COMPARISON OF PHOTOMETRIC VARIABILITY BEFORE AND AFTER STELLAR FLARES

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ABSTRACT
The energy in the solar acoustic spectrum is known to be correlated with flares, but it is not known if the same is true for stellar flares. In order to answer this question, we have analyzed 73 flares in 39 solar-like stars. These flares were identified in the 854 solar-like stars observed by the Kepler spacecraft that have stellar parameters measured with asteroseismology. Though we were not able to identify a statistically significant enhancement of the energy in the high-frequency part of the post-flare acoustic spectra compared to the pre-flare spectra of these stars, we did identify a larger variability between the energy in the high-frequency part of the post- and pre-flare acoustic spectra compared to spectra taken at random times.

Key words: stars: flare – stars: oscillations – stars: solar-type

1. INTRODUCTION
Solar flares are large explosions on the solar surface that release $10^{29}$ to $10^{32}$ erg of energy on timescales from a few minutes to hours (Benz 2008). The physical mechanism behind solar flares likely involves the emergence of magnetic fields from the solar interior to the atmosphere and magnetic reconnection of these fields in the corona (Shibata & Magara 2011). Flares are known to occur on other stars as well. So-called super flares with energies between $10^{33}$ to $10^{38}$ erg have been observed on F–K main-sequence stars (e.g., Schaefer et al. 2000; Walkowicz et al. 2011; Maehara et al. 2012). Though these flares could be explained by a mechanism similar to that operating in the Sun, it is more difficult to explain flares on M dwarfs. These flares have been found to be able to increase the integrated flux from the stars by up to ~200 times in the $U$-band (Kowalski et al. 2010), on Mire Type stars (Schaefer 1991), which are giants and therefore only expected to have weak magnetic fields, on RS CVn binaries (Mathioudakis et al. 1992), and recently on A stars, which are not expected to have a significant near-surface convection zone (Balona 2012).

It was first suggested by Wolff (1972) that large solar flares could stimulate free modes of oscillations to observable amplitudes. Later, the detection of global low-degree $p$-mode oscillations was confirmed in observations of disk-integrated sunlight (by, e.g., Brookes et al. 1976; Claverie et al. 1981) and it was soon generally accepted that global $p$-mode oscillations were driven by stochastic excitation from granulation (Goldreich & Kumar 1988) and not by solar flares. Nonetheless, significant effort has been invested in detecting any correlation between flares and oscillations in the Sun—here we will limit the discussion to the analysis of low-degree or disk-integrated observations (for high-degree observations we refer the reader to: Haber et al. 1988; Braun & Duvall 1990; Kosovichev & Zharkova 1998; Donea et al. 1999; Donea & Lindsey 2005; Moradi et al. 2007; Kosovichev & Sekii 2007; Martínez-Oliveros et al. 2008; Reinard et al. 2010; Kosovichev 2011; Zharkov et al. 2011a, 2011b, 2013.)

Gavryusev & Gavryuseva (1999) found a high correlation between temporally varying $p$-mode power measured at low degrees in observations from the Global Oscillation Network Group (GONG) and the coronal mass ejection event number. Ambastha & Antia (2006) on the other hand found no correlation between a longer disk-integrated GONG data set, flares, and coronal mass ejection indices. An analysis of observations from the Birmingham Solar Oscillations Network (BiSON) also revealed that though the strength of the $p$ modes follows the distribution expected from stochastic excitation by near-surface convection, there is evidence of a few very large events than predicted by theory, but these events show only a poor correlation with flares (Chaplin et al. 1995). Foglizzo (1998) and Foglizzo et al. (1998) performed a statistical analysis similar to that by Chaplin et al. (1995) and found a mean correlation between the $p$ modes of degree 0 and 1 of 0.6% in observations from the Global Oscillations at Low Frequencies (GOLF) instrument on board the Solar and Heliospheric Observatory (SOHO) spacecraft obtained from 1996–1997 and 10.7% ± 5.9% in observations from the Interplanetary Helioseismology (IPHIR) experiment on the Phobos spacecraft obtained in 1988, which could suggest a relation between the $p$ modes and solar events; but no matches between the events in the $p$ modes and in the flares were made. Brown et al. (1992) analyzed the correlation between acoustic energy and activity, not in time but in space, and found that, while the energy of the $p$ modes with frequencies between 2.5 and 4.0 mHz is suppressed in active regions, the energy in the 5.5–7.5 mHz frequency range is enhanced around the active regions.

The discovery by Karoff & Kjeldsen (2008) of a high correlation between the energy in the high-frequency part of the acoustic spectrum (calculated from observations from the Variability of Solar Irradiance and Gravity Oscillations (VIRGO) instrument on SOHO) and the solar X-ray flux was therefore the first evidence that supported Wolff’s idea. The reason why Karoff & Kjeldsen (2008) were able to see a correlation where others had failed was that Karoff & Kjeldsen (2008) did not look at the frequency range where most of the $p$-mode energy is positioned (around 3 mHz). Instead they looked at frequencies higher than the atmospheric acoustic cut-off frequency (5.3 mHz).

Kumar & Venkatakrishnan (2009) analyzed the effect of the 2003 October 28 flare and found that the oscillations were
significant enhanced during the flare in the high-frequency band (5–6.5 mHz) of the acoustic spectrum from GONG observations. This study was followed up by a larger study using wavelet techniques on observations of major flare events in solar cycles 23 from both the Michelson and Doppler Imager (MDI) and the GOLF instrument (both on board SOHO) by Kumar et al. (2010), who found clear indications of enhancements of the high-frequency part of the spectra from MDI, but only marginal indications of enhancements in the high-frequency part of the spectra from GOLF. Recently, these studies were extended by a study of the 2006 December 13 flare, which was followed by an enhancement in the high-frequency part of the spectra from both GONG and GOLF (Kumar et al. 2011).

Chakraborty et al. (2011) preformed an independent confirmation of the results by Karoff & Kjeldsen (2008) using observations from both VIRGO and GONG. Here, the correlation was found to be slightly smaller for the radial velocities calculated from GONG observations compared to the intensity observations from VIRGO. The physical interpretation of different responses in velocity and intensity has been discussed by Karoff (2009).

On the other hand, Richardson et al. (2012, p. 27) found that a diminution was just as likely as an enhancement of the high-frequency part of the acoustic spectra taken after 31 flares, which led them to conclude that “flare-related variations are probably no different from the variations during quiet times that arise from the stochastic driving of the modes.”

Though the super flares we observe on solar-like stars with, e.g., the Kepler spacecraft (Walkowicz et al. 2011; Maehara et al. 2012), might be fundamentally different from the flares that we observe on the Sun, they still provide an opportunity to test the hypothesis that flares can excite oscillations in stars in general. Unfortunately, the analysis of other stars cannot be performed in the same way as for the Sun. This is mainly because the observations we have available, even from Kepler, are not of the same quality as the solar observations, but also because we do not have continuous X-ray observations of the flares on other stars, as we do for the Sun. We have therefore analyzed the 854 stars with oscillations excited to sufficiently high amplitudes to allow an asteroseismic analysis (Verner et al. 2011b) from the Kepler observations.1 Using 37 months of observations from Kepler, we have identified 73 flares in 39 of these solar-like stars, using the same technique as in Maehara et al. (2012), and made a simple comparison of the energy in the high-frequency part of the acoustic spectra taken before and after the flares and of acoustic spectra taken at random times.

2. OBSERVATIONS

For the analysis we used all available short cadence (58.85 s sampling, Gilliland et al. 2010) observations from the Kepler mission (Koch et al. 2010) of the 854 stars for quarter 1 to quarter 13 (2009 June 18 to 2012 June 27). As the aim of this study is to analyze the high-frequency part of the acoustic spectra, short cadence observations were needed. In order to lower the risk of artifacts affecting the analysis, the observations were corrected with the Presearch Data Conditioning Maximum A Posteriori (PDC-MAP) algorithm (Smith et al. 2012). For most of the stars only one month of observations were available, but for a limited number of stars (~150) observations were available for up to 28 months.

3. ANALYSIS

Flares were identified in the light curves using the technique described by Maehara et al. (2012), i.e., flare candidates were found by calculating the distribution of brightness changes between all pairs of two consecutive data points and then using a flare candidate threshold of three times the value of the top 1% of these distributions. The criteria used by Balona (2012), that no flares in any star were allowed to take place at the same time, was also applied to the flare candidates and finally the duration and shape of the light curves were examined along with the pixel-level data before the flare candidates were confirmed as flare events.

In this way 83 flares in 40 stars were detected. An example of a flare event is shown in Figure 1. In fact two flares can be seen in this figure. The presence of two or more flares closely separated in time in the light curve is likely to influence the analysis of the photometric variability. The flare event shown in Figure 1 was therefore withdrawn, along with four others, from the analysis—leaving 73 flares in 39 stars for the rest of the analysis.

Although the flares were identified using the same technique that was used by Maehara et al. (2012), some of the flares identified in this study are likely smaller than the flares identified by Maehara et al. (2012) as the short cadence observations allow the detection of smaller flares.

All the stars analyzed are shown in a Hertzsprung–Russell diagram in Figure 2 with the 39 stars marked. It is seen that flares are found all over the main sequence. More surprisingly, it is also seen that five stars on the sub-giant branch show flares. This is unexpected, as evolved stars are generally believed to be slow rotators (Skumanich 1972) and thus not host strong magnetic fields (see Notsu et al. 2013, for a discussion of the relation between flares and rotation).

The next step in the analysis was to calculate pre- and post-flare acoustic spectra. These spectra were calculated from substrings of different lengths before and after the flares. From all the time strings one hour before and one hour after, the flares were excluded from the analysis (indicated by the vertical lines in Figure 1) in order to lower the contamination from transients in the analysis.

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1 Originally, oscillations were only found in 642 out of 1948 F–K main-sequence stars using Kepler observations from quarter 1 to 3, but this analysis was extended using all of the observation form the survey phase (including quarter 4, Karoff et al. 2010), which resulted in the detection of oscillations in 854 out of 2641 F–K main-sequence stars (Verner et al. 2011a).
The acoustic spectra were calculated as least squares spectra (Lomb 1976) and normalized by the effective length of a given substring. As it is not known on which time scale the seismic responses to the flares, if any, take place, the lengths of the substrings were varied between one and 80 hr.

4. RESULTS

The photometric variability associated with the flares was evaluated by measuring the total energy in the high-frequency part of both the pre- and post-flare acoustic spectra. Here high frequency means the region in which Karoff & Kjeldsen (2008) saw the largest correlation, i.e., the region around the atmospheric acoustic cut-off frequency (in the Sun this frequency is located around 5.3 mHz). For the analysis, the high-frequency region was defined to be located between the frequency of maximum power plus ten times the large frequency separation and the frequency of maximum power plus 20 times the large frequency separation. For the Sun this means the region between 4.5 and 5.8 mHz. The evaluation was done by calculating the distribution of the relative difference between the total energy in the high-frequency part of the pre- and post-flares acoustic spectra for all 73 flares (the flare distributions). These distributions were then compared to the distributions of the relative difference between the total energy in the high-frequency part of two acoustic spectra taken at random times separated by 2 hr (as in the flares’ case) for the same stars (the random distributions). We then used a Kolmogorov–Smirnov test to evaluate if this was a general phenomenon for all substring lengths, i.e., the mean values of the flare distributions were not significantly different from zero. In other words, the Kepler observations do not show a significant enhancement of the photometric variability at high frequency at the time of the flares in the 39 solar-like stars analyzed in this study.

In Figure 3 it can also be seen that the significant difference between the flare distribution and the random distribution is caused by a larger width and different shape of the flare distribution compared to the random distribution. In order to evaluate if this was a general phenomenon for all substring lengths, we measured the widths of the flare distributions (calculated as the variance of the relative difference between the total energy of the high-frequency part of the acoustic spectra). Figure 5 shows these widths as a function of the length of the substrings. Here the solid line represents the width of the flare distributions whereas the dashed line represents the width of the random distributions. It is seen that the widths of the flare distributions are significantly larger than the widths of the random distributions.

On the other hand, Figure 3 also shows that there is not a significant general enhancement in the high-frequency part of the post-flare acoustic spectra compared to the pre-flare acoustic spectra. The same was the case for the other substring lengths, i.e., the mean values of the flare distributions were not significantly different from zero. In other words, the Kepler observations do not show a significant enhancement of the photometric variability at high frequency at the time of the flares in the 39 solar-like stars analyzed in this study.

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random distributions for substring lengths shorter than 45 hr. It can therefore be concluded that the photometric variability at high frequency for solar-like stars is significantly modified at the time of flares, but the modification is equally likely to be a diminution as an enhancement.

In order to test the robustness of this conclusion, the analysis was repeated using slightly different definitions for the high-frequency region and we also tried to measure the relative energy enhancement between a high-frequency and a low-frequency region, instead of just the energy enhancement in the high-frequency region. All of these tests confirmed that the above conclusion is robust against changing these parameters.

The modulation of the photometric variability could be caused by additional smaller flares located in the light curves, either before or after the main flare events. In order to eliminate this possibility, a Kolmogorov–Smirnov test was applied to compare the distributions of the numbers of such tiny photometric events before or after the main flare events. No dependency between the tiny events found before and after the main flare events, respectively. The distributions of the amplitudes of the highest change in brightness were also compared in the same way, which returned a p-value of 0.43 for the tiny events found both before and after the main flare events. No dependency between the lengths of the subtrings and the p-values was found in any of the tests. It is therefore safe to conclude that the modulation of photometric variability is not caused by additional smaller flares located in the light curves, either before or after the main flare events.

5. DISCUSSION

It seems likely that the super flares we observe on other solar-like stars are caused by a physical mechanism similar to that operating in the Sun (Notsu et al. 2013) and therefore it also seems likely that flares would affect oscillations in other stars in a similar way to how they appear to affect the oscillations in the Sun (Karoff & Kjeldsen 2008). On the other hand, super flares can be up to six orders of magnitude stronger that the strongest flares we have observed on the Sun (Schaefer et al. 2000), so the scenario could also be rather different.

Using observations from Kepler of 73 flares on 39 solar-like stars, it was possible to conclude that the photometric variability of solar-like stars is significantly modified at the time of the flares. If this is indeed caused by a seismic response to the flares, it provides a very strong argument in favor of the interpretation that the correlation between flares and the energy in the high-frequency part of the acoustic spectrum of the Sun found by Karoff & Kjeldsen (2008) is due to a causal relation between flares and global oscillations. On the other hand it is not possible to eliminate other scenarios.

The analysis also revealed that the modification of the photometric variability at high frequencies of solar-like stars at the time of flares was equally likely to be a diminution as an enhancement. This could point to some, hitherto unknown, mechanism in the flares that can lead to either excitation or damping of global oscillations.

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Figure 5. Width of the distributions as a function of the length of the substrings. The solid line shows the width of the flare distributions whereas the dashed line shows the width of the random distributions. The larger width of the flare distributions compared to the random distributions suggests that the photometric variability of solar-like stars is significantly modified at the time of flares.
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