Seismic Emission from Solar Flares

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I. Introduction

Based on the detection of more than a dozen seismic transients from MDI observations of flares during Solar Cycle 23, we tentatively expect 2–3 dozen such "sun quakes" with the high-resolution, high-quality, nearly continuous coverage of Cycle 24 by SDO/HMI. Seismic emission from flares offers major new insight both into flare physics and helioseismology, ranging from a greatly improved understanding of basic flare MHD to a prospective acoustic flash light to calibrate how seismic emission is generated differently by turbulence in magnetic subphotospheres from noise generated in the quiet Sun. The technical challenges are formidable, but entirely appropriate for the advent of HMI. If these are addressed successfully, there is good reason to expect major scientific rewards from HMI-based studies of seismic emission from flares during Cycle 24.

II. Review

The first known instance of seismic emission from a solar flare was discovered by Kosovichev and Zharkova (1998) in MDI observations of the X2.6-class flare of 1996 July 09, who introduced the term "sun quake" for the phenomenon. It soon became clear that flare acoustic emission at detectable levels was far from ubiquitious, even in much more energetic flares. Indeed, no further seismic emission transients from flares were discovered in Cycle 23 until an exhaustive survey of the entire MDI database by Donea and Besliu-Ionescu (`http://www.maths.monash.edu.au/~adonea/DATABASE_SUNQUAKES/DIANA/-site_statie/sunquakes.html`) uncovered more than a dozen flare acoustic transients over the past year. These ranged from considerable seismic transients emitted from relatively small (M9.5-class) flares to the most conspicuous seismic transient of Cycle 23 (at this writing), which emanated from the moderate X2.6-class flare of 2005 January 15. With excellent supporting observations from other modern space-borne observatories (e.g. RHESSI and TRACE) and ground-based facilities (e.g. GONG), Donea and Besliu-Ionescu's survey has led to a remarkably consistent and compelling perspective into some of the basic physical processes whose operation could underlie seismic emission from flares. This perspective can be broadly summarized by the following points:

1) The sites of flare acoustic emission are generally compact, and concide closely, both spatially and temporally, with compact, impulsive sources of hard X-ray emission (Donea & Lindsey 2005). This is consistent with the suggestion by Kosovichev and

Zarkova (1998) that flare acoustic transients are the subphotospheric continuation of shocks driven by thick-target heating of the chromosphere by energetic particles.

2) The sites of seismic emission are generally sites of similarly compact, sharply red-shifted chromospheric line emission, indicating chromospheric shock propagating downward toward the photospheric site of the seismic emission. However, significant acoustic emission does not always occur where the red-shifted chromospheric emission occurs.

2) The sites of seismic emission concide strongly with impulsive visible continuum emission, i.e. white-light flares. This suggests that transient seismic emission from flares could be largely driven by impulsive heating of the low photosphere.

3) Signatures of high-energy protons in some flares, such as the large X10 and X17-class flares of 2003 October, suggested direct photospheric heating caused by protons penetrating into the low photosphere (Donea & Lindsey 2005).

4) Apparent magnetic transients in GONG and MDI magnetograms (Donea et al. 2005) suggest the possibility of seismic emission due to sudden shifts in magnetic tension forces in the photosphere as a result of reconnection.

Prospective contributions to seismic emission from flares are by no means exhausted at this point, nor are the more promising prospects by any means secured. The contribution of transient magnetic forces in the photosphere to seismic emission remains an open question, due to concerns of transient molecular contamination during flares. Indeed, both Doppler and magnetic signatures in sunspots are subject to spurious transient signatures in sunspots in white-light flare conditions due to contamination by molecular lines. This concern is briefly outlined in §III, below.

Heating of the chromosphere by energetic electrons drives a well-known downward-propagating shock (Fisher, Canfield & McClymont 1985a,b,c), whose signature appears in the spectral profiles of chromospheric lines such as H-α (Zarro et al. 1988) and NaD_1 (Donea & Lindsey 2005). However, this shock is thought to be largely dissipated by radiation long before its arrival into the low photosphere (Machado, Emslie & Avrett 1989).

Radiative losses would be substantially circumvented in the case of seismic emission driven by *heating of the low photosphere* during a flare. This suggestion, by Donea and Lindsey (2005) was reinforced by the signature of high-energy protons in the flares of 2003 October. However, Donea and Besliu-Ionescu proceeded to discover major instances of seismic emission from relatively small, non-protonic flares.

In fact, evidence of flare acoustic emission driven by heating of the low photosphere remains compelling even in non-protonic flares. At this writing *all instances of seismic emission are characterized by a close spatial correspondence between seismic emission and sudden white-light emission during the impulsive phase of the flare.* This includes the seismically spectacular but non-protonic X2.6 flare of 2005 January 15 (Moradi et al. 2006).

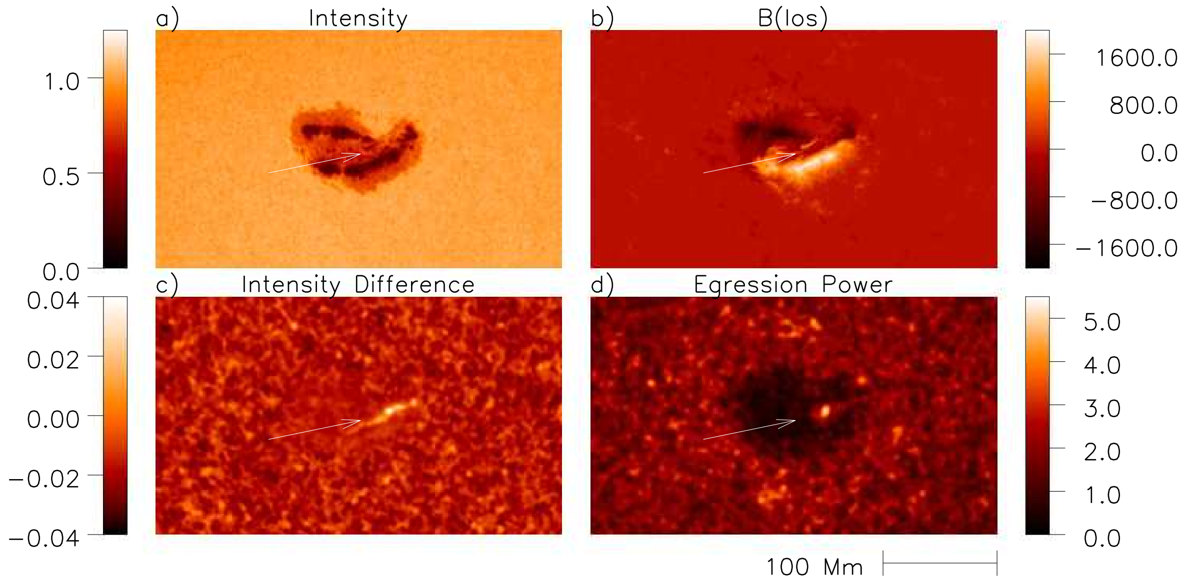

Figure 1. Close correspondence between sudden visible continuum emission in the impulsive phase of the X2.6-class flare of 2005 January 15 and seismic emission in the 4.5–5.5 mHz spectrum. Panels a and b show continuum intensity and line-of-sight magnetic maps respectively of NOAA AR10720 at 01:36 UT. Panel c shows the difference in continuum intensity between 01:41 UT and 01:37 UT. Panel d shows the egression power at 01:40 UT. Taken from Moradi et al. 2006.

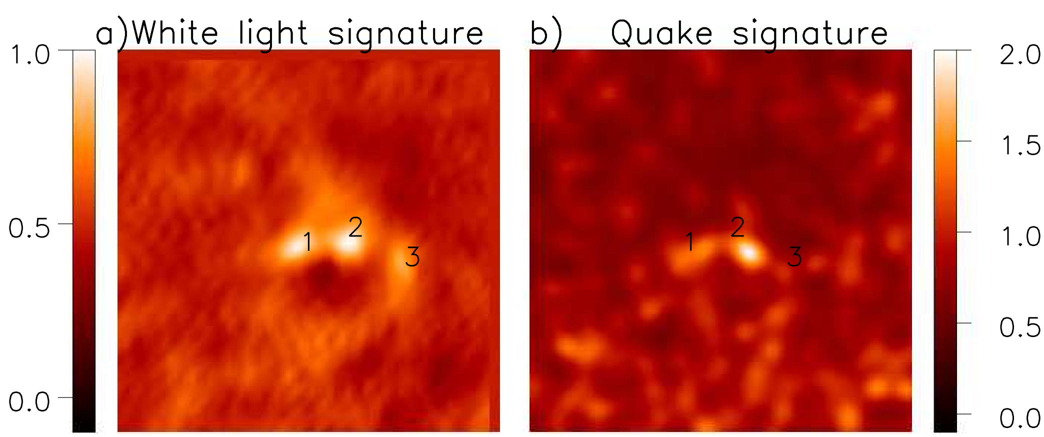

Figure 2. Visible continuum emission (Frame a) and 4.5–5.5 mHz seismic emission (Frame b) from the M9.5-class flare of 2001 September 09 from NOAA AR9608 at 20:44 UT. Taken from Donea et al. 2005.

How photospheric photospheric heating occurs in the relatively small, non-protonic is a problem of considerable interest both to helioseismologists and flare mechanics, given that our present understanding that the significant source of white-light emission is the chromosphere, not the photosphere (Hudson 1972, Metcalf et al. 2003). In fact, the radiative fluxes characteristic of the emission seen in all acoustically active flares, if emitted downward from the chromosphere as well as upward, are sufficient to heat the photosphere a few percent within a few seconds of the onset of the incoming radiative flux. This process, described by Machado, Emslie & Avrett (1989), is called "back-warming." Metcalf, Canfield & Saba 1990

Based on a rough physical model of acoustic transient emission in response to sudden heating of the low photosphere, Donea et al. (2005) estimate the efficiency of seismic emission from a non-magnetic photosphere to be of order

$$E = \frac{1}{12} \frac{\Delta I_c}{I_c} U, \tag{1}$$

where $\Delta I_c/I_c$ is the sudden compoent of fractional variation in the continuum intensity, I_c, over the emitting region and U is the thermal energy invested into sudden heating of the photospheric medium. The latter, U, can be roughly equated to half of the total excess energy radiated by the flare in the ideal case of infinitely sudden heating with no gradual component. The continuum signatures for the flares of 2005 January 15 (Moradi et al. 2006, see Fig 1) and 2001 September 9 (Donea et al. 2005, see Fig 2) were quite sudden, and the relation between E, U and $\Delta I_c/I_c$ was comfortably consistent with equation (1) for both of these.

The rough model based on sudden photospheric heating is consistent with the relative seismic inefficiency of all acoustically active flares cited by Donea & Lindsey (2005). To the extent that U itself is in linear proportion to ΔI_c, we might expect flare acoustic emission in proportion to $(\Delta I_c)^2$, meaning that the seismic transient emanating from a large highly energetic white-light flare could be undetectable if the source of excess continuum emission is spread over a relatively large area. This would reinforce the strong tendency for seismic emission to emanate from sources that are relatively compact even when the signature white-light emission is quite diffuse.

At the same time, acoustic emission from flares offers positive evidence of actual kinetic heating of the photosphere during white-light flares even in the absence of protons. Seismic emission from non-protonic flares can therefore be regarded as significantly supporting the back-warming theory (Machado et al. 1989).

Prospective Science Based on HMI Observations of Seismic Emission from Flares

Following is a brief summary of scientific issues and applications of HMI observations of seismically active flares:

- *Modeling of flare emission driven by photospheric heating.* Evidence for this as a major contributor based on rough approximations is now considerable, certainly enough to justify the development detailed models. Detailed models of seismic emission in realistic active region subphotospheres would greatly improve our understanding of acoustically active flares both for the benefit of helioseismologists and flare mechanics. Credible models would need to include (1) realistic subphotospheric thermal anomalies to represent penumbral and perhaps umbral subphotospheres, and (2) realistic photospheric magnetic fields extrapolated to depths of a few hundred km beneath the photosphere. The latter should include an account for the highly inclined magnetic fields that characterize sunspot penumbrae. Inclined fields appear to be critical in seismic signatures of the "penumbral acoustic anomaly" (Lindsey & Braun 2005a) and crucial to an effect called "inclined magnetic phase parallax" (Schunker et al., 2005), which we interpret as a signature of conversion of p-modes to "slow magneto-acoustic" waves in the shallow subphotosphere.

- *The question of magnetic force transients in the photosphere.* The technical challenges of this issue, listed in Item (4) above, are considerable. They are summarized in §III.
- *Applications to magnetohelioseismology.* Observations of flare emission in inclined magnetic regions from two vantages may be practical in the advent of the ESA's Solar Orbiter, planned for launch in 2015. This could give us a powerful control facility for the discrimination of slow magnetoacoustic wave excitation, and considerations relative to issues respecting mode conversion.
- *Applications to subphotospheric diagnostics.* Seismically active flares can be applied as "seismic flash lights" with which to examine the subphotospheres that underly sunspot penumbrae. In fact, sun quakes are the single example we have of seismic sources that are directly visible to our view. A careful comparison of "local egression control correlations" focused on acoustic emission from flares and on waves otherwise generated by turbulence could give us some insight into the difference between turbulence-generated waves in magnetic subphotospheres and the same in quiet subphotospheres. The considerable technical challenges are summarized below.

III. Technical Considerations

- *Scattered light.* Flare acoustic emission usually comes predominantly from sunspot penumbrae. Some part of the source may extend into the umbra in certain instances (e.g. seismic emission from δ-configuration sunspots). The opticl performance of the HMI in these relatively dim regions is therefore a major concern. However highly the HMI performs, we anticipate the need for a careful account of the effects of scattered light in Doppler and magnetic signatures of sunspot photospheres.
- *Supporting observations.* Observations from other space-borne and ground-based solar observing facilities (e.g. RHESSI, TRACE, GONG) have been critical to what we now understand of seismic emission from flares based primarily on MDI. We should suppose that this will remain the case, with Solar B and possibly the ESA's Solar Orbiter to be added to the list.
- *Magnetic transients.* The discrimination of real magnetic transients from spurious trasients due to sudden changes in molecular contamination during white-light flares and various other possible RT effects should be regarded as a major issue. One possible approach would be to compare line-of-sight magnetic transients signatures of

white-light flares observed at various distances from Sun center. If line-of-sight measurements effectively measure flux, and field lines are frozen into the medium on a short time scale, magnetic transients due to reconnection should give a significant line-of-sight signature only if viewed obliquely (in principle). As weunderstand them spurious transients due to molecular the sudden removal of molecular contamination would be prevalent from any vantage.

- *Molecules.* Molecules, such as TiO and CH, contaminate the spectra of sunspot umbrae and possibly penumbrae with a forest of contaminants. These are known to shift both Doppler and magnetic signatures in sunspots (Harvey, private communication). To the extent that the molecular constituency of the photospheric medium remains stable, these shifts can be supposed constant, and therefore not to contaminate the acoustic spectrum. However, it is evident that this contamination can change suddenly during a white light flare, as the molecules that give rise to the spectral contamination are disassembled by intense Balmer and Paschen continuum edge radiation from the overlying chromosphere. Such a transient reduction in molecular contamination would introduce corresponding transients into magnetic and Doppler signatures. A conscientious assessment of the potential of transient signatures due to molecular destruction would be very worthwhile for flare diagnostics during the term of HMI.

  There are a number of ways to approach the foregoing problem: An interesting experiment that may help considerably in addressing concerns of molecular contamination would be observations of molecular formation in sunspot umbrae. Molecular formation probably occurs on a time scale of seconds or less for diatomaic molecules, such as CH, in which one of the constituents is hydrogen, but perhaps up to thousands of seconds for molecules such as TiO, for which both constituents are thousands of times less abundant than hydrogen in the photosphere. Even these times are short compared to the time required for sunspots to form. However, an intense white light flare very likely destroys some or all of these molecules within seconds. Observations of the recovery a TiO line following a white light flare observed by HMI would be most interesting in its own right, and could give us some useful insight into what molecular contamination does to HMI Doppler and magnetic signatures.

- *A white light flare alarm.* HMI could provide an excellent real-time white-light flare alarm. There are many potential applications for such a facility. This should be considered a highly beneficial service, very much in demand, that helioseismology can offer to the solar community at large.

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