

LOCAL PROPERTIES OF THE SUN'S SEISMIC EVENTS

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1. Introduction

We made simultaneous high resolution observations of the solar granular field and the Sun's seismic events. We find that these events occur in the dark intergranular lanes. The events are preceded by the darkening of an already dark lane. On the leading edge of each event, there is a second more abrupt and precipitous darkening lasting a minute or two.

The events are the by-product of the local excitation of the Sun's p-modes. We see the quake energy being directly converted to normal mode energy. The total energy in the effluvia is of the order of magnitude necessary to power the entire p-mode spectrum. The newly created p-modes travel about 30% faster over the nearest bright granules than they do over the local dark lanes.

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 arising in certain places in the dark intergranular lanes there are seismic events which they associated with the excitation of solar oscillations. Nordlund (1997) and co-workers used simulations of convection to argue that these places where events occur are ones in which there is a small, weak local granulation which disappears (this is the phase of gradual darkening of the lane in which we mightn't resolve the small granular features). After the disappearance, the lane catastrophically

cools and collapses (this is the second phase for which the observations and simulations give a 1-2 minute timescale).

2. The Data

Our observations were made at the Vacuum Tower Telescope of the National Solar Observatory in Sunspot, New Mexico. The quiet Sun dataset discussed here is from Sept. 5, 1994. The data and the reduction of it are described in detail in 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" x 60" patch of quiet Sun near disk center), Rimmele, et al. measured the velocity as a function of altitude in the photosphere for 65 min 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.

3. The Sun's Seismic Events

We searched our velocity field for phase changes with altitude and found they fit one behavior pattern—uniformly looking like an ascending wave followed by a wave coming back down from above (with a time lag of about 4 to 5 minutes). The signature of these seismic events was detected in the solar photosphere which 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 power from seismic events from that of normal modes which should show only a small phase change with altitude caused by dissipation, Restaino, et al. (1993)

In order to study the properties of the average event, we superposed slightly more than two thousand of the largest seismic events. This is also 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 Figure 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.

In Figure 1, we see the time evolution of the "seismic flux" shown as white contours of the averaged events. The events are pinned in time with $T=0$ is the time of peak seismic flux. The seismic flux contours in Figure 1 are normalized to the mechanical flux as defined in Rimmele, et al. The flux is superimposed on the averaged, evolving local granulation which is pinned in time to the peak

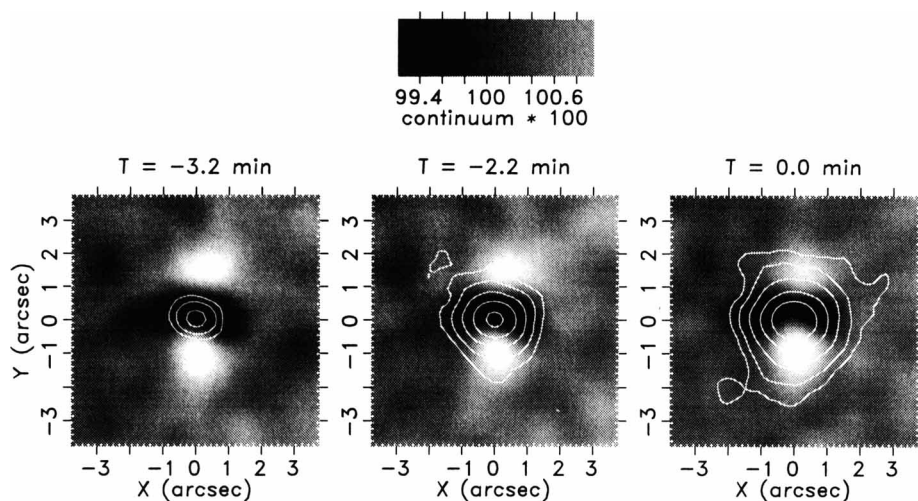


Figure 1. The superposed seismic flux, shown in white contours, is superposed on its local, averaged granulation. The contours are $0.25, 0.5, 1, 2, 4 \times 10^7$ ergs/cm²/s. The flux is shown for $T = -3.2, -2.2$ and 0 min. The time steps in the data collection are about 30 s, and one time step before $T = -3.2$ min, the seismic flux is below 0.25×10^7 ergs/cm²/s everywhere in the field of view .

flux. The fact that a dark lane with a bright granule on either side survives the averaging strongly emphasizes 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).

Further, 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 three minute span shown, increasing seismic energy can be seen being fed into the aggregated events. After the $T=0$ peak in the figure, the seismic flux gradually subsides. The total duration of the expansive phase of the event is about five minutes because immediately after $T=0$ the flux begins to subside due of reflection from above. The fact that the duration of the expansive phase of the events is closer to five minutes 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 five minute timescale of the events is consistent with that calculated in a linear, one dimensional model of seismic events, Goode, Gough and Kosovichev (1992). In their simulations, they showed that the mean velocity and phase properties of data like that of Rimmele, et al. are described well only if the typical event endures for about five minutes at its subsurface point of origin immediately beneath the base of the photosphere. They demonstrated, for instance, if the sub-photospheric model disturbance were more impulsive, the model signal would be too impulsive in the photosphere to describe the data.

4. The Driving of 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 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 $k - \omega$ 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 center of 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 a noticeably supersonic speed out to about $1.5''$. The speed can be estimated from Fig. 2a by measuring the time evolution of the peak in the v^2 power. The large apparent supersonic speed in this inner region probably reflects the finite horizontal size of the events there, as they erupt. Since the lane size is about $1''$, the horizontal extent of the events is no more than that. So, beyond $1.5''$ the speed mostly likely represents the true horizontal propagation of the disturbance resulting from the event. In that region, the speed is no more than modestly supersonic. It is likely that most of this power is in f-modes which are *asymptotically* (in terms of horizontal wavelength) surface waves. We first note that the region of the f-mode ridge is apparent in our $k - \omega$ diagram (see Figure 3). The f-modes form the lowest frequency ridge in the p-mode $k - \omega$

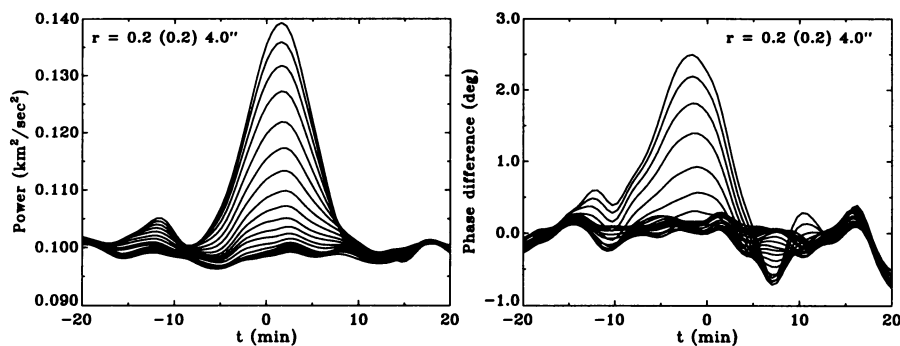


Figure 2. a) The average excess power (v^2) in the neighborhood of more than two thousand seismic events, superposed as in Figure 1, are as shown as a function of distance and time—starting at $r=0.2''$ (the curve with the highest peak power) in steps of $0.2''$ out to $4.0''$. Successive distances show successively decreasing peak power out to about $3.0''$. b) The averaged phase difference between two altitudes in the photosphere (150 km and 330 km above the base of the photosphere) as a function of time and distance in steps of $0.2''$ as in a). The formal standard error on the averaged phase difference is about 0.1deg 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.

diagram.

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 five 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. However, the normal modes we see are not ones that provide a deep seismic sampling of the Sun's interior. We emphasize that the f-modes are the only ones we could hope to see converted with our technique of following the power from individual sunquakes, since higher order p-modes would skip out of our field of view in a single refraction (see next paragraph).

The events occur just beneath the photosphere, and what we observe is the photospheric effluvia which 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.

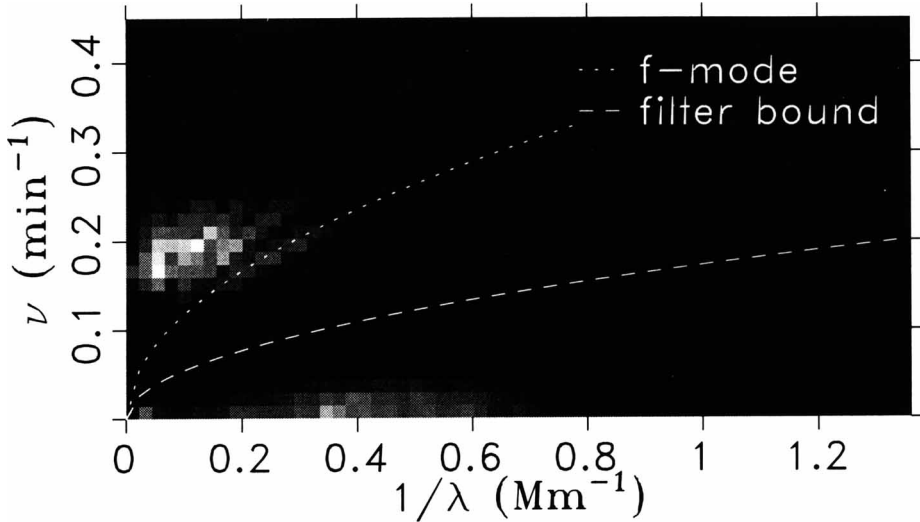


Figure 3. The $k - \omega$ diagram for our data. Model predictions for the f-mode ridge and subsonic filter bound (separating convective power from oscillatory power) are indicated by the bold white curves. Note that the sonic and subsonic powers are well-separated. Note also, that there is significant power in the region of the f-mode ridge .

The inward directed noise is eventually refracted back to the surface where it is partially reflected back into the Sun. Kumar (1993) 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 dataset, since the typical distance for a single refraction of, say a five minute period p_1 mode is much greater in extent on the solar surface than our field of view. Thus, we don't (and can't) 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. Still, the seismic events can power the entire p-mode spectrum, Rimmele, et al. (1995).

5. Discussion

In the collapse of intergranular lanes that generates the events, one can 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. Owing to the non-impulsive nature of the events, we might anticipate that they are dominated by linear effects. This would be consistent with the power in our $k - \omega$ diagram being dominated by two distinct regimes—one dominated by the p-modes and the other by the convective power.

The commonly accepted picture of the excitation of solar oscillations is one in which stochastic driving is done by turbulent convection, Goldreich and Kumar (1988), The theory has enjoyed success in explaining the distribution of power within the p-mode spectrum. The theory relies, to some extent, on mixing length formalism in which there is a full symmetry between the role of upgoing and downgoing flows. However, we clearly see from our seismic events there is no such symmetry. Thus, we believe that it would be valuable to account for this asymmetry in a future theoretical effort to quantitatively explain 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. Owing to the many similarities, it would seem our seismic events are associated with the downgoing convective plumes predicted by Nordlund (1985).

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