Simulations of Acoustic Emission by Turbulence

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Abstract

Acoustic emission from solar granulation is thought to be relatively localized and episodic, emanating largely as relatively discrete wavepackets emitted from convective plumes falling into the solar interior from near-surface layers at which granular convection takes place. This quality, if it actually does characterize seismic emission from the quiet Sun, is crucial, in certain respects, to meaningful diagnostics of how waves are generated by turbulence. Local helioseismology has developed a formidable diagnostic tool case to test this hypothesis and similar questions regarding wave generation in the upper convection zone. Comparative seismic diagnostics applied both to the quiet Sun and to simulations of convection on powerful computing facilities offer a much needed control facility for this purpose.

I. Introduction

The physics of the excitation of the p-modes has been a problem of long-standing interest (Stein 1967; Stein & Leibacher 1974; Goldreich & Keeley 1977; Goldreich & Kumar 1988; Samadi et al. 2003; Balmforth 1992; Stein et al. 2004a,b; and many others). Based largely on work by Goldreich & Kumar (1988), Brown (1991) proposed that wave generation by turbulence should be relatively episodic and localized, even if quite stochastic. Wave generation by turbulence at any particular location is proposed to be characterized by momentary periods during which the acoustic power being generated is discernibly greater than would be characteristic of stationary Gaussian noise with the same average power. This localized, episodic character of wave sources, if such it is, is critical to the discrimination of waves generated by turbulence from stationary, Gaussian noise. Simulations of tubulence taking advantage of powerful computing facilities at the advent of HMI are the key to the basic control work needed to understand what the signatures of seismic diagnostics applied to the quiet Sun actually signify.

Seismic power spectra computed from computations Stein et al. have done to date are most encouraging (see Figure 1). They suggest that the turbulence computations are reproducing wave generation realistically. However, diagnostics of localized, episodic emission are more particularly in the province of local than spectral helioseismology. Indeed the term "episodic" refers to localization in time just as "local" refers to localization in space. In either domain "locality" is significantly antithetical to "spectrality," as expressed by the Heisenberg principle. Spectral discrimination, either in wave number or temporal frequency, is attained at significant expense in both spatial and temporal discrimination for purposes of discriminating stochastic seismic emission by turbulence. In reducing the observations to high-resolution power spectra, either temporally or spatially, information respecting local, episodic behavior is essentially lost.

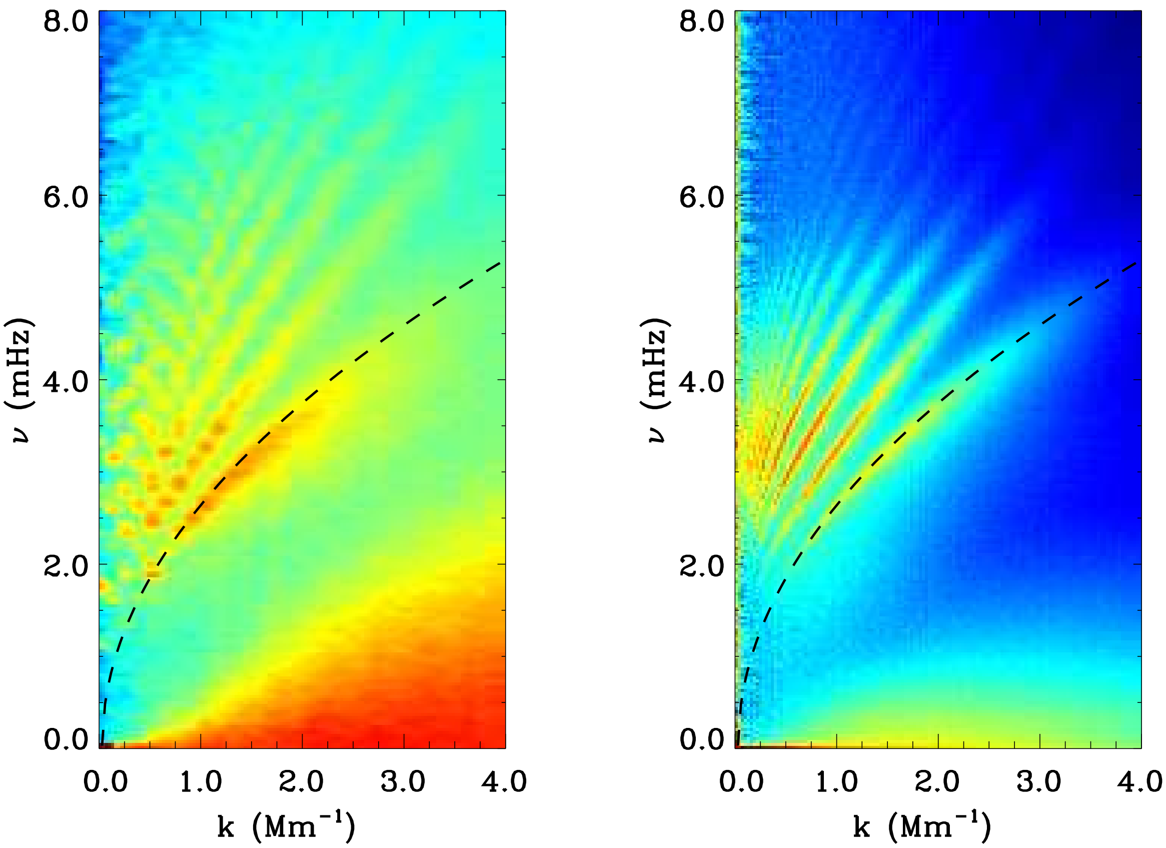

Figure 1: Power spectra of seismic emission from simulations of turbulence (left) match those of the quiet Sun (right) remarkably well.

II. Holographic Signatures of Acoustic Emission

Helioseismic holography (Lindsey & Braun 2000) is the computational reconstruction of the acoustic field, $\psi(\mathbf{r}', \omega)$, observed at the solar surface, $\mathbf{r}'$, into the solar interior $\mathbf{r}$, to render a phase-coherent representation, $H_+(\mathbf{r}, \omega)$, of subsurface acoustic field whose propagation to the surface from locations specified by $\mathbf{r}$ has given rise to the surface disturbance at $\mathbf{r}'$. In effect, acoustic disturbances observed at the solar surface, $\mathbf{r}'$, are applied to the surface of a model of the quiet Sun and propagated backwards in time into the model interior to reconstruct the field $H_+(\mathbf{r}, \omega)$, which is called the "coherent acoustic egression." Any particular point in the model at which the regressed acoustic field is sampled is called a focus, or focal point of the computation. A surface of constant depth over which the regressed acoustic field is sampled is called a "focal plane," if the plane-parallel approximation applies. In practice computation of the acoustic egression at a given focus takes into account surface disturbances within a limited region overlying the focus, called the pupil of the computation.

Because nearly all of the acoustic radiation from a surface refracts back to the surface, mostly within 50 Mm, holography can image surface sources many from the pupil. The technique for this is called “subjacent vantage holography” (see §4 of Lindsey & Braun 2000). The practical application of subjacent vantage holography is illustrated for a simple dipole wavepacket emitter in Figure 2, below. We solve the wave equation in the standard solar model of Christensen-Dalsgaard (1993) for the acoustic field emanating from a single dipole emitter. A “snapshot” of the resulting acoustic field is shown in the left and middle frames of Fig 2. Subjacent vantage seismic holography applied to the surface disturbance shown in the middle frame of Fig 2 with a 15–60 Mm pupil over the a 2 hr period gives rise to the regressed acoustic field shown in the right frame of Figure 2. A comparison between left and right frames illustrates of how seismic holography actually works in practice.

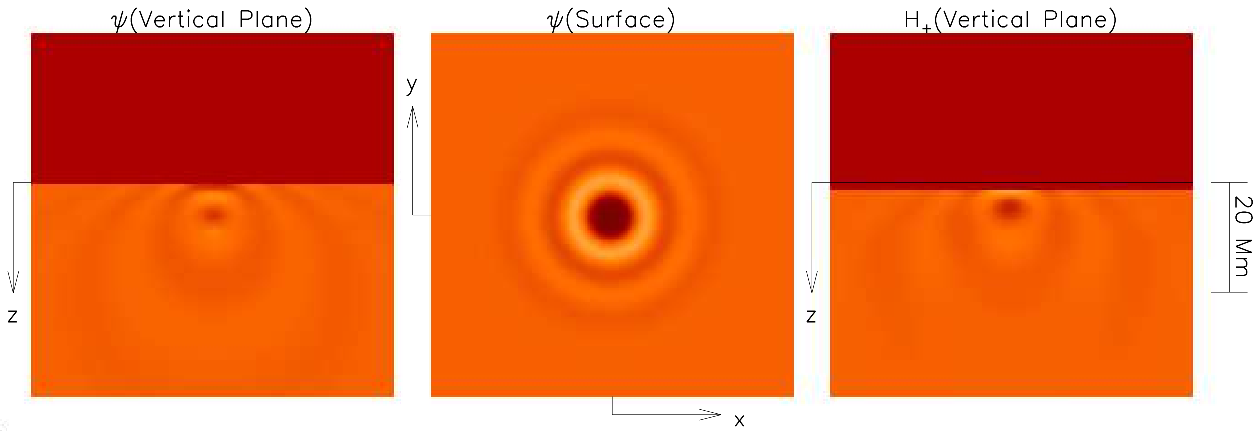

Figure 2: Holographic regression applied to a simulation of the surface acoustic disturbance of a submerged dipole emitter, computed as prescribed by Birch & Kosovichev (2004). A vertically oriented dipole oscillator 7 Mm beneath the surface of a solar model emits a Gaussian wave packet with a wave period of 5 min and half-power duration 8.5 min. Left frame shows the acoustic field, ψ, in a vertical plane containing the emitter 10 min after maximum source power. Middle frame shows ψ at the overlying photosphere at the same moment. Right frame shows the egression, H_+, in the same vertical plane as the left frame at the same moment below 1.4 Mm, computed from the surface signature over a 2 hr period with a 15–45 Mm pupil.

Seismic holography is specifically designed for optimum local discrimination of acoustic sources, both temporally and spatially. As such, it has been particularly useful in the reconstruction of the sources of obviously local, episodic emission such as acoustic transients emitted from solar flares (Donea, Lindsey & Braun 1999; Donea & Lindsey 2005; Donea et al. 2005, see Fig 3) and acoustic emission halos surrounding active regions (Donea, Lindsey & Braun 2000).

To study the episodic nature of acoustic emission in the quiet Sun, it is best to focus on the spectrum above 4.5 mHz. At lower frequencies, where the photosphere acts as an efficient specular reflector, accumulated acoustic energy multiply reflected at the solar surface from a great distance competes with locally generated energy to the great disadvantage of the latter.

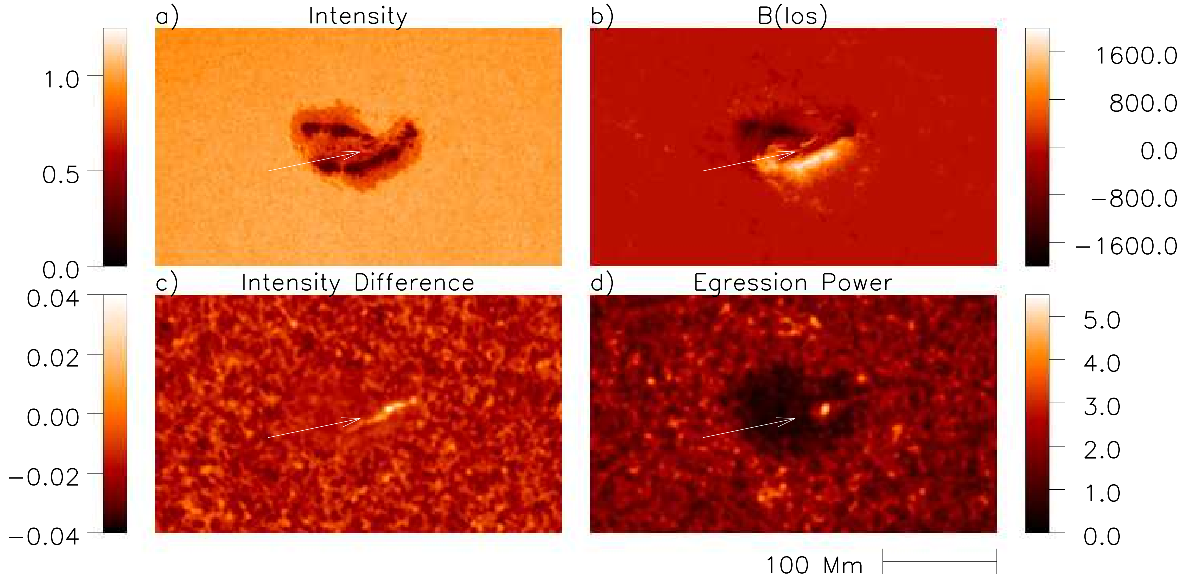

Figure 3. Using seismic holography to map seismic emission from flares, Moradi et al. 2005 discovered the spectacular seismic transient (sun quake) from the X2.6-class flare of 2005 January 15 in the 4.5–5.5 mHz spectrum. Panels a and b show continuum intensity and line-of-sight magnetic maps respectively of NOAA AR10720 at 01:36 UT. Panel c shows impulsive continuum emission from the photosphere between 01:41 UT and 01:37 UT. Panel d shows surface egression power at 01:40 UT, representing radiation emitted into the active region subphotosphere in the 4.5–5.5 mHz spectrum and refracted back to the surface over the next hour from 15–45 Mm the flare.

Braun & Lindsey (1992) and Brown et al. (1992) independently discovered enhanced acoustic disturbances on the outskirts of active regions, based on acoustic power maps in the 5–7 mHz spectrum. Brown et al. (1992) suggested that the localized nature of these enhancements was statistically characteristic of wave generation by turbulence. However, the statistical character of acoustic power in the quiet Sun is quite different in many respects from that in the neighborhoods of active regions. Donea, Lindsey & Braun (2000) saw no evidence of episodic emission in the quiet Sun in statistics of holographic signatures. However, Goode et al. (1998) and Strous, Goode & Rimmele (2000) report statistics compiled from a large number of individually identified seismic events in the quiet-Sun acoustic field that support some degree of localized wave generation.

III. A Statistical Experiment

To illustrate what we see as major issue of the problem of discriminating local episodic seimsic emission from stationary Gaussian noise, we simulate acoustic emission from the solar granulation by randomly distributing episodes of dipole emission beneath a plane-parallel model subphotosphere. The episodes are distributed over a surface domain whose horizontal extent is 256 Mm in both dimensions and over a period of 4 hr, and linearly superposing the resulting surface disturbances.

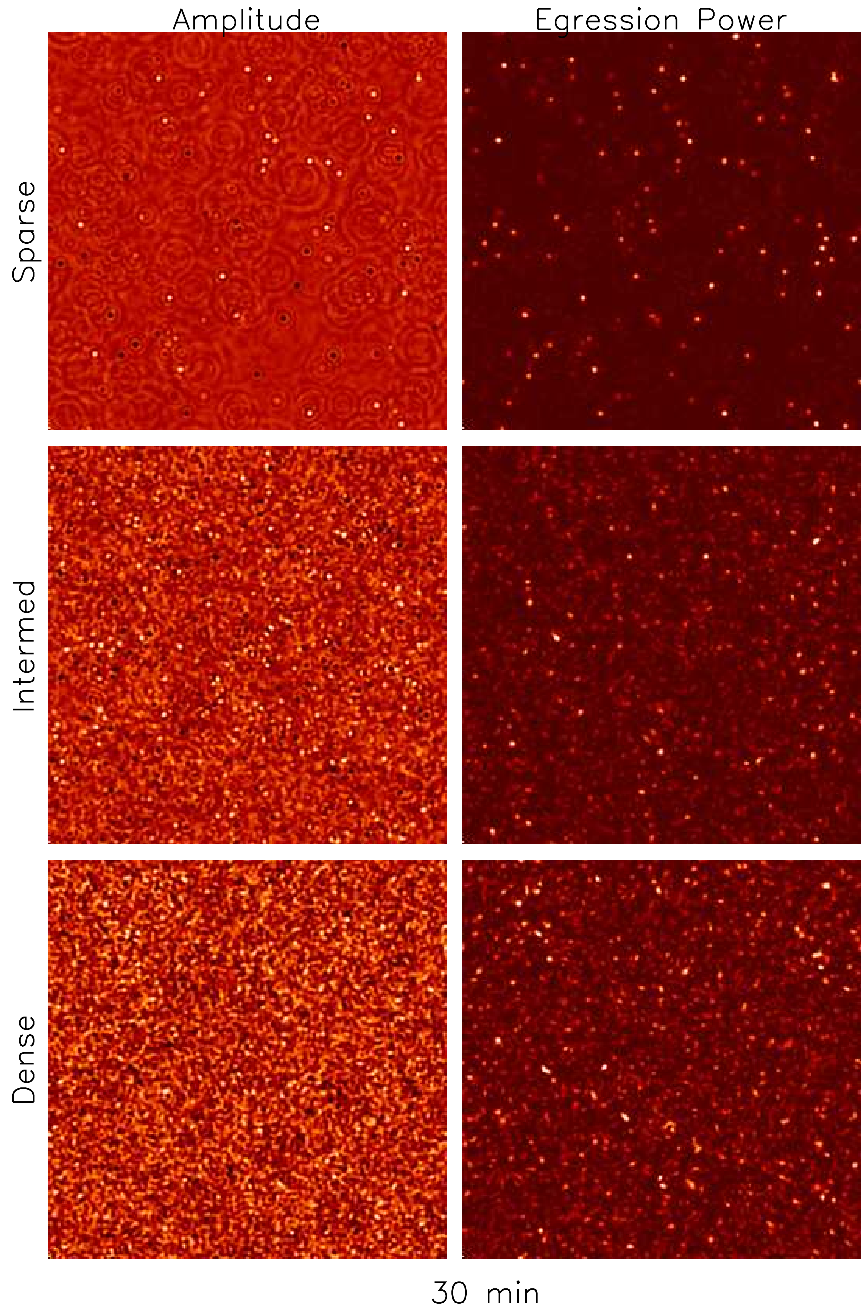

Figure 4: Simulations of surface seismic disturbances from random dipole wave packet emitters (left column) computed as prescribed by Lindsey & Braun (2004) and concurrent egression power snapshots (right column). In the top row, labeled "Sparse," dipolar wavepackets are excited at a mean rate of 10^{-4} episodes/Mm^2/min, and circular ripples from individual episodes are easily discriminated by eye. In the middle and bottom rows, labeled "Intermed" and "Dense," the rates are 10^{-3} and 10^{-2} episodes/Mm^2/min, respectively.

Snapshots sampling acoustic fields corresponding to different mean episodic rates are shown in the left column of Figure 4. For these examples the emitters are at a depth of 1 Mm, the nominal frequency is 5 mHz, and the wave packets have a half power duration of 500 s. The top row, labeled "Sparse," shows a snapshot of the acoustic amplitude for a mean rate of 10^{-4} episodes/Mm^2/min. For the middle and bottom rows, "Intermed" and "Dense," the rates are 10^{-3} and 10^{-2} episodes/Mm^2/min, respectively.

The right column of Figure 4 shows egression power snapshots concurrent with respective frames in the left column. The egression power signatures tend to be somewhat more localized (point-like) and transient than those of the acoustic field itself, the latter showing circular ripples spreading outward from each source from 15 to 45 min after the source itself has died.

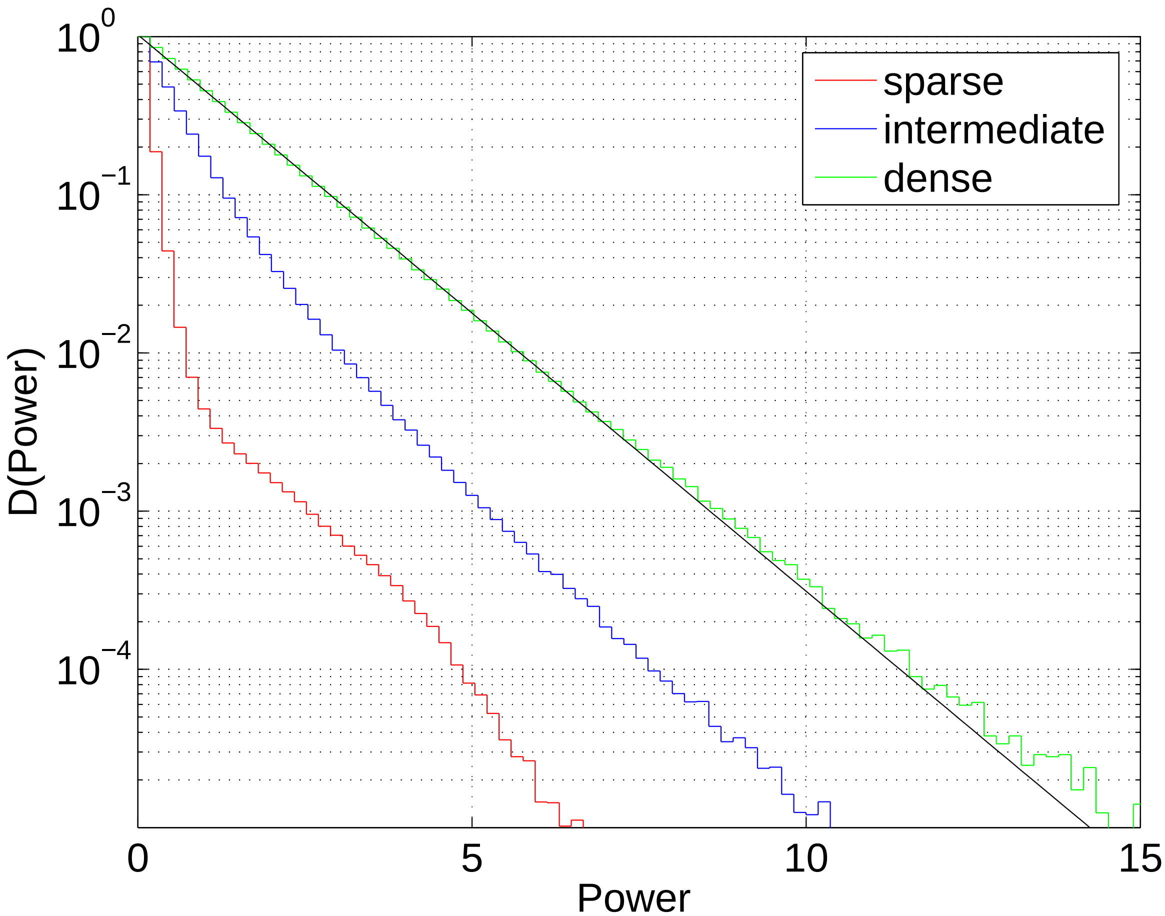

Figure 5: Histograms of egression power corresponding to simulated acoustic fields represented in Figure 4. As the density of episodes increases, the log of the distribution in egression power approaches a straight line, characteristic of random Gaussian noise. In the case of a dense distribution of episodes (0.01 episodes/Mm^2/min, green curve labeled "dense"), the episodic character of the acoustic emission is indicated by the slight positive curvature of the log of the distribution. An approximately parallel straight line through the dense distribution reveals the positive curvature by comparison.

We now compile statistics from egression power snapshots over the 4-hr duration of the computation illustrated in Figure 4. These are plotted logarithmically in Figure 5. If acoustic emission from the quiet solar photosphere were stationary Gaussian noise, the distribution in the egression power would be exponential, which in the logarithmic plots of Figure 5 would be straight lines. If it is episodic or relatively localized to a significant degree, the acoustic power distribution should depart discernably from exponential and generally must be concave over some part of the domain.

As the density of acoustic emission episodes increases, the log of the distribution in egression power spreads to higher values and approaches a straight line. In these simulations the log of the distribution of acoustic power for the largest density of episodes, 0.01 episodes/Mm^2/min, may appear straight at first glance. However, it's concavity is apparent by comparison with a roughly parallel straight line.

IV. Discussion/Summary

Rast (1999), Skartlien & Rast (2000), and Rast (2005 private communication) suggest that downflowing plumes over a region of $\sim$1 Mm^2 in area should give rise to episodes of seismic emission with an average interval of $\sim$15 min between episodes, about 6 times the episode rate represented by the "Dense" distribution plotted in Figure 4.

The logarithm of the egression power distribution Donea, Lindsey & Braun (2000) found for the quiet in 4.5–6.5 mHz acoustic noise was straight to within the errors of their statistics, the curvature significantly less than that shown by the logarithm of the "Dense" distribution plotted in Figure 4. Preliminary indications are that the egression power time series computed by Donea, Lindsey & Braun (2000) were simply of insufficient spatial resolution (approximately 4 Mm) to resolve episodes as frequent as those predicted by Rast (1999), Skartlien & Rast (2000), and Rast (2005 private communication). If this is the case, a repeat of the computations of Donea, Lindsey and Braun computations with smaller pupils applied to high-resolution MDI observations should secure the finer spatial resolution needed to discriminate the profile of episodic emission.

The advantages of control computations on realistic simulations of acoustic emission by turbulence should be evident. These allow us to compare the diagnostic signatures directly with what is happening in the emitting layers in a way that is impractical in the subphotosphere of the Sun itself. We are presently working out plans to do this with R. Stein. These have been shown to give rise to realistic facsimiles of the solar p-mode spectrum. We expect major new insight into local seismic diagnostics from these tests.

A large variety of other prospective tests promise insight into the generation of waves by turbulence. These include statistical correlations between egression power and proximity of the focus to an intergranular lane, for example, bearing in mind that the intergranular lanes are the source of downflows that Rast proposes are the primary sources of seismic emission. However, these correlations are subject to the influence of magnetic flux tubes, which in the quiet Sun are known to suppress seismic emission, and these tend to be swept into intergranular lanes. This reinforces the need for simulation that achieve as realistic as possible a representation of magnetic flux elements. It also reinforces the need for the simultaneous, high-quality Doppler, intensity, and Stokes magnetic observations HMI will give us.

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