J. Astrophys. Astr. (2008) **29,** 93–101

Helioseismic Effects of Energetic Transients

Ashok Ambastha
Udaipur Solar Observatory, Physical Research Laboratory, Udaipur 313 001, India.
e-mail: ambastha@prl.ernet.in

Abstract. Photospheric and chromospheric signatures related to large, energetic transients such as flares and CMEs, have been extensively reported during the last several years. In addition, energetic solar transients are expected to cause helioseismic effects. Some of the recent results are reviewed here; in particular, the helioseismic effects of the powerful flares in superactive region, NOAA 10486, including the 4B/X17 superflare of October 28, 2003. We also examine the temporal variations of power in low-l modes during the period May 1995–October 2005, and compare with daily, disk-integrated flare- and CME-indices to infer the effect of transients on the scale of whole solar disk.

Key words. Helioseismic effects—solar activity—solar transients.

1. Introduction

Solar flares release large amounts of energy at different layers of the solar atmosphere, including at the photosphere in the case of exceptionally major events. Therefore, it is expected that large flares would be able to excite acoustic waves on the solar surface, thereby affecting the p-mode oscillation characteristics. Acoustic modes that are always present on the Sun are generally accepted to be excited by turbulence in the convection zone (e.g., Goldreich & Kumar 1988). It was first suggested by Wolff (1972) that flares could excite solar oscillations as a result of the mechanical impulse produced by the thermal expansion exerted by a large flare towards the solar interior. He estimated the damping times to be longer than a day for the free modes. However, the earlier attempts to detect flare associated effects were mostly contradictory and inconclusive. For example, Haber *et al.* (1988) found a 14% greater power in the flaring region, while Braun and Duvall (1990) found no such effect for the energetic flares in NOAA AR 5395 of March 10, 1989. The difficulty in detecting any flare-related change is caused by the absorption of mode power by large sunspots which can absorb as much as 50–70% of the power of the p-modes (*c.f.*, Abdelatif *et al.* 1986; Braun *et al.* 1987; Rajaguru *et al.* 2001). Therefore, any excitation induced by the shorter-lived flares has to essentially compete with the effects of absorption associated with the intense magnetic fields of the sunspots.

Ambastha *et al.* (2003) have investigated characteristics of high-degree p-modes in several active regions of Cycle 23 that produced large flares. Using ring diagram technique, they found that the power in high-degree p-modes was larger during the period of high flare activity as compared to non-flaring regions of similar magnetic field. Several workers have also studied the large, energetic flares that occurred in NOAA 10486 during October–November 2003 (Ambastha *et al.* 2004; Donea & Lindsey 2005; Kosovichev 2006). It is expected that the most detectable changes should occur during the most energetic flares. In the following sections, we present a review of recent studies of the helioseismic response associated with the super-flare of October 28, 2003 using different techniques. Finally, we discuss the correlation of disk-averaged daily flare- and CME-indices with power in the low-l modes during Cycle 23.

2. The 4B/X17 super-flare of October 28, 2003

Observations of photospheric magnetic fields have shown abrupt and persistent changes in time scales of the order of 10–100 minutes during flares. These are much larger than the time scales of a few minutes associated with the expected photospheric line profile changes with transients. In order to distinguish between transients, normal field evolution, and the abrupt and persistent changes in the magnetic field to be associated with solar flares, a few hour long data-cube of high magnetic sensitivity, high-cadence, high spatial resolution data are needed. Similarly, for studies pertaining to helioseismic response, a day long data-cubes of dopplergrams are required before, during and after the flare. GONG+ and SOHO-MDI provide the required data to explore flare-associated effects.

High cadence H_α filtergrams were obtained from Udaipur Solar Observatory (USO) providing chromospheric coverage of the active region NOAA 10486 during the period of October 18–November 5, 2003. In addition, magnetograms and dopplergrams were also obtained at a cadence of 1-minute by the GONG+ instrument operated at USO. Using movies made from the photospheric doppler velocity, line-of-sight magnetic field and the chromospheric H_α observations, the sites of velocity flows, magnetic flux emergence, and chromospheric restructuring in the active region were identified.

From the GONG+ magnetogram images obtained during the super-flare of October 28, 2003, "magnetic" features were observed moving rapidly from the flare site in a short duration from 10:56 UT to 11:15 UT. Both GONG and MDI data showed this feature. A portion of the feature was observed moving away from the neutral line, near the site of the flare onset towards the leading sunspot, and the other perpendicularly to it (Fig. 1). The scenario appeared like a blast wave, or Moreton wave observed in chromosphere (Fig. 2). Velocity of the moving magnetic feature was found to be of the order of 40 km/s, i.e., much larger as compared to the usual separation speed of two-ribbon flares, but similar to the velocity $\approx$ 45 km/s of seismic waves reported

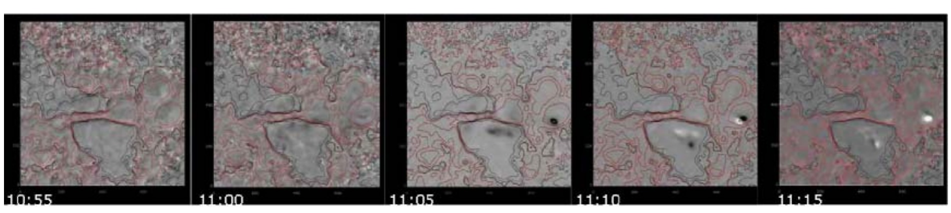

Figure 1. A moving "magnetic" feature propagating away from the site of the 4B/X17 flare as seen in the time-sequence of successive difference GONG magnetogram images.

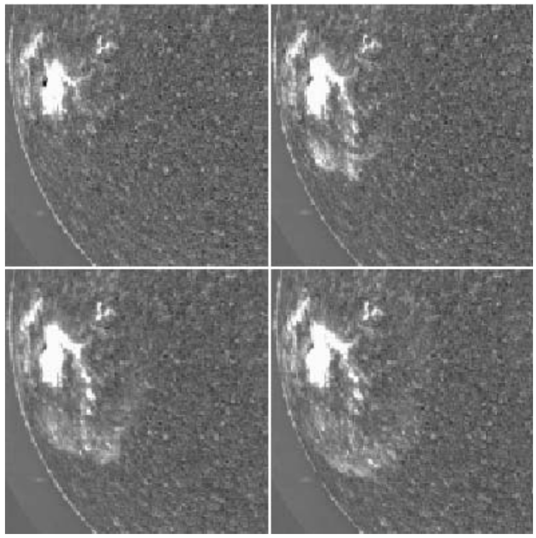

Figure 2. Moreton wave from the site of a X6 flare of 6 December 2006.

by Kosovichev and Zharkova (1998). If the moving feature is caused due to line profile changes, it is expected to show a relationship with the slower speed of flare ribbons separation. Also, it does not appear to be instrumental artifact either, as both the GONG+ and MDI images exhibit this feature. It is to note that GONG magnetic field measurements are not found very sensitive to line shape variation as shown by computer simulation of flare (Edelman *et al.* 2004). The exact nature of the moving feature requires further detailed investigation.

3. Helioseismic response of large flares

Locally excited acoustic modes interact with local variations in sound speed, flow fields, and magnetic activity which alter their propagation characteristics. A careful analysis of the acoustic waves in a localized patch of the solar photosphere can potentially reveal a great deal about the subsurface dynamics. Local helioseismology investigates small-wavelength acoustic waves that are confined principally to the near-surface layers, i.e., $r \leq 0.97\,R_{\odot}$. There are several local helioseismology techniques in use, including the ring-diagram analysis (Hill 1988), time-distance method (Kosovichev *et al.* 2000), and acoustic holography (Lindsey & Braun 2000). Some of the important results derived from these are mapping of horizontal flows in the surface layers of the Sun revealing the meridional and zonal circulation patterns, as well as, smaller-scale flows associated with active regions and supergranulation, or solar subsurface weather, (SSW). Local helioseismology has also been used to study the acoustic and flow structure underlying sunspots, and to image active regions on the far side of the Sun (*c.f.*, Gizon & Birch 2005, for a review).

3.1 *Sun-quakes associated with flares – A photospheric wave phenomena*

Response of flares in solar atmosphere is observed in a variety of effects such as Moreton waves, eruptive mass ejections, X-ray, $H\alpha$ and white-light brightenings,

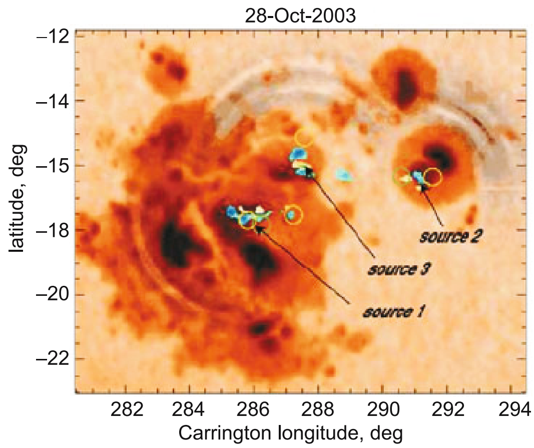

Figure 3. A white-light image of active region NOAA 10486 observed on October 28, 2003, superimposed with the Doppler signal at the impulsive phase, 11:06 UT (blue and yellow spots show up and down photospheric motions with variations in the MDI signal stronger than 1 km s^{-1}), positions of three wave fronts at 11:37 UT, and also locations of the hard X-ray (50–100 keV) sources (yellow circles) at 11:06 UT and 2.2 MeV γ-ray sources (green circles) (adopted from Kosovichev 2006).

etc. Waves have been observed everywhere on the Sun including the helioseismic, photoseismic, chromoseismic, as well as corona-seismic phenomena.

Traditionally, traveling waves or *Moreton waves* have been observed to originate from some flaring sites in the chromosphere (Fig. 2). A theoretical model proposed by Kosovichev & Zharkova (1995) predicted traveling waves or seismic waves, as opposed to the standing waves which constitute the normal modes of solar oscillations. These seismic waves are predicted to propagate away from the site of energetic flares with speeds increasing with distance. Kosovichev & Zharkova (1998) later observed the predicted seismic waves associated with a X2.6 flare of July 9, 1996. The source of the seismic response was suggested to be strong shock-like compression wave propagating downwards in the photosphere (Kosovichev 1986).

Observations of the seismic waves generated by the sunquake of 9 July 1996 is remarkably similar to the pattern of ripples generated by a stone dropped into a pond (Podesta 2003). They used a model of an inviscid, incompressible fluid in analogy to water waves, and found that the distances between successive wave crests were larger than observed, and concluded that the sunquake is composed primarily of acoustic (p-mode) waves rather than f-modes. Detection of sunquakes depends on their amplitude relative to the background solar noise. Presumably, all flares are expected to have seismic consequences at some level, but because of the high solar noise, the seismic waves may not easily be seen on individual Dopplergram images. It is easier to recognize these as expanding wave fronts in Dopplergram movies.

Seismic wave-like feature for the X17 superflare of October 28, 2003 in NOAA 10486 has been recently reported by Kosovichev (2006) using SOHO-MDI data. This was one of the largest events observed ever. It is interesting to note that some flares, having much weaker soft X-ray emission, produced higher amplitude seismic waves than the X17 flare (Kosovichev 2006). The study of sunquakes revealed some interesting features: (i) highly anisotropic nature of the seismic waves; (ii) the delay

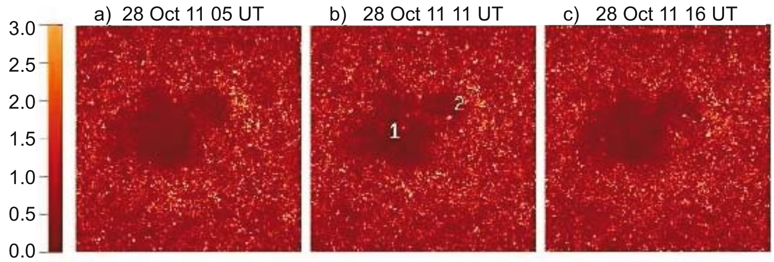

Figure 4. Egression power images for flare of October 28, 2003 obtained before, during and after the flare, showing compact acoustic sources of seismic waves (adopted from Donea & Lindsey 2005).

of 15–20 minutes after the initial impact, reaching the highest amplitude 20–30 minutes after the flare; (iii) traveling to large distances, exceeding 120 Mm, but in some cases, decaying more rapidly; (iv) propagation through sunspots without much distortion or significant decay, thus showing no evidence for conversion into other types of MHD waves. These observations indicate that the wave absorption by magnetic field is perhaps much weaker than expected by previous studies. The weak interaction of the seismic waves with sunspots can be explained by the fact that acoustic waves on the Sun do not propagate horizontally along the surface but travel through the deep interior. Therefore, the acoustic waves pass through the subsurface sunspot regions where the magnetic pressure is much smaller than the gas pressure, and reappear at the surface without much effect. The penetration depth of these waves depends on the travel distance. Therefore, the magnetic effects perhaps play a role only for shorter distances (i.e., smaller depths). The interaction of sunquakes with sunspots requires further analysis as the observations and analysis of sunquake events opens opportunities for developing new methods of helioseismic analysis of flaring active regions, similar to the methods of earthquake seismology.

3.2 *Seismic sources of p-mode power associated with flares*

Using helioseismic holography to image the seismic sources of the waves, Donea *et al.* (1999) obtained "egression" power maps for high-frequency acoustic waves during the flare studied by Kosovichev and Zharkova (1998). Interestingly, sunquake signals were not reported for any subsequent solar flares, thereby implying that sunquakes are rather rare phenomenon. However, recently Donea & Lindsey (2005) have reported that several flares in the declining phase of the Cycle 23 did show strong "egression" signals, which may be indicative of potential sunquakes. They have also detected compact sources of seismic waves emitted from powerful solar flares that occurred in NOAA 10486 on 2003 October 28 and 29 (Fig. 4). Interestingly, these acoustic sources were strongly associated with the foot-points of a coronal loop that hosted the flares and hard X-ray signatures.

3.3 *Amplification of p-mode power by flares in NOAA 10486*

The effect of flares on solar oscillation modes has been explored for several active regions using ring diagram analysis (Ambastha *et al.* 2003). This study gives evidence

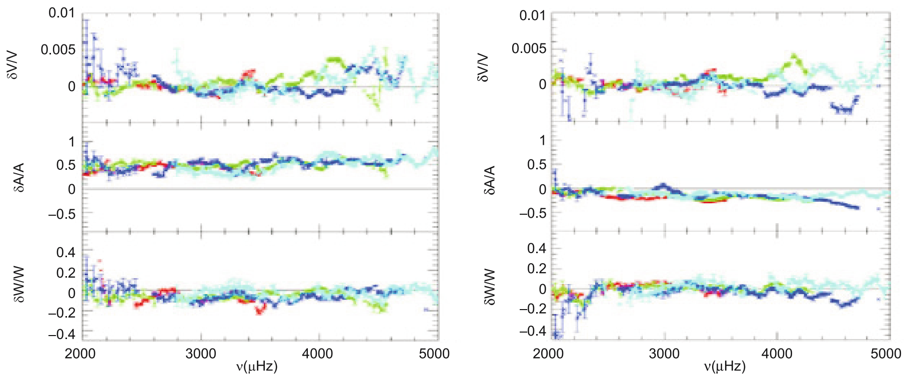

Figure 5. Relative difference in mode frequencies, widths and ratio of peak power for NOAA 10486 using ring-diagram analysis. The left and right panels respectively show the results for p-modes with $n = 0, 1, 2, 3$ obtained for the flare/preflare (i.e., Oct 28/Oct 27) and the flare/postflare (i.e., Oct 28/Oct 29) phases (adopted from Ambastha *et al.* 2004).

of flare-associated variation in mode characteristics such as frequency, width, power and asymmetry parameter. Average variation in p-mode amplitude for 11 active regions showed a good correlation with flare index after correcting the mode amplitude for magnetic field strength of the active region (*cf.*, Rajaguru *et al.* 2001). For the 4B/X17 superflare of October 28, 2003 also it was found that the p-mode power increased substantially after the flare. In fact, the mode-power increased even further on October 29, 2003 as a result of more flares occurring in the active region as shown in Fig. 5. Recent studies have shown that subsurface flows may also lead to p-mode characteristic variations (Zhao & Kosovichev 2004; Haber *et al.* 2004).

4. Subsurface signatures of flaring active regions

There have been searches for the subsurface signatures of large flares. For example, it is interesting to compare the velocity profiles with depth in flare-active and flare-inactive regions (Ambastha *et al.* 2004). The meridional velocity, u, in flaring active regions such as NOAA 10486, is found to possess a steep gradient below a depth of 4 Mm (Fig. 6a). Similar behaviour was obtained for active regions NOAA 9026 and 9393 (Ambastha *et al.* 2003), that appears to be a common feature of flare-productive active regions. In some regions, e.g., NOAA 9026, it was found that the steep gradient vanished after the flare (Ambastha *et al.* 2004). Similarly, Komm *et al.* (2005) found strong signal in each of the vorticity components, and hence in the kinetic helicity as a function of latitude and depth at the location of the active region during the epoch when the flares occured (Fig. 6b). The sign of the kinetic helicity remained the same at depths greater than about 5 Mm at the locations of AR 10486, while closer to the surface, the sign changed with depth indicating a more complicated behaviour. This is similar to the result obtained by Ambastha *et al.* (2004). Horizontal flows surrounding NOAA 10486 and variation with depth in the upper 14 Mm of the convection zone were studied by Haber *et al.* (2004). They reported large-scale shear flows that may contribute to conditions conducive to intense flaring activity.

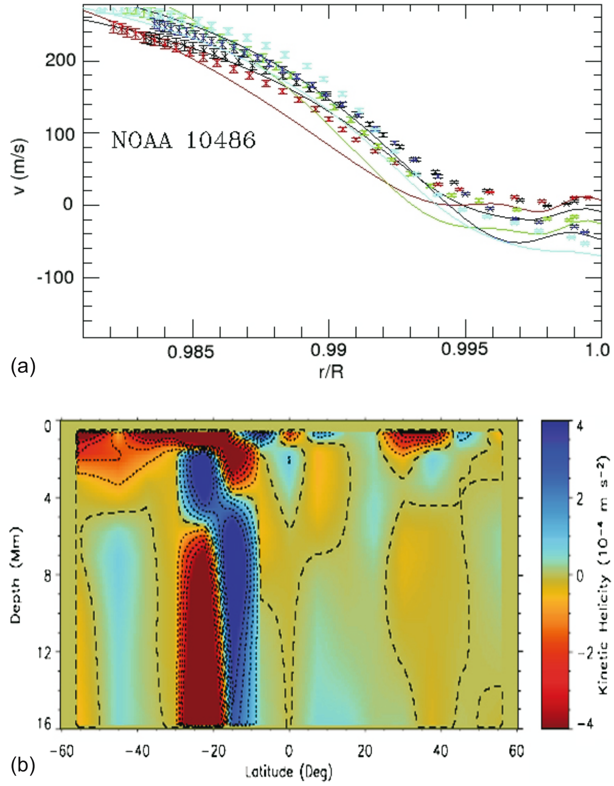

Figure 6. (a) The meridional (u) and zonal (v) components of velocity for NOAA 10486 at different stages of evolution. The *lines* show the results obtained by *RLS* inversions while *points* mark those obtained by *OLA* (adopted from Ambastha *et al.* 2004). **(b)** Kinetic helicity with depth. The sign of kinetic helicity remains the same at depths greater than about 5 Mm at the location of NOAA 10486. Closer to the surface, the sign changes with depth indicating a more complicated behaviour (adopted from Komm *et al.* 2005).

5. Excitation of *p*-modes by energetic transients on the global scale

The acoustic modes, always present on the Sun, are generally expected to be excited by turbulence in the convection zone (Goldreich and Kumar 1988). The energetic transient phenomena, that contribute additional energy to these modes at the local spatial scales of active regions, could also be expected to contribute energy to the solar modes on a global scale. For example, Chaplin *et al.* (1997) found excess of excitation events at the highest powers in comparison with the model based on stochastic excitation of modes (Goldreich *et al.* 1994). Gavryusev & Gavryuseva (1999) reported that the power distributions derived from radial mode observations contained a significant pulse of power at large energies, which they attributed to energetic coronal mass ejection (CME) events. However, Chaplin *et al.* (2004) found no convincing response of CMEs on the solar mean magnetic field data acquired by the BiSON Instruments using the correlation technique. The existence of high power events in the p-mode data, if indeed found to be significant, raises the question of their origin that needs to be addressed.

In order to examine whether disk-integrated flare and CME activity have such effects, Ambastha & Antia (2006) re-investigated the temporal variation of power in low-l modes using a 3816-day long time-series of mode power available from GONG over the period May 1995–October 2005, covering the solar minimum to maximum and a good part of the descending phase of Cycle 23. Theoretical model of mode excitation by turbulence predicts a random distribution of χ^2-type for the running mean power, decreasing monotonically after maximum with increasing $E_T/\langle E\rangle$ (Kumar *et al.* 1988), where E_T represents the mode energy and $\langle E\rangle$ is the average mode energy over the interval of interest. According to the theoretical model, as T is increased, the width of the distribution function narrows, the peak shifts towards the mean energy, and eventually the distribution approaches a δ-function at very large T. A long-period time series of mode power, such as the time-series now available from the GONG network, is required for obtaining the observed distribution function and its comparison with the theoretical distribution. The comparison is expected to help resolve the problem of mode excitation by checking if there is a departure from the theoretically expected distribution at high power. Ambastha & Antia (2006) reported that the observed power distribution of low-l modes essentially followed the theoretically expected stochastic distribution with no significant features seen at large power for data averaged over large (or small) running windows. This finding supports the generally accepted mechanism of excitation of p-modes by turbulence. However, the mean level of running mean power was found to vary; decreasing from solar minimum to maximum, i.e., during the ascending phase and then increasing in the descending phase of solar Cycle 23. The temporal variation in power of the modes, between the minimum and maximum, was found to be about 20–30%; consistent with the known variation in mode power (e.g., Elsworth *et al.* 1993). Also, a mild anti-correlation is found on global scale with disk-integrated flare-index and CME-counts (Ambastha & Antia 2006).

6. Conclusions

Using ring diagram technique, significant increase in mode power of acoustic modes has been found during large flares, beyond the normal value expected from the influence of magnetic fields. Compact seismic sources of p-mode power were identified at some locations using holographic egression maps (Donea & Braun 2005). Propagating seismic waves were also observed from the site of the X17 superflare (Kosovichev 2006). Meridional velocity in the flaring region was found to possess a steep gradient below a depth of 5 Mm (Ambastha *et al.* 2004), and a similar feature was observed in kinetic helicity (Komm *et al.* 2005).

On the global scale of the solar disk, however, the observed power distribution of low-l modes followed the expected theoretical χ^2-type distribution for mode excitation by turbulence. No feature at large power, corresponding to energetic transients, was found. In fact, the correlation of the daily, disk-averaged flare- or CME-indices with low-l mode power was found to be poor (Ambastha & Antia 2006). However, temporal variation in power of modes between the minimum and maximum of Cycle 24 was found to be about 20–30%, consistent with the known variation, e.g., Elseworth *et al.* (1993).

References

Abdelatif, T. E., Lites, B. W., Thomas, J. H. 1986, *ApJ*, **311**, 1015.

Ambastha, A., Basu, S., Antia, H. M. 2003, *Solar Phys.*, **218**, 151.

Ambastha, A., Basu, S., Antia, H., Bogart, R. 2004, *Proc. SOHO 14/GONG 2004 Workshop*, **ESA SP-559**, p. 293.

Ambastha, A., Antia, H. M. 2006, *Solar Phys.*, **238**, 219.

Braun, D. C., Duvall, T. L. Jr., LaBonte, B. J. 1987, *ApJ*, **319**, L27.

Braun, D. C., Duvall, T. L. Jr. 1990, *Solar Phys.*, **129**, 83.

Chaplin, W. J., Elsworth, Y., Howe, R., Isaak, G. R., McLeod, C. P., Miller, B. A., New, R. 1997, *MNRAS*, **287**, 51.

Chaplin, W. J., Dumbill, A., Elsworth, Y., Isaak, G. R., McLeod, C. P., Miller, B. A., New, R., Pinter, B. 2004, *Solar Phys.*, **220**, 307.

Donea, A.-C., Braun, D. C., Lindsey, C. 1999, *ApJ*, **513**, L143.

Donea, A.-C., Lindsey, C. 2005, *ApJ*, **630**, 1168.

Edelman, F., Hill, F., Howe, R., Komm, R. 2004, In: *Proc. SOHO 14/GONG 2004 Workshop*, **ESA SP-559**, p. 416.

Elsworth, Y., Howe, R., Isaak, G. R., McLeod, C. P., Miller, B. A., Speake, C. C., Wheeler, S. J., New, R. 1993, *MNRAS*, **265**, 888.

Gavryusev, V. G., Gavryuseva, E. A. 1999, *MNRAS*, **303**, L63.

Gizon, L., Birch, A. C. 2005, *Living Rev. Solar Phys.*, **2(6)**, (http://solarphysics.livingreviews.org/Articles/lrsp-2005-6/).

Goldreich, Kumar 1988, *ApJ*, **326**, 462.

Goldreich, P., Murray, N., Kumar, P. 1994, *ApJ*, **424**, 466.

Haber, D. A., Toomre, J., Hill, F., Gough, D. O. 1988, In: *Seismology of the Sun and Sun-Like Stars* (eds) Domingo, V., Rolfe, E. J., **ESA SP-286**, p. 301.

Haber, D. A., Hindman, B. W., Toomre, J., Bogart, R. S., Thomson, M. J., LohCo Team 2004, *Astron. Astrophys. Suppl.*, **204**, 02.11.

Hill, F. 1988, *ApJ*, **333**, 996.

Komm, R., Howe, R., Hill, F., Gonzalez Hernandez, I., Toner, C. 2005, *ApJ*, **631**, 636.

Kosovichev, A. G. 1986, *Bull. Crimean Astrophys. Obs.*, **75**, 6.

Kosovichev, A. G., Zharkova, V. V. 1998, *Nature*, **393**, 317.

Kosovichev, A. G., Zharkova, V. V. 1995, In: *Helioseismology, Proc. 4th SOHO Workshop* (eds) Hoeksema, J. T., Domingo, V., Fleck, B., Battrick, B., Paris: European Space Agency (ESA), p. 341.

Kosovichev, A. G., Zharkova, V. V. 1999, *Solar Phys.*, **190**, 459.

Kosovichev, A. G., Duvall, T. L. Jr., Scherrer, P. H. 2000, *Solar Phys.*, **192**, 159–176.

Kosovichev, A. G., Zharkova, V. V. 2001, *ApJ*, **550**, L105.

Kosovichev, A. G. 2006, *Solar Phys.*, **238**, 1–11.

Kumar, P., Franklin, J., Goldreich, P. 1988, *ApJ*, **328**, 879.

Lindsey, C., Braun, D. C. 2000, *Solar Phys.* **192**, 261–284.

Podesta, J. J. 2003, *Solar Phys.*, **218**, 227.

Rajaguru, S. P., Basu, S., Antia, H. M. 2001, *ApJ*, **563**, 401.

Wolff, C. L. 1972, *ApJ*, **176**, 833.

Zhao, J., Kosovichev, A. G. 2004, *ApJ*, **603**, 776.