

ON THE ORIGIN OF SOLAR OSCILLATIONS

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ABSTRACT

We have made high-resolution observations of the Sun in which we identify individual sunquakes and see power from these seismic events being pumped into the resonant modes of vibration of the Sun. A typical event lasts about 5 minutes. We report the physical properties of the events and relate them to theories of the excitation of solar oscillations. We also discuss the local seismic potential of these events.

Subject headings: Sun: granulation — Sun: oscillations — Sun: photosphere

1. INTRODUCTION

Earthquakes shake the Earth, allowing one to sound our planet's interior. In an analogous way, sunquakes enable a sounding of the solar interior. The two kinds of quakes are also alike in that both are near-surface phenomena. However, sunquakes are occurring somewhere on the Sun all the time, so that energy is being continuously fed to the Sun's resonant modes, implying that in principle one could continuously sound the Sun. From the global solar seismic data, we have learned a great deal about the Sun's interior. However, the precise origin of individual sunquakes has been shrouded in mystery, unlike the origin of earthquakes.

The resonant or normal modes of vibration of the Sun are compressional waves. These so-called *p*-modes have long been known to have a period of about 5 minutes, and in the solar photosphere they are evanescent vertically and traveling horizontally. It is generally agreed that these solar oscillations are excited near the Sun's surface by convection. Until recently, it was widely believed that this deceleration of the upgoing granules induced a steady drumming that fed the resonant acoustic modes. However, Rimmele et al. (1995) observed that there are seismic events that they associated with the excitation of solar oscillations. These events originate in the dark intergranular lanes. Furthermore, they observed that the seismic events were preceded by a further darkening of an already dark lane, and on the temporal leading edge of the seismic event there is a still further and more abrupt darkening. From this, Rimmele et al. suggested that the excitation of the resonant modes was caused by the occasional catastrophic cooling and collapse of the lanes. However, they were unable to show a causal link between the seismic events and the resonant modes of vibration of the Sun.

In establishing the causal link here, we show that a seismic event is a local power surge that feeds the normal modes.

2. DATA

Our observations were made at the Vacuum Tower Telescope of the National Solar Observatory in Sunspot, New Mexico. The quiet-Sun data set discussed here is from 1994 September

5. The data and the reduction of it are described in detail in Rimmele (1994), Rimmele et al. (1995), and references therein. One of the basic observational problems here is to distinguish the seismic event power from the dominant resonant mode power. To distinguish the two in our field of view (60" × 60" patch of quiet Sun near disk center), Rimmele et al. measured the velocity as a function of altitude in the photosphere for 65 minutes by observing the Doppler shift in the 543.4 nm Fe I absorption line. The Doppler shift as a function of depth in the line corresponds to the velocity as a function of altitude in the atmosphere the line spans. In our analyses here, we further explore the data of Rimmele et al.

We note that in earlier spectrographic observations of the Fe I line (Stebbins & Goode 1987), with a faster cadence and a one-dimensional field of view, the basic life cycle of the events was the same (see Restaino, Stebbins, & Goode 1993). Also, observations measuring other lines show the same basic results for the events [e.g., the well-known Fe I 5576 Å (*g* = 0) line].

3. SEISMIC EVENTS

We searched our velocity field for phase changes with altitude and found that they fit one behavior pattern: uniformly looking like an outgoing wave followed by a wave coming back down from above (with a time lag of about 4–5 minutes). The signature of these seismic events was detected in the solar photosphere that is not quite isothermal, implying that any outgoing wave would be followed by a partially reflected wave. This combination of phase behaviors eased our effort to distinguish between power from seismic events and that from normal modes, which should show only a small phase change with altitude caused by dissipation (Restaino et al. 1993).

In the analysis, we superposed slightly more than 2000 separate seismic events, each of which constitutes an event covering more than 100 voxels (pixels in all frames combined). This is a convenient and efficient way to separate significant seismic events from background noise. The superposed events were pinned in time, with *T* = 0 being the peak in the product of the square of the acoustic velocity and the vertical phase gradient for each event. After superposing the seismic events, each was oriented such that the intergranular lane was along the *x*-axis (see the three panels of Fig. 1). If the events were purely traveling acoustic waves, the aforementioned product would be proportional to the acoustic or mechanical flux. Regardless, the product is a convenient measure of seismic events. Our use of standard formulae for calculating the mechanical flux of linear, traveling waves predicts energy deposition that may have no better than an order-of-magnitude accuracy for

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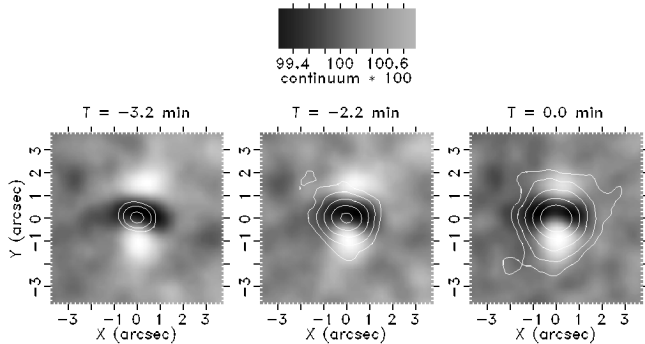


FIG. 1.—The superposed seismic flux, shown in white contours, is superposed on its local, averaged granulation altitude 150 km above the base of the photosphere. The contours are 0.25, 0.5, 1, 2, 4×10^7 ergs $\text{cm}^{-2} \text{s}^{-1}$. The flux is shown for $T = -3.2$, -2.2 , and 0 minutes. The time steps in the data collection are about 30 s, and at one time step before $T = -3.2$ minutes, the seismic flux is below 0.25×10^7 ergs $\text{cm}^{-2} \text{s}^{-1}$ everywhere in the field of view.

the waves considered here. After all, the waves from the sunquakes may not be fully linear and are not waves supported by the atmosphere; rather, they are the result of a temporal forcing of the photosphere.

In Figure 1, $T = 0$ is the time of peak “seismic flux,” and the seismic flux contours in Figure 1 are normalized to the mechanical flux as defined in Rimmele et al. The fact that a dark lane with a bright granule on either side survives the averaging strongly emphasizes that this geometry is a common feature of seismic events. The granular contrast is small because granular images are smeared by the averaging. It is also obvious that more than $2''$ from the center of the field of view, the granular structure is completely washed out by the averaging of many hundreds of events. In the figure, the bright contours represent the outgoing seismic flux. Clearly, the seismic events originate in the lanes (for more detail, see Rimmele et al. 1995).

Furthermore, immediately after the peak in the seismic flux, the lane begins to narrow as though the granules on either side of the lane are being pulled together to fill the void left behind.

From Figure 1, it is also clear that seismic events have a finite duration. Over the 3 minute span shown, the increasing seismic energy can be seen being fed into the aggregated events. After $T = 0$ in the figure, the seismic flux gradually subsides. The total duration of the expansive phase of the event is about 5 minutes. The apparent finite duration of the events needs to be emphasized for several reasons. The fact that the peak in the observed spectrum of global solar oscillations corresponds to modes with a period of about 5 minutes may well be connected to the comparable temporal duration of the seismic events. That is, because the events are not impulsive, and in fact endure for a time comparable to the period of the oscillations, resonance may play a role in the excitation of the oscillations. The conventional wisdom has been, however, that turbulent convection excites acoustic waves in a broad frequency range, including waves above the acoustic cutoff.

Arguments for seismic power above the cutoff are predicated on the assumption that the excitation is nearly instantaneous, so that the power in the stably stratified solar photosphere will be above the acoustic cutoff. Lamb (1909) first idealized the description of a seismic event by considering the response of an infinite, stably stratified isothermal atmosphere to a thumping from below. If an impulsive, Lamb-like picture were cor-

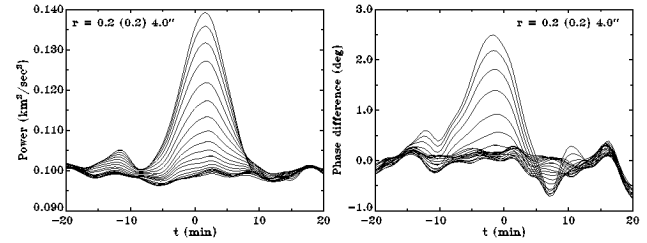


FIG. 2.—Left panel: the average excess power (v^2) in the neighborhood of more than 2000 seismic events, superposed as in Fig. 1, is shown as a function of distance and time—starting at $r = 0.2$ (the curve with the highest peak power) in steps of 0.2 out to $4.0''$. Successive distances show successively decreasing peak power out to about $3.0''$. Right panel: the averaged phase difference between two altitudes in the photosphere (150 and 330 km above the base of the photosphere) as a function of time and distance in steps of 0.2 as in the left panel. The formal standard error on the averaged phase difference is about 0.1 at each spatial and temporal point. The largest positive phase change is for $r = 0.2$. A positive phase change corresponds to an upgoing wave. Successive distances show successively decreasing peak positive phase change out to about 1.4 . A typical event has a peak phase difference significantly larger than that of the superposed, and therefore smeared, result in the figure.

rect, then observers could employ simpler techniques than we did. Observers could simply look for the signature of seismic events above the acoustic cutoff, instead of below the acoustic cutoff, where the power is dominated by p -modes. Such an approach was taken by Brown et al. (1992), but like them, we find no appreciable seismic event power in the quiet Sun above the cutoff. This is not a great surprise since the seismic flux power spectrum has a fairly narrow peak near a 5 minute period. Thus, to look for seismic event power, one has to look where the power is—this means having to distinguish seismic events from resonant modes. As discussed, we do this by identifying individual events by their characteristic large phase shift with altitude, which is a strong function of time.

4. POWERING THE OSCILLATIONS

In Figure 2, we show the superposition of the power at 150 km above the base of the photosphere and the instantaneous phase difference between that altitude and 180 km higher. The specific model altitudes were provided by S. Keil (1997, private communication). Both quantities in Figure 2 are shown as a function of time and horizontal distance from the event, with $T = 0$ being the peak in the seismic flux for the superposed events. We remark that what is generally regarded as being convective power is subsonic and has been filtered out. The k - ω diagram for our data is shown in Figure 3.

The phase signature characteristic of seismic events is apparent clear out to about $1.4''$ from the events. Beyond that distance, the phase change with altitude is essentially zero. However, there is excess power from the events going out almost $3''$. Beyond that distance, no excess power is apparent. The tendency of the power is to decrease as the square of the distance from the events. This tendency is what one might anticipate. The power propagates with an apparent supersonic speed out to about $1.5''$, but in all likelihood, that speed reflects the horizontal extent of the events rather than a true propagation speed (imagine a piston emerging from a fluid; the horizontal speed measured from the axis to the edge of the piston reflects only the shape of the top of the piston; Strous, Goode, & Rimmele 1998). Beyond $1.5''$, and beyond the edge of the

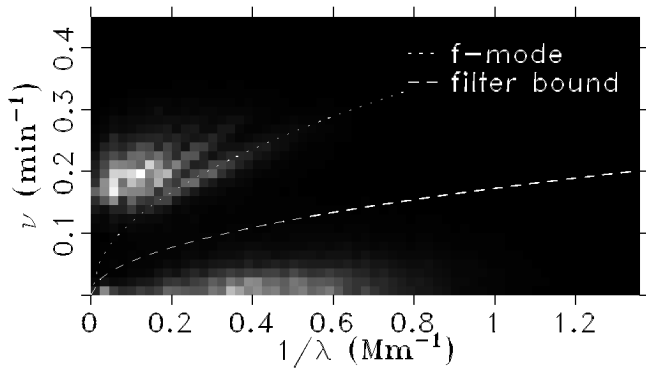


FIG. 3.—The k - ω diagram for our data. Selected sonic cutoff and model predictions for the f -mode ridge are indicated by the dotted and dashed white curves. Note that the sonic and subsonic powers are well separated. Note also that there is significant power in the region of the f -mode ridge.

events, there is a true propagation speed that is slightly supersonic. It is likely that most of this power is in f -modes that are *asymptotically* (in terms of horizontal wavelength) surface waves. We first note that the region of the f -mode ridge is apparent in our k - ω diagram (see Fig. 3). The f -modes form the lowest frequency ridge in the p -mode, k - ω diagram. Physically, they are somewhat distinct from the rest. The two particularly distinct properties of the f -modes are as follows: they are *asymptotically* incompressible and may propagate horizontally with a slightly supersonic group velocity.

Our contention that power has been fed from seismic events into the f -mode part of the spectrum of solar oscillations is greatly strengthened because the acoustic power delivered by the events to beyond $1''4$ is (1) characterized by no vertical phase change, which means an essentially infinite vertical phase speed, (2) characterized by a 5 minute period and a group velocity roughly appropriate for f -modes, and (3) dominated by horizontal wavelengths consistent with those of the f -modes. Thus, power has been fed from seismic events into the Sun's normal modes.

The events occur just beneath the photosphere, and what we observe is the photospheric effluvia that is converted into atmospheric p -modes. However, much of the energy from these events is directed into the Sun. The process by which this latter energy is converted into p -modes is somewhat different. The inward-directed noise is eventually refracted back to the surface, where it is partially reflected back into the Sun.

Kumar (1993, 1994) has shown theoretically that after only a few refractions, white noise would be converted into resonant modes. We cannot expect to detect the signature of such skips from our data set, since the typical distance for a single refraction of, say, a 5 minute period p_1 mode is much greater in extent on the solar surface than our field of view. Thus, we do not (and cannot) see power being pumped into all modes, but we see power pumped into a part of the spectrum—the f -mode part for which the skip times are very short. The seismic events can power the entire p -mode spectrum: if half the power of the events is fed into the Sun's resonant cavity, there is ample power to drive the Sun's entire spectrum of oscillations (Rimmele et al. 1995).

Figure 1 also clearly reveals a seismic potential for the events

low in the photosphere where the convective overshooting occurs. In particular, the events from the lane collapse seem to travel horizontally about 30% faster over brighter regions. Furthermore, these seismic data will aid in diagnosing flaws in any forthcoming three-dimensional model of the events.

5. DISCUSSION

In the collapse of an intergranular lane that generates the seismic events, one could invoke linear and nonlinear processes. Linear processes would be rarefaction waves generated by the collapse and the subsequent downgoing blob acting like a piston. Nonlinear ones would be the implosion of the blob on itself and the infall of material behind the blob (see Rast & Toomre 1993b).

Near the center of a seismic event, the disturbance seems quite supersonic, which would imply an origin that is at least partially nonlinear. However, this speed probably reflects the finite size of the events and thus provides no evidence for the presence of nonlinear effects. Nonlinear effects here would take convective power and convert it into acoustic power. From the k - ω diagram, nonlinear effects would seem to be small since the convective and acoustic powers are well separated. Furthermore, in a linear theory, the subsonic velocities that should correspond to the convective velocities do in fact correspond to the granular velocities we observe. Thus, the events seem to be nearly linear in origin.

Following Goldreich & Keely (1977), the commonly accepted picture of the excitation of solar oscillations is one in which stochastic driving is done by turbulent convection. This theory has been further developed by Goldreich & Kumar (1988) and has enjoyed success for explaining the distribution of power within the p -mode spectrum. The theory relies, to some extent, on a mixing-length formalism in which there is a full symmetry between the roles of upgoing and downgoing flows. However, we clearly see from our seismic events that there is no such symmetry. To the contrary, strong events occur exclusively in the dark intergranular lanes. Thus, we believe that it would be valuable to account for this asymmetry in a future theoretical effort, to explain quantitatively the p -mode spectrum.

Our observations were motivated by the pioneering, large-scale simulations of convection by Nordlund (1985), in which he predicted narrow, supersonic downdrafting plumes. The simulations of Rast & Toomre (1993a, 1993b) predict a role for the plumes in the excitation of solar oscillations. We do not know if the predicted plumes are associated with the seismic events we observe, but we are working with Nordlund and coworkers to resolve this.

Seismic events would seem to have the seismic potential to probe the neighboring granular structure and small-scale magnetic fields. We have made observations in regions of weak magnetic structure to determine the magnetoseismic potential of the seismic events.

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