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An interpretation of the $I - V$ phase background based on observed plasma jets

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Abstract. The presence of a solar background in the phase difference between the intensity and velocity ($I - V$) p-mode oscillation signals recently has been interpreted in terms of downflows due to convection (Skartlien & Rast 2000) or due to chromospheric explosive events (Moretti et al. 2001a). In support of the latter, we present I and V characteristics of impulsive brightenings observed in the NaI D lines, show that these reproduce the frequency dependence of the $I - V$ modulation background, and show that explanations invoking more frequently occurring phenomena such as seismic events are not likely in low-l modulation data.

Key words. Sun: oscillations – Sun: flares

1. Introduction

The presence of a background in the spectra of the phase difference between the solar intensity and velocity oscillation signals ($I - V$) was first discovered in ground observations by Deubner et al. (1990) as a negative phase "plateau" between $f = 1$ and $f = 2$ mHz frequencies and at l values between 100 and 1000 (where l is the azimuthal mode number).

The initial explanation given by Deubner et al. (1992, cf. Marmolino & Severino 1991; Marmolino et al. 1993) proposed a superposition of downward and upward waves. Such a superposition reproduces the observed frequency and height dependences of the $I - V$ phase difference background fairly well, but it requires low-frequency wave sources and reflections that have not yet been identified.

Recently, Skartlien & Rast (2000) have proposed that the $I - V$ phase difference background is dominated by localised sudden convective downflows corresponding to the "acoustic events" observed by Espagnet et al. (1996), Goode et al. (1998), Strous et al. (2000), and thought to represent the principal sources of the global p-mode oscillations (Goode et al. 1998). Note, however, that Skartlien & Rast (2000) base this proposal on the $I - V$ signature of a single event. We show below that the detectability in low-l oscillation measurements of the phase of many such events could be similar to that of other events whose contribution in the IV cross-spectrum is comparable.

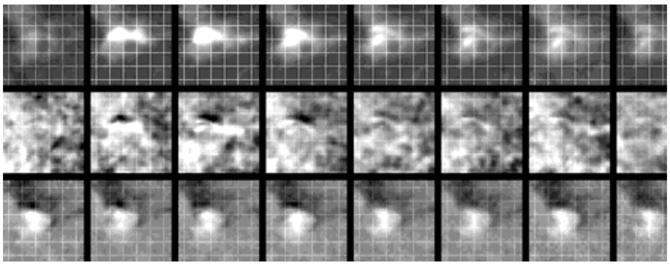

Fig. 1. A selection of the intensity (top), velocity (center) and longitudinal magnetic field maps (bottom) obtained on 1 June 2000 in the NaI D lines. Time goes from left to right in 2-min steps starting from 07:25:57 UT. Velocity is black if downward. A 20″ × 20″ grid is superimposed.

A totally different explanation of the $I - V$ phase difference background was recently forwarded by Moretti et al. (2001a), proposing that downward directed plasma jets due to explosive events in the upper solar atmosphere contribute to the observed $I - V$ signatures in the photosphere.

In this paper we add further evidence for an explosive-event explanation of the $I - V$ modulation background between $f = 1$ and $f = 2$ mHz and at low-ls by analysing the $I - V$ phase behaviour of observed impulsive brightenings of the NaI D lines. The observations are described in Sect. 2. We then construct a

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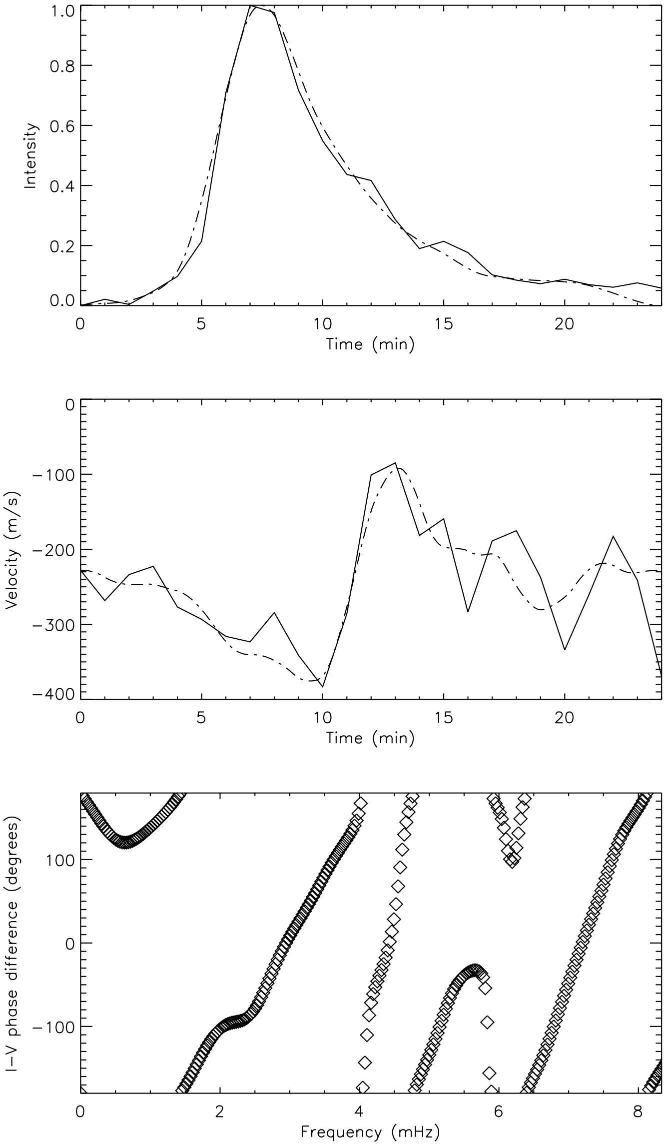

Fig. 2. The observed one-minute cadence intensity (top panel, solid) and velocity (center panel, solid) on a 12″ × 12″ area centered on the brightest pixel in Fig. 1. The plots refers to data obtained in the NaI D lines on June 1, 2000. The intensity signal has been scaled to a 0 to 1 interval, where zero is the intensity averaged in a surrounding 100″ × 100″ area and 1 is the maximum intensity (approximately 1.7 times the mean 100″ × 100″ value). The velocity error is 3 m/s. These intensity and velocity signals have been isolated, interpolated to a 8 s cadence and smoothed with a 40 s running window (dashed curves). The time-series have been zero-padded to obtain a 9 h observing run. In the lowest panel the $I - V$ phase difference is plotted. The phase depends on the reference system chosen for the velocity axis: a positive velocity for upward flows has been chosen. The shown phase difference spectrum spectrum is reliable up to $f = 4$ mHz. The negative $I - V$ signature follows from the delay between the intensity brightening and the velocity minimum (dashed curve in second panel). The other events all share this negative $I - V$ behaviour around $f = 2$ mHz.

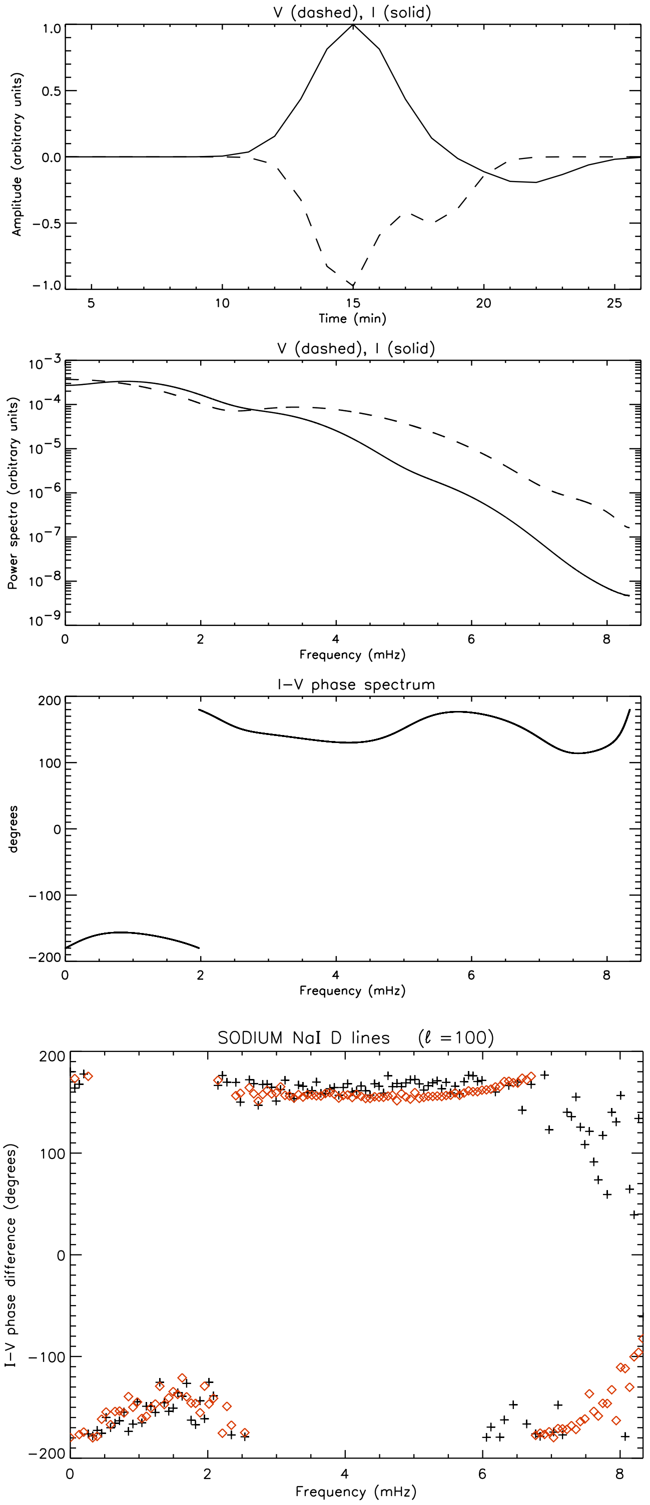

Fig. 3. Left, from top to bottom **a–d)** a simulation at 1 minute cadence of the intensity and velocity impulses **a)**, the power spectra of the signals **b)** and the intensity-velocity phase spectrum **c)** for a 9h zero-padded time-series. **d)** the observed phase spectra at $l = 100$ for the NaI D lines obtained with 256 min runs at Naples (crosses) and Kanzelhöhe (diamonds), Moretti et al. (2001a). The main properties of the measured $I - V$ phase spectrum is reproduced by the simulation based on the observed characteristics of the impulsive events detected with similar systems and at the same spatial resolution. The step-like behaviour in the phase fades when the second velocity impulse is not included in the model.

model describing the phase difference signature of many such impulsive events (Sect. 3). We show that, at the NaI D line formation layers, the signature in low-l data of such impulsive events at the global occurrence rates of the explosive events in the chromosphere is dominant. We suspect that these are indeed related phenomena.

2. The observations

Many impulsive brightenings in the NaI D lines have been detected at the Solar Kanzelhöhe Observatory (Warmuth et al. 2000; Moretti et al. 2001b).

The data consist of intensity, velocity and longitudinal magnetic field full-disk images acquired at one-minute intervals through a magneto-optical filter (Cacciani et al. 1999; Cacciani et al. 1997). The spatial resolution is $\simeq 4''$ per pixel. Our results are reliable for ℓ values between 20 and 400. The data have been calibrated as shown in Moretti and the MOF Development Group (2000) and Cacciani & Moretti (1997).

A number of 25 min long I, V and B sequences were selected containing impulsive brightenings respectively for April 2, June 1 and 6, July 12, 17, 19 and 22, and September 12, 2001. High resolution ultraviolet spectra of the outer solar atmosphere show transient brightenings often referred to as explosive events. These explosive events have also been detected in Hα observations (Canfield & Metcalf 1987; Chae et al. 1998). These are localised regions of small spatial extent that show sudden enhancements in the intensities in the lines accompanied by strong non-Gaussian profiles (Sarro et al. 1999; Berghmans et al. 1998).

The physical mechanisms advanced to explain these phenomena depend on the observed velocities, momentum, energy etc. The explosive chromospheric evaporation model (Fisher et al. 1985) explains the main observed characteristics of those events whose spatial scales are of the order of a few arcsec and last for a few minutes (Canfield et al. 1987; Canfield & Metcalf 1987). The same scales are those obtained by the analysis of the background locations maintaining spatial resolution (Moretti et al. 2001a). Recently, observations in Hα and NaI D lines have shown a simultaneous occurrence of the impulsive brightenings (Warmuth et al. 2000; Moretti et al. 2001b). For this reason we suggest the impulsive brightenings are related to the explosive events in the upper atmosphere.

Due to the geometrical asymmetry and the complexity of the structures, the contribution of the impulsive event in the velocity signal from the surrounding oscillations is often difficult, since they are comparable (of the order of some hundreds of m/s at these solar heights). We have chosen the case of June 1 2001 as the clearest and simplest example of the induced perturbations. Figure 1 shows partial regions of the I, V and B sequences. Figure 2 shows the intensity and velocity behaviour with time for the brightest pixel in Fig. 1.

3. Event simulation

In low-l or full-disk helioseismology using long observing time-series, many impulsive events such as the one displayed in Fig. 2 are averaged. The characteristic $I-V$ phase of such events may survive such averaging if it dominates over other signals. Since our data do not permit us to clearly separate the impulsive velocity signal from the global oscillation signals, the question arises whether impulsive event phase differences as in Fig. 2 contribute significantly to long-duration large-area $I-V$ phase difference measurements.

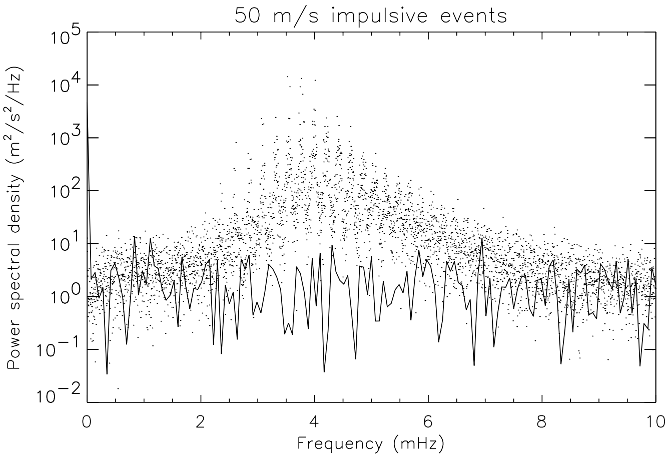

Fig. 4. Class prototype impulses randomly distributed in time and space as described in Fig. 3 have been added and the resulting power spectrum for the velocity signal is shown for a 40^{-1} global-sun occurrence. A one-month GONG spectrum for $\ell = 55$ is shown for comparison. The contribution at each low and intermediate ℓ, except for $\ell = 0$ and $\ell = 1$ $m = 0$, is approximately the same. The spherical harmonics masks select the events over an area whose sign morphology is of the order of a half of the solar disk.

We address this issue by using a model event shown in Fig. 3. The intensity peak has a duration similar to the pulse in Fig. 2. The velocity pulse describes downflow with a time profile that generates $I-V$ phase differences close to those of the actual observations in the bottom panel of Fig. 3.

We use this model event as a prototype and compute the velocity power spectra after superposition of many such events, randomly distributed in space and time over the whole solar surface.

Dopplergrams every second at an 8 arcsec/pixel sampling and 60 s acquisition time (as GONG does) have been obtained, and each ℓ coefficient's time series and its power spectrum have been computed. A 40 s^{-1} global sun occurrence has been chosen as the one reported for the chromospheric explosive events by Berghmans et al. (1988).

The downflowing plasma jets we observed at the NaI D line formation layers have not yet been detected at the lower photospheric heights such as those investigated with the GONG data (with the exception of the high energy event reported by Kosovichev & Zharkova 1998). For this reason, we use reduced peak values for the prototype event: of -50 m/s and 0.1 excess for velocity and intensity signals respectively. The resulting power is comparable with that observed by GONG (see Fig. 4 for $\ell = 55$). Even if seismic events have a 4000 s^{-1} global sun occurrence, their spatially averaged intensity and velocity signals are comparable to or lower than those estimated for the impulsive events and their typical area extension is at least 10 times smaller (Strous et al. 2000). This implies that the detection of the phase of the seismic events should compete with that of the impulsive brightenings.

At higher layers, where the seismic events are not detected, the impulsive brightenings events do dominate in the low frequency phase spectrum.

4. Conclusions

In this paper we show how the perturbations induced by the impulsive events detected in the NaI D lines can reproduce the low frequency behaviour of the solar $I - V$ phase background and that this contribution is more likely to furnish the Fourier power background in the low-ℓ measurements employed in helioseismology than the acoustic events described by Goode et al. (1998).

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