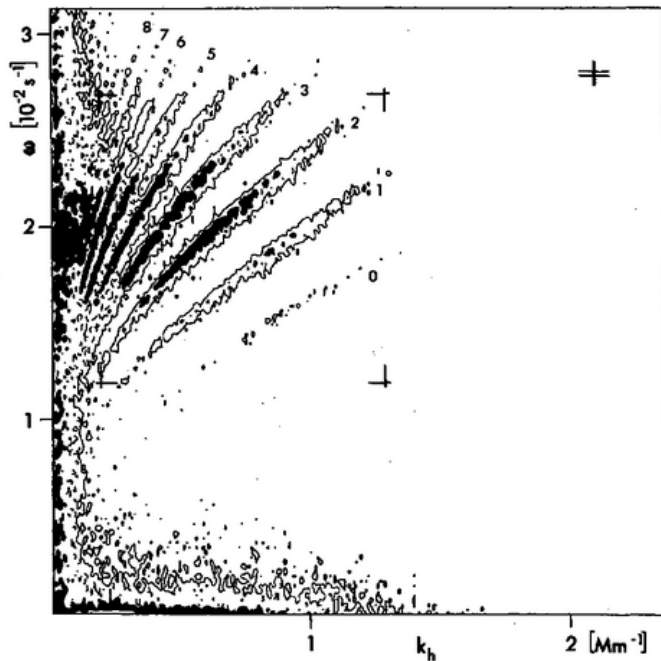


Fig. 1. Average  $k, \omega$  diagram of solar  $p$ -modes, observed on May 6 and 7, 1977. The contours correspond to quadratically increasing relative power levels, the lowest one at 2.8% of maximum power. Power values are multiplied by a factor of  $\sqrt{k}$  for convenient display. The section of the diagram marked by corners was used for the differential rotation analysis. Crossed double bars in the upper right indicate the spectral resolution element  $\Delta\omega\Delta k$

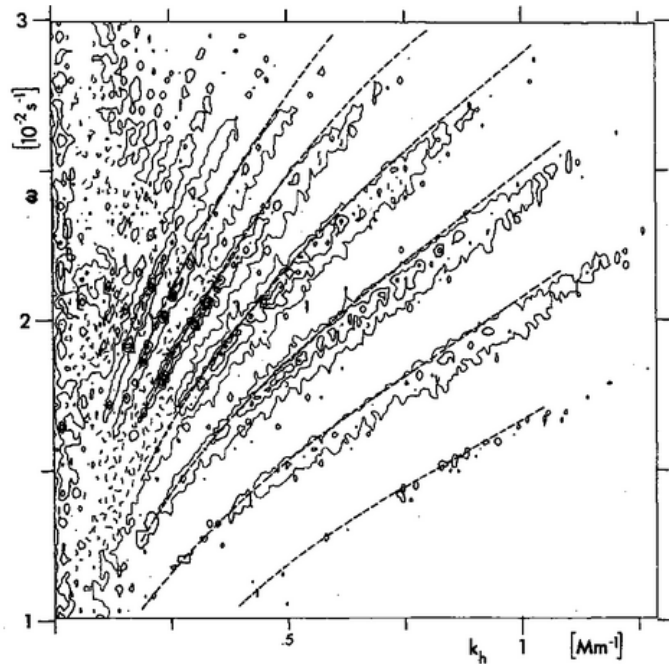
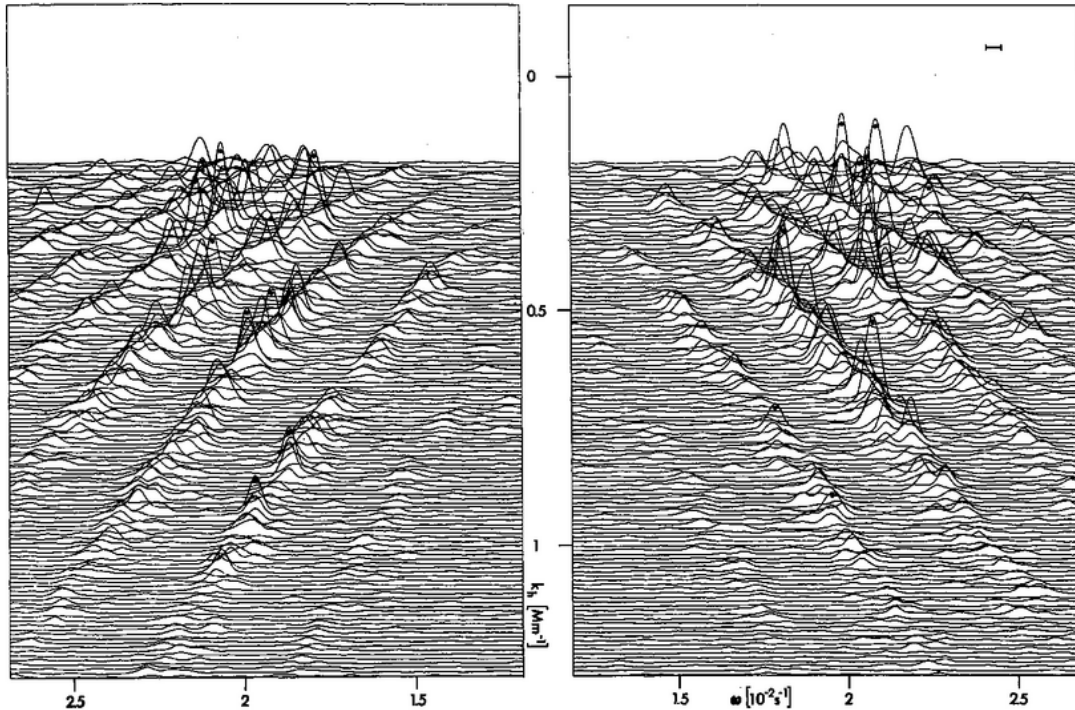


Fig. 2. Enlarged section of Fig. 1, displaying also the theoretically predicted  $p$ -modes for a solar envelope model with  $l/H=2$

by the inverse Fourier transform the data were restored into a temporal sequence. (We realize that this procedure is exact only when there is no simultaneous spatial shift  $\Delta X(t)$  of the wave

# $p$ -MODE ROTATION

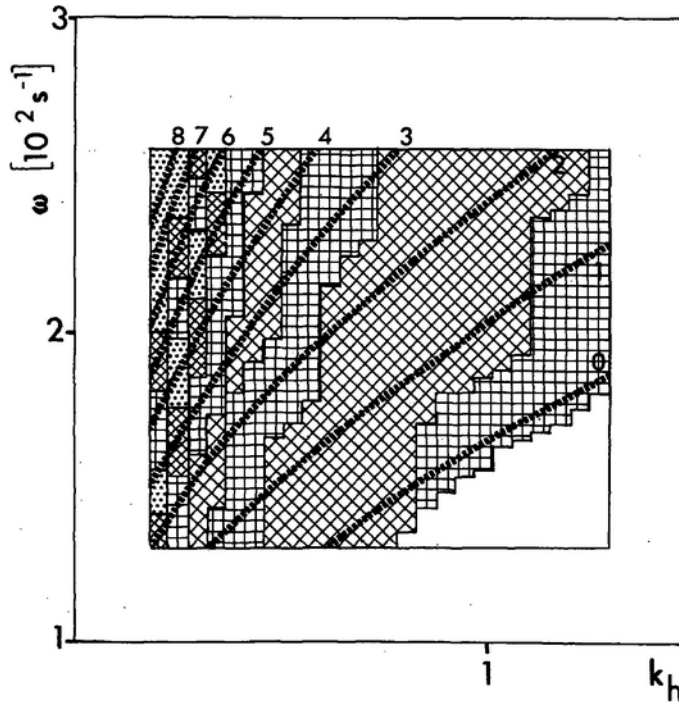
Deubner, Ulrich & Rhodes 1979A&A....72..177D



**Fig. 3.** Section of the  $k, \omega$  diagram after interpolation of the raw spectral data (see Sect. 3.11), plotted separately for “eastbound” and “westbound” wavetrains, on a linear power scale. 20 peaks, used to determine the width of the  $p$ -mode ridges are marked with dots

# *p*-MODE ROTATION

Deubner, Ulrich & Rhodes 1979A&A....72..177D

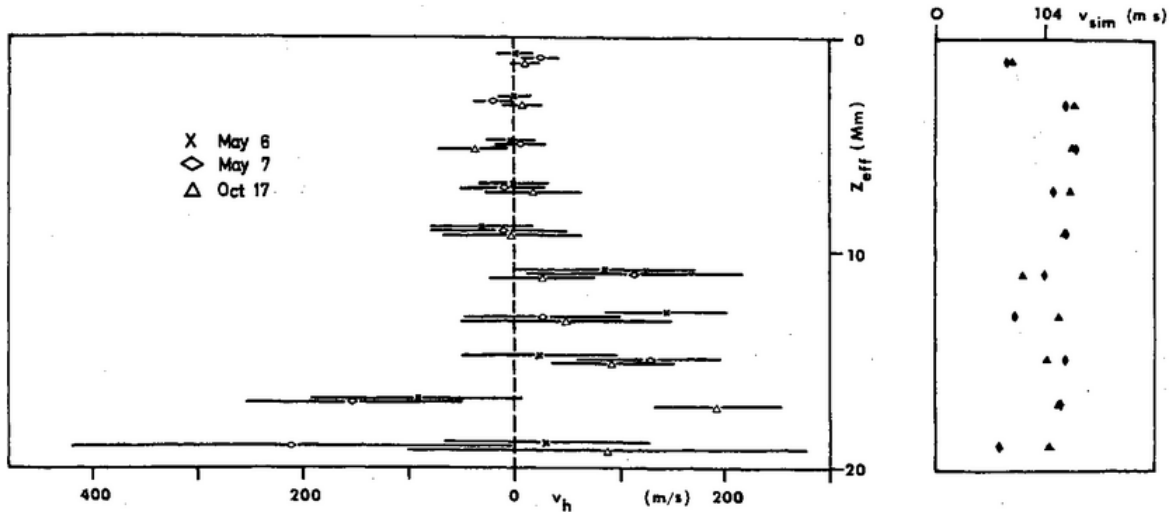


**Fig. 4.** Isobath regions in the  $k, \omega$  diagram, defining levels of constant effective depth for the determination of differential rotation. Beginning at the right edge of the diagram 10 different levels are distinguished by different shadings, corresponding to depth ranges from 0–2 Mm, 2–4 Mm, etc. to 18–20 Mm in the upper left corner



# *p*-MODE ROTATION

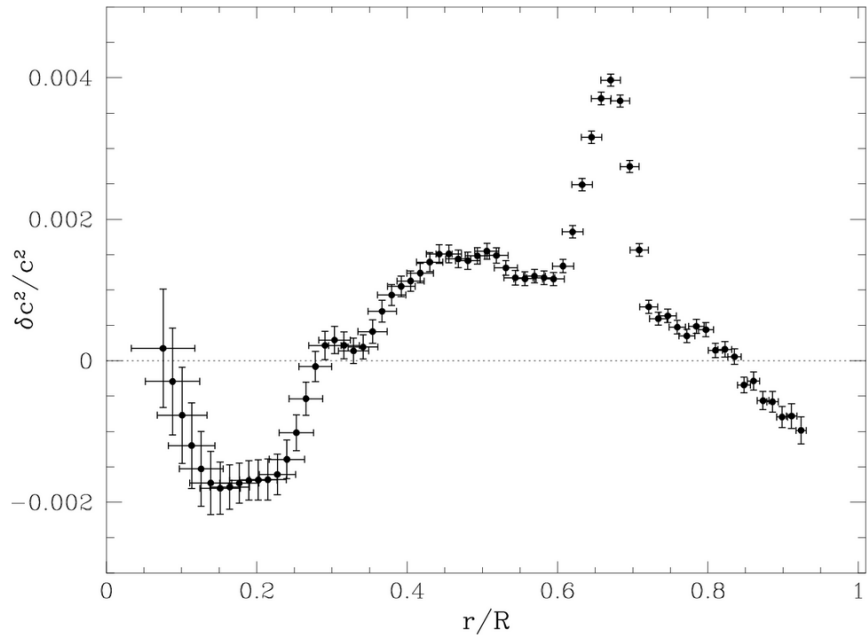
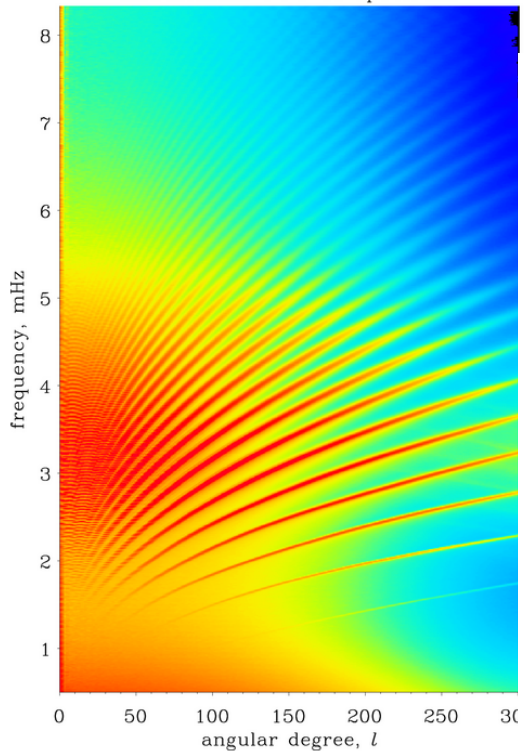
Deubner, Ulrich & Rhodes 1979A&A....72..177D



**Fig. 5.** Observed differential rotation rates as a function of depth below the photosphere. The average rotation rate in the upper four levels (0–8 Mm) is normalized and put equal to zero for each set of observations. Probing the significance of the numerical results, a uniform drift velocity of  $+104 \text{ ms}^{-1}$  was introduced numerically into the data sets of May 6 and 7. The results obtained with these faked data are plotted in the small box

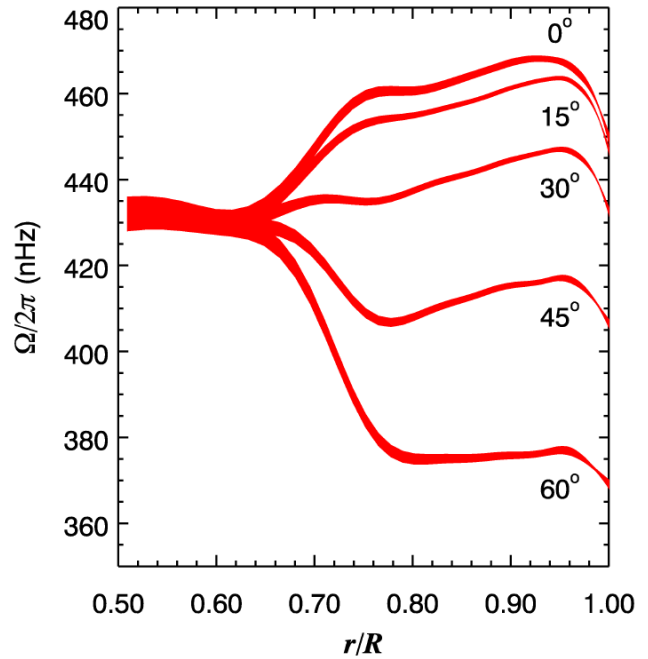
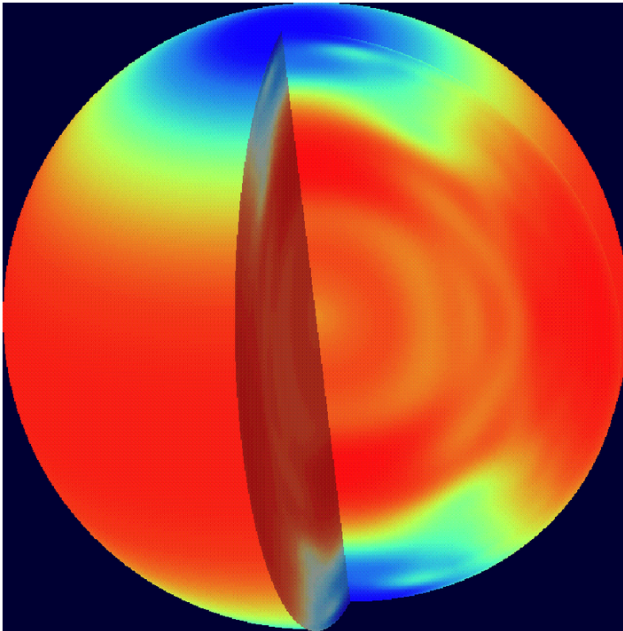
# SOHO HELIOSEISMOLOGY

<http://sohowww.nascom.nasa.gov/gallery/MDI>



# SOHO HELIOSEISMOLOGY

<http://sohowww.nascom.nasa.gov/gallery/MDI>



# SOHO LOCAL HELIOSEISMOLOGY

<http://sohowww.nascom.nasa.gov/gallery/MDI>

[tachocline movie](#)

[local helioseismology](#)

[underneath a sunspot](#)

[sunspot tomography](#)

[AR9393 nearside + backside](#)

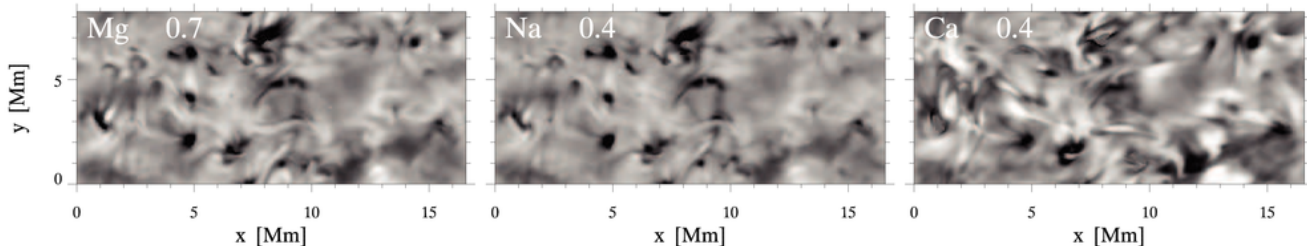
# FIVE-MINUTE OSCILLATION: OBSERVATIONS

Robert J. Rutten

<http://www.staff.science.uu.nl/~rutte101>

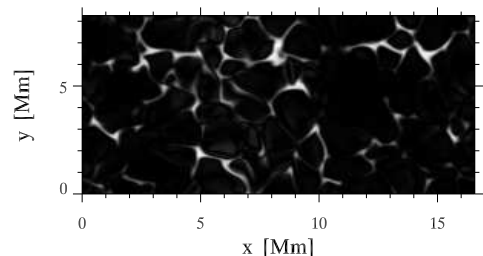
- *discovery*
  - (Plaskett 1954), Leighton et al. 1960
  - chromospheric 3-min: Noyes 1967
- *confusion*
  - restoring force: pressure, gravity, magnetic field?
  - nature: propagating, standing, evanescent?
  - periodicity: piston, cavity, filter?
  - origin: subsurface, surface, atmosphere?
- *enlightenment*
  - prediction: (Leibacher & Stein), Ulrich 1970
  - spherical sun: Wolff 1972, Ando & Osaki 1975
  - identification: (Ulrich & Rhodes), Deubner 1975
- *deployment*
  - helioseismology: low- $l$  networks, South Pole  $\Rightarrow$  GONG, SOHO/MDI, SDO
  - time-distance local helioseismology & far-side mapping
  - asteroseismology

Rutten et al. 2011A&A...531A..17R

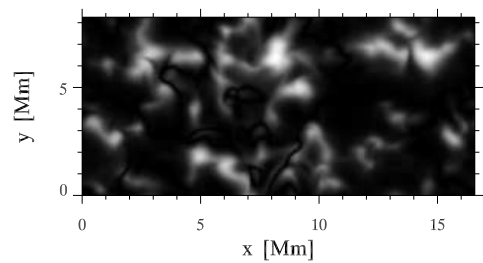


**Fig. 16.** Dopplergrams from the simulation as in the bottom row of Figure 7 but closer to line center and with only CRISP spectral smearing, no spatial PSF smearing.

$|B_z|$  at  $h = 0$  km



$|B_z|$  at  $h = 500$  km



A corollary is that searches for global  $g$ -modes and so-called “chromosphere seismology” using full-disk resonance-cell sampling of the Na line as with GOLF-NG (e.g., [Turck-Chièze et al. 2006](#); [Salabert et al. 2009](#)) will suffer noise from reversed granulation just as classical helioseismology suffers noise from granulation. Magnetic concentrations contribute much noise (literally) by their shocks. GOLF-NG’s 15 passbands, spread over  $\Delta\lambda = \pm 9 \text{ km s}^{-1}$ , have  $FWHM = 30 \text{ m\AA}$ , half CRISP’s passband in this line and clearly narrow enough. Interpretation of such multi-passband oscillation sampling that relies on one-dimensional height-of-formation interpretation, for example to diagnose upward propagation from inward phase difference, is likely to fail since the clapotospheric signals are better described as clouds of varying opacity at varying height of which the varying Dopplershifts act as shutters obscuring the inner line wings.

- discovery
  - (Plasket 1954), Leighton et al. 1960
  - chromospheric 3-min; Noyes 1967
- confusion
  - restoring force: pressure, gravity, magnetic field?
  - nature: propagating, standing, nonresonant?
  - periodicity: piston, cavity filter?
  - origin: subsurface, surface, atmosphere?
- enlightenment
  - prediction: (Lambacher & Stein, Ulrich 1970)
  - spherical sun; Wolff 1972; Ando & Osaki 1975
  - identification: (Ulrich & Rhodes), Deubner 1975
- deployment
  - helioseismology: low- $\ell$  networks, South Pole – GONG, SCHOUMI, SDO
  - time-distance local helioseismology & far-side mapping
  - asteroseismology

clickers: left = previous top-left = overview top-right = thumbnails bottom = ADS page

1

DISCOVERY

Leighton, Noyes & Simon 1962AJL...135..474L

VELOCITY FIELDS IN THE SOLAR ATMOSPHERE

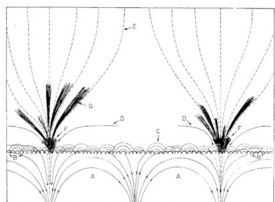
I. PRELIMINARY REPORT\*

ROBERT A. LEIGHTON, ROBERT W. NOYES, and GEORGE W. SIMON  
California Institute of Technology, Pasadena, California  
Received October 29, 1961

Velocity fields in the solar atmosphere have been detected and measured by an adaptation of a technique previously used for measuring Doppler shifts. Data obtained during the summer of 1960 and 1961 have been carefully analyzed and yield the following principal results:  
1. Large "cells" of horizontal moving material are distributed roughly uniformly over the entire solar surface. The motion within each cell is essentially rotational about the fine structure inside the cell. Typical diameters are  $1.0 \times 10^4$  km, spacings between centers,  $3 \times 10^4$  km ( $\approx 5 \times 10^4$  km over the solar surface);  $\pm 0.5$  velocity of center,  $0.2$  km sec<sup>-1</sup> (between  $90^\circ$  and  $180^\circ$ ). There is an anticlockwise appearance to the Ca<sup>+</sup> network. The appearance and properties of these cells suggest that they are a surface manifestation of a "supergranulation" pattern of convective currents which come from radiatively generated energy near the top.  
2. A similar correlation is observed between local brightness fluctuations and vertical velocities. Local elements tend to move upward, at the levels at which the lines Fe I 4052 and Ca I 8502 are formed. In the line Fe I 4052, the correlation coefficient is  $\sim 0.5$ . This correlation appears to reverse in sign in the bright spots observed by the Doppler wings of the Na D<sub>1</sub> line and remains reversed in polarity in the tail of Ca<sup>+</sup> I 8542. At the level of Ca I 8502, an estimate of the radiational energy transport yields the usual large value  $2$  W cm<sup>-2</sup>.  
3. The characteristic "cell size" of the vertical velocities appears to increase with height from  $\sim 100$  km at the level of Fe I 4052 to  $\sim 1000$  km at that of Na I 8196. The  $\pm 0.5$  velocity of  $\sim 0.4$  km sec<sup>-1</sup> appears nearly constant over the height range  $100$  km to  $1000$  km.  
4. A similar repetitive correlation, with a period  $\tau = 206 \pm 8$  sec. This quasi-stationary motion has been followed for three half periods in the line Ca I 8502, and also clearly present in Fe I 4052, Na I 8196, and other lines. The energy contained in this oscillatory motion is about  $100$   $\mu$ W cm<sup>-2</sup>; the "stirrer" can apparently be compensated for by the energy transport ( $\dot{Q}$ ).

SUPERGRANULATION CARTOON

Noyes 1967VAUS...28..293N



7

- Jain et al.: Fifty Years of Seismology of the Sun and Stars 2013ASPC...478...J
- William (Bill) Chaplin (2006): Music Of The Sun: The Story Of Helioseismology
- Jack B. Ziker (2003): Sunquakes: Probing the Interior of the Sun
- Deubner & Gough: Helioseismology: Oscillations as a Diagnostic of the Solar Interior 1984ARAAS...22..503D
- Stein & Lelbachter: Wave generation in "The Sun as star" (orange book) 1981NASSP...650..289S
- Stein & Lelbachter: Waves in the solar atmosphere 1974ARAAS...12..407S
- Bray & Loughhead: The Solar Chromosphere 1974soch.book...B
- Lelbachter: PhD thesis [1971PMDT.....1] @ ADS?

2

SUPERGRANULATION

Leighton, Noyes & Simon 1962AJL...135..474L

1. Large "cells" of horizontal moving material are distributed roughly uniformly over the entire solar surface. The motion within each cell suggest a horizontal outflow flow from a source inside the cell. Typical diameters are  $1.0 \times 10^4$  km, spacings between centers,  $3 \times 10^4$  km ( $\approx 5 \times 10^4$  km over the solar surface);  $\pm 0.5$  velocity of center,  $0.2$  km sec<sup>-1</sup> (between  $90^\circ$  and  $180^\circ$ ). There is an anticlockwise appearance to the Ca<sup>+</sup> network. The appearance and properties of these cells suggest that they are a surface manifestation of a "supergranulation" pattern of convective currents which come from radiatively generated energy inside the sun.



5

REVERSED GRANULATION

Leighton, Noyes & Simon 1962AJL...135..474L

3. A similar correlation is observed between local brightness fluctuations and vertical velocities. Local elements tend to move upward, at the levels at which the lines Fe I 4052 and Ca I 8502 are formed. In the line Ca I 8502, the correlation coefficient is  $\sim 0.5$ . This correlation appears to reverse in sign in the bright spots observed by the Doppler wings of the Na D<sub>1</sub> line and remains reversed in polarity in the tail of Ca<sup>+</sup> I 8542. At the level of Ca I 8502, an estimate of the radiational energy transport yields the usual large value  $2$  W cm<sup>-2</sup>.

- DOT movie 2002-12-08-Q5-gb-cv-L7.mpg
- DOT comparison G-band - Ca II H intensities 2004ABA...416..338R
- HIS comparison G-band - Ca II H intensities 2005AAA...431..687L
- SST comparison Mg [td] and Na I D1 2011AAA...321A..17R
- Na I D1 seismology 2011AAA...321A..17R

8

1956MNRAS...114..219D

MOTIONS IN THE SUN AT THE PHOTOSPHERIC LEVEL

V. VELOCITIES OF GRANULES AND OF OTHER LOCALIZED REGIONS

H. H. Plasket

(Received 1954 May 5)

Summary

Velocities and surface brightness in three Oxford spots, showing granulation, have been measured. The results are in good agreement with those earlier found by Richardson and Schwarzschild as a Mount Wilson spectrum. In two of the three Oxford spots a significant correlation coefficient of  $r = -0.48$  has been found between the surface brightness and the  $\pm 10$  m.p.s. component of the velocity, showing that the bright granular matter is moving vertically upwards. Assuming that the top of the granulation zone occurs at an optical depth of unity,  $0.75$  km sec<sup>-1</sup> is a lower limit to the velocity of ascent of the bright granular matter. The oscillation, or in one specimen the absence, of any correlation between surface brightness and velocity suggests that the granular velocities are being partially or completely masked by some other perturbation of velocity. Removal from the observed velocities that part due to granulation, the perturbing velocities are found to originate in an oscillatory velocity field with an average period of  $5^{\circ}$  of arc and an amplitude of the order of  $0.3$  km sec<sup>-1</sup>.

3

SUPERGRANULATION MEASUREMENT

Noyes 1967VAUS...28..293N

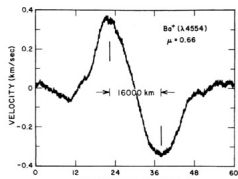


FIG. 8. Microphotometer tracing across an individual supergranulation cell, perpendicular to the solar limb (Stein and Loughhead, 1964).

6

FIVE-MINUTE OSCILLATION

Leighton, Noyes & Simon 1962AJL...135..474L

3. The characteristic "cell size" of the vertical velocities appears to increase with height from  $\sim 100$  km at the level of Fe I 4052 to  $\sim 1000$  km at that of Na I 8196. The  $\pm 0.5$  velocity of  $\sim 0.4$  km sec<sup>-1</sup> appears nearly constant over this height range.

4. The vertical velocities exhibit a striking repetitive correlation, with a period  $\tau = 206 \pm 8$  sec. This quasi-stationary motion has been followed for three half periods in the line Ca I 8502, and also clearly present in Fe I 4052, Na I 8196, and other lines. The energy contained in this oscillatory motion is about  $100$   $\mu$ W cm<sup>-2</sup>; the "stirrer" can apparently be compensated for by the energy transport ( $\dot{Q}$ ).

5. A similar repetitive time correlation, with nearly the same period, seems to be present in the brightness fluctuations observed in ordinary sunspot brightness minima in the center of the Na D<sub>1</sub> line. We believe that we are observing the transformation of potential energy into wave energy through the brightness-velocity correlation in the atmosphere; the greatest proportion of this energy by waves of rather well-defined frequency, and its dissipation into heat in the lower chromosphere.

MDI Dippler movie  
DOT movie 2002-12-08-Q5-gb-L7-H17-2xsmooth7.mpg

9

10

**CHROMOSPHERIC DYNAMICS**  
Leighton, Noyes & Simon 1962*A&J*, 135, 474L

6. Doppler velocities have been observed at various heights in the upper chromosphere by means of the Fe I line. At great heights one finds a granular structure with a mean size of about 2000 km, but at lower heights one finds predominantly horizontal motions, which are concentrated in "prominence" which penetrate to lower magnetic fluxes and are geometrically related to the  $\lambda_4$  pattern. The Doppler field changes its appearance very rapidly at higher levels, typical lifetimes being about 30 seconds.

DOT movie 2004-10-15: filament-gb-cs-haw-haac-act: quiet area with filament  
DOT movie 2005-07-13: AR10789-gb-csaw-haac-had.mpg: quiet region with small spot  
SST movie 2005-10-04: active region near limb  
DOT movie 2006-04-24: very rapid stuff

13

**PHOTOGRAPHIC CROSS-CORRELATION**  
Leighton, Noyes & Simon 1962*A&J*, 135, 474L

16

**SPECTROHELIOGRAM SCANNING**

$t = 0$

$t = 2 \text{ m}$

$t = 4 \text{ m}$

$t = 6 \text{ m}$

$t = 8 \text{ m}$

$\Delta t = 0$

$\Delta t = 4 \text{ m}$

$\Delta t = 8 \text{ m}$

11

**SPECTROHELIOGRAPH TRICKS**

Spectroheliograph and two-slit spectroheliograph:

14

**SPECTROHELIOGRAPH TRICKS**

Difference and sum plates:

17

**FIVE-MINUTE OSCILLATION**  
Leighton, Noyes & Simon 1962*A&J*, 135, 474L

12

**PHOTOGRAPHIC DOPPLER ANALYSIS**  
Leighton, Noyes & Simon 1962*A&J*, 135, 474L

15

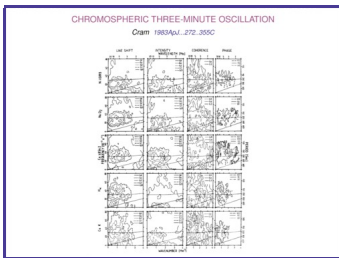
**SUPERGRANULATION**  
Leighton, Noyes & Simon 1962*A&J*, 135, 474L

18

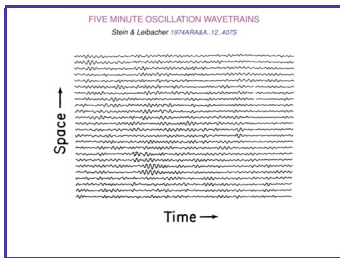
**OSCILLATION POWER WITH HEIGHT**  
Noyes 1967*AUS*, 28, 293N



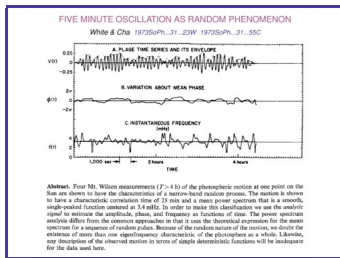
19



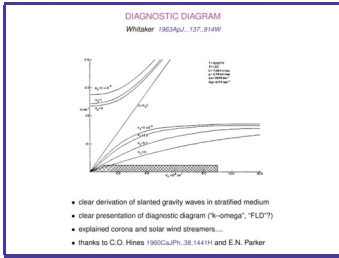
20



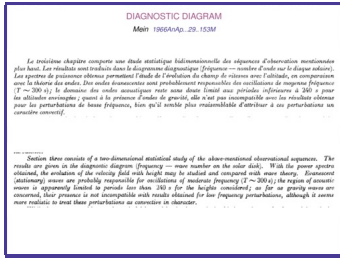
21



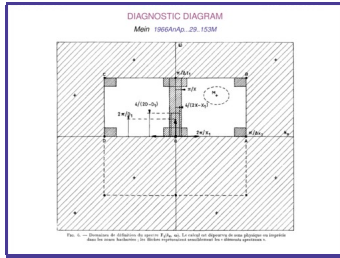
22



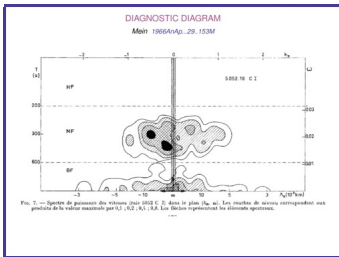
23



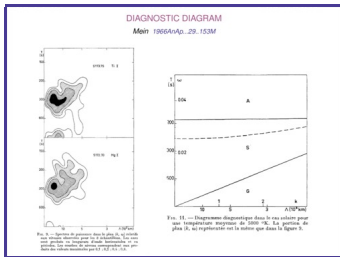
24



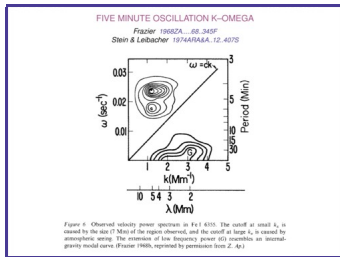
25



26



27



The most interesting results are the following:

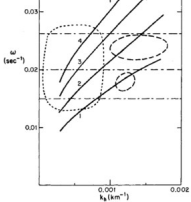
(1) The 2-min oscillations appear in our power spectra as smooth peaks, although the spectra would easily resolve a  $\mu$ -mode peak structure like that in Frazer's spectra. The appearance of multiple peaks (in smaller samples) does not depend on high spatial resolution. On the other hand we have new arguments that even a  $10'' \times 10''$  area is not large enough to sample the solar surface to provide statistical stability. We therefore conclude that only observations which cover the duration of several wave trains in many physically independent positions - an area of  $100'' \times 100''$  observed for 2 hr might be appropriate - give us a consistent picture of the average dynamical properties of the solar photosphere. Nevertheless, it will still be interesting to study carefully the properties of isolated wave trains in order to learn more about their propagation and their possible sources. The low photospheric layers, where the oscillations are less ubiquitous, provide a suitable layer for such studies.

(2) Large wavelengths of  $30''$  to  $60''$  are found to be most prominent among the 5-min oscillations in the  $k-\omega$  power spectra. This agrees with earlier measurements from which a phase coherence length comparable to supergranular size had been derived. These wavelengths are compatible with a model which assumes the oscillatory field consisting of statistically independent elements with a  $10''$  to  $20''$  diameter. It is

28

FIVE MINUTE OSCILLATION: FIRST LIGHT

Ulrich 1970a;J. 162, 893U



31

NUMERICAL  $\mu$ -MODE PREDICTION

Ando & Osaki 1979PASJ, 27, 501A

The stability of acoustic modes trapped in the solar convection zone is studied by solving the equations of linear nonadiabatic nonradial oscillations. The radiative transfer of perturbations is treated by the Edlinding approximation which can be applied both for the optically thick and thin cases. The growth or damping rates of oscillations are determined from the imaginary part of eigenfrequency. The results are shown in the diagnostic  $(k_r, \sigma)$ -diagram, where  $k_r$  is the horizontal wave number and  $\sigma$  is the angular frequency of oscillation. It is found that many of the acoustic modes are overstable and that the most unstable modes occupy a long mountain-range-like region in the  $(k_r, \sigma)$ -diagram centered with a period of 300 s and with a wide range of horizontal wavelength, which is in good agreement with observations of the five-minute oscillation. It is shown that the driving of oscillations is mainly due to the  $\sigma$ -mechanism of the hydrogen ionization zone, while the radiation loss in the optically thin layers contributes appreciably to the damping.

34

FIVE MINUTE OSCILLATION: FIRST LIGHT

Ulrich 1970a;J. 162, 893U

THE FIVE-MINUTE OSCILLATIONS ON THE SOLAR SURFACE\*

ROGER K. ULDRICH

University of California, Los Angeles  
Resend 1970;P.L. 22, 283D

ABSTRACT

The acoustic properties of the adiabatic photospheric layers are examined. It is shown that standing acoustic waves in the dispersive diagram of horizontal wavenumber versus frequency lie in the dispersive diagram of the solar convection zone. The positions of these lines are derived from a model analysis of the solar convection. The five-minute mode and the five-overmode mode pass through the centers of the two peaks observed by Frazer. An examination of the energy balance of the oscillation theory that they are overstable. When they are assumed to equal the dispersion of the 5-minute oscillations above the temperature minimum is responsible for heating the chromosphere and corona.

1062

ROGER K. ULDRICH

I would like to thank Dr. E. N. Frazer for suggesting that the 5-minute oscillations might be dependent on the photospheric layers. I am grateful to Professor R. F. Chlebik for suggesting that my unexpected result that the oscillations are self-exciting might be more than a numerical error. I wish to thank the Kellogg Laboratory at Caltech for their hospitality and support during the initial phases of this work.

29

THE SUN IS A SPHERE

Wolf 1970a;J. 177L, 87W

THE FIVE-MINUTE OSCILLATIONS AS NONRADIAL PULSATIONS

OF THE ENTIRE SUN

Charles L. Wolff

Laboratory for Solar Physics, NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771

Resend 1970;P.L. 22, 283D

ABSTRACT

Calculations of the stability confirm those that the Sun should be pulsating in a suit in nonradial modes of high order. The pulsation are driven by the nonadiabatic product of the low attenuation and the low mean adiabatic exponent. It is shown that the Sun is pulsating in a suitable way. The nature of the modes are similar to those of the large mode systems observed in the well known 5-minute oscillations of the solar atmosphere.

An obvious way to test this theory is to search for velocities distributed over the solar surface according to some physical parameter. Because of the long wavelengths involved, large scale convective motions,  $10^4$  scale motions of sun do not and this would have the added advantage of eliminating the relative contribution of the solar granulation noise. But the data for the small modes must be carefully restricted to narrow bands of acoustical frequency; otherwise, one will average over many modes and obtain only the transient and complicated patterns which have been seen many times before. If solar pulsations can be measured with enough precision, they will ultimately prove valuable probes of the solar interior structure and will place additional experimental limits on stellar convection theory.

32

NUMERICAL  $\mu$ -MODE PREDICTION

Ando & Osaki 1979PASJ, 27, 501A

(a) *Basis Equations and Boundary Conditions*  
The basic equations governing nonadiabatic radial pulsations in the radiative atmosphere were formulated by Unno (1963), in which the radiative transfer was treated in the Edlinding approximation. Unno and Szymon (1966) have demonstrated that the Edlinding approximation in the radiative heat equation is very useful in three-dimensional time-dependent problems. We thus utilize this in the present paper. The basic equations governing nonadiabatic nonradial oscillations in the radiative atmosphere are then given as

$$\frac{\partial \rho}{\partial t} + P(\omega) = 0, \quad (1)$$

$$\frac{d\omega}{dt} - \frac{1}{2} P P - g, \quad (2)$$

$$c \rho \left( \frac{\partial T}{\partial t} + r_{\mu} \frac{\partial \rho}{\partial r} \right) = -r F F, \quad (3)$$

$$F = -\frac{1}{2} P J, \quad (4)$$

and

$$J = \frac{\partial \rho}{\partial t} + c \rho \left( \frac{\partial T}{\partial t} + r_{\mu} \frac{\partial \rho}{\partial r} \right), \quad (5)$$

35

FIVE MINUTE OSCILLATION: FIRST LIGHT

Ulrich 1970a;J. 162, 893U

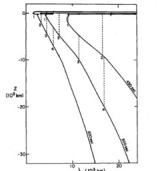


Fig. 1.—Altitude  $z$  of the reflecting layer versus horizontal wave length  $\lambda$ , for three periods of oscillation. Horizontal oscillations are shown in the right of the plot. Dashed lines indicate positions of the eigenfrequencies listed in §11. These solutions are labeled by their modal numbers defined as the number of nodes between the reflecting layer and pole.

30

THE SUN IS A SPHERE

Wolf 1970a;J. 177L, 87W

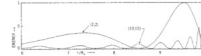
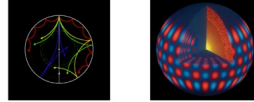


Fig. 3.—Radial distribution of kinetic energy (arbitrary units) in spherical shells of thin thickness for four overmode modes of five-minute oscillation.



33

NUMERICAL  $\mu$ -MODE PREDICTION

Ando & Osaki 1979PASJ, 27, 501A

We assume as usual that the small perturbation of a physical quantity  $f$  is written as

$$\begin{aligned} f'(r, \theta, \varphi, t) &= \frac{f'(r)}{Y(\theta, \varphi, t)}, \\ \frac{\partial f'(r, \theta, \varphi, t)}{\partial t} &= \frac{\partial f'(r)}{\partial t} Y(\theta, \varphi, t), \end{aligned} \quad (6)$$

where  $(r, \theta, \varphi)$  is the spherical polar coordinates, the Eulerian and the Lagrangian perturbations are denoted by prime ( $'$ ) and  $\delta$ , and  $Y(\theta, \varphi, t)$  is the spherical harmonics. We introduce a nondimensional frequency  $\omega$  and five-dimensional variables  $\alpha, \beta, \delta, J$ , and  $\lambda$  defined by

$$\begin{aligned} \omega &= (\delta T / \delta T) \omega', \\ \alpha &= \beta r c, \quad \beta = P / g r, \quad \delta = \delta T T, \\ J &= \beta J J', \quad \lambda = \beta \lambda \lambda', \end{aligned} \quad (7)$$

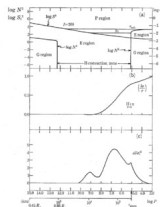
where  $L = 4\pi r^2 P$  is the luminosity at radius  $r$  and  $L_0$  is the luminosity at the surface. By linearizing equations (1)–(5), we then obtain four first-order linear differential equations and one auxiliary equation:

36

37

NUMERICAL  $\mu$ -MODE PREDICTION

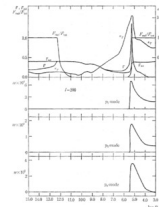
Ando &amp; Osaki 1975PASJ...27...581A



38

NUMERICAL  $\mu$ -MODE PREDICTION

Ando &amp; Osaki 1975PASJ...27...581A



39

NUMERICAL  $\mu$ -MODE PREDICTION

Ando &amp; Osaki 1975PASJ...27...581A

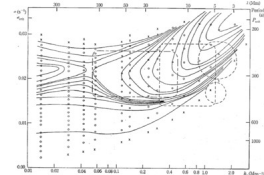


Fig. 7. The diagnostic ( $k, l$ )-diagram showing unstable (x) and stable (o) modes. The solid curves along the contour map of equal growth rates  $\gamma$ . The regions of observed power of oscillations are also indicated.

 $\mu$ -MODE IDENTIFICATION

Deubner 1975A&amp;A...44...371D

## Observations of Low Wavenumber Nonradial Eigenmodes of the Sun\*

Frank-J. Deubner  
 Potsdam Institute for Physics, P.O. Box Germany  
 Received April 18, 1975

**Summary.** New photometric observations of the photospheric velocity field with high resolution in horizontal wavenumber and frequency have been carried out in the C3 1108 line. From the five distinct stable modes of the five-minute oscillations are reached in the  $k$ - $l$  diagram, which agree in many respects with the predicted fundamental modes of subphotospheric standing acoustic waves.

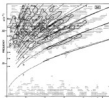
Some interesting aspects of the combination of a "pitched" oscillation mechanism of the five-minute oscillations are pointed out. Several apparently disjunct modes of previous observations are rediscussed, and it is shown that they can be reconciled with the present results.

**Key words:** solar atmosphere — photospheric oscillations — nonradial eigenmodes

40

 $\mu$ -MODE IDENTIFICATION

Deubner 1975A&amp;A...44...371D



Since the five-minute oscillations very likely contribute significantly to the heating of the upper chromosphere and corona (for a review of literature see Sten and Lathander 1974) it seems likely that the production of this energy flux which has to be supplied continuously and over the whole surface of the Sun, does not depend on localized events of a shallow surface layer. The observational results therefore evidence that the basic process of the solar envelope is indeed deeply and firmly rooted in the solar body.

43

 $\mu$ -MODE IDENTIFICATION

Deubner 1975A&amp;A...44...371D

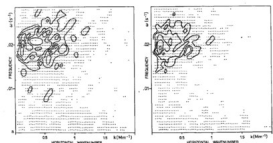


Fig. 8. Diagnostic diagram of the photospheric velocity field computed from Doppler shifts of the C3 1108 line. The different pattern profiles, bounded by solid curves from within, indicating instability (x) and stability (o) are shown. The lowest horizontal dashed line defines 1.5% of the maximum. Values are marked by broken lines. The line is obtained with different combination of the scale for

41

 $\mu$ -MODE ROTATION

Deubner, Ulrich &amp; Rhodes 1975A&amp;A...72...177D

**Summary.** We present new photometric observations of the solar  $\mu$  modes with improved resolution in wave number and frequency. An analysis of the width of the strongest peaks in the  $k$ - $l$  diagram suggests that the  $\mu$  modes pervade the solar convection zone as a globally coherent phenomenon.  $Q$  will probably much larger than 100.

The nodal pattern of the  $\mu$  modes can be regarded as being "frozen in" at well-defined levels within the convection zone, and therefore, as a tracer of large scale horizontal motions. Differences in the depth dependence of different eigenmodes permit the measurement of the solar rotation rate as a function of depth. The rotation rate is found to be non-uniform, larger at about 15,000 km below the photosphere rotating faster than the surface at about the rotation rate of sunspots.

**Summary**

The identification of the  $\mu$  mode oscillations as a global phenomenon which is highly phase coherent in space and time, has given us a tool to observe directly systematic large scale motions in the solar interior. Extension of the present work to solar latitudes other than the equator will eventually provide a quantitative three-dimensional picture of the large scale circulation patterns of the solar interior.

44

 $\mu$ -MODE IDENTIFICATION

Deubner 1975A&amp;A...44...371D

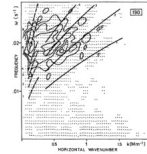


Fig. 8. Diagnostic diagram of the photospheric velocity field obtained by combining the radially independent power spectra of Fig. 14 and 15. The general mode pattern with the number of degrees of freedom  $l$  given in the upper right corner. Theoretical curves of equal growth rates are drawn and their radial spectrum are given according to the solid lines and half-filled bars. The two new modes indicated by Fraser (1966) are indicated by a capital  $Q$ .

42

 $\mu$ -MODE ROTATION

Deubner, Ulrich &amp; Rhodes 1975A&amp;A...72...177D

instead of 10% on the Sun. Three hours of 22 modes were placed on either side of the  $l = 0$   $\mu$  mode.

1. A network of 1-1.5  $\mu$  and 1.5-2  $\mu$  modes is observed. The rotation rate is about 10% of the surface rate. The rotation rate is about 10% of the surface rate. The rotation rate is about 10% of the surface rate.

2. For most modes, and position along the  $l$ , indicates the depth of the rotation rate. The rotation rate is about 10% of the surface rate. The rotation rate is about 10% of the surface rate.

3. A network of 1-1.5  $\mu$  and 1.5-2  $\mu$  modes is observed. The rotation rate is about 10% of the surface rate. The rotation rate is about 10% of the surface rate.

45

46

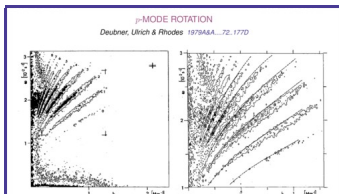


Fig. 3.  $k$ - $\omega$  diagrams of solar modes, obtained on May 6 and 7, 1977. The common component is approximately 1000 consecutive wave packets, and the right panel shows the difference between the common component and the original data. Color scale has an 8-bit difference between adjacent values. Color scale has an 8-bit difference between adjacent values.

Fig. 4.  $k$ - $\omega$  diagrams of solar modes, obtained on May 6 and 7, 1977. The common component is approximately 1000 consecutive wave packets, and the right panel shows the difference between the common component and the original data. Color scale has an 8-bit difference between adjacent values.

47

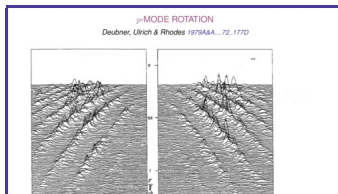


Fig. 5. Section of the  $k$ - $\omega$  diagrams after subtraction of the low spatial data (see box 111), plotted separately for "background" and "residual" sections, on the two given dates (see box 111), plotted separately for "background" and "residual" sections, on the two given dates (see box 111), plotted separately for "background" and "residual" sections, on the two given dates (see box 111).

48

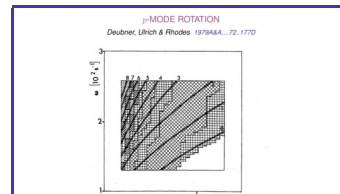


Fig. 6.  $k$ - $\omega$  diagram, defining levels of constant effective depth for the determination of differential rotation. Beginning at the right edge of the diagram 50 different levels are distinguished by different shading, corresponding to depth ranges from 0-2 Mm, 2-4 Mm, 4-8 Mm in the upper left corner.

49

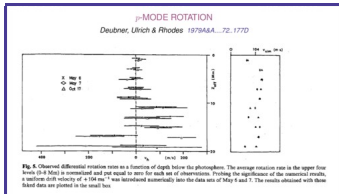
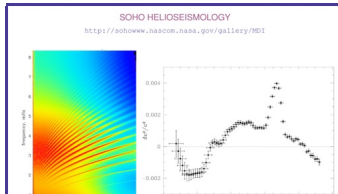
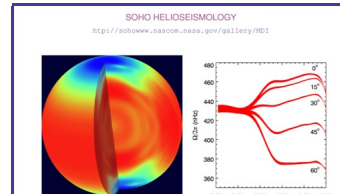


Fig. 8. Observed differential rotation rate as a function of depth below the photosphere. The average rotation rate in the upper four days (0-4 Mm) is considered and the result is also for each day of observations. The slope of the observed result, a surface differential velocity of  $4.04 \text{ m s}^{-1}$  was introduced eventually (see the data set of May 1 and 7). The results obtained with this fixed data are printed in the next box.

50



51



52

SOHO LOCAL HELIOSEISMOLOGY  
<http://sohoweb.nascom.nasa.gov/gallery/901>

tachocline movie  
 local helioseismology  
 underneath a sunspot  
 sunspot tomography  
 AR9303 nearside + backside

53

FIVE-MINUTE OSCILLATION: OBSERVATIONS  
 Robert J. Rutten  
<http://www.staff.science.uu.nl/~rutte101>

- discovery
  - (Pickett 1954), Leighton et al. 1960
  - chromospheric 3-min; Noyes 1967
- confusion
  - restoring force: pressure, gravity, magnetic field?
  - nature: propagating, standing, evanescent?
  - periodicity: piston, cavity, filter?
  - origin: subauroral, surface, atmosphere?
- enlightenment
  - prediction (Lambacher & Stein), Ulrich 1970
  - spherical sun; Wolff 1972; Ando & Osaki 1975
  - identification: (Ulrich & Rhodes), Deubner 1975
- deployment
  - helioseismology: low- $l$  networks, South Pole = GONG, SOHO/MDI, SDO
  - time-distance local helioseismology & far-side mapping
  - astroseismology

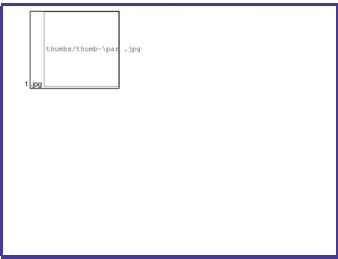
clickers: life = previous top-left = overview top-right = thumbnails bbcode = ADS page

54

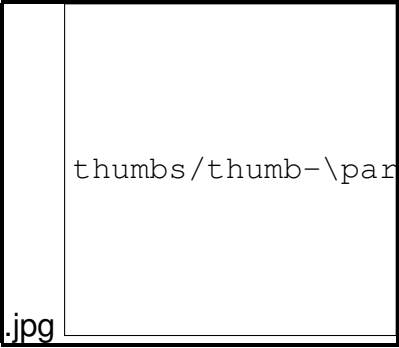
STAGGERMULTIDOD Na I D<sub>2</sub> DOPPLERGRAMS AS UNSIGNED MAGNETOGRAMS  
 Rutten et al. 2011AAS...531A..17R

Fig. 14. Dopplergrams from the calculation as in the bottom row of Figure 7. Not clear to line center and only CRSP spectral weighting, no useful PMF weighting.

A corollary is that searches for global modes and so-called "chromosphere seismology" using full-disk resonance-cell sampling of the Na I lines as with GOLF (e.g., Terek-Chirva et al. 2006; Sabbert et al. 2009) will suffer noise from reversed granulation just as classical helioseismology suffers noise from granulation. Magnetic concentrations contribute much noise (filterability by their blocks: GOLF-NG's 13 pseudobands, spread over  $\Delta\lambda = 49 \text{ km}^{-1}$ , have  $\text{FBW} = 30 \text{ km}$ , half CRSP's pseudoband in this line and clearly narrow enough. Incorporation of such multi-pseudoband oscillation sampling that relies on one-dimensional height-of-emission interpretation, for example to diagnose upward propagation from inward phase difference, is likely to fail since the chromospheric signals are better described as clouds of varying opacity at varying height of which the varying Doppler shifts are an illusion obscuring the near line wings.



55



56 .jpg