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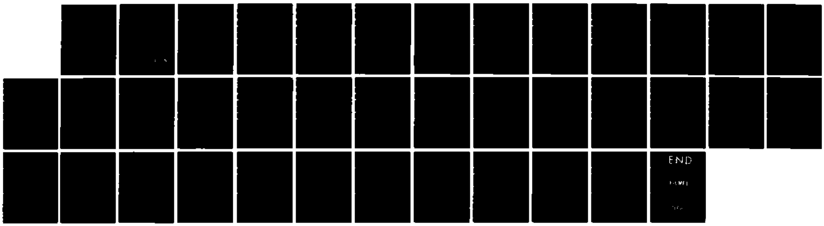

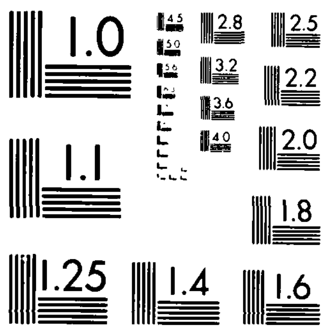

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SOLAR CONVECTION

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Stephen Keil, Captain, USAF
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A thorough study of convective penetration into the solar atmosphere and convective motions in sub-atmospheric layers on the sun was made. Non-linear anelastic and Boussinesq modal equations were developed and solved to describe solar and stellar convection. An explanation was developed for the lack of penetration of large-scale convective motions into the observable solar atmosphere through the discovery of buoyancy braking near the top of a supposedly unstable layer. Observations of motions in the solar atmosphere led to the discovery of a new scale of solar motion, the so-called mesogranulation. A technique was developed to use changes in the solar five-minute oscillations as a probe of internal solar structure. Using this technique, large-scale, subatmospheric convective eddies were discovered.

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A. OVERVIEW OF RESEARCH GOALS

The research supported by this contract has been directed toward improving our understanding of the turbulent convection that is present below the solar surface and of the penetration of these motions into the solar atmosphere. The dynamics of this convection has a critical role in determining the magnetic activity of the Sun and thus is fundamental to all studies of solar-terrestrial relations. The work during the first two years of effort as Part I of this contract concentrated partly on the development of nonlinear anelastic and Boussinesq modal equations to describe solar and stellar convection. The solution of such highly nonlinear equations required the use of major computing facilities and of asymptotic analysis. The research dealt with observational studies of supergranular scales of convective motion over a broad range of heights in the solar atmosphere. It also lead to the discovery of apparently a new discrete scale of convection on the Sun called mesogranulation. The coordinated ground-based and satellite observations utilized the Sacramento Peak Observatory (SPO) diode array and the Orbiting Solar Observatory 8 (OSO-8) satellite's ultraviolet spectrometer.

The work during the next three years of effort as Part II turned to coordinated observations of persistent flows ranging from the photosphere to the transition region using the Solar Maximum Mission (SMM) satellite's UVSP instrument and the SPO diode array. The studies dealt with supergranular and mesogranular scales of motion within and outside magnetically active regions. The height variation of the flow amplitudes, their correlation with magnetic structures, and the degree of isotropy were of primary concern. A major effort was also initiated to use the five-minute oscillations inherent in our Doppler velocity data sets to search for the presence of large scale, spatially periodic flows (akin to giant cells) below the solar surface. The oscillation studies required the development of inversion procedures to be able to deduce the variation with depth of giant cell flows. The continuing theoretical work on anelastic modal descriptions for solar convection concentrated on the time dependence achieved when multiple modes are introduced into the representation, and dealt with the essential issue of implementing subgrid modelling of the turbulence. Such theoretical modelling of convective flows in the subphotosphere yielded predictions of mechanisms that serve to prevent the largest scales of convection from roaring into the atmosphere. It also predicts that strong horizontal flows may well be present at relatively shallow depths below the surface.

B. RESEARCH ACCOMPLISHMENTS

The research work supported in substantial part by this contract has resulted in 20 published papers in refereed scientific journals, the cover pages of which are attached as Papers A to P. A further 18 published abstracts of talks at national conferences have also been cited in the quarterly reports, and there have been over 22 other seminars given describing aspects of the research. Of equal importance are the 6 Ph.D. theses (Theses A to F) that have been completed at the University of Colorado under the supervision of the PI's of this contract; this is of considerable significance to the long-term development of such research endeavors in solar physics.

The Ph.D. thesis studies supported in part by this contract are entitled:

Thesis A. "Mesogranulation and Supergranulation in the Sun", L.J. November, 1979.

Thesis B. "Internal Gravity Waves in the Solar Atmosphere", B.R. Mihalas, 1979.

Thesis C. "Convection in Rotating Layers with Thermal Winds and Applications to Jupiter", D.H. Hathaway, 1979.

Thesis D. "Mesoscale Entrainment Instability as the Cause of Mesoscale Cellular Convection", B.H. Fiedler, 1982.

Thesis E. "Oscillating Probes and Direct Observations of Solar Convection", F. Hill, 1982.

Thesis F. "Nonlinear Compressible Convection with Penetration", N.E. Hurlburt, 1983.

The published research papers that serve as the primary reporting of the scientific results from this contract are conveniently reviewed by considering four groupings of the papers and the theses:

GROUP 1. (Papers A to D; Theses A,E)

Observations and Interpretation of Large-Scale Persistent Velocity Fields in the Solar Atmosphere:

Coordinated SPO, OSO-8 and SMM Observations

The calibration of theoretical models of solar convection requires high quality data about the variation with height of persistent flows in the solar atmosphere. Since observations may well lead such theory, we believe it essential that there be a close interplay between these two disciplines and therefore have accordingly organized our research programs. Thus we have sought to measure and interpret the manner in which convective flows are able to penetrate upward into the photosphere, chromosphere and transition regions. Velocity observations in the upper portions of the atmosphere have required the use of ultraviolet spectrometers aboard spacecraft like OSO-8 and SMM. Doppler measurements being made simultaneously from the ground at SPO permitted us to link these flows to ones in the photosphere and near the temperature minimum, thereby yielding a coherent sampling of the velocity fields over a broad range of heights.

Papers A and D, and Thesis A, showed that persistent flows of supergranular scale can be traced all the way up to the transition region, with such velocity patterns able to penetrate well over 11 density scale heights. The character of the flows has changed with height, with horizontal rms flow amplitudes increasing from about 400 m/s in the photosphere to over 1500 m/s in the middle chromosphere. A distinctive change also occurs in the flow structure: although horizontal flows predominate in the photosphere, the flows become increasingly isotropic with height. These properties suggest that supergranulation experiences strong braking of vertical momentum in the subphotosphere, while the horizontal shearing flows in the chromosphere must be shear unstable and a source of internal gravity waves. Thus convective flows of large horizontal scale have a remarkable ability to penetrate into the atmosphere, and hardly have a benign role there.

Paper E reports studies with SMM of persistent flows in the transition region, revealing that their spatial rms increases to over 4000 m/s as sampled in C IV. There is a striking correlation between intensity and vertical velocity across the field of view that often shows two distinct branches when these variables are plotted against each other: the sites of strongest emission in the UV often possess vertical velocity amplitudes substantially lower than those on the primary branch. This led us to discover that such a signature is associated with regions of emerging magnetic flux. This will serve as a means of predicting sites that should show substantially enhances soft X-ray emission known as X-ray bright points, and such observations will be a key aspect of SMM operations after the repair of the satellite. We should emphasize that all of the coordinated observations have been very demanding, requiring extensive development of procedures and calibrations on both the OSO-8 and SMM satellites and their spectrometers, along with considerable improvements on the SPO echelle spectrometer and diode array.

The study of persistent flows also requires careful filtering out of strong contributions from five-minute oscillations. We devoted considerable attention to this question, and as a consequence discovered a new scale of convective flow, with its horizontal scale of 7 Mm being intermediate between that of granulation and supergranulation.

Papers B and I, and Theses A and E, discuss the properties of such mesogranulation possessing spatial rms vertical velocities of about 60 m/s. Mesogranulation my represent the missing scale of convection driven largely by the He+ ionization zone.

Paper A.
November, L.J., Toomre, J., Gebbie, K.B., and Simon, G.W., 1979, "The height variation of supergranular velocity fields determined from simultaneous OSO 8 satellite and ground-based observations", Astrophys. J., **227,** 600-613.

Paper B.
November, L.J., Toomre, J., Gebbie, K.B., and Simon, G.W., 1981, "The detection of mesogranulation on the Sun", Astrophy. J. Letters, **245,** L123-L126.

Paper C.
Gebbie, K.B., Hill, F., Toomre, J., November, L.J., Simon, G.W., Gurman, J.B., Shine, R.A., Woodgate, B.E., Athay, R.G., Bruner, E.C., Rehse, R.A., and Tandberg-Hanssen, E.A., 1981, "Steady flows in the solar transition region observed with SMM", Astrophys. J. Letters, **251,** L115-L118 (1981).

Paper D.
November, L.J., Toomre, J., Gebbie, K.B., and Simon, G.W., 1982, "Vertical flows of supergranular and mesogranular scale observed on the Sun with OSO 8", Astrophys. J., **258,** 846-859.

GROUP 2. (Papers E and F; Thesis B)

Internal Gravity Waves in the Solar Atmosphere: Theory and Observational Consequences

This work represents a detailed assessment of how internal gravity waves (IGWs) propagate through the solar atmosphere. Paper E and Thesis B describe the first research effort to calculate IGWs within a realistic model of the vertical stratification, and thus clears up many misconceptions about partial reflections and diffractions that arise when modelling the solar atmosphere as a sequence of slabs with abrupt changes in properties. The paper provides explicit predictions about wave amplitudes and relative phases betwen velocities and thermodynamic fluctuations. Further, it discusses criteria for the nonlinearities that must come about as the waves travel upward and increase their velocity amplitudes (due to conservation of momentum). These criteria lead to estimates of heights at which IGW with differing horizontal wavenumbers and frequencies may be expected to break and thus deposit their energy. Paper F expands the analysis to include effects of radiative dissipation on such waves, and reveals that IGWs may survive the cooling effects of H- ions as they propagate upward, provided the waves are either produced by shear instabilities in the photosphere or provided their wavelengths fall within a specific range. Thus our work, contrary to previous predictions, strongly suggests that IGWs should be a substantial component of velocity fields within the photosphere, chromosphere and transition regions. However, explicit observations of such waves through Doppler measurements of spectral lines may well be inconclusive, since IGWs often have vertical wavelengths short compared to contribution functions for many lines. This leads to line broadening rather than simple shifts; phasing relations in thermodynamic fluctuations further produce asymmetries and skewness that may confound spectral line measurements. The IGWs are likely to be one of the main causes for the observed line broadening, and thus micro/macro-turbulence may largely be a superposition of many wave modes that are just not being resolved. Further, the breaking of these waves over a range of heights in the chromosphere may provide a significant fraction of the mechanical energy deposition needed to sustain the chromosphere.

Paper E.
Mihalas, B.W., and Toomre, J. 1981, "Internal gravity waves in the solar atmosphere. I. Adiabatic waves in the chromosphere", Astrophys. J., **249,** 349-371.

Paper F.
Mihalas, B.W., and Toomre, J. 1982, "Internal gravity waves in the solar atmosphere. II. Effects of radiative damping", Astrophys. J., **263,** 386-408.

GROUP 3. (Papers G to P; Theses C, D, F) Development of Nonlinear Modal Descriptions for Solar and Stellar Convection: Theory Incorporating Effects of Penetration, Rotation, Stratification

We have carried out a broad collaboration on the development of nonlinear convection theory that has involved Drs. Jean Latour and Jean-Paul Zahn from Observatories of Nice and Pic du Midi at Toulouse, Edward Spiegel from Columbia University, Douglas Gough and Nigel Weiss from University of Cambridge, Peter Gilman from HAO/NCAR, and Daniel Moore from Imperial College. Since the salaries of our collaborators are borne largely by their home institutions, and because we have obtained access to large computers without explicit charges to the contract, we believe this major aspect of our research program has been especially cost effective.

In Papers G and H are considered the development of boundary conditions for convection penetrating into stable surroundings, and the consequences of this on loss of angular momentum. Papers I and J discuss the major issues of what occurs when convective motions are explicitly treated as being compressible. The roles of rotation, curvature and north-south temperature gradients upon the preferred forms of convection cells are considered in Papers K and L. This work is vital in interpreting whether the giant cells on the Sun should be dominantly banana modes aligned with the rotation axis, as contrasted to the axisymmetric rolls aligned in the east-west direction that might be realized on Jupiter. Papers M, N, O and

PAPER I.

OVERSHOOTING MOTIONS FROM THE CONVECTION ZONE AND THEIR ROLE IN ATMOSPHERIC HEATING

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1. INTRODUCTION

Chromospheres and coronae in stars appear to require vigorous convection zones just below the surface. If we wish to understand how various dynamical instabilities contribute to the mechanical heating that is required to produce chromospheres, then we must be concerned both with fluid motions in the atmosphere and with the nature of their driving below the surface. One cannot really separate these two subjects. In order to emphasize this link, we will raise some basic questions about convective flows in a stellar envelope and of their penetration into the atmosphere. The significant puzzles between what is observed and what can be theoretically explained should serve to indicate some of the issues that need to be pursued. We will concentrate on the Sun in our discussions: the observations here are sufficiently detailed to provide the explicit challenges to theory unavailable in most other stars. However, we will also turn to A-type stars to illustrate a theoretical procedure for describing convection that may do better than the mixing-length approach in predicting the vertical structure in these flows.

2. DYNAMIC COUPLING OF THE CONVECTION ZONE WITH THE ATMOSPHERE

The solar atmosphere and the convection zone are linked by a number of dynamic and magnetic processes that have the potential for depositing energy in the chromosphere. The principal couplings are provided by: a) Some sort of magnetic dynamo action deep within the convection zone must be responsible for producing and shaping the observed magnetic fields near the surface. A variety of associated magnetic instabilities and magnetohydrodynamic waves have a major role in locally heating the atmosphere. But we are unable to predict theoretically how magnetic features on the solar surface really come about or what controls them, largely since detailed solar dynamo models are still beyond our grasp. b) The 5-minute oscillations which now have been identified as standing acoustic waves in the envelope and largely evanescent waves in the atmosphere provide another strong link between these two regions.

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 571–580.

PAPER H.

Geophys. Astrophys. Fluid Dynamics, 1978, Vol. 9, pp. 241–255

Printed in Great Britain

On the Angular Momentum Loss of Late-type Stars

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(Received June 23, 1977)

The observed surface angular velocity of main-sequence stars shows a sharp decrease at about spectral type F6. We suggest that stars more massive than F6 cannot experience an appreciable angular momentum loss because their convection zones cannot sustain a magnetic dynamo: without a magnetic field the angular momentum loss is very small. The influence of rotation on the convective motions is essential for the existence of a solar type dynamo. Rotation can influence these convective motions only if the typical convective time is larger than the rotation time, i.e., if $l/u_c > 1/\Omega$, where u_c and l are typical values of the convective velocity and mixing length in the lower part of the convection zone and Ω is the star's angular velocity. For main-sequence stars of different masses and chemical compositions we evaluate the dimensionless parameter $u_c/\Omega_\odot l$ and show that it increases very sharply for stars whose mass, M, exceeds that defined by $\log(M/M_\odot) = 0.1$ ($\Omega_\odot$ and $M_\odot$ are the sun's angular velocity and mass, respectively). Thus even for large angular velocities, magnetic dynamos are not feasible if $\log(M/M_\odot)$ appreciably exceeds 0.1.

1. INTRODUCTION AND THEORY

Figure 1 (from Kraft, 1969) shows the variation of average angular momentum density with stellar mass for main-sequence stars ($\langle \mathcal{J} \rangle$ is the average angular momentum, assuming solid body rotation, of main-sequence stars with a given mass, divided by the star's mass, M, and $\mathcal{M} = M/M_\odot$). The extrapolated line, $\langle \mathcal{J} \rangle \propto \mathcal{M}^{2/3}$ was added by Dicke (1970). The striking feature about Fig. 1 is the sharp decrease in $\langle \mathcal{J} \rangle$ for stars less massive than about $1.5 M_\odot$. Schatzman (1962) attributed this break in $\langle \mathcal{J} \rangle$ to the angular momentum loss experienced by stars with convection zones according to the following conception: the surface layers of convection zones are efficient in generating sound waves which propagate upwards, shock, and deposit their energy in the

†The National Center for Atmospheric Research is sponsored by the National Science Foundation

PAPER G.

Geophys. Astrophys. Fluid Dynamics 1978, Vol. 10, pp. 311–318

On the Boundary Conditions Imposed by a Stratified Fluid

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(*Received November 2, 1977, in final form February 27, 1978*)

Generalizing the results obtained by Stix (1970) and by Whitehead (1971), we present the homogeneous boundary conditions that are imposed by a fluid of stable but otherwise arbitrary stratification. These penetrative conditions are strictly valid only in the limit of steady linearized flow, but under some conditions they can also be applied to nonlinear problems. An example of linear penetrative convection is treated in order to illustrate the use of these boundary conditions.

1. INTRODUCTION

In many problems encountered in geophysical or astrophysical fluid dynamics, the unstable region which gives rise to the motions is relatively small compared with, for example, the whole atmosphere or the whole star. When one deals numerically with those motions, one is therefore tempted to describe them only in the unstable region and its immediate vicinity. This however raises the question of what conditions are to be imposed at the boundaries of the computational domain.

Since the motions are damped in the stable region, one might try to compute a numerical model on a domain large enough, so that the amplitude of the solution would be very small on its boundaries. This could be achieved with a computational domain encompassing several *e*-folding distances of the solution in the region of stability. Stress-free or rigid boundary conditions could then be applied at these points, but with the shortcoming of imposing physical constraints that are qualitatively different from those prevailing in the stably stratified fluid, where no

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G

THE ASTROPHYSICAL JOURNAL, 263:386–408, 1982 December 1

INTERNAL GRAVITY WAVES IN THE SOLAR ATMOSPHERE. II. EFFECTS OF RADIATIVE DAMPING

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ABSTRACT

Radiative damping of internal gravity waves in the solar atmosphere is considered in a linearized approximation *with a height-dependent Newtonian cooling time. A linear fit is made to Stix* damping times for the photosphere, and this linear relation is simply extended into the chromosphere. Initial energy fluxes of 10^8, 10^7, and 10^6 ergs cm^{-2} s^{-1} are assumed for monochromatic gravity waves with a wide range of frequencies and horizontal wavenumbers.

It is found that damping has the least effect on waves with small values of the vertical wavenumber. For such waves energy fluxes of 10^5–10^6 ergs cm^{-2} s^{-1} can reach the temperature minimum from an initial flux of 10^7–10^8 ergs cm^{-2} s^{-1} in the low photosphere. The energy flux of these gravity waves at chromospheric heights appears to be limited by development of nonlinearities more than by radiative damping.

Gravity waves have larger horizontal than vertical velocities; radiative damping causes the ratio of the velocities to increase and the velocity amplitudes to diminish with height from the low photosphere to the temperature minimum region. These waves may play an important role in the broadening and strengthening of photospheric spectral lines; like granulation flows, the center-to-limb variation and the height dependence of the velocities have the same sense as those deduced from observations.

Phase lags between vertical velocity and the pressure, temperature, and density perturbations are strongly affected by the damping. Also altered are vertical wavelength, group velocity, and ray path. Amplitudes of the thermodynamic perturbations change relative to one another and to the velocity amplitudes. These effects are discussed both in terms of the comparison between adiabatic and damped gravity waves and in relation to the effects of waves on spectral lines.

Subject headings: gravitation — Sun: atmosphere — Sun: atmospheric motions — Sun: chromosphere

I. INTRODUCTION

In the solar photosphere, temperature fluctuations associated with acoustic-gravity waves may be rapidly smoothed by the transfer of radiation between hotter and cooler regions. In addition, high emissivities in the presence of an open boundary allow rapid loss of radiation to space, with hotter regions radiating more strongly than cooler regions. The most important contributors to the high opacity and emissivity in the low photosphere are processes involving the H$^-$ ion, primarily simple dissociation and recombination with accompanying absorption and emission of continuum radiation. The opacity in the photosphere decreases exponentially with height: its scale height is about 60 km, and thus about half the density scale height. Since the rate of energy loss is directly proportional to the emissivity, the effects of radiative damping are expected to be greatest low in the photosphere. Under the simplifying assumptions that the gas is optically thin, isotropic, and isothermal (Spiegel 1957; Stix 1970), one obtains damping times that are inversely proportional to the opacity and thus increase rapidly with height.

Radiative damping is a dissipative process that acts directly to diminish the magnitude of the temperature perturbation associated with the wave. In doing so it decreases the wave amplitude and thereby the energy flux as well. Because the Newtonian cooling term adds new terms to the linearized energy equation, damping modifies the dispersion relation and all linear relations among perturbation quantities; in particular, it alters the

[1] NCAR is sponsored by the National Science Foundation.
[2] JILA is operated jointly by the University of Colorado and the National Bureau of Standards.

PAPER E.

THE ASTROPHYSICAL JOURNAL, 249: 349–371, 1981 October 1

INTERNAL GRAVITY WAVES IN THE SOLAR ATMOSPHERE. I. ADIABATIC WAVES IN THE CHROMOSPHERE

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ABSTRACT

Properties of adiabatic and linear internal gravity waves propagating in a solar model are presented and discussed. Nonlinearity criteria unique to gravity waves are employed to estimate wave-breaking heights, and the results are used to deduce information on the possible role of gravity waves in the chromospheric energy balance.

We find that in the photosphere and low chromosphere the ratio of horizontal to vertical velocity is large, and thus line-of-sight velocities of gravity waves are much greater near the solar limb than at disk center. This ratio, which is approximately proportional to the Brunt-Väisälä frequency divided by the wave frequency, becomes much smaller and may approach unity in the upper chromosphere, where the Brunt-Väisälä frequency is very small. This probably implies much stronger center-to-limb variation of line broadening low in the atmosphere than in the mid-chromosphere. Maximum vertical velocity amplitudes for gravity waves are estimated to be of the order of 2 km s^{-1} or less, and maximum horizontal velocity amplitudes are around 6 km s^{-1} or less, while temperature perturbations may be as large as 1000–2000 K. Substantial phase lags exist between the fluid velocity and the temperature and density perturbations, and the height variations of these phase lags clearly show an interference pattern that results from partial reflection.

We estimate that gravity waves with an incident energy flux of 10^6 ergs cm^{-2} s^{-1} can propagate upward to a maximum height of around 900–1000 km above the visible surface before nonlinearities lead to wave breaking, while those with an energy flux of 10^5 ergs cm^{-2} s^{-1} can attain maximum heights of around 1400–1600 km. Comparison with estimated energy losses indicates that gravity waves could contribute significantly to the energy balance in the low and mid chromosphere, but are not likely to be an important source of heating at greater heights.

Subject headings: gravitation — Sun: atmosphere — Sun: chromosphere

I. INTRODUCTION

The acoustic-gravity wave spectrum in the solar atmosphere comprises waves with frequencies that permit free propagation in the atmosphere, waves that are evanescent throughout much or all of the atmosphere, and propagating waves that are reflected in the chromosphere and thus may set up standing waves. The acoustic waves (*p*-modes) are present at the higher frequencies and internal gravity waves (*g*-modes) at the lower ones. Both classes of waves can be excited readily by the turbulent convection below the surface and by the penetration of those motions into the overlying stable atmosphere. It is the propagating acoustic waves that first received attention, largely because they appeared to be capable of transporting mechanical energy upward and depositing it in the chromosphere and transition region (e.g., Schatzman 1949; Ulmschneider 1971, 1974; Stein and Leibacher 1974). It now appears that the steepening of these short-period waves into shocks may indeed serve to heat the lower chromosphere but that they cannot provide the necessary heating higher in the atmosphere (Jordan 1977; Cram 1977; Athay and White 1978).

More recently, extensive study of evanescent acoustic waves has been inspired by observations showing that the 5-minute oscillations have ridge structures in their spatial and temporal (k_x, ω) power spectra (Deubner 1975; Rhodes, Ulrich, and Simon 1977; Deubner, Ulrich, and Rhodes 1979). The ridges suggest dispersion relations that are consistent with longer period acoustic modes

[1] NCAR is sponsored by the National Science Foundation.
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PAPER D.

THE ASTROPHYSICAL JOURNAL, 258:846–859, 1982 July 15

VERTICAL FLOWS OF SUPERGRANULAR AND MESOGRANULAR SCALE OBSERVED ON THE SUN WITH *OSO 8*

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Received 1982 January 11; accepted 1982 February 9

ABSTRACT

Steady flows have been observed at disk center on the quiet Sun using the University of Colorado Ultraviolet Spectrometer on *OSO 8* and the diode-array instrument at Sacramento Peak Observatory. Simultaneous observations in Fe I λ5576, Mg I λ5173, and Si II λ1817 allow us to compare time-averaged Doppler velocities over a height range of 1400 km from the photosphere to the middle chromosphere. It is shown that patterns of steady vertical velocity with the largest spatial scales of supergranulation are present in the middle chromosphere, where they correlate well with those seen lower in the atmosphere. Such patterns are seen to persist for at least 9 hr, with downflow generally occurring in regions of enhanced intensity, and upflow in the darker areas. Observed with 10" × 20" spatial resolution, the spatial rms velocity amplitudes increase from about 30 m s⁻¹ in Fe I and Mg I to about 350 m s⁻¹ in Si II. Higher spatial resolution reveals that variations on smaller horizontal scales of about 10" are also present in the Si II velocity data, although these do not correlate directly with the mesogranulation seen in Fe I and Mg I. With 2" × 20" resolution, the spatial rms of the time-averaged velocity is about 700 m s⁻¹, compared with about 40 m s⁻¹ in Fe I and 50 m s⁻¹ in Mg I.

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

I. INTRODUCTION

The overshooting of convective motions into the solar photosphere, chromosphere, and transition region provides a direct coupling between the atmosphere and the vigorous turbulence below the surface. The height dependence of such overshooting motions is affected by both the vertical stratification of the stable atmosphere and the nature of the forcing in the subphotosphere. In principle, if we could measure the height dependence of the vertical and horizontal components of the motion in the atmosphere, we should be able to place constraints on the nature of the associated flows below the surface. In addition, it should be possible to estimate the mechanical energy transported by these motions and its possible conversion into wave modes through instabilities. Theoretical solutions for convection suggest that cellular motions with the large horizontal scales of supergranulation originate deeper in the interior and penetrate higher into the stable atmosphere than those with the smaller scale of granulation. With this in mind, we have carried out a program of observations to study the penetration of supergranular flows over a broad range of heights in the solar atmosphere. Steady Doppler velocities are determined from observations of a Si II spectral line using the University of Colorado Ultraviolet Spectrometer on the *Orbiting Solar Observatory 8* (*OSO 8*) satellite and Fe I and Mg I lines with the diode-array instrument on the vacuum telescope at Sacramento Peak Observatory (SPO). The heights of formation of these spectral lines span about 1400 km or nearly 11 density scale heights from the photosphere to the middle chromosphere.

The traditional view of supergranulation based on photospheric observations is that it is a cellular motion dominated by horizontal velocities with amplitudes of about 1000 m s⁻¹. Extensive searches for [illegible]

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PAPER C.

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STEADY FLOWS IN THE SOLAR TRANSITION REGION OBSERVED WITH *SMM*

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ABSTRACT

Steady flows in the quiet solar transition region have been observed with the Ultraviolet Spectrometer and Polarimeter (UVSP) experiment on the *Solar Maximum Mission* (*SMM*) satellite. The persistent vertical motions seen at disk center have spatial rms amplitudes of 1.4 km s^{-1} in the C II line, 3.0 km s^{-1} in Si IV, and 4.2 km s^{-1} in C IV. The amplitudes of the more horizontal flows seen toward the limb tend to be somewhat higher. Plots of steady vertical velocity versus intensity seen at disk center in Si IV and C IV show two distinct branches.

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

I. INTRODUCTION

The results reported here for the transition region were obtained as part of a continuing program designed to study the height dependence of steady flows in the quiet Sun and near active regions. The earlier observations were made simultaneously in the Fe I λ5434, λ5576, Mg I λ5173, and Si II λ1817 spectral lines, using the Sacramento Peak Observatory (SPO) diode array instrument and the University of Colorado Ultraviolet Spectrometer on the *OSO 8* satellite (November *et al.* 1979, 1981). The heights of formation of those lines span about 1400 km from the photosphere to the middle chromosphere. We have now extended these observations of steady flows into the lower transition region ($< 10^5$ K), using the UVSP experiment on the *SMM* satellite. The results presented here were obtained from observations in C II λ1336 ($\sim 2 \times 10^4$ K), Si IV λ1393 ($\sim 8 \times 10^4$ K), and C IV λ1548 ($\sim 10^5$ K).

Previous measurements of steady flows in the transition region have been made by Lites *et al.* (1976) using the Ultraviolet Spectrometer on *OSO 8*. Time averaged velocity images in Si IV λ1393, observed with 20″ × 20″ spatial resolution, revealed persistent motions with a dynamic range of 5 km s^{-1} at $\mu = 0$ in the quiet Sun. Nonsteady Doppler velocities in the transition region have been studied by Doschek, Feldman, and Bohlin (1976), Chipman (1977), Brueckner (1980), and Athay *et al.* (1980).

II. OBSERVATIONS AND REDUCTION

Our observations are made with the spectrometer operating in its Dopplergram mode, in which two

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[5] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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PAPER B.

THE ASTROPHYSICAL JOURNAL 245:L123–L126, 1981 May 1

THE DETECTION OF MESOGRANULATION ON THE SUN

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ABSTRACT

Time averages of velocity measurements at disk center on the quiet Sun reveal the presence of a fairly stationary pattern of cellular flow with a spatial scale of 5–10 Mm. Such mesogranulation has a spatial rms vertical velocity amplitude of about 60 m s^{-1} superposed on the larger scale supergranular flows. The lifetimes of mesogranules appear to be at least 2 hr.
Subject headings: Sun: atmospheric motions — Sun: granulation

I. INTRODUCTION

One of the striking properties of the observed convective motions on the Sun is the discrete spectrum of their horizontal scales. Granules have scales of order 1 Mm (10^3 km), supergranules of order 30 Mm, and giant cells may be of order 150 Mm or greater. Although the cellular patterns of both granulation and supergranulation show a range of sizes, their characteristic scales differ by a factor of 30. The existence of giant cells is much less certain, being inferred mainly from magnetic field patterns and possible variations in differential rotation.

We report here recent observations of steady vertical velocity that show strong evidence for yet another scale of convective motion, intermediate between granulation and supergranulation. Time-averaged Doppler measurements made at disk center with the Sacramento Peak Observatory (SPO) diode array instrument reveal a fairly uniform pattern of motion that alternates in sign on a spatial scale of 5–10 Mm and persists for at least 2 hr. These structures, which we have called mesogranules, correlate well between velocity images in a photospheric Fe I line and a chromospheric Mg I line formed just above the temperature minimum.

The results presented here for mesogranulation were obtained in the course of a program of coordinated ground-based and *OSO 8* satellite observations aimed at determining the height dependence of the large-scale steady flows associated with supergranulation (November 1979; November *et al.* 1979). The traditional view of supergranulation in the photosphere is that it is a cellular motion dominated by horizontal velocities with amplitudes of about 1000 m s^{-1}. Extensive searches for systematic cellular flow at disk center have been largely inconclusive. Distinct sites of downflow of order 50–100 m s^{-1} have been identified, many of which correlate strongly with regions of enhanced magnetic fields; upflow is generally more elusive or below the limit of detection (Simon and Leighton 1964; Frazier 1970; Musman and Rust 1970; Deubner 1971; Worden and Simon 1976). The difficulty in measuring the large-scale, low-amplitude vertical flows associated with supergranulation is that they overlap in both time and space with the granulation and 5 minute oscillations, which have amplitudes about an order of magnitude larger. Our observations of vertical velocity, time averaged over 60 minute periods, show clear evidence of flows on a supergranular scale as well as revealing for the first time the presence of mesogranulation.

II. OBSERVATIONS

The SPO diode array operates at the exit slit of the echelle spectrograph attached to the vacuum tower telescope (Dunn, Rust, and Spence 1974; Rust and Bridges 1975). For our observations at disk center, the array is divided into seven strings of 64 diodes with 1″ spacing arranged parallel to the slit. Pairs of diode strings are located in the magnetically insensitive Fe I λ5434 and Mg I λ5173 spectral lines; for the Fe I line, the strings are centered at $\lambda_0 \pm 0.095$ Å with 0.075 Å masks, for Mg I, they are at ± 0.066 Å with 0.090 Å masks. The Fe I line allows us to measure Doppler velocities in the lower photosphere (Altrock *et al.* 1975), while the Mg I line is representative of the temperature minimum region (Altrock and Canfield 1974). Sites of enhanced magnetic field in the photosphere are identified from a third pair of diode strings located on the magnetically sensitive Fe I λ8468 line. The remaining string of diodes is used to map the chromospheric emission network in the center of Ca II λ8542.

Two-dimensional intensity, velocity, and magnetic

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PAPER A.

THE ASTROPHYSICAL JOURNAL, 227:600-613, 1979 January 15

THE HEIGHT VARIATION OF SUPERGRANULAR VELOCITY FIELDS DETERMINED FROM SIMULTANEOUS *OSO 8* SATELLITE AND GROUND-BASED OBSERVATIONS

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ABSTRACT

Simultaneous satellite and ground-based observations of supergranular velocities in the Sun were made using the University of Colorado UV Spectrometer on *OSO 8* and the Sacramento Peak Observatory diode array instrument. We compare our observations of the steady Doppler velocities seen toward the limb in the middle chromosphere and the photosphere: the observed Si II λ1817 and Fe I λ5576 spectral lines differ in height of formation by about 1400 km.

The striking results of these observations are that supergranular motions are able to penetrate at least 11 density scale heights and that, in doing so, the motion increases from about 800 m s^{-1} in the photosphere to at least 3000 m s^{-1} in the middle chromosphere. Further, a distinct change appears to occur in the flow structure: whereas the horizontal component of the velocity predominates in the low photosphere, suggesting strong braking of vertical momentum, the motions higher in the atmosphere are more isotropic. These observations imply that supergranular velocities should be evident in the transition region.

The strong horizontal shear layers in supergranulation must produce turbulence and internal gravity waves. These smaller scale motions have bearing on chromospheric heating and nonthermal line broadening.

Subject headings: convection — Sun: atmospheric motions — Sun: granulation — Sun: spectra — ultraviolet: spectra

I. INTRODUCTION

Observations of velocity fields originating deep in the solar interior would greatly aid theoretical models of solar convection and magnetic dynamos. If mixing-length descriptions of convection are any guide, convective motions with the largest horizontal scales originate deepest in the interior. This suggests that observations of the velocity fields of giant cells and supergranules would be particularly useful, the former being of global scale and the latter having horizontal scales of about 30,000 km. The giant cells and associated variations in differential rotation on the Sun have proved difficult to observe because of their very low velocity amplitudes. Supergranular velocity fields, which have at least tenfold larger amplitudes, are more readily measured and thus are good candidates for detailed observations.

Supergranular motions are probably driven mainly by buoyancy forces in the second ionization zone of helium at a nominal depth of 17,000 km. This is also the region of greatest convective driving in the Sun, as determined by the Rayleigh number based on the local superadiabatic gradient and the density scale height. The details of the convection may be fairly sensitive to the structure of the layer between this depth and the surface, and supergranular motions may therefore serve as a probe of this intervening region as well. For such probing to be effective, measurements of supergranular velocities are needed over a broad range of heights in the solar atmosphere, requiring both ground-based and satellite observations in a number of spectral lines. The vertical variation of the velocities and the intensity fluctuations could then be used as benchmarks against which to calibrate the functional forms that may soon become available from advanced theories of convection, based for instance on anelastic modal equations (Toomre *et al.* 1976; Nelson and Musman 1977, 1978).

Supergranular motions are also of considerable interest for theories of chromospheric heating. Theoretical solutions for convection suggest that cellular motions with the large horizontal scale typical of supergranulation should penetrate much higher into the stable atmosphere than those with the smaller scale (about 1000 km) of granulation. It is

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Paper R.

Gough, D.O., and Toomre, J. 1983, "On the detection of subphotospheric convective velocities and temperature fluctuations", Solar Phys., **82**, 401-410.

Paper S.

Hill, F., Toomre, J., and November, L.J. 1983, "Variability in the power spectrum of solar five-minute oscillations", Solar Phys., **82**, 411-425.

Paper T.

Hill, F., Gough, D.O., and Toomre, J. 1984, "Attempt to meassure the solar subsurface velocity", in Proc. Conference on Solar Oscillations, (ed. G. Belvedere and L. Paterno), to appear, (Univ. Catania Press).

GROUP 4. (Papers Q to T; Thesis E)

Solar Five-Minute Oscillations as Probes of Dynamics and Structure in the Subphotosphere: Observations and Theory

Our work with the five-minute oscillations of the Sun has sought to use these wave modes to probe the structure of large convection cells and of differential rotation below the surface of the Sun. The necessary Doppler velocity data sets have been a natural adjunct of our observational work on the persistent flows. The results to date appear very promising, for we believe we have been able to detect strong flows below the surface that may be evidence of giant cells there. The results of the observations are reported in Papers Q, T and S, and in Thesis E, and the necessary theoretical analysis of the advection of waves by large-scale flows is discussed in Paper R. This will be a major area of inquiry in solar physics, and we have enjoyed being present at its beginnings. However, there is a great deal of work to be done with inverse theory to help interpret the rapidly improving observations, and thus this subject is also one of long-term research investments, much like convection theory itself.

Paper Q.
Hill, F., Toomre, J., November, L.J. 1982, "Solar five-minute oscillations as probes of structure in the subphotosphere", in Pulsations in Classical and Cataclysmic Variable Stars, (eds. J.P. Cox and C.J. Hansen), pp. 139-146, (JILA).

Paper O.
Zahn, J.-P., Toomre, J., and Latour, J. 1982, "Nonlinear modal analysis of penetrative convection", Geophys. Astrophys. Fluid Dynam., **22**, 159-193.

Paper P.
Latour, J., Toomre, J., and J.-P. Zahn 1983, "Nonlinear anelastic modal theory for solar convection", Solar Phys., **82**, 387-400.

medium below the solar convection zone. This has major implications for magnetic dynamo models, for it may permit dynamo action in this region and thereby overcome many of the difficulties with magnetic buoyancy of the evacuated flux tubes.

Paper G.
Latour, J., and Zahn, J.-P. 1978, "On the boundary conditions imposed by a stratified fluid", Geophys. Astrophys. Fluid Dynam., **10**, 311-318.

Paper H.
Durney, B.R., and Latour, J. 1978, "On the angular momentum loss of late type stars", Geophys. Astrophys. Fluid Dynam., **9**, 241-245.

Paper I.
Toomre, J. 1980, "Overshooting motions from the convection zone and their role in atmospheric heating", Highlights Astron., **5**, 571-580.

Paper J.
Zahn, J.-P. 1980, "Stellar convection theory", in Stellar Turbulence, Proc. IAU Colloq. 51, (eds. D. Gray and J.L. Linsky), Lecture Notes in Physics **114**, pp. 1-14 (Springer).

Paper K.
Hathaway, D.H., Gilmam, P.A., and Toomre, J. 1979, "Convective instability when the temperature gradient and rotation vector are oblique to gravity. I. Fluids without diffusion", Geophys. Astrophys. Fluid Dynam., **13**, 289-316.

Paper L.
Hathaway, D.H., Toomre, J., and Gilman, P.A. 1980, "Convective instability when the temperature gradient and rotation vector are oblique to gravity. II. Real fluids with effects of diffusion", Geophys. Astrophys. Fluid Dynam., **15**, 7-37.

Paper M.
Latour, J., Toomre, J., and Zahn, J.-P. 1981, "Stellar convection theory. III. Dynamical coupling of the two convection zones in A-type stars by penetrative motions", Astrophys. J., **248**, 1081-1098.

Paper N.
Toomre, J., Gough, D.O., and Spiegel, E.A. 1982, "Time-dependent solutions of multimode convection equations", J. Fluid Mech., **125**, 99-122.

P tackle the highly nonlinear descriptions of solar and stellar convection using modal equations, and are essential ingredients in the development of our theoretical approach that promises to unravel the flow structures with depth in the solar envelope.

These constitute a wide series of papers, and it may be best to summarize the main results of our theoretical work to date. Firstly, compressibility yields considerable asymmetries between upward and downward velocities within three-dimensional convection cells. The fluctuations in pressure, ignored in Boussinesq and nearly incompressible treatments but not here, can even lead to buoyancy braking near the top of a supposedly unstable layer. Thus penetration upward, as into the stable atmosphere, can be either impeded or sharply diminished, whereas penetration below the convection zone can be very strong indeed. The role of buoyancy braking should lead to the lateral deflection of rising motions within the giant cells as they approach the He++ and He+ ionization zones at depths of about 20 Mm and 7 Mm below the surface. Thus we may expect to find strong horizontal motions there, and possibly only very feeble counterparts in the atmosphere itself. A similar lateral deflection of supergranular flows would occur at shallower depths below the surface, and thus a greater horizontal velocity would be evident in the photosphere. Our work has revealed the very nonlocal character of nonlinear convection, unlike what has been assumed within mixing length treatments. We also find that penetrative motions are much more vigorous than predicted by linear theory, and can serve to modify the mean stratification very significantly over the extent of penetration, such as in the

STELLAR CONVECTION THEORY

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1. INTRODUCTION

This meeting, which deals with turbulence in stars, opens with a review on thermal convection. There is no better way to state from the start that among all instabilities that are likely to arise in stars, it is thermal convection which is the most firmly established as a cause for the turbulence that we observe on their surface. Our confidence in this comes mainly from the theoretical prediction that convective instability sets in whenever the density stratification becomes superadiabatic, as is expected in late type stars whose outer layers are very opaque, due to the ionization of the two most abundant elements, hydrogen and helium. And, in these stars at least, thermal convection occurs close enough to the photosphere to influence, be it indirectly, the profile of spectral lines.

A whole IAU colloquium has been devoted three years ago in Nice to the topic of stellar convection, and one finds in its proceedings an extensive account of what was the state of the problem. Some progress has been accomplished since then, and naturally I will spend most of my time describing recent work, and even work in progess that I am aware of. But on the assumption that some of you are not too familiar with the subject, let me first recall some generalities.

2. A HIGHLY NONLINEAR PROBLEM

Thermal convection is described by a set of well-known equations, which state the conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \underline{V} = 0 \quad , \qquad (1)$$

that of momentum

$$\rho \left(\frac{\partial \underline{V}}{\partial t} + (\underline{V}\nabla)\underline{V} \right) = -\nabla P + \underline{g}\rho + \underline{f}_V \qquad (2)$$

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PAPER K.

Convective Instability when the Temperature Gradient and Rotation Vector are Oblique to Gravity. I. Fluids without Diffusion

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We carry out a linear stability analysis of fluid layers under uniform rotation which possess both vertical and horizontal temperature gradients. In order to represent various latitudes with these plane parallel layers we use a rotation vector which is generally oblique to gravity. We consider ideal fluids without diffusion within a Boussinesq approximation. This simplified configuration is used to assess the preferred convective modes as a function of latitude on a planet like Jupiter. The tilted rotation vector introduces a preference for roll-like disturbances with north-south orientations, while the horizontal temperature gradient produces a thermal wind shear which favors convective rolls oriented parallel to the flow in an east-west direction. With both these effects present we find that the horizontal temperature gradient needed to produce a preference for the axisymmetric or east-west rolls increases with increasing rotation rate and decreasing latitude. The results also indicate that shells with warm-equators have a much stronger preference for east-west rolls than do shells with cold equators. In addition we find that the tilted rotation vector serves to make the symmetric

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PAPER L.

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Convective Instability when the Temperature Gradient and Rotation Vector are Oblique to Gravity. II. Real Fluids with Effects of Diffusion

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The linear stability analysis of Hathaway, Gilman and Toomre (1979) (hereafter referred to as Paper I) is repeated for Boussinesq fluids with viscous and thermal diffusion. As in Paper I the fluid is confined between plane parallel boundaries and the rotation vector is oblique to gravity. This tilted rotation vector introduces a preference for roll-like disturbances whose axes are oriented north-south; the preference is particularly strong in the equatorial region. The presence of a latitudinal temperature gradient produces a thermal wind shear which favors axisymmetric convective rolls if the gradient exceeds some critical value. For vanishingly small diffusivities the value of this transition temperature gradient approaches the inviscid value found in Paper I. For larger diffusivities larger gradients are required particularly in the high latitudes. These results are largely independent of the Prandtl number. Diffusion tends to stabilize the large wavenumber rolls with the result that a unique wavenumber can be found at which the growth rate is maximized. These preferred rolls have widths comparable to the depth of the layer and tend to be broader near the equator. The axisymmetric rolls are similar in many respects to the cloud bands on Jupiter provided they extend to a depth of about 15,000 km.

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PAPER M.

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STELLAR CONVECTION THEORY. III. DYNAMICAL COUPLING OF THE TWO CONVECTION ZONES IN A-TYPE STARS BY PENETRATIVE MOTIONS

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ABSTRACT

Anelastic modal equations are used to examine thermal convection occurring over many density scale heights in the entire outer envelope of an A-type star, encompassing both the hydrogen and helium convectively unstable zones. Single-mode anelastic solutions for such compressible convection display strong overshooting of the motions into adjacent radiative zones. Such mixing would preclude diffusive separation of elements in the supposedly quiescent region between the two unstable zones. Indeed, the anelastic solutions reveal that the two zones of convective instability are dynamically coupled by the overshooting motions. The nonlinear single-mode equations admit two solutions for the same horizontal wavelength, and these are distinguished by the sense of the vertical velocity at the center of the three-dimensional cell. The upward directed flows experience large pressure effects when they penetrate into regions where the vertical scale height has become small compared to their horizontal scale. The fluctuating pressure can modify the density fluctuations so that the sense of the buoyancy force is changed, with buoyancy braking actually achieved near the top of the convection zone, even though the mean stratification is still superadiabatic. The pressure and buoyancy work there serves to decelerate the vertical motions and deflect them laterally, leading to strong horizontal shearing motions. Thus the shallow but highly unstable hydrogen ionization zone may serve to prevent convection with a horizontal scale comparable to supergranulation from getting through into the atmosphere with any significant portion of its original momentum. This suggests that strong horizontal shear flows should be present just below the surface of the star, and similarly that the large-scale motions extending into the stable atmosphere would appear mainly as horizontal flows.

Subject headings: convection — stars: atmospheres — stars: interiors — stars: metallic line

I. INTRODUCTION

Typically A-type stars possess two convection zones, one directly below the surface driven predominantly by the ionization of hydrogen and another deeper down driven by the second ionization of helium. According to most mixing-length models, these two unstable zones are separated by a quiescent, purely radiative zone. We have studied in Paper II (Toomre *et al.* 1976) the convective motions in the deeper of these zones, using anelastic modal equations in their simplest version to describe the dynamics. Our solutions were substantially different from those based on mixing-length treatments: the maximum convective flux in the second convection zone was about 6% of the total flux, a value about two orders of magnitude greater than in most mixing-length models (Latour 1970), though mixing-length representations can be adjusted to yield comparable fluxes (Böhm-Vitense 1977; Nelson 1978). These anelastic solutions further revealed that the convective motions driven by He are not just confined to the region of unstable temperature gradients. Rather, the flows penetrate several scale heights both upward and downward into the stable material surrounding this region and even drive a series of countercells. We concluded that convective motions from the deeper unstable zone would extend to the overlying hydrogen convective zone, although the latter was not explicitly included in the analysis. This strongly suggests that the two convective zones in an A-type star are dynamically coupled, a result contrary to most mix-

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PAPER N.

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Time-dependent solutions of multimode convection equations

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Truncated modal equations are used to study the time evolution of thermal convection. In the Boussinesq approximation these nonlinear equations are obtained by expanding the fluctuating velocity and temperature fields in a finite set of planforms of the horizontal coordinates. Here we report on numerical studies dealing with two or three modes with triad interactions. We have found rich time dependence in these cases: periodic and aperiodic solutions can be obtained, along with various steady solutions. Three-mode solutions reproduce the qualitative appearance of spoke pattern convection as observed in experiments at high Prandtl numbers. Though the values of the periods of the time-dependent solutions do not agree with those of the experiments, their variation with Rayleigh number compares favourably. Except at the highest Rayleigh number we have considered (10^7), the theoretical Nusselt numbers agree well with experiment.

1. Introduction

In the predecessors of this paper we attempted to describe the gross features of a convecting fluid by a simple if crude approximation procedure (Gough, Spiegel & Toomre 1975*a*, hereinafter referred to as I; Toomre, Gough & Spiegel 1977, hereinafter II). We expanded the fluctuating temperature and velocity in terms of the planform functions of linear theory and kept only a few terms, or modes as we shall call them. In I and II we described calculations in which only one mode was kept, and we solved the resulting equations for the vertical structure with accurate numerical schemes. Of course, the choice of planform remains arbitrary, but nevertheless it was encouraging to learn in II that a choice exists that leads to a tolerably good representation of the mean properties of laboratory convection.

In the case of single-mode convection the solutions always evolved to steady states, which satisfy the system of equations first given by Roberts (1966). However, laboratory studies of convection become time dependent at high enough Rayleigh number, and we would like to know whether and how well the modal approach represents this. Indeed, in two- and three-mode studies we have found sustained time dependence, both periodic and aperiodic, and we report here on these results.

PAPER 0.

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Nonlinear Modal Analysis of Penetrative Convection

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The modal expansion procedure has been used to analyze penetrative convection that arises when a thin unstable layer is embedded between two stable regions. The Boussinesq approximation is applied in which the effect of compressibility and stratification are neglected. Various calculations have been made, with one and two modes, for Rayleigh numbers ranging from the critical value to more than 10^5 times critical. The effect of decreasing the Prandtl number has also been investigated.

It is found that in the nonlinear regime, the convective motions penetrate substantially into the stable regions. The flux of kinetic energy plays a crucial role in such penetration, and its existence puts some requirements on the motions: in the single-mode case, they need to be three dimensional. The extent of penetration amounts to about half of the thickness of the unstable layer on each side of it when the degree of instability and that of stability are comparable in the two domains; it increases as the stability of the outer region is lowered. The penetration depth appears to be independent of all other parameters defining the problem.

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PAPER P.

NONLINEAR ANELASTIC MODAL THEORY FOR SOLAR CONVECTION[*]

(Invited Review)

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Abstract. Preliminary solar envelope models have been computed using the single-mode anelastic equations as a description of turbulent convection. This approach provides estimates for the variation with depth of the largest convective cellular flows, akin to giant cells, with horizontal sizes comparable to the total depth of the convection zone. These modal nonlinear treatments are capable of describing compressible motions occurring over many density scale heights. Single-mode anelastic solutions have been constructed for a solar envelope whose mean stratification is nearly adiabatic over most of its vertical extent because of the enthalpy (or convective) flux explicitly carried by the big cell, a sub-grid scale representation of turbulent heat transport is incorporated into the treatment near the surface. The single-mode equations admit two solutions for the same horizontal wavelength, and these are distinguished by the sense of the vertical velocity at the center of the three dimensional cell. It is striking that the upward directed flows experience large pressure effects when they penetrate into regions where the vertical scale height has become small compared to their horizontal scale. The fluctuating pressure can modify the density fluctuations so that the sense of the buoyancy force is changed, with buoyancy braking actually achieved near the top of the convection zone. The pressure and buoyancy work in the shallow but unstable H^+ and He^+ ionization regions can serve to decelerate the vertical motions and deflect them laterally, leading to strong horizontal shearing motions. It appears that such dynamical processes may explain why the amplitudes of flows related to the largest scales of convection are so feeble in the solar atmosphere.

1. Introduction

The structure of the solar atmosphere is determined largely by the convection just below the surface and the waves that it can generate. The coupling of these turbulent motions with magnetic fields must cause most of what is observed on the Sun. However, theoretical understanding of the dynamics of the solar convection zone and associated motions in the atmosphere is still very incomplete. For instance, no detailed theoretical

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Variable stars (ed. J.P. Cox & C.J. Hansen),
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SOLAR FIVE-MINUTE OSCILLATIONS AS PROBES OF STRUCTURE IN THE SUBPHOTOSPHERE

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ABSTRACT

Power spectra of solar five-minute oscillations display prominent ridge structures in (κ,ω) space, where k is the horizontal wavenumber and ω is the temporal frequency. The positions of these ridges in k and ω are sensitive to large-scale velocity and temperature fields over a range of depths below the surface. We have compared observations on separate days to search for shifts in the ridge centroids that can be related to different velocity and temperature patterns having been brought into our sampling region by solar rotation. The results suggest that we may have detected convective flows with scales akin to giant cells. Comparison of ridge centroids on two observing days separated by 27 days, or about one solar synodic rotation period, show no significant ridge displacements. Other pairs of days generally display measurable differences in ridge centroids, with these corresponding roughly to changes in horizontal subphotospheric velocities of order 50 m s^{-1}. Our limited data suggests that the horizontal pattern scale of the cells is about 5/27 of the solar circumference, or about 800 Mm.

INTRODUCTION

Two-dimensional power spectra of high degree ($100 < \ell < 1000$) solar oscillations possess striking ridge structures. Such concentrations in power for the five-minute oscillations appears to arise because these acoustic modes are resonantly trapped in the convection zone (e.g. Ulrich 1970; Leibacher and Stein 1971; Deubner 1975; Rhodes, Ulrich and Simon 1977). As reviewed in these proceedings by Christensen-Dalsgaard (1982) and Gough (1982), the observed horizontal wavenumber k and temporal frequency ω of the modes contributing to such ridges provide information on the mean stratification of the Sun; they can also serve as probes of large-scale velocity and thermal fields in the subphotosphere. Indeed, Deubner, Ulrich and Rhodes (1979) sought to probe how solar rotation varies with depth by using the five-minute oscillations of high degree, though Gough (1978) cautions that the inversion of such data involves considerable delicacy. Here we report on some aspects of our continuing program of observations designed to search for variations in the position of the ridges that may be due to different large-scale subphotospheric convection patterns being brought into view of our observing window by solar rotation. We shall show that the possible presence of giant

PAPER R.

ON THE DETECTION OF SUBPHOTOSPHERIC CONVECTIVE VELOCITIES AND TEMPERATURE FLUCTUATIONS*

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Abstract. A procedure is outlined for estimating the influence of large-scale convective eddies on the wave patterns of five minute oscillations of high degree. The method is applied to adiabatic oscillations, with frequency ω and wave number k, of a plane-parallel polytropic layer upon which is imposed a low amplitude convective flow. The distortion to the $k-\omega$ relation has two constituents: one depends on the horizontal component of the convective velocity and has a sign which depends on the sign of ω/k, the other depends on temperature fluctuations and is independent of the sign of ω/k. The magnitude of the distortion is just at the limit of present observational sensitivity. Thus there is reasonable hope that it will be possible to reveal some aspects of the large-scale flow in the solar convection zone.

1. Introduction

The structure of the waves that produce the five-minute oscillations of the Sun depend principally on the mean vertical stratification of temperature. That stratification determines a fairly well defined sequence of relations between the frequency and the horizontal wave number of the oscillations. This has been exhibited for the real Sun in power spectra of Doppler measurements (e.g., Deubner *et al.*, 1979), and compared with theory to determine the adiabat in the isentropic part of the convection zone (e.g., Berthomieu *et al.*, 1980; Lubow *et al.*, 1980). However, these relations are not perfectly maintained: frequency is not precisely determined because the modes do not persist indefinitely, and the wave patterns are distorted by rotation and the inhomogeneities associated with convection. It is the purpose of this paper to report a preliminary theoretical assessment of the magnitude of the distortions, with a view to the eventual measurement of the velocity and temperature fluctuations in the convection zone. In an accompanying paper (Hill *et al.*, 1983) observational evidence for such distortions is presented.

We restrict our attention to modes of high degree. In that case the oscillations are trapped in a shallow wave guide just beneath the photosphere: the base of the trapping region is at a depth of about $nl^{-1}R$, where n and l are the order and degree of the mode

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PAPER S.

VARIABILITY IN THE POWER SPECTRUM OF SOLAR FIVE-MINUTE OSCILLATIONS*

(Invited Review)

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Abstract. Two-dimensional power spectra of solar five-minute oscillations display prominent ridge structures in (k, ω) space, where k is the horizontal wavenumber and ω is the temporal frequency. The positions of these ridges in k and ω can be used to probe temperature and velocity structures in the subphotosphere. We have been carrying out a continuing program of observations of five-minute oscillations with the diode array instrument on the vacuum tower telescope at Sacramento Peak Observatory (SPO). We [illegible] to establish whether power spectra taken on separate days show shifts in ridge locations; these may arise from different velocity and temperature patterns having been brought into our sampling region by solar rotation. Power spectra have been obtained for six days of observations of Doppler velocities using the Mg I λ5173 and Fe I λ5434 spectral lines. Each data set covers 8 to 11 hr in time and samples a region 256″ × 1024″ in spatial extent, with a spatial resolution of 2″ and temporal sampling of 65 s. We have detected shifts in ridge locations between certain data sets which are statistically significant. The character of these displacements when analyzed in terms of eastward and westward propagating waves implies that changes have occurred in both temperature and horizontal velocity fields underlying our observing window. We estimate the magnitude of the velocity changes to be on the order of 100 m s^{-1}; we may be detecting the effects of large-scale convection akin to giant cells.

1. Introduction

Ridge structures are evident in spatial and temporal (k, ω) power spectra of the observed five-minute oscillations of the Sun (e.g., Deubner *et al.*, 1979). Such ridges in power arise because acoustic waves trapped in the thermal structure below the solar surface possess a fairly specific relationship between their frequency ω and horizontal wavenumber k. Since the character of the oscillations is determined largely by the vertical stratification of temperature below the solar surface, the observed positions of the ridges could be compared with theory to determine at least the adiabat in the isentropic part of the convection zone (e.g., Berthomieu *et al.*, 1980; Lubow *et al.*, 1980). However, the dispersion relations linking k and ω will be perturbed by temperature and velocity structures associated with the convection, and so too by differential rotation. The purpose of this observational study is to attempt to detect shifts in ridge positions that

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ATTEMPT TO MEASURE THE SOLAR SUBSURFACE VELOCITY

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ABSTRACT -- The five-minute oscillation modes will be advected by horizontal velocities below the solar surface, and thus can be used as probes there of rotation and large-scale convective flows. Results of inverse theory applied to observations of high-degree modes carried out on six separate days reveal variations in horizontal velocities with depth from day to day that may be the result of giant convection cells, though noise in the data makes this interpretation somewhat tentative.

1. INTRODUCTION

This paper reports a preliminary attempt to determine the subphotospheric velocity field from the positions of the ridges in the (k,ω) power spectra of five-minute oscillations, where k is the horizontal wavenumber and ω is the temporal frequency. An optimal averaging inversion procedure, used originally by geophysicists and which was suggested by the work of Backus and Gilbert (1968,1970), is applied to the perturbations to the ridge positions that we believe are induced by large-scale horizontal flow. The motion is composed primarily of depth-dependent rotation and possibly a contribution from giant convection cells.

Previously Deubner, Ulrich and Rhodes (1979) sought to determine from the ridge position how solar rotation varies with depth. Similar analysis applied to subsequent observations (Rhodes, Harvey and Duvall 1983) failed to reproduce the earlier results. Hill, Toomre and

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