SOLAR PULSATIONS

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ABSTRACT

Recent observational evidence on solar oscillations is reviewed; this evidence strongly favors the global interpretation for much of the observed spectrum. Implications of these observations for the study of the solar interior and atmosphere are discussed.

1. INTRODUCTION

The observational study of solar oscillations has now produced results of sufficient accuracy to test models of the solar interior and the physical processes occurring there. The use of these oscillations as a solar probe has been accompanied by an increase in our knowledge of their own properties. Some of the more important advances which have developed from the study of solar oscillations are given below. A measure of the mean sound speed in the sun has been obtained, and the depth of the convection zone is shown to be accessible. Improved observations of the eigenfunctions in the photosphere have become available which clearly demonstrate the need for a major change in previous theoretical treatments. A new driving mechanism for waves in the photosphere has been identified, strongly suggesting that gravity waves are present in the lower photosphere from both an observational and theoretical point of view.

An important underlying question in much of this work concerns whether the reported oscillations should be interpreted as global or local. A review of the status of this question is given below, followed by a discussion of the topics outlined above. For an extensive picture of the work in this field as of 1979, reference is made to the solar oscillations section of the 1979 workshop proceedings on nonradial and nonlinear stellar pulsation (Hill and Dziembowski 1980) and the earlier review of Hill (1978).

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2. GLOBAL CHARACTER OF OSCILLATIONS

The global character of an oscillation is most dramatically established by the demonstration of its long-term stability. In addition, such a demonstration speaks directly to the issue of the origin of the oscillation, solar or nonsolar. With the exception, of course, of diurnal effects, it is very difficult for a nonsolar mechanism to generate a highly stable oscillating signal in a set of solar observations. Long-term phase stability has been examined in each of the three major period regimes which have been observed: a peak in the power spectrum at 2^h40^m, many oscillations with periods ranging between $\sim 1^h$ and $<5^m$, and the well known 5 min mode.

Velocity pulsations having periods of 2^h40^m have been observed at the Crimea (Severny, Kotov and Tsap, 1976, Kotov, Severny and Tsap, 1978), Birmingham (Brookes, Isaak and van der Raay, 1976; Brookes et al., 1978) and Stanford (Scherrer et al., 1979, 1980). The observations at the Crimea have been confirmed with a significant confidence level by the agreement of the Stanford findings with those from the Crimea. Scherrer et al. (1980) find that the observations at the two sites before 1979 show a period of 160.01 minutes and that new observations exhibit the same period with a phase of maximum expansion as predicted from earlier data. Further confirmation is reported in the recent work of Fossat et al. (1980) where again this period and phase have been found in the observations at the South Pole. These findings represent a very strong case for the solar origin and global character of the oscillations.

Oscillations with periods in the range from 5 min to ~1 hr are observed at SCLERA[1] as oscillations in the solar diameter. Caudell et al. (1980) reported on the phase stability of 12 oscillations covering a period of 23 days. The probability that any <u>one</u> of the 12 phase plots is the result of a random noise source was found to be $\lesssim 10^{-3}$, making it highly probable that the observed oscillations were solar in origin and global.

The best observed solar oscillation is the 5 min mode. However, demonstration of its global character has proven more difficult than for the other oscillations. Deubner, Ulrich and Rhodes (1979) and Claverie et al. (1980) have examined observationally the long-term stability of these modes and have found coherence times at least as long as the length of the observation, i.e., 9 hours. However, as discussed by Gough (1980), this is not sufficiently long to demonstrate their global character.

3. ASYMPTOTIC LIMITS

One of the more interesting new results has been the work of Claverie et al. (1979, 1980) using Doppler observations of the 5 min oscillations in integrated sunlight. They have resolved these

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oscillations into a number of essentially equally spaced frequencies. This portion of the 5 min spectrum most certainly consists of low ℓ, high n p-modes and the spacing between contiguous peaks should be a good approximation of the asymptotic limit for n >> 1 (Christensen-Dalsgaard and Gough, 1980a). This difference, as given by Vandakurov (1967), is:

$$\omega_{n\ell} - \omega_{n-1,\ell} = \frac{\pi}{2}\left[\int_0^R \frac{dr}{c}\right]^{-1} \quad \text{for } n \gg 1 \qquad (1)$$

where r is the radial coordinate, c the sound speed and $\omega_{n\ell}$ the eigenfrequency. The initial comparison of the peak separation with theoretical expectations indicated that the sound speed was somewhat lower than that for standard models (Christensen-Dalsgaard and Gough, 1980a; Claverie et al., 1980). However, more recently, Christensen-Dalsgaard and Gough (1980b) found satisfactory agreement with the results of their standard solar model. They reported that their earlier suspicion of a discrepancy was based on an immediate response using calculations that ignored the solar atmosphere.

In addition to the work described above pertaining to the asymptotic limit of $\omega_{n\ell}$ for $\ell \lesssim 1$, Caudell (1980) has examined the possibility of studying the asymptotic limit of $\Delta\omega_{n\ell}$ for $\ell \sim 20$. This work would involve the diameter observations made at SCLERA.

4. OBSERVED PROPERTIES OF EIGENFUNCTIONS IN THE PHOTOSPHERE

It was recognized early in the SCLERA program on solar oscillations that the theoretical properties generally ascribed to photospheric oscillations did not furnish an adequate description of the phenomenon. This inconsistency was first described in the comparison of various types of observations (Hill, 1978). The early conclusions were later supported more directly in the work of Hill and Caudell (1979). However, many of the observational results were very difficult to obtain, leaving open to some measure the question of the reality of the oscillations themselves. Recent developments in the observations permit a much sharper examination of this area.

The underlying question of the reality of the low order global modes used in the above analyses has been addressed by Caudell et al. (1980) and was discussed in Section 2 of this paper: they have found a very high probability that the reported oscillations are excited normal modes of the sun. Knapp, Hill and Caudell (1980) used the high phase stability found by Caudell et al. (1980) to identify in an unambiguous manner the Eulerian perturbation of the radiation intensity, I', near the solar limb. These results are a direct measure of I' and cannot be understood in terms of the usually linear stellar pulsation theory (cf. Keeley, 1977; Hill, Rosenwald and Caudell, 1978).

The apparent inadequacy of the linear stellar pulsation theory is also indicated in the work by Stebbins et al. (1980) on the 5 min oscillation. They measured the radial dependence of the velocity amplitude of the 5 min oscillation and found that the rate of growth with height is lower than that predicted theoretically by approximately a factor of two.

The earlier indications of the inadequacy of the linear pulsation theory have now been supported by a considerable body of strong observational evidence. It would appear that it is necessary to examine this theory more closely.

5. THEORY OF OSCILLATIONS IN THE PHOTOSPHERE

The unsuccessful attempts to reconcile, within the framework of the traditional linear stellar pulsation theory, the various observational results on solar oscillations (cf. Hill, 1978; Hill and Dziembowski, 1980 and references listed there) have stimulated both observational and theoretical work. The new observational work, such as that reported by Knapp, Hill and Caudell (1980), has more clearly defined the question while the theoretical work has served to reduce the number of options in which a resolution might be found.

It has been noted that the observations relating to the photosphere could be understood theoretically if what have been called "incoming" and "outgoing" solutions (referred to as β_+ and β_- solutions respectively) were both present (Hill, Rosenwald and Caudell, 1978). This does pose a problem, however, because as Gough (1980) observed, the presence of an evanescent β_+ solution requires a driving of the atmosphere from the top.

A driving mechanism in the photosphere has recently been identified by Hill and Logan (1980) in the nonlocal properties of the mean radiation intensity, J. The nonadiabatic term, $\nabla \cdot \overline{F}'$, in the linearized energy equation is related to J' by the radiative transfer equation:

$$\nabla \cdot F' = -4\kappa\rho(J' - B') \qquad (2)$$

where the prime (') refers to the Eulerian perturbation. Hill and Logan (1980) have shown that the nonlocal nature of J for low order oscillations causes J' to be greater than B' in the lower photosphere. This leads to a new driving mechanism for photospheric waves and may be the source of the incoming, i.e., β_+-like, solution.

The nonlocal treatment of $\nabla \cdot F'$ brings additional complexity to the wave equation: solutions to the wave equation cannot be decomposed into linear combinations of the solutions to the linearized wave equation without nonlocal terms. However, the new solutions will have a classification similar to that of incoming and outgoing solutions. It is in this spirit that reference was made to generation of a β_+-type solution.

An intuitive picture based on solutions in linear theory for an isothermal atmosphere has been shown to be an unreliable guide to the actual behavior of the oscillations. Numerical solutions of the wave equation with the nonlocal treatment of $\nabla \cdot F'$ are required to evaluate the extent to which this new driving mechanism can resolve the gaps between theory and observation described above. A theoretical program is under way at SCLERA for this evaluation. However, preliminary results are very promising.

In regard to the existence of gravity waves in the lower photosphere, the new driving mechanism has been shown to be quite important in that it invalidates the previous theoretical analyses dealing with this region. These analyses, based on the Newtonian radiative cooling law, concluded that gravity waves could not exist in the lower photosphere. However, the inclusion of nonlocal effects may contribute significantly to generation of gravity waves in the photosphere and to energy transport in the solar atmosphere (Logan and Hill, 1980).

6. DEPTH OF THE CONVECTION ZONE

The resolution of observed power of the 5 min mode into ridges in the k-ω (horizontal wavenumber-frequency) diagnostic diagram (Deubner, 1975; Rhodes, Ulrich and Simon, 1977; Deubner, Ulrich and Rhodes, 1979) has permitted an initial examination of the structure of the envelope and, in particular, the convection zone. Because the modes exist in a layer only a few percent of the solar radius deep, they give us no direct information about most of the interior. However, as noted by Gough (1980), the oscillations do penetrate beneath the upper boundary layer in the convection zone, to regions in which we are fairly confident that the stratification is approximately adiabatic. This enables us to extrapolate to the base of the convection zone and so to estimate its depth. Analyses of this type by Berthomieu et al. (1980) and Lubow, Rhodes and Ulrich (1980) gave a convection zone depth of approximately 2×10^5 km (about 30% of the solar radius), deeper than in standard solar models.

However, Hill and Rosenwald (1980) modified the upper boundary conditions applied in the computation of the 5 min oscillations, within the framework of linear theory, to account for the observations discussed in Section 5. They found that the location of the ridges in the k-ω diagram were altered to a sufficiently large degree as to render it impossible to draw any conclusion concerning the depth of the convection zone.

The roadblock in obtaining new values for the depth of the convection zone is inadequate knowledge of the eigenfunctions in the photosphere. The observations such as those of Knapp, Hill and Caudell (1980) and Stebbins et al. (1980) only serve as a test of any theory

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of oscillations in the photosphere; an adequate theory must be in hand before eigenfrequencies can be calculated. In this area, the recent work of Hill and Logan (1980) on the nonlocal treatment of $\nabla \cdot F'$ in the energy equation may lead to eigenfunctions which are sufficiently accurate to continue the study of the convection zone via the 5 min oscillation. Work in this area is continuing at SCLERA.

7. PHOTOSPHERIC GRAVITY WAVES

Attempts to identify the presence of gravity waves in the solar atmosphere have been many (Whitaker, 1963; Uchida, 1965, 1967; Thomas, Clark and Clark, 1971). They range from the early interpretation of the 5 min mode as a gravity wave to the recent observational work of Brown and Harrison (1980). The early interpretations did not hold up because the observed 5 min mode exhibits a k-ω relationship consistent with acoustic waves trapped in the convection zone. The low signal to noise ratio in the work of Brown and Harrison (1980) precluded a definitive resolution with respect to the existence of gravity waves.

A new technique is evolving that may be useful in the search for gravity waves. Instead of measuring frequency vs horizontal spatial characteristics to help classify the wave, it may be possible to measure the frequency vs vertical spatial characteristics. Certainly the potential resolution in ℓ from the horizontal characteristics is much greater than from the vertical characteristics. However, with an ℓ value of several thousand, it may be observationally easier to work with the latter type of observation. This appears to be the situation in the case of the work by Stebbins et al. (1980).

The observational study of the vertical properties of the 5 min mode eigenfunction by Stebbins et al. (1980) contains information about the 5 min mode. However, there is also an additional signal in the observations which is manifested as large scatter in the velocity-velocity and phase-velocity correlation curves. The observed properties of this second signal are not consistent with those associated with instrumental or atmospheric noise sources. On the other hand, two possible processes which might produce this signal are: (1) nonlinear coupling between low frequency perturbations in the photosphere and the 5 min mode, yielding power in the 5 min window; and (2) gravity waves with periods near 5 min and ℓ values of several thousand. The characteristics of the velocity-velocity correlation curves and the large phase shifts apparent in the phase-velocity correlation curves make the second interpretation the most likely. It is for this reason that it is suggested that evidence for gravity waves in the photosphere is contained in the observations of Stebbins et al. (1980). In any case, the study of the velocity-velocity correlation may have identified a procedure to investigate gravity waves with quite high signal to noise ratios. An analysis of the Stebbins et al. (1980) observations is under way for the express purpose of studying the properties of this second signal.

7. SUMMARY

Many new results have been obtained during the last few years from research into the phenomenon of solar oscillations. These range from constraints on the structure of the solar interior to modification of the theory used to describe atmospheric oscillations. It appears that equally important results are to be expected from further work in this field.

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NOTE

[1]SCLERA is an acronym for Santa Catalina Laboratory for Experimental Relativity by Astrometry, jointly operated by the University of Arizona and Wesleyan University.

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DISCUSSION

KEELEY: Are these very high ℓ modes that we are seeing in the atmosphere?

HILL: The ℓ values have to be of the order of 2000. Below 3 mHz the waves become evanescent.

KEELEY: Do these have a deep propagation region?

HILL: All this says observationally is that we have a region in the photosphere where travelling waves must have an ℓ value above the critical acoustical frequency.

KEELEY: If you have modes that propagate deeper in the interior, do you have any outer boundary of the propagation region?

HILL: Our treatment for the nonadiabatic part is valid only in the photosphere, and is simplest at its base.

M. SMITH: ℓ values of 4000 imply a scale not too different than the granulation size. Can you comment?

HILL: This is why we are looking. If there is a region of convective overshoot and where there are gravity waves, there can be strong excitation of these waves.