Observation of the Excitation of Solar Oscillations

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Abstract. The acoustic event effluents observed in the Sun’s photosphere are spatially and temporally isolated local by-products of the excitation of solar oscillations occurring just beneath. We determine that the effluents appear preferentially in the dark intergranular lanes and are preceded by a few minutes of slow and then abrupt darkening of the continuum. Events are immediately followed by a local brightening. We conclude that the excitation of solar oscillations seems more closely associated with the rapid cooling occurring in the upper convection layer than with the overshooting of turbulent convection itself. So-called “exploding” granules play no major role in the excitation of solar oscillations. The acoustic events appear to be organized on a roughly meso-granular scale, but their effluent does not trace out the mesogranules. The observations were made in regions of quiet Sun. There we find that the local magnetic field appears to diminish both the average acoustic flux and the p-mode power. We argue that acoustic events directly pump power into the solar p-modes, and that this power is sufficient to drive the spectrum of p-modes. We suggest that acoustic events be exploited as local three dimensional probes of the Sun’s near surface in close analogy to terrestrial time-distance seismology.

Key words: Excitation of Solar Oscillations, Time-Distance Seismology

1. Introduction

The excitation of the Sun’s global acoustic oscillations occurs just beneath the photosphere as a consequence of the process in which turbulent convection overshoots into the photosphere. It is from the study of the global oscillations that all of the impressive helioseismic results follow. Our purpose here is to illuminate the process by which the oscillations are excited and discuss the meaning and use of this knowledge. Simulations of convection, pioneered by Nordlund (1985), have shown that the subsurface character of solar granulation is one in which there is a gradual, broad convective
updraft co-existing with narrow, downdrafting plumes which are sometimes hypersonic; for a review see Nordlund and Stein (1991). Since the character of the two primary components of the flow are so different, one wonders whether one part might dominate in the excitation of the oscillations—either the bright convective updrafts or the dark downdrafts which define the intergranular lanes. Prior to the aforementioned simulations of subsurface convection, no significant role in the excitation was anticipated for the downdraughts. However, since some of the downdraughts are faster and narrower than the updrafts, perhaps the they are "noisier" too. One further wonders whether rapidly expanding granules which become dark in their middle, i.e. "exploding" granules, might be a special contributor to the excitation of the oscillations. Rast (1995) argued from simulations of sub-surface convective flows that particularly sharp downdrafting plumes arise at the center of exploding granules.

Goode, Gough and Kosovichev (1992) used the data of Stebbins and Goode (1987) to show that localized, individual events that excite at least some solar oscillations are identified by the events' proximate effluents. They showed that the events are centered less than 200 km beneath the photosphere. The effluent from an event is observed in the photosphere. An acoustic event arises from an impulsive action which feeds mechanical energy into the oscillations beneath the photosphere while causing an acoustic effluent in the photosphere. This effluent is literally the "smoke" from the "fire" of the acoustic event. Lamb (1909) first idealized the problem of acoustic events by determining the response of a stably stratified, isothermal atmosphere to an impulsive force, as well as to a finite string of impulsive forces. He showed that subsequent to the impulsive action, an acoustic front passes through the atmosphere and is followed by an oscillating wake in which the frequency quickly goes to the acoustic cut-off while the vertical wavenumber and amplitude of the wake quickly become vanishingly small. The problem of observing the effluents from real acoustic events is difficult because it turns out that they have their significant power in the p-mode region of the $k-\omega$ diagram. However, the problem is tractable for three basic reasons. First, the events we see are sufficiently spatially and temporally isolated that we see them occurring one at a time. Second, the effluents have a small spatial scale compared to, say, the coherence patches associated with solar p-modes. Third, the effluent is characterized by appearing to correspond to an upgoing travelling wave early in its life and a downgoing travelling wave late in its life. The Sun's global oscillations are evanescent in the photosphere (except for a relatively small phase change due to dissipation). This travelling wave behavior of the effluent has it origin in the response of the acoustic event effluents to the Sun's not-quite-isothermal photosphere. The problem idealized by Lamb becomes more complicated; in particular, there is reflection, as well. Thus, the effluent from a real acoustic event is characterized by an upgoing flux followed by a downgoing flux which is due to reflection and the hypersonic nature of the wake of the event.

Goode, Gough and Kosovichev (1992) performed realistic one-dimensional calculations to determine the transient response of the photosphere, as a function of altitude, to an impulsive event occuring beneath the photosphere. Individual acoustic events feed energy into the Sun's normal modes while inducing a photospheric effluent. They found that their calculated acoustic effluent had average properties consistent with those Stebbins and Goode (1987) observed in their data. Stebbins and Goode (1987) measured
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Doppler shifts at various heights in the non-magnetic Fe I line at 5434 Å. The line spans the photosphere—yielding acoustic velocities as a function of altitude. These observations were performed simultaneously at 100 spatial points, enabling Stebbins and Goode to simultaneously select five minute period power, which is below the acoustic cut-off, and power below the minimum horizontal wavenumber for traveling atmospheric gravity waves. This focus enabled the authors to be sure that the sizeable positive and negative phase changes they measured had horizontal wavenumber, \( k \), and frequency, \( \omega \) belonging to the region of the \( k - \omega \)-diagram in which the non-transient power should be acoustic and evanescent rather than being due to some kind of propagating wave. From their two dimensional data, they found, on average, that the ratio of velocity amplitude at the top of the photosphere to the bottom increases sharply with decreasing velocity amplitude. Likewise, the phase difference between the top and bottom of the photosphere increases sharply with decreasing velocity amplitude. Subsequently, Restaino, Stebbins and Goode (1993) re-analyzed the data of Stebbins and Goode (1987) to demonstrate that the aforementioned average properties arise from acoustic event effluents which have the same temporal sequencing and spacing predicted in the model calculations of Goode, Gough and Kosovichev (1992). That is, the effluent is characterized by a peak in the upgoing flux followed in about one minute by a peak in the velocity amplitude which is then followed in about five minutes by a peak in the downgoing flux.

Rimmele et al. (1995a) made simultaneous high resolution observations of the quiet Sun's granular field and observations of the Sun's velocity field in three spatial dimensions in the same field of view. They used these data to show that the Sun's acoustic event effluents occur preferentially in the dark, intergranular lanes. From this they argued that the excitation of the solar oscillations is closely associated with the cooling and collapse of the solar surface which follows the convective overshooting—rather than arising from the drumming by convective overshooting itself. They also demonstrated that the energy flux in the effluents is comparable to that required to power the entire p-mode spectrum. Later, Rimmele et al. (1995b) showed that magnetic fields in these quiet Sun regions tend to suppress the acoustic effluents.

We have two primary purposes here. The first is to review the two works of Rimmele et al. (1995a, 1995b) concerning the role of the dark, intergranular lanes and magnetic fields in the excitation of solar oscillations. Some of the text here is from Rimmele et al. (1995a). The second is to show that the acoustic events directly feed power into the Sun's p-modes and emphasize that the acoustic events can be used to probe the near surface region using a terrestrial-like time-distance seismology.

2. The Observations and Data Reduction

The observations used in Rimmele et al. (1995a, 1995b) and here were carried out on February 15, 1994, and September 5, 1994, using the Vacuum Tower Telescope of the National Solar Observatory at Sacramento Peak, New Mexico. The high resolution observations of acoustic event effluents and granulation were performed on a roughly 90" × 75" (Feb. 15th) and a 60" × 50" (Sept. 5th) patch of quiet Sun near disk center. The real-time H-\( \alpha \) image provided by the Hilltop Facility was used to identify active regions which then were avoided. We obtained velocity and phase information on the

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acoustic event effluents at altitudes spanning the photosphere. The 20-mÅ passband filter consisting of the Universal Birefringent Filter (UBF) and a Fabry-Perot interferometer (Bonaccini and Stauffer 1990) was used to scan the profile of the magnetically insensitive (g = 0) FeI 5434Å line. The narrow band filtergrams were recorded with a RCA504 CCD-camera; the pixel resolution width was 0.29"/pixel (Feb. 15th) and 0.19"/pixel (Sept. 5th), respectively. The pixels have a height/width ratio of 4/3. Exposure times were typically 150 - 300 ms. In addition to the narrow band filtergrams, broad band images were recorded simultaneously with a second CCD-camera.

The profile of the line FeI 5434Å was scanned repeatedly. Each scan was performed at 14 wavelength positions including the continuum. It took 32.5 s to complete one scan, and we recorded a time sequence consisting of 200 (Feb. 15th) and 122 (Sept. 5th) line scans implying a total observing time of 108 and 65 minutes, respectively. The seeing conditions varied between good and excellent during these times. The images were stabilized using a correlation tracker (Rimmele 1991).

In the data reduction process, we performed standard dark current and flat field corrections. In addition, the presence of atmospheric distortion in the white light and filtergram images was removed using a destretching algorithm. This process was described in detail by Rimmele (1994).

From the FeI 5434Å spectral profiles recorded at each spatial position in the field of view (FOV), we computed bisector velocities at 10 different intensity levels in the line profile. These bisector velocities represent a measure of the velocity at different altitudes in the solar atmosphere. With this, we arrive at a 4-dimensional data structure, v(x, y, z, t), giving the velocity as a function of the two spatial coordinates x and y on the solar surface, the altitude z in the photosphere, and time t. The time sequence of velocity maps at each altitude was further processed by applying a Fourier filter in k - ω space in order to eliminate those temporal frequencies from the velocity signal which do not belong to the frequency domain of the five minute acoustic oscillation. Then, the velocities are returned to the time domain employing a Hilbert transform; for further details see Restaino, Stebbins and Goode (1993) and references therein.

As the final step of the data reduction, we calculated the acoustic flux as a function of time, spatial position in the FOV, and altitude in the photosphere. Following Restaino, Stebbins and Goode (1993), we note that in the part of the k - ω diagram of interest to us, the mechanical flux, u can be accurately approximated by the product of a kinetic energy density and the group velocity. In terms of quantities we measure,

\[ u \propto \frac{V^2}{\omega} \frac{\Delta \phi}{\Delta z}, \]

where V is the velocity amplitude and \( \frac{\Delta \phi}{\Delta z} \) is the observed phase gradient with altitude of the effluent of the event.

3. Dark Intergranular Lanes and Acoustic Events

We produced video movies that show a time sequence of destretched granulation images with the acoustic flux (the effluent) overlaid as a contour plot. Both the movies
produced from the Feb. 15th and the Sept. 5th data clearly show that the acoustic flux lies predominately in the dark intergranular lanes. The spatial extent of the flux from an typical event is on the order of 1°. The flux in an ordinary case arises in a dark lane. As time proceeds, the flux continues to grow for a few minutes, while at the same time the continuum intensity decreases at the same spatial location. As the upgoing-flux fades away into the dark lane, a downward flux develops at the same location primarily as a result of reflection in the atmosphere. The downward flux grows for a minute or two and then also fades away. Occasionally acoustic flux appears at the edge of a bright granule. In these cases the granule darkens as the flux grows while typically a lane forms at the same location. In a few cases, we observed acoustic flux to grow in the center of a bright granule. Usually preceding the growth in flux, a thin dark lane develops passing through the effluent. The thin lane has a spatial scale close to the limit of the achieved resolution. These occasional events may be associated with exploding granules, but most exploding granules are not particularly associated with strong flux events.

![Diagram](image-url)

**Figure 1.** Mean intensity (*solid line*) measured at the location of large acoustic flux as a function of time in minutes. The mean of the flux (*dotted line*) at each time point is overlayed. The *dashed line* is the mean intensity of all the granulation.

We computed the mean intensity of the granulation where the acoustic flux is large. We define large here to be above 0.8×10^8 ergs cm^{-2}sec^{-1}. For Figure 1, we average the flux at pixels which exceed this threshold, and show the mean flux and the mean intensity at consecutive time steps. The figure clearly indicates that large flux predominantly occurs in regions where the intensity is well below the mean intensity of the granulation.
Figure 2. Time evolution of acoustic flux (dotted line) and normalized granular intensity (solid line) at one spatial location is shown. Two large flux outbursts are observed toward the end of the sequence. On the rising edge of each of outburst a sharp drop in the granular intensity is observed.

(dashed line). The figure suggests that there are long stretches of time during which the FOV is fairly “silent” (no large acoustic effluents).

To get a feel for when the granular darkness peaks in the life of an acoustic effluent, we show in Figure 2 the evolution in time of the acoustic flux and the normalized continuum intensity at one typical spatial location. The two large acoustic outbursts toward the end of the sequence are accompanied by a relatively rapid drop in the continuum intensity which precedes the maximum of the acoustic flux. The time lag between intensity minimum and flux maximum is typically 2 minutes but a substantial variation in this time lag is observed. Shortly after reaching its minimum the intensity is observed to increase again to a value, which in general is still slightly below the mean. In our data, we found numerous examples of flux outbursts that show the same behavior of flux and intensity seen in Figure 2. Figure 3 (top) gives a further indication that this behavior is common to most flux occurrences. It shows the average of a large number of such occurrences which were registered in time by using the flux maximum of each as the common temporal reference point. The fluxes were then averaged. In addition, the corresponding average continuum intensity profile was computed. The intensity profile shows a dip at the rising edge of the average flux outburst with a subsequent increase in intensity. The sharp intensity variations seen in the examples of Figure 2 are to a large extent smeared out in the averaged intensity profile in Figure 3. This is mainly due to the variations in the time lag mentioned above and due to insufficient resolution caused by seeing. However, Figure 3 shows that, also on average, the local granulation
begins to darken several minutes before the maximum in the flux and the granulation becomes darkest 2 minutes before the mechanical flux peaks. The darkening followed by brightening is as though the surface collapses into a downflow and warmer matter rushes in to fill the void.

**Figure 3.** The time evolution of the averaged flux profile (top) and corresponding averaged intensity profile (bottom) are shown. Several hundred flux outbursts were registered in time and then averaged. After averaging several hundred of them, the intensity signal shows a dip on the rising edge of the averaged flux. The bottom of the dip is 2 minutes before the flux maximum. This dip indicates that the drop in intensity at the rising edge of the event is a common feature of the majority of flux outbursts.

The acoustic flux appears on a granular scale. Is there a larger scale organization to the acoustic events? Mesogranulation is the next larger scale of granulation. If exploding granules were an important source of acoustic events, then one might expect a correlation between acoustic events and diverging mesogranular flows. That is, the diverging parts of the flow are thought to stretch granules and induce exploding granules. The mesogranular flow field was determined by Rimmelle et al. (1995a) from the proper motion of granules seen in the one hour long Sept. 5th time sequence of broad band filtergrams using the algorithm described by November and Simon (1988). The spatial scale of the
mesogranulation in the figure is of the order 10". November et al. (1981) argued that mesogranules are about 10" in extent and live about an hour. Rimmemele et al. (1995a) found that the acoustic outbursts are not uniformly distributed. Instead, they appear in patches which are about the same size as a mesogranule. They also found that acoustic events are temporally isolated. In detail, they inferred from their video movies that there some intervals that are several minutes long during which no appreciable acoustic effluent appears in the FOV. Even though in the time-averaged flux map the patches of acoustic flux have about the spatial scale as mesogranules, they do not seem to be correlated with either the diverging or converging mesogranules. Instead Rimmemele et al. (1995a) suggest that the patches may be associated with the regions and times of greatest cooling in the intergranular lanes. They also pointed out that the FOV has more flux cover than one would expect if a significant part of the acoustic events came from exploding granules alone. In addition, the events are not nearly as spatially or temporally isolated as Brown (1991) argued.

Assuming that the FOV is typical of the Sun, Rimmemele et al. (1995a) argued that the power expended in the acoustic event effluent near the base of the photosphere \(10^{28} - 10^{29} \text{ ergs/sec}\) is comparable to that required power the entire spectrum solar oscillations \(\sim 10^{28} \text{ ergs/sec}\) as determined from linewidth data, Libbrecht (1988).

### 4. Acoustic Events and the Driving of the P-Modes

We have argued that the acoustic events power the Sun’s p-modes. To demonstrate this we employ the data of Rimmemele et al. (1995a) and an argument due to Kumar(1993). The p-modes are trapped in a cavity inside the Sun. In their cavity, they are refracted away from the center of the Sun and reflected back from the surface with a small leakage to the atmosphere. The inner turning point of an individual mode depends of the angular degree of the oscillation.

Kumar(1993) has calculated that localized acoustic sources can feed power into the oscillations, and this power should appear on the \(k - \omega\) ridges after only one or two refractions. This means that for the p-modes to which we are sensitive, power should begin to appear on the ridges within a few arc seconds of an acoustic event. With this in mind, we divide the FOV into 24 subfields and make a scatter plot of the small-scale acoustic event effluent against the p-mode power in each subfield. We emphasize here that our observations were made in regions of quiet Sun. However, some of the subfields are “noisier” than others. In fact some subregions are nearly “silent”. We use “noisy” and “silent” as the extremes of acoustic flux, while employing “quiet” and “active” as the extremes of magnetic activity. The scatter plot is shown in Figure 4. There is a strong correlation between the acoustic effluent and the p-mode power(correlation coefficient of 0.71). From this we are tempted to conclude that acoustic events feed power to the p-mode ridges, and in particular, that noisy regions feed more power into the p-modes and silent regions feed less. However, could it be that the local magnetic field is the causal mechanism here? After all, Braun, LaBonte and Duvall(1990) have shown that sunspots absorb p-mode power and Rimmemele et al. (1995b) have shown that magnetic fields suppress acoustic events.
Figure 4. Scatter plot of p-mode power vs. acoustic flux averaged in each of 24 subfields of the Sept. 5th observations.

Figure 5. Scatter plot magnetic flux proxy vs. p-mode power(left) and acoustic flux(right) from each of the 24 subfields.

The observations of Rimmle et al. (1995a) were made in quiet Sun regions, but even in such regions the magnetic field can be sizeable. No Stokes $V$ values are available for the current data sets, but the correlation between acoustic and magnetic flux can still be studied because of the well-known line weakening (i.e. intensity increase) in the presence of magnetic flux (see, e.g., Chapman and Sheeley 1968 and Solanki 1993). Brightening which is significantly greater than the average "granular" variation at some wavelength.
in a spectral line indicates magnetic field of either polarity. For small flux tubes, the 
brightness increases with increasing magnetic flux density. In the temporally averaged 
Sept. 5th observations, the magnetic signal vs. granular noise ratio is up to ~12.

To test the role of the local magnetic field, we made scatter plots of the line weakening 
as a proxy for the magnetic flux against the p-mode power and against the acoustic flux 
from each the 24 subfields. The results are shown in Figure 5. There are weak anticorrela-
tions between the magnetic flux and both the p-mode power and the acoustic flux. Thus, 
even in the quiet Sun the local magnetic field suppresses the acoustic power (correlation 
coefficient of -0.43). And as shown by Rimmelé et al. (1995b), the local magnetic field 
suppresses the acoustic power (correlation coefficient of -0.43). In the suppression of the 
acoustic events it is not clear whether the magnetic field suppresses the number of events 
or their individual intensity.

We conclude that the dominant correlation is between the acoustic events and p-
modes rather than between either and the magnetic flux. This correlation provides 
observational confirmation of the calculations of Goode, Gough and Kosovichev (1992) 
and Kumar (1993). Thus, we infer that the acoustic events drive the solar p-modes. We 
emphasize that Rimmelé et al. (1995a) showed that the acoustic events are powered by 
processes associated with convective downflows.

The acoustic events are spatially and temporally isolated probes of the Sun's near 
surface layers. We intend to exploit the seismic potential of the Sun's acoustic events 
in a time-distance seismology analogous to terrestrial seismology in which earthquakes 
are the acoustic events. The seismology should be especially valuable in probing the 
structure of sunspots and and Sun's near surface rotation.

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