ARTICLE NO. 79-0318R

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Solar Pulsations

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Oscillations of the surface of the sun, with periods between 5 and 160 min, have been observed by several spectroscopic techniques, and preliminary interpretations have been offered. The 5-min oscillations are global, nonradial, acoustic standing waves in the subsurface convection zone. Internal differential rotation speeds have been deduced from the Doppler splitting of these waves. Oscillations with longer periods have been reported, but need confirmation. The longest periods offer a tool for investigating the solar interior.

I. Introduction

THE sun exhibits a great variety of surface phenomena that embody hydrodynamic and hydromagnetic flows. Many of these phenomena have not been interpreted properly and offer rich opportunities to the inventive theorist.

Hydrodynamic flows occur on all temporal and spatial scales. The differential rotation of the sun, in which the surface equatorial layers rotate more rapidly than the polar, is an example of steady flow. High-speed wind streams emerge from the outer solar atmosphere and vary slowly in time. Oscillatory and wave phenomena abound and this paper will focus on two varieties. Transient hydrodynamic flows also occur in the form of spicules, prominence eruptions, and flare ejecta.

Another sequence of solar phenomena can be classified most readily according to their spatial scales. Some forms of oscillation or pulsation occur with a truly global scale. Giant convective cells with diameters of the order of a solar radius have been postulated, and some evidence for them has been found. Supergranulation, a form of convective cell with a diameter one-twentieth of the solar radius, is a well-known phenomenon that covers the entire solar surface. Ordinary granulation, a fine-scale convective cell, with diameters 0.002 of the solar radius, also cover the solar surface. Subtelescopic motions with scales between meters and tens of kilometers have traditionally been treated as random turbulence, but may, in fact, include a wave component.

The field of solar hydrodynamics is too broad to cover adequately in a short paper. Instead, we will focus on recent developments on solar oscillations, with periods of 5 min or longer.

Several good reviews have been published recently for the interested reader.[1-6]

II. 5-min Oscillations

In 1961, Leighton at Cal Tech discovered that the sun's visible surface, the photosphere, oscillates with a period of about 5 min. For 15 years thereafter, solar physicists collected a great deal of detailed observational data on the properties of the oscillations and generated a variety of models to interpret them. The correct interpretation has only been confirmed within the past two years, however. The results are of considerable interest for all of stellar physics.

It is worthwhile to review some of the properties of the oscillations that needed interpretation. At a fixed point on the sun, the photosphere oscillates nearly vertically. The oscillations occur in wave packets four or five cycles long. Fourier analysis of time series of velocity measurements gives a mean frequency of 3.4 mHz with a bandwidth of 0.9 mHz. In the deep photosphere, the velocity amplitude is about 100 m/s and increases with height to about 1600 m/s. Because the atmospheric density decreases rapidly throughout this height range, however, the energy density of the oscillations decreases with height. Until recently, the horizontal scale of the oscillating elements has been a matter of considerable debate. Phase coherence has now been demonstrated over distances as large as 60,000 km; i.e., nearly 0.1 of the solar radius.

The physical nature of the oscillations began to emerge when measurements were made over one or two spatial dimensions as a function of time. Figure 1 shows a Fourier representation of a set of observations by Frazier.[7] The square of the amplitude (i.e., the "power") has been plotted as a function of frequency ω and horizontal wavenumber k. Compare this diagram with Fig. 2, which shows the boundaries of propagating and nonpropagating sound and gravity waves for three isothermal atmospheres. The location of the 5-min oscillations in the k, ω diagram suggested that they were sound waves with a period near the acoustic cutoff frequency of the photosphere. Further observations that showed that the vertical phase velocity (30-100 km/s) was much larger than the sound velocity (6 km/s), and that the intensity in the oscillation leads the velocity by 90 deg in phase, suggested that the oscillations were standing waves and not propagating waves.

Two classes of models were suggested to interpret the observations. In the first of these, a stable atmosphere is excited by the emergence of a discrete rising convective cell (granule). A pulse of propagating sound waves spreads throughout the atmosphere and, because of atmospheric dispersion, the high frequencies outrun the lower frequencies. Ultimately, the pulse decays into standing vertical waves at the acoustic cutoff frequency of the atmosphere. This type of model was eliminated because no firm association between new granules and new wave trains was found. Moreover, the cutoff period of the photosphere turned out to be 180-220 s rather than the observed 300 s. A second type of model came into vogue, therefore, in which the observed oscillations consist of trapped sound waves within a resonant cavity. Such a cavity can be formed in an atmosphere like the sun's where the temperature profile has a definite minimum. As Fig. 2 shows, waves can be trapped in a region bounded by a hot layer on one side and a cold layer on the other (the shaded areas). Early models that place the cavity either at the region of the temperature minimum or higher were eliminated on observational grounds.

Presented as Paper 79-0318 at the AIAA 17th Aerospace Sciences Meeting, New Orleans, La., Jan. 5-17, 1979; submitted March 19, 1979; revision received July 23, 1979. Reprints of this article may be ordered from AIAA Special Publications, 1290 Avenue of the Americas, New York, N.Y. 10019. Order by Article No. at top of page. Member price $2.00 each; nonmember, $3.00 each. **Remittance must accompany order.**

Index categories: Atmospheric and Space Sciences; Nonsteady Aerodynamics; Wave Motion and Sloshing.

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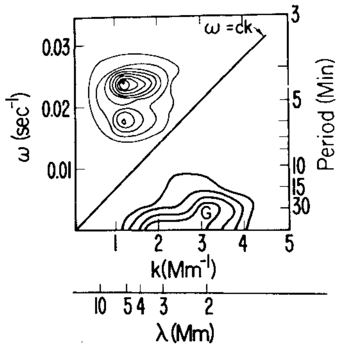

Fig. 1 Fourier representation of the velocity field in the "5-minute" oscillations. The square of the velocity amplitude has been plotted as a function of frequency ω and horizontal wavenumber *k*. Reprinted with permission from Ref. 5.

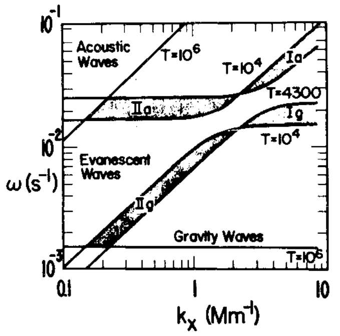

Fig. 2 Propagating and nonpropagating acoustic (upper) and gravity (lower) waves in an isothermal atmosphere. Boundaries are shown for three atmospheric temperatures: 4000, 10,000 and 1,000,000 K. The shaded areas indicated possible regions of wave trapping in the solar atmosphere. Reprinted with permission from Ref. 5.

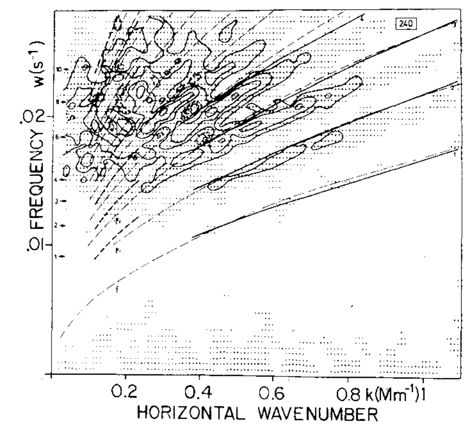

Fig. 3 Observational confirmation that 5-minute oscillations are *p*-modes trapped in the solar convection zone. Data from Deubner, 1975; theoretical curves (radial *p*-modes) from Ando and Osaki.[13] Reprinted with permission from Ref. 12.

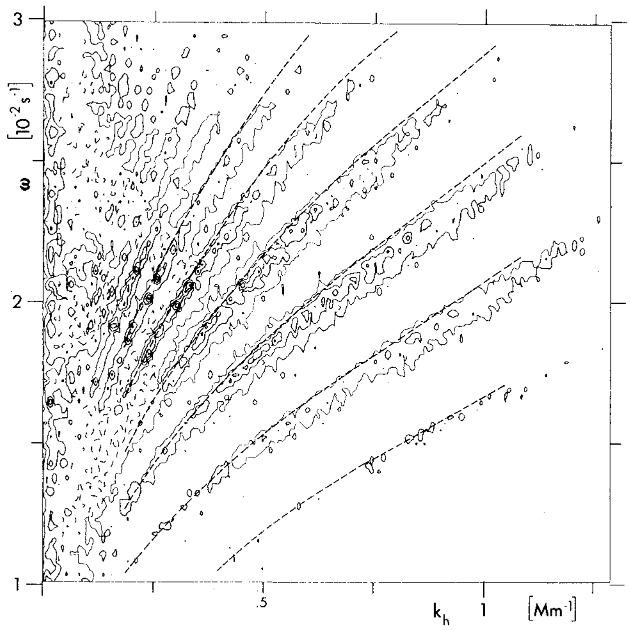

Fig. 4 Improved resolution of the "ridges" in the *k*, ω diagram. At least eight modes are detectable. Reprinted with permission from Ref. 14.

Real progress began with the suggestion by Ulrich,[8] Leibacher and Stein,[9] and Wolff[10] that the cavity lay below the temperature minimum, where energy is carried partly by ordered convection motions. Wave reflection occurs at the top of the zone at a level where the increasing cutoff frequency equals the wave frequency. Reflection occurs deep within the convection zone at a level where the sound speed equals the horizontal phase velocity.

Ulrich[8] points out in an important paper that sound waves can be trapped in such a subphotospheric cavity and that the system of standing waves set up within the cavity should be observable as ridges of power in the *k*, ω plane. Each ridge corresponds to a different radial eigenmode. To arrive at these conclusions, Ulrich solved the linear nonadiabatic, nonradial equations of motion in a plane parallel atmosphere. Wolff[10] noted that, since the waves were observed to maintain phase coherence over distances nearly 0.1 of the solar radius, a proper theoretical treatment would consider a spherical shell rather than a plane parallel layer. He also suggested two possible mechanisms for wave excitation. The first of these (the "Kappa mechanism") was originated by Eddington in his discussion of Cepheid pulsation. If the radiative opacity of a gas increases with increasing temperature, the compression phase of an oscillation will heat the gas and dam up radiation. This will lead to further heating and nonadiabatic expansion, which will tend to amplify the original oscillation.

The second mechanism, "thermal overstability," was suggested by Moore and Spiegel.[11] They showed that compressible, convectively unstable fluids will develop growing oscillations if they can dissipate their thermal energy by radiation or conduction. Because of the finite time required to exchange heat, a parcel of gas that has cooled on its rise returns to its initial position with a higher density than when it passed upward through the same point. Thus, the buoyancy force is smaller when the parcel falls to its initial point than when it rises through it. The amplitude of the oscillation continues to increase secularly.

According to this interpretation of the oscillations as trapped sound waves within a subphotospheric cavity, the waves are evanescent in the visible layer; i.e., they tunnel through the top boundary into a region of nonpropagation. Moreover, the observed waves represent the lowest order radial modes ($p = 1$-10) and high-order lattitude modes; i.e., the spherical harmonic index l for these oscillations lies in the range 100-1000.

In 1975, Deubner[12] confirmed the existence of the predicted ridges in the *k*, ω diagram. Figure 3 shows a comparison between Deubner's observations and the theoretical eigenmodes of Ando and Osaki.[13] Subsequently, both Deubner[14] and Rhodes et al.[15] improved the resolution of the ridges. In Fig. 4 taken from Deubner's paper, the first eight radial modes are easily observable as ridges. Thus, the real origin of the oscillations has been finally determined.

Rhodes et al. were able to determine limits on the depth of the solar convection zone—an important physical quantity—from the fit of the observed and predicted ridges. They varied the ratio of mixing length to scale height (L/H) in their convective zone models to fit the observations. Table 1 shows their results. Deubner[14] points out that the discrepancy between observations and theory, even with $L/H = 3$, is larger than the experimental errors, and this suggests to him some inadequacy of the existing model. Nevertheless, the degree of agreement is remarkable.

Table 1 Inferences on the mass and depth of the solar convection zone

Quantity	Shallow limit	Deep limit
Envelope mass	0.011 M⊙	0.095 M⊙
Base radius	0.75 R⊙	0.62 R⊙
Base temperature	1.7×10^6 K	3.2×10^6 K
Base density	0.10 g cm^{-3}	0.73 g cm^{-3}
Base pressure	2.3×10^{13} dynes cm^{-2}	3.2×10^{14} dynes cm^{-2}

Reprinted by permission from Rhodes, Ulrich, and Simon (Ref. 15)

In a very recent application, Rhodes et al.[16] have determined the radial variation of rotation speed within the invisible convection zone by using the properties of the 5-min oscillations. Any standing wave can be decomposed into two oppositely directed sets of propagating waves. In the sun, the waves that propagate in the sense of solar rotation are Dopler shifted to higher frequencies, while the converse is true of those waves that propagate against the sense of rotation. Thus, by decomposing the oscillations within a large two-dimensional area on the sun into eastward and westwardly propagating waves, it was possible to search for the predicted Doppler shift. This shift was found and varies in a systematic way with frequency. The variation was interpreted as evidence for the depth variation of the linear speed of rotation within the convection zone. Higher wave frequencies are trapped primarily in the upper layers of the convection zone, whereas the lower frequencies sample the deeper layers. Thus, an effective depth can be assigned from Ulrich's models to each wave frequency. The observed frequency shift $\Delta\omega$ translates into a rotational velocity v through the simple expression $v=\Delta\omega/k$. Figure 5 shows the depth profile of the rotational speed v. The convection zone rotates more rapidly than the surface at depths between 10 and 15,000 Mm. At greater depths it may rotate more slowly than the surface. These preliminary results are capable of great refinement. They are important because they give an observational constraint on models of convection, differential rotation in latitude, and the operation of the solar dynamo.

III. Long-Period Oscillations

We have seen in the previous section, the photospheric 5-min oscillations are well observed and now have a convincing explanation. In contrast, observations of oscillations with periods longer than 5-min are conflicting and are highly controversial at the present time. The subject is intensely interesting to astrophysicists because, if the normal modes of the sun can be detected, they would offer a new variety of diagnostic data with which to probe the solar interior.

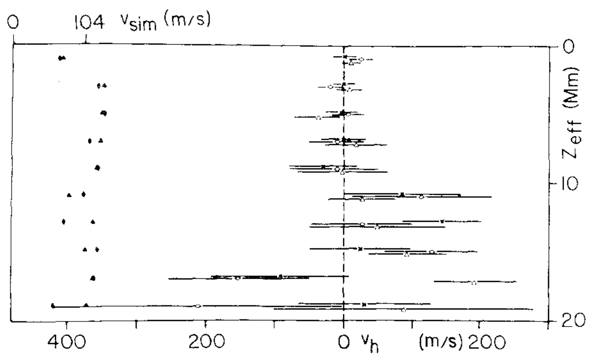

Fig. 5 Depth profile of the linear speed of rotation in the sun at the equator. Speeds are measured relative to the surface value. Reprinted with permission from Ref. 14.

In 1976, Hill et al.[17] reported fluctuations in the diameter of the sun with periods in the 10-60 min range. Figure 6, taken from Brown et al.,[18] shows the low-frequency end of their spectrum. The amplitude of the longest period (6 miliarc sec at 60 min), corresponds to a fluctuation of only three parts in a million of the solar diameter.

Hill's group obtained these data with an instrument built especially for the detection of solar oblateness. The instrument scans the solar limbs at opposite ends of a diameter with a slit whose width can be adjusted. The intensity recording is analyzed to define the instantaneous "edge" of the sun, with a sensitivity of a few milliarc seconds (the solar diameter is approximately 2000 arc-s).

Hill et al. compared their observed frequencies with predicted frequencies of the sun's normal modes of vibration, and concluded that they had observed these normal modes. More extensive calculations of the normal mode frequencies were made by Christensen-Dalsgaard and Gough[19] and, as Table 2 shows, the predicted frequencies overlap or coincide with several observed frequencies. Soon afterward, Severny et al.[20] and Brookes et al.[21] reported oscillations of the radial velocity of the solar surface with a period of 160 min. In addition, Brookes et al. detected periods of 45 and 58 min, the latter with an amplitude of only 0.87 m/s.

Many other observers have attempted to detect long period oscillations of intensity or velocity, and all have obtained null results. Table 3 summarizes these efforts, beginning in 1976. Upper limits on radial velocity of 1 m/s were set by Grec and Fossat[23] and by Dittmer et al.[25] An upper limit on temperature fluctuations of 0.4 K was set by Livingston et al.,[26] using a temperature sensitive C I line.

The question arose as to what amplitudes of velocity and temperature are expected from the apparent diameter amplitude of 6 milliarc sec observed by Hill et al.[17] If one equates the observed amplitude to the true displacement (i.e., expansion) of the solar diameter, then a radial velocity of 4 m/s would be expected, for example. But is this identification valid?

Hill et al.[28] examined this question. They pointed out that an acoustic wave would amplify markedly in the upper layers of the atmosphere. The fractional change in density, pressure, and temperature in these layers can exceed by an order of magnitude the fractional change in radius. Because the Hill et al.[17] experiment examined the solar limb, it is particularly sensitive to pulsations of the upper atmosphere; whereas radial velocity measurements generally refer to much deeper

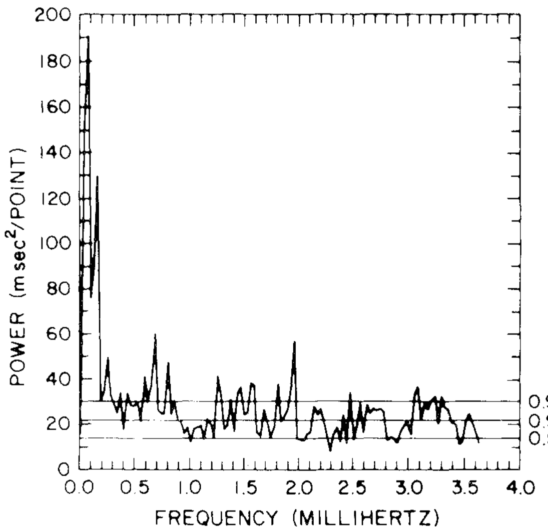

Fig. 6 Spectrum of long period oscillations detected by Hill *et al.* 1976. The horizontal bars indicate 50%, 95%, and 99% confidence levels. Reprinted with permission from Ref. 18.

Table 2 Observed and predicted frequencies of solar normal mode vibrations[a]

Observed period, min	Apparent amplitude, mil	Predicted period: Christensen-Dalsgaard and Gough	Predicted period: Homogeneous model
			167
66.16	6.2	62.22	
44.66	4.6		46.9
		41.98	
39.0	4.6		
32.1	4.2	32.32	30.0
28.7	5.5		
24.8	6.9	26.00	
21.0[b]	6.1	21.51	22.3
19.5	4.3	18.33	17.84
		15.95	
13.3	5.5	14.13	14.88
12.1	4.4	12.64	12.77
11.4	4.9	11.54	11.19
10.7	5.1	10.60	9.96
9.9	3.5	9.81	
9.3	5.0	9.12	8.98
8.5[b]	6.6	8.52	8.17
7.8	5.2	7.94	
7.6	5.1	7.53	7.50
6.9	4.7	7.12	
6.7	5.7	6.75	6.93
6.5	5.4	6.41	6.44

[a] Reprinted with permission from Hill (Ref. 18).
[b] Peak may be due to unusually high power levels on only 1 or 2 days' spectra.

Table 3 Evidence for/against global pulsations

Reference	Measure	Period, m	Comments
For			
21	Δv	160, 60, 45	$\Delta v = 0.8$ m/s
20	Δv	160	
Against			
22	Δv	20-50	Guiding errors?
23	Δv	10-60	Atmospheric refraction
24	Δv	5-90	$\Delta v < 0.7$ m/s
26	$\Delta I(c)$	5-60	$\Delta I/I < 0.06\%$
25	Δv	>5	$\Delta v \lesssim 1$ m/s
30	$\Delta I(k)$	30-80	$\Delta I < 0.02\%$

Searches for long period oscillations.

layers, where the enhancement factor between fractional radius and fractional temperature changes is much smaller.

Taking into account this "enhancement factor," they predicted an expected velocity amplitude of 0.81 m/s for a period of 60 min, consistent with the limits of Grec and Fossat and with the 0.87 m/s amplitude observed by Brookes et al. They also predicted a temperature amplitude of 6 K, in apparent conflict with the 0.04° seen by Livingston et al., but this result was also explained in a later paper.[29]

Beckers and Ayres[30] attempted to test the ideas of Hill et al.[28] They searched for long period oscillations in the intensity of a chromospheric absorption line (Ca II λ3933). They designed their experiment to sample radiation from the same height that Hill et al.[17] observed. Using the theory of Hill et al.,[28] they estimated they should detect an intensity amplitude of 5% at a period of 50 min. Their measurements, however, set a limit 25 times smaller than predicted. Hill et al.[31] suggest Beckers and Ayres confused Eulerian and Lagrangian perturbations, which may invalidate their estimates. A rigorous treatment of the oscillations and radiation transfer in the chromosphere remains to be done, however; and, at present, the Beckers-Ayres result remains unexplained.

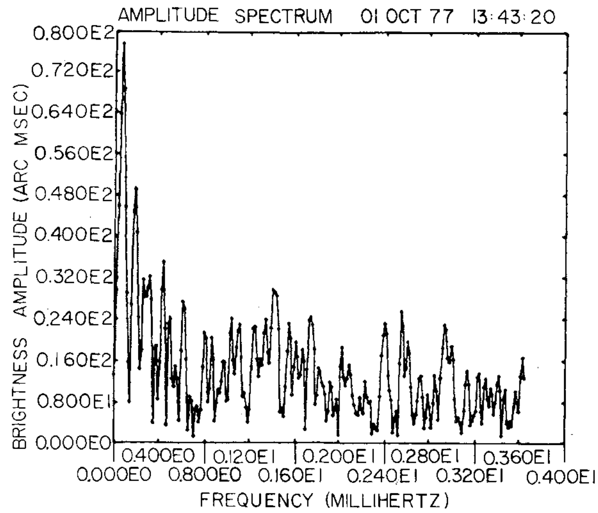

Fig. 7 An amplitude spectrum of brightness fluctuations of the solar limb, obtained by Stebbins, 1977. Reprinted with permission.

Very recently, Stebbins[32] has remeasured the intensity fluctuations of the solar limb using a different telescope than Hill's and using a different experimental method. Stebbins sampled the radial intensity profile of the solar limb at 64 positions by stepping the image across a slit of a spectrograph. Only one limb was examined, which eliminates the criticism raised by Fossat et al.[33] that the long period oscillations might be caused by changes in the refractive index across the solar diameter in the earth's atmosphere.

Stebbins subjected a time series of 18.2 h (with gaps) of such profile measurements to a sophisticated analysis, which simulates an observation of the profile with different spatial resolutions, similar to Hill's technique of varying the width of his scanning aperture. For each effective spatial resolution, Stebbins constructed an amplitude spectrum of limb oscillations. Figure 7 shows one typical spectrum, with peaks at periods 21 and 64 min. To test the solar origin of these, Stebbins examines the variation in amplitude at a given frequency as the effective spatial resolution is varied. If the amplitude increases with increasing spatial resolution, the signal must arise on the sun, and, conversely, Stebbins applies this criterion to both the peaks and valleys in his individual amplitude spectra. He finds that the peaks satisfy the criterion for a signal that arises on the sun, whereas the lowest valleys represent instrumental or atmospheric noise. Although Stebbins' analysis is not complete as yet, his results indicate that he has achieved a signal-to-noise ratio an order of magnitude better than the original results by Hill et al.[17] Moreover, his results tend to confirm those earlier results in saying that the long period oscillations are truly solar.

A similar conclusion has been reached by Brown (private communication), but Brown finds the long period oscillations arise much deeper in the photosphere than Hill et al.[28] suggest. His results may agree better with the most recent calculations of Hill et al.[31] Neither the theoretical nor the observational picture is clear at this time, and the controversy is far from settled. We look forward in the near future to a convincing resolution of the question: "Does the sun pulsate?"

Acknowledgment

Operated by the Association of Universities for Research in Astronomy, Inc. under Contract AST 78-17292 with the National Science Foundation.

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