DARK LANES IN GRANULATION AND THE EXCITATION OF SOLAR OSCILLATIONS

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ABSTRACT

We made simultaneous, high-resolution observations of the Sun’s granulation and solar acoustic events in the photosphere. We find that the acoustic events, which are a local by-product of the excitation of solar oscillations (Goode, Gough, & Kosovichev 1992), occur preferentially in the dark, intergranular lanes. At the site of a typical acoustic event the local granulation becomes darker over several minutes leading up to the event with a further, abrupt darkening immediately preceding the peak of the event. Further, the stronger the acoustic event the darker the granulation. Thus, the excitation of solar oscillations seems more closely associated with the rapid cooling occurring in the upper convection layer, rather than the overshooting of turbulent convection itself.

We find no substantial role for so-called “exploding” granules in the excitation of solar oscillations.

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

1. INTRODUCTION

It is commonly acknowledged that 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 clarify the process by which the oscillations are excited.

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 coexisting with narrow, downdrafting plumes which are sometimes hypersonic, for a review see Nordlund & Stein (1991). Since the characteristics 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 downdrafts. However, since they are faster and narrower than the updrafts, perhaps the downdrafts are “noisier” too. One further wonders whether a special contributor to the excitation of the oscillations might be rapidly expanding granules which become dark in their middle, i.e., “exploding” granules. Rast (1995) argued from simulations of subsurface convective flows that particularly sharp downdrafting plumes arise at the center of exploding granules.

Goode, Gough, & Kosovichev (1992) used the data of Steb-
at 100 spatial points, enabling them to simultaneously select 5 minute period power, which is below the acoustic cutoff, and power below the minimum horizontal wavenumber for traveling atmospheric gravity waves. This focus enabled them 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 nontransient 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, & Goode (1993) realanalyzed the data of Stebbins & Goode (1987) to demonstrate that the aforementioned average properties arise from acoustic events which have the same temporal sequencing and spatial predicted in the model calculations of Goode et al. (1992). That is, an event is characterized by a peak in the ongoing 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.

Here we report and discuss the implications for our understanding of the excitation solar oscillations from the results of our new, simultaneous, high resolution observations of granulation in white light and acoustic events in three dimensions.

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out on 1994 February 15 and 1994 September 5 at the Vacuum Tower Telescope of the National Solar Observatory at Sacramento Peak, New Mexico. Our high-resolution observations of acoustic events and granulation were performed on a roughly 90° x 90° (February 15) and a 60° x 60° (September 5) patch of quiet Sun at disk center. The real time Ha image provided by the Hilltop Facility was used to identify active regions which then were avoided. We obtained velocity and phase information on the acoustic events at altitudes spanning the photosphere. The 20 m\(^2\) passband filter consisting of the Universal Birefringent Filter (UBF) and a Fabry-Perot interferometer (Bonaccini & Stauffer 1990) was used to scan the profile of the magnetically insensitive (\( g = 0 \)) Fe I 5344 Å line. The narrowband filters were recorded with a RCA504 CCD-camera; the pixel resolution was 0.29 pixel\(^{-1}\) (February 15) and 0.19 pixel\(^{-1}\) (September 5), respectively. Exposure times were typically 150-300 ms. In addition to the narrow band filters, broadband images were recorded simultaneously with a second CCD-camera.

The profile of the line Fe I 5343 Å 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 (February 15) and 122 (September 5) 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 (Rimmmele et al. 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 Rimmmele (1995).

From the Fe I 5344 Å spectral profiles recorded at each spatial position in the 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 four-dimensional data structure, \( (x, y, z, t) \), 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 \( k - \omega \) space in order to eliminate those contributions to the velocity signal which do not belong to the temporal-spatial frequency domain of the five minute acoustic oscillation. In detail, we bandpass temporal frequencies; no spatial filter was applied. Then, the velocities are returned to the time domain employing a Hilbert transform, for further details see Restaino et al. (1993) and references therein.

As the final step of the data reduction, we calculate the acoustic flux as a function of time, spatial position in the FOV and altitude in the photosphere. Following Restaino et al. (1993), we note that in the part of the \( k - \omega \) 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,

\[
\frac{V^2}{\omega} \frac{\Delta \phi}{\Delta \sigma},
\]

where \( V \) is the velocity amplitude and \( \Delta \phi/\Delta \sigma \) is the observed phase gradient with altitude of the event.

3. GRANULATION AND ACOUSTIC EVENTS

We produced video movies that show a time sequence of destretched granulation images with the acoustic flux overlaid as a contour plot. Both the movies produced from the February 15 and the September 5 data clearly show that acoustic flux events predominately occur in dark intergranular lanes. In Figure 1 (Plate L13), the time evolution of typical acoustic events is shown illustrating their spatial and temporal isolation. The acoustic flux was computed from the bisector velocities measured at two intensity levels in the wings of the Fe I 5344 Å line, i.e., for altitudes near the base of the photosphere. Time proceeds from the upper left to the lower right. The spatial extent of the flux events seen is on the order of 1". The largest acoustic event in the plate starts off in a dark lane (arrow). As time proceeds, the event continues to grow for a few frames while at the same time the continuum intensity decreases at the location of the flux event. As the upward-flux event (bright contours) fades away into the dark a downward flux event (dark contours) develops at the same location as a result of reflection in the atmosphere. The downward flux grows for a few frames and then also fades away. A second event, that apparently started off a few frames before the first frame in Figure 1, appears at the edge of a bright granule. Also in this case the granule begins to darken during the event and a lane forms at the same location. Quite often, lane formation and acoustic events go together in this way. In a few cases, we observed flux events to start off in the center of a bright granule which during the event developed a thin dark lane with 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 associated with strong flux events.

We computed the mean intensity of the granulation at the
Fig. 1.—20 panels show the time evolution, in 30 s steps, of an acoustic event superposed on the granulation. The spatial coverage of each frame is about $8'' \times 10''$. Each acoustic event is represented in a contour plot which reveals its spatial extent and intensity. Positive (upward) flux is plotted as white contour lines, negative (downward) flux is shown as dark contour lines. The contour lines shown correspond to flux amplitudes of $0.6 \times 10^8$, $1.0 \times 10^8$, $1.4 \times 10^8$ and $-0.2 \times 10^8$, $-0.5 \times 10^8$ (ergs cm$^{-2}$ s$^{-1}$), respectively. The acoustic event indicated by the arrow begins to appear in a), grows and fades away after about 10 frames (5 minutes). Subsequently a downward flux begins to grow at the same location and also fades away.

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Fig. 2—Mean intensity (solid line) measured at the location of large flux events as a function of the time in minutes. The amplitude of the flux events (dotted line) is overlayed. The dashed line is the mean intensity of all the granulation.

location of large flux events by locating events in space and time that reach amplitudes above a certain threshold ($0.8 \times 10^8$ ergs cm$^{-2}$ s$^{-1}$) and averaging the intensity values at the pixels that have an acoustic flux above this threshold. Figure 2, we show the mean flux amplitude and the mean intensity at consecutive time steps. The figure clearly indicates that flux events predominantly occur in regions where the intensity is below the average intensity of the granulation (dashed line). Also apparent is an anticorrelation between flux and intensity indicating that the strongest flux events occur in darkest regions of the granulation.

From Figure 1, it is not easy to say when the granular darkness peaks in the life of the two acoustic events discussed there. Figure 3a shows the evolution in time of the acoustic flux and the normalized continuum intensity at one spatial location. The two large flux events 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 events that show the same behavior of flux and intensity seen in Figure 3a. Figure 3b gives a further indication that this behavior is common to most flux events. A large number of flux events were registered in time by using the flux maximum of each event as the common reference point. The flux events were then averaged. In addition, the corresponding average continuum intensity profile was computed. The intensity profile shows a dip bottoming on the rising edge of the average flux event followed by a subsequent increase in intensity. The sharp intensity variations seen in the examples of Figure 3a are to a large extent smeared out in the averaged intensity profile in Figure 3b. This is mainly due to the variations in the time lag mentioned above and due to insufficient resolution caused by seeing. However, Figure 3b 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. Perhaps this darkening (cooling) reflects an increasingly substantial downdraft. Further analysis concentrating on the connection between acoustic flux and convective velocities, preferably measured at deep photospheric layers, is required to verify this hypothesis.

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In Figure 4 (Plate 14), the time average of the acoustic flux is shown superposed on the mesogranular flow field. The mesogranular field is determined from the proper motion of granules seen in the one hour September 5th time sequence of broadband filtergrams using the algorithm described by November & 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. From Figure 4, we emphasize that the acoustic events are not uniformly distributed. Instead, they appear in patches which are about the same size as a mesogranule. Although it cannot be seen from the figure, the events are temporally isolated, as well. As can be inferred from the video movies, there are some intervals that are several minutes long in which no large acoustic events appear in the FOV. Even though in the time averaged flux map the patches of acoustic flux have about the same spatial scale as mesogranules, they do not seem to be correlated with either the diverging or converging mesogranules. Instead the patches may be associated with the regions and times of greatest cooling in the intergranular lanes. It also should be noticed 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.

4. DISCUSSION

Solar oscillations are preferentially excited just beneath the photosphere in the dark lanes of convective downflows in the granulation. Typically, the formation or expansion of a dark lane immediately precedes the appearance of an acoustic event in that lane, and the largest events arise from the most severe darkening. This suggests that the most rapidly cooling regions of the surface generate the most acoustic noise. The abrupt darkening on the leading edge of the typical acoustic event is promptly followed by an increase in intensity as though the acoustic events arose from a combination of the noise made by the rapid cooling and collapse of the surface and the filling of the void left behind. Based on simulations Rast (1993) indeed proposed this mechanism as a possible source of acoustic noise.

If the most rapidly cooling regions coincident with the strongest convective downdrafts, then our results could be consistent with numerical simulations of subsurface convection in which the strongest downdrafts tend to be confined to narrow plumes which are fast moving. That is, the onset of these narrow plumes at the surface is abrupt and might disproportionately induce acoustic waves, Rast (1995). The time-averaged acoustic flux map reveals that the acoustic events are organized on a roughly mesogranular scale, but their clustering does not appear to coincide with the surface mesogranulation. The degree of spatial and temporal isolation of the events is very likely associated with a corresponding isolation of regions of most rapid surface cooling.

If we assume the FOV is typical of the Sun, then the power expended in the acoustic events near the base of the photosphere (10^{18}–10^{19} ergs s^{-1}) is comparable to that required to power the solar oscillations (10^{28} ergs s^{-1}).

We see no major role for exploding granules in the creation of acoustic events, and thereby, solar oscillations. However, our resolution is insufficient to say that exploding granules play no role. Furthermore, we require better resolution to more clearly see the contemporaneous evolution of acoustic events, granulation and mesogranulation. To these ends, we need to probe deeper into the Sun's atmosphere. For this sharper probing, we are currently studying lines which are formed more deeply—the 5380 Å C I line in the visible and the 15648 Å Fe I line in the infrared.

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Fig. 4.—Time average of the acoustic events is shown superposed on the divergence of the mesogranular flow field. The FOV is 53" x 52". The acoustic events are represented by a contour plot of sharp white lines. The contour levels shown correspond to flux amplitudes $0.8 \times 10^7$, $1.2 \times 10^7$, and $1.5 \times 10^7$ ergs cm$^{-2}$ s$^{-1}$, thus representing the upper end of the histogram of the time averaged flux, which has its median at $0.7 \times 10^7$ ergs cm$^{-2}$ s$^{-1}$. The mesogranulation is shown in gray-scale and is determined by tracking the flow of the granules over the hour-long dataset. The brighter the gray scale, the more divergent the flow, and conversely, the darker the scale, the more convergent the flow.

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