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SOLAR AND STELLAR FLARES

Soft X-Ray Pulsations in Solar Flares

P.J.A. Simões[1] · H.S. Hudson[1,2] · L. Fletcher[1]

Abstract The soft X-ray emissions ($h\nu > 1.5$ keV) of solar flares mainly come from the bright coronal loops at the highest temperatures normally achieved in the flare process. Their ubiquity has led to their use as a standard measure of flare occurrence and energy, although the overwhelming bulk of the total flare energy goes elsewhere. Recently Dolla *et al.* (*Astrophys. J. Lett.* **749**, L16, 2012) noted quasi-periodic pulsations (QPP) in the soft X-ray signature of the X-class flare SOL2011-02-15, as observed by the standard photometric data from the GOES (*Geostationary Operational Environmental Satellite*) spacecraft. In this article we analyse the suitability of the GOES data for this type of analysis and find them to be generally valuable after September, 2010 (GOES-15). We then extend the result of Dolla *et al.* to a complete list of X-class flares from Cycle 24 and show that most of them (80 %) display QPPs in the impulsive phase. The pulsations show up cleanly in both channels of the GOES data, making use of time-series of irradiance differences (the digital time derivative on the 2-s sampling). We deploy different techniques to characterise the periodicity of GOES pulsations, considering the red-noise properties of the flare signals, finding a range of characteristic time scales of the QPPs for each event, but usually with no strong signature of a single period dominating in the power spectrum. The QPP may also appear on somewhat longer time scales during the later gradual phase, possibly with a greater tendency towards coherence, but the sampling noise in GOES difference data for high irradiance values (X-class flares) makes these more uncertain. We show that there is minimal phase difference between the differenced GOES energy channels, or between them and the

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hard X-ray variations on short time scales. During the impulsive phase, the footpoints of the newly forming flare loops may also contribute to the observed soft X-ray variations.

Keywords Flares, impulsive phase · Oscillations, solar · X-ray bursts, hard · X-ray bursts, soft

1. Introduction

The soft X-ray (SXR) emission of a solar flare (its GOES class) has practically supplanted the Hα brightening as the defining property of a solar flare (*e.g.* Fletcher *et al.*, 2011). The *Geostationary Operational Environmental Satellite* (GOES) is a satellite series initially deployed in 1974, with GOES-15 being the latest in the line. The GOES "Sun-as-a-star" soft X-ray observations, standardised in essentially the same form since the 1970s, come from two photometers that sample $1-8$ and $0.5-4$ Å bands.

We understand the soft X-ray sources to consist of plasma ablated (evaporated) from the lower solar atmosphere into coronal magnetic structures, and that the residence time scale (for cooling and draining) substantially exceeds the injection time scale. The time of injection corresponds to the impulsive phase of the flare, although it can be prolonged in some cases to tens of minutes; the subsequent gradual phase sees continued X-ray emission for many hours in extreme cases.

The $1-8$ Å and $0.5-4$ Å bands reflect a complicated mixture of line and continuum contributions (*e.g.* White, Thomas, and Schwartz, 2005) and respond to temperatures above about 4 MK. The temperature sensitivity of this filter pair strongly favours flare emissions, but there is sufficient sensitivity in the long-wavelength band to detect quiescent active regions as well, at least during active times. The two broad passbands overlap the thermal/nonthermal regions of solar X-ray emission; they generally reflect bound-bound transitions at lower temperatures and continuum components (thermal free-free and free-bound) at higher temperatures. Although the spectral response extends above 10 keV, the GOES time histories of solar flares typically do not show an impulsive-phase signature and invariably lag the hard X-ray peak emission time, a manifestation of the so-called Neupert effect (Neupert, 1968). We attribute this to the rapid filling of the coronal magnetic reservoir with hot plasma, which gradually obscures the hot footpoint sources detectable in soft X-ray images (McTiernan *et al.*, 1993; Hudson *et al.*, 1994; Mrozek and Tomczak, 2004; Simões, Graham, and Fletcher, 2015). By comparison with the extreme ultraviolet (EUV) passbands (*e.g.* O'Dwyer *et al.*, 2010), the GOES photometry isolates the hottest part of the coronal plasma.

Pulsations in the X-ray emission of solar flares were discovered in hard X-rays (above 20 keV) by Parks and Winckler (1969) in the impulsive phase of a major flare (SOL1968-08-08T18) and had a timescale of about 16 s. Simultaneous and closely synchronous peaks appeared at 15.4 GHz, identifiable as gyrosynchrotron radiation from MeV-range electrons, and Janssens and White (1969) noted earlier pulsations at longer radio wavelengths with somewhat longer (24 s) spacings. These longer-wavelength microwaves normally would be interpreted as thermal free-free radiation, and so in this early example we could already see pulsation signatures in very different physical domains. In our current interpretation of flare hard X-ray emission, this behaviour reflects time variations in an ill-understood mechanism for particle acceleration, by which the flare magnetic energy release predominantly goes into fast electrons at energies above about 20 keV.

The term "quasi-periodic pulsations" (QPP) is usually employed to refer generally to this kind of behaviour – short trains of roughly periodic emissions. Throughout the literature, the QPPs are usually identified by periodic signatures in the Fourier or wavelet power spectrum of the flare signal.

Since these early observations, a great deal of progress has been made in coronal seismology, in which one attempts to identify the QPP with resonant MHD wave properties and thereby learn something about the physical conditions in the corona (*e.g.* Nakariakov and Verwichte, 2005). Nakariakov and Melnikov (2009) specifically reviewed the now extensive observations of flare-related QPP mainly in this context. The identification of discrete eigenmodes during the early stages of a solar flare may not make much sense, however, since the flaring structure must evolve rapidly during this time and thus substantially change its geometry until the energy release subsides. On the other hand, structures external to the flare site clearly react to the disturbance in an oscillatory fashion (Aschwanden *et al.*, 1999), which may also involve a relaxation to a new equilibrium state (*e.g.* Simões *et al.*, 2013). Far-reaching disturbances have long been known to emanate from flares (*e.g.* Švestka, 1976) and can frequently be identified with the shock-wave exciters of type II radio bursts (Hudson and Warmuth, 2004). Today, the EUV observations from the TRACE and SDO satellites in particular have provided a wealth of new observations through high-resolution movies of coronal structures.

Soft X-ray data (and EUV imaging at wavelengths corresponding to higher temperatures) in principle probe a frontier area between the dynamical process of energy release and the possibly oscillatory relaxation into the new equilibrium of the flaring active region. We note early observations of X-ray emission lines by the soft X-ray spectrometer onboard the *Yohkoh* satellite (Mariska, 2005, 2006), making use mainly of S XV and Ca XIX lines. These observations reveal average oscillation periods of 5.5 ± 2.7 min, which is shorter than the typical periods associated with the large-scale structures seen in the EUV. The flare QPP phenomena discovered by Parks and Winckler (1969) typically have time scales more than one order of magnitude shorter, generally suggesting smaller scale lengths, stronger magnetic fields, and lower altitudes.

In an important recent comment, Gruber *et al.* (2011) (see also Vaughan, 2005, 2010) pointed out that an underlying power-law distribution of variability could mimic the appearance of a resonant process for a short time-series as an artefact of band-limited noise. In this case, the apparent discrete frequencies of power-spectrum analyses such as that of Parks and Winckler (1969) and many subsequent examples might readily be misinterpreted (Ireland, McAteer, and Inglis, 2015; Inglis, Ireland, and Dominique, 2015).

In this article we characterise the time variability of the GOES soft X-ray fluxes, following the discovery by Dolla *et al.* (2012) of QPP in the $1-30$ s period range in the first X-class flare of Cycle 24, the well-studied SOL2011-02-15. Such QPPs were also noted by Simões *et al.* (2013) in the M-class flare SOL2012-03-09, with a similar behaviour observed in SDO/AIA EUV hot channels. We analyse the whole set of X-class flares from this cycle to date, a total of 35 at the time of writing, in an effort to understand the relationship between the relatively fast impulsive-phase QPP seen in the non-thermal signatures, with the longer periods with possible resonant properties seen in thermal signatures formed in coronal magnetic structures with relatively low plasma temperatures.

2. GOES Data Analysis

To sharpen the variability, we took advantage of the excellent signal-to-noise ratio of the current GOES soft X-ray irradiance data and mainly studied the *digital time-derivative* of

Figure 1 Empirical noise levels for GOES irradiance measurements in the 1 – 8 Å band. The dashed line shows the estimated Poisson noise from photon-counting statistics, the data points show the irradiance steps resulting from the digitization of the data. We derived these levels from a series of flares covering the range of irradiance values shown in the plot.
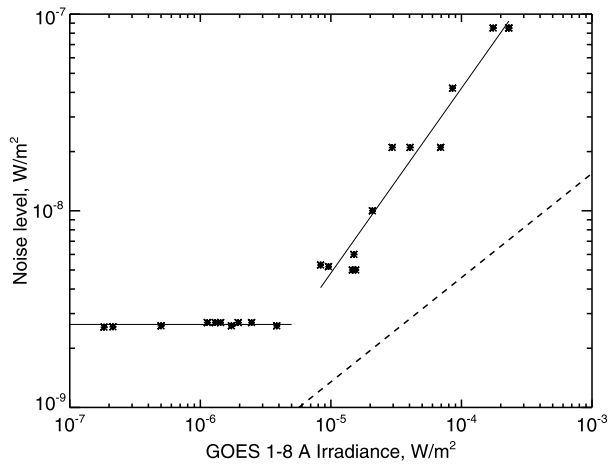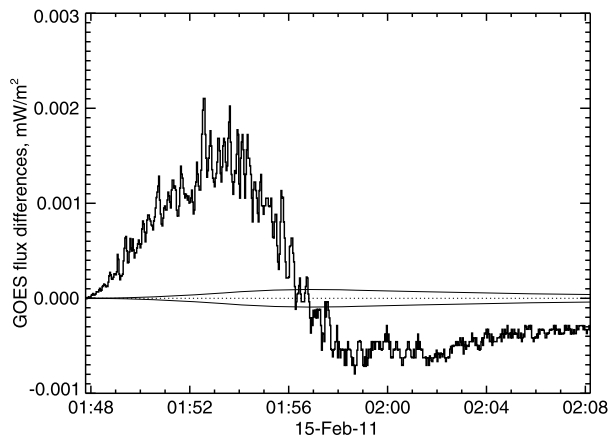

Figure 2 The time derivative of 1 – 8 Å GOES data for SOL2011-02-15, with the solid lines showing the digitization errors ± from the fit in Figure 1.

the original high-resolution (2 s sampling) time-series. The data before GOES-13 had poorer sampling and thus are not so useful for this type of analysis. Since the time derivative of the SXRs is known to track the hard X-rays (HXR), peaks in the derivative time series should correspond well with HXR spikes, if both reflect the impulsive energy release (the Neupert effect). However, differencing data can degrade their precision, therefore we first studied this problem. A casual inspection of the GOES irradiance data shows discrete steps in the noise level imposed by the digitization, and Figure 1 characterises this as a function of irradiance level for the 1 – 8 Å band. We have taken observed irradiance digital steps from several flares, ranging from C to X class, in the time frame 2012 – 2014, and the solid lines show a fit to the points. We estimated the Poisson noise from counting statistics and also show this, noting that it lies below the digital step size. Because of this, the precision of the GOES data does not increase with irradiance level, as should be the case for finer sampling (see also Chamberlin *et al.*, 2009).

The iconic flare SOL2011-02-15 illustrates some of the properties of the differenced time-series; see Figure 2. For the purposes of this article we note a working definition of the two phases of this flare: we identify the impulsive phase as between GOES onset and the first zero crossing of the 1 – 8 Å differences, with the gradual phase the time between that

Figure 3 Correlation of the time-derivative of GOES 1 – 8 Å with GOES 0.5 – 4 Å (scaled up by a factor 2.35) for SOL2011-09-07.
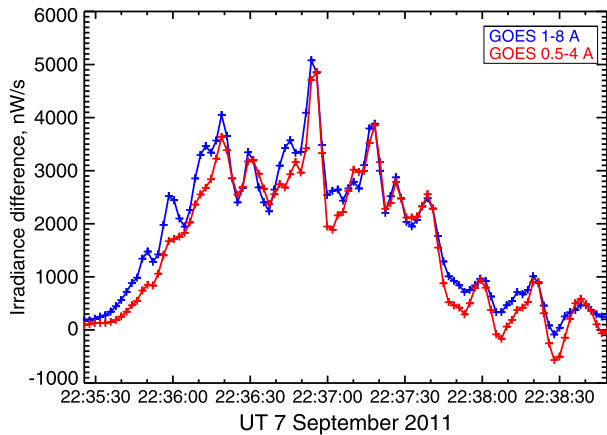
zero crossing and the GOES end time. In this flare the zero-crossing time is 01:56:49 UT, whereas the listed time of GOES maximum is 01:56 UT, and this distinction will normally not matter. The strong variability seen in the impulsive phase of this flare has a rough time scale of about 12 s, estimated either by peak-counting or a power spectrum, which is similar to the original observation of hard X-ray pulsations (about 16 s) by Parks and Winckler. The variability in the gradual phase is much less pronounced and indeed has a magnitude generally comparable to the digitization error (Figure 1).

We conclude from this representative event that the differencing technique properly reveals the QPP of the impulsive phase, but that the variability in the gradual phase competes in a complicated way with the digitization levels of the GOES data; we do not believe that this can be characterised quantitatively because the digital levels do not adequately sample the noise, meaning that successive points may have identical values reported. This limitation should be borne in mind for the survey material presented below, which deals with X-class flares of comparable magnitudes to SOL2011-02-15.

As further evidence of the fidelity of the QPP signature in the time derivative of GOES data for the impulsive phase, we show another example (Flare 4 of the survey; see below) in Figure 3. This compares the two independent GOES bands (0.5 – 4 Å and 1 – 8 Å), whose ratio characterises the spectral hardness. The variations match well at the shorter time scales (the QPP), with some soft-hard-soft pattern indicated by the hardness ratio (*e.g.* Fletcher *et al.*, 2011) on the longer time scales as well.

3. Survey of X-Class Flares

We have used the time derivative of GOES time series with all of the X-class flares in Cycle 24, up to the time of writing and commencing with Event 0 (SOL2011-02-15), the subject of the article of Dolla *et al.* (2012) and Figure 2. This sample contains 35 events, the strongest of which was Flare 2, SOL2011-03-09 (X6.9). The basic analysis tool was wavelet transforms, as described below (Section 3.1), with additional checks. All of these events showed QPP in the impulsive phase.

3.1. Wavelet Analysis

To characterise the variability in the SXR signal, we employed the wavelet analysis using the methods and routines provided by Torrence and Compo (1998). To evaluate the red-

noise spectrum, we used the method described in their Section 4 and provided by their wavelet software. The power-law slope that resulted from this was -1.9 for all the events in our sample. As described, we used the time derivative of the GOES channels instead of the more usual approach of detrending the signal (*e.g.* Dolla *et al.*, 2012), *i.e.* subtracting a smoothed curve, which depends on an arbitrarily chosen time scale. The time derivative maintains the fluctuations in the signal, retaining the original periodicity (if present). For completeness, however, we also applied the detrending approach and found similar results. We investigated the presence of periodic signals in the local wavelet power spectrum (WPS) and in the WPS averaged over the impulsive and gradual phases of each event in our sample. The significance of the WPS was tested against a red-noise model at 95 % and 99.7 % confidence levels; see Gruber *et al.* (2011), Inglis, Ireland, and Dominique (2015), Ireland, McAteer, and Inglis (2015) for a discussion of this type of analysis. We used the Morlet mother wavelet (parameter $w = 6$), but note that similar results were found for varying w and also for the Paul mother wavelet (see Torrence and Compo, 1998, for details). In short, we defined the presence of QPP as the identification of power in the wavelet power spectrum (averaged over the impulsive phase) above the red-noise model, with a confidence level of 99.7 %.

3.2. Survey Results

For our sample of 35 X-class flares, we characterised the time variability in several basic ways, as summarised in Table 1. For each event, we found the period range where the wavelet power spectrum, averaged for the impulsive and gradual phases, was above the 95 % confidence level of the red-noise model. We also verified the periods of peaks in the wavelet power spectrum.

As an example, in Figure 4 we show the results of the wavelet analysis for our first event, SOL2011-02-15, also analysed by Dolla *et al.* (2012). The four panels of Figure 4 show a) the wavelet power spectrum, b) and c) the time-averaged power spectrum for the two GOES spectral bands, d) the GOES timeseries, e) the time derivative of the time series of both channels, and f) the cross-correlation between the two channels, confirming the oscillatory non-dispersive nature of the signals (0.94 correlation coefficient with effectively zero lag). The wavelet power spectrum shows a periodic signal above the red-noise 99.7 % confidence level during the impulsive phase in the range $12 – 24$ seconds, in agreement with the findings of Dolla *et al.* (2012). In the gradual phase, the periodic power starts to vanish, but still appears to last for about 150 seconds, with a period range $20 – 40$ seconds (see Figure 2 for the caveat about sampling precision).

We show time derivative of the timeseries plots for each of the 35 events in Figure 5, normalised to the irradiance values. From the wavelet analysis, we found an average characteristic time scale of $16 – 53$ seconds (at 95 % confidence level) and $22 – 42$ seconds (at 99.7 %) (Table 1). Overall, periodic signals in the range $8 – 112$ seconds (at a confidence level of 99.7 %) appear across our flare sample. For most of the events, we detected similar characteristic time scales in both channels during the rise impulsive phase. During the gradual phase, only seven flares (20 % of the sample) had QPPs detected in the average wavelet power spectrum, although some events gave the appearance of weak broad-band power in the accessible time range. Moreover, during the impulsive phase of some events (indicated in Table 1 by †), the average WPS level of the low channel was below the red-noise 95 % confidence level, yet there are significant regions clustered together in time and period, indicating processes with a less random nature. For these cases, the high channel average WPS confirmed the presence of quasi-periodic power at the confidence level of 95 %; but we found very low persistent quasi-periodic power for these 7 events at 99.7 %.

Table 1 X-class flares of Cycle 24 along with the results of the wavelet analysis, where we show the characteristic time scale of the WPS above the red-noise level for confidence levels of 95 % and 99.7 %. † indicates events with quasi-periodic power found locally, but not evident in the average WPS.

No.	Flare ID	Class	Characteristic time scale		QPP gradual
			95 %	99.7 %	
0	SOL2011-02-15	X2.2	$10-30$	$12-24$	no
1	SOL2011-03-09	X1.5	$10-30^{\dagger}$	–	no
2	SOL2011-08-09	X6.9	$10-55$	$14-46$	yes
3	SOL2011-09-06	X2.1	$10-25$	$12-23$	no
4	SOL2011-09-07	X1.8	$10-45$	$10-37$	no
5	SOL2011-09-22	X1.4	$25-80^{\dagger}$	–	no
6	SOL2011-09-24	X1.9	$10-40$	$10-34$	no
7	SOL2011-11-03	X1.9	$10-25$	–	no
8	SOL2012-01-27	X1.7	$50-200$	$65-99$	yes
9	SOL2012-03-05	X1.1	$25-70$	$30-54$	yes
10	SOL2012-03-07	X5.4	$15-50$	$20-26$	no
11	SOL2012-03-07	X1.3	$30-55^{\dagger}$	–	no
12	SOL2012-07-06	X1.1	$10-30$	$12-25$	no
13	SOL2012-07-12	X1.4	$9-20, 50-200$	$70-106$	yes
14	SOL2012-10-23	X1.8	$10-20^{\dagger}$	$10-14$	no
15	SOL2013-05-13	X1.7	$10-60$	$17-45$	no
16	SOL2013-05-13	X2.8	$15-40$	$19-31$	yes
17	SOL2013-05-14	X3.2	$10-90$	$16-29$	yes
18	SOL2013-05-15	X1.2	$30-70$	$35-57$	no
19	SOL2013-10-25	X1.7	$10-45$	$11-25$	no
20	SOL2013-10-25	X2.1	$10-25$	$10-18$	no
21	SOL2013-10-28	X1.0	$15-65$	$17-24$	no
22	SOL2013-10-29	X2.3	$20-65$	$24-54$	no
23	SOL2013-11-05	X3.3	$9-12^{\dagger}$	–	no
24	SOL2013-11-08	X1.1	$8-20$	$10-18$	no
25	SOL2013-11-10	X1.1	$9-25$	$18-22$	no
26	SOL2013-11-19	X1.0	$10-30$	$12-26$	no
27	SOL2014-01-07	X1.2	$9-18^{\dagger}$	–	no
28	SOL2014-02-25	X4.9	$8-45$	$12-40$	no
29	SOL2014-03-29	X1.0	$8-60$	$8-56$	no
30	SOL2014-04-25	X1.3	$15-54$	$17-48$	yes
31	SOL2014-06-10	X2.2	$24-45^{\dagger}$	–	no
32	SOL2014-06-10	X1.5	$22-82$	$26-35$	no
33	SOL2014-06-11	X1.0	$10-16$	$11-14$	no
34	SOL2014-09-10	X1.6	$28-126$	$80-112$	no

3.3. Association with Hard X-Rays

For a subset of six of our sample, we compared the SXR time series with hard X-rays (HXR) data from *Fermi*/GBM (Meegan *et al.*, 2009; Paciesas, 2011; Schwartz *et al.*, 2010). We detrended the intensity signals by subtracting their smoothed component using a boxcar of 30 s
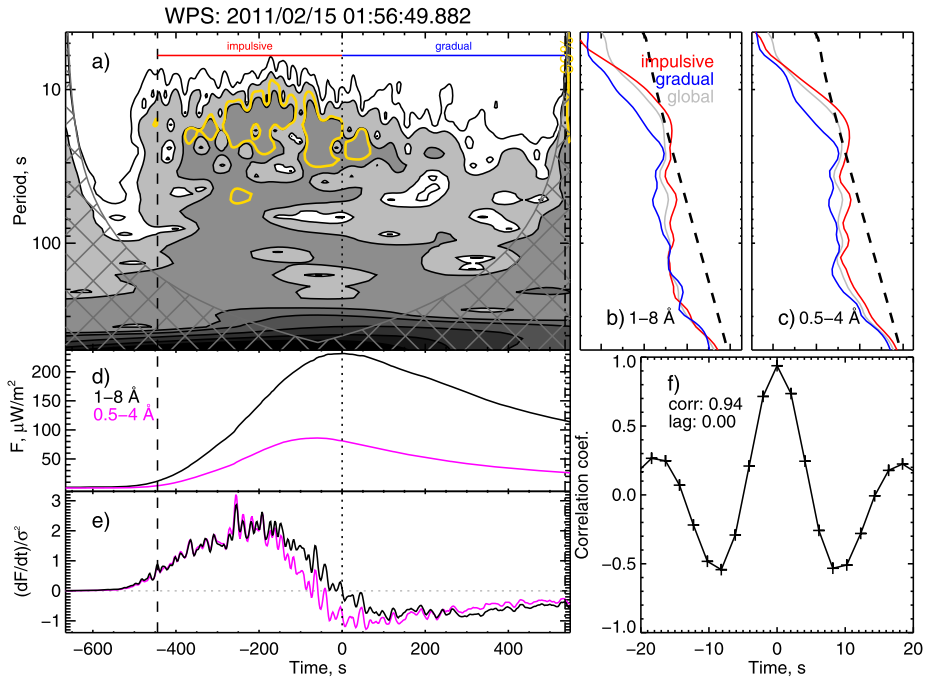
Figure 4 Results of the wavelet analysis of SOL2011-02-15. Reference times are indicated by the vertical lines: onset (dashed), peak (dotted), and end (dash-dotted). a) Wavelet power spectrum of the time derivative of the signal of the $1-8$ Å channel, with the power above the red-noise model (99.7 % confidence level) shown in yellow, b) the time-averaged power spectrum for the low channel ($1-8$ Å) for the impulsive phase (red) and gradual phase (blue) compared to the 99.7 % confidence level of the red-noise spectrum model (thick dashed curve), and c) same for the high channel ($0.5-4$ Å), d) time series of both GOES channels, e) time derivative of both channels, and f) lag cross-correlation between the time derivative of the signal of both channels.

(note that Dolla *et al.* (2012) used 20 s). The time derivative of SXR and HXR light curves and the detrended components are shown in Figure 6. The SXR and HXR detrended signals were cross-correlated, and the results found are listed in Table 2. The SXR and HXR pulsations are positively correlated in general, with the cross-correlation coefficient r frequently greater than 0.5. For these cases of $r > 0.5$, no delays were found between the signals. For events 18, 21, 25, and 30 (see Table 2), we found a good correlation for many HXR energy bands; for the event 17, a good correlation appeared for the higher energy channels (> 25 keV), and finally, for event 28, we derived $r \approx 0.4$ at all energy channels, with delays of $12-20$ sec. This particular example, SOL2014-02-25, exhibited periods with an anti-correlation between detrended > 25 keV and the GOES. This may result from a well-known artefact present in many scintillation-counter spectrometers that operate at excessively high count rates, as explained below. We note that this particular flare was an unusual and powerful γ-ray event that showed sustained emission of > 100 MeV photons (*e.g.* Ackermann *et al.*, 2014). The correlations, although not perfect, indicate that this is a typical situation in which the QPP excitations detected in the GOES time series closely match those seen in hard X-rays.

We note that applying a filter (*e.g.* Fourier) to remove the slowly varying component would encounter the same problems as the detrending technique, *i.e.* the possibility of
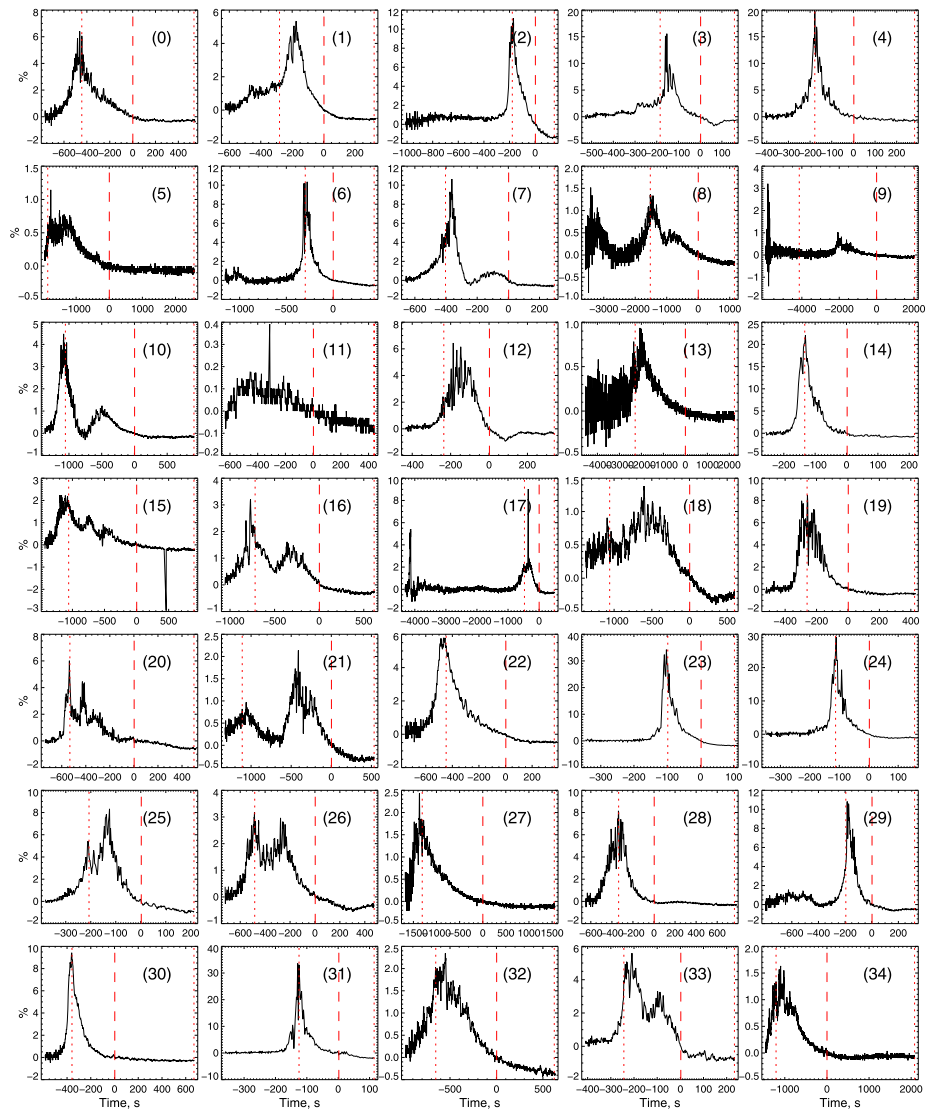
Figure 5 Time derivative of the GOES 1–8 Å time series normalised to the irradiance values, showing a wide variety of patterns, but the general presence of the QPP in the impulsive phase. Vertical dashed lines indicate the 1–8 Å peak, and dotted lines indicate the arbitrarily defined flare onset (5 % of the maximum flux density) and end times.

introducing spurious signals. We chose the latter because 1) it is easily reproducible and 2) it is the preferred method of the majority of authors investigating QPPs, and in particular, Dolla *et al.* (2012), making it easy to compare the results of different authors. Moreover, our point here is to show the correlation of the variability at small amplitudes of soft and hard X-ray data and the implications of this, and not to perform a strict periodicity analysis. Periodic or not, this variability is real (as noted by *e.g.* Gruber *et al.* 2011; Inglis, Ireland, and Dominique 2015) and possibly affecting a wide range of the flare emission spectrum, as shown here and by Dolla *et al.* (2012).

Table 2 Cross-correlation results between GOES SXR $0.5 - 4$ Å and *Fermi*/GBM HXR channels (in keV).

No.	Flare ID	NaI det.	$4-9$	$9-12$	$12-15$	$15-25$	$25-50$	$50-100$
17	SOL2013-05-14	n1	0.25	0.19	0.23	0.22	0.42	0.75
18	SOL2013-05-15	n4	0.30	0.73	0.75	0.71	0.65	0.54
21	SOL2013-10-28	n1	0.67	0.29	0.31	0.67	0.61	0.46
25	SOL2013-11-10	n4	0.59	0.62	0.59	0.67	0.65	0.33
28	SOL2014-02-25	n4	0.34	0.38	0.37	0.40	0.44	0.40
30	SOL2014-04-25	n4	0.38	0.72	0.75	0.67	0.37	0.22

As an important caveat regarding the hard X-ray data from *Fermi*, we note that in many cases the archived light curves clearly exhibit nonlinear responses as a result of high counting rates (note that our sample specifically contains only the most energetic events). We have not tried to understand these effects in detail and are unaware of any published analysis of such effects in the *Fermi* data, but past experience with scintillation counters at high rates suggests that both the spectrum and the time series can suffer. At high rates the photomultiplier gain may change, for example, affecting the energy calibration of the detectors. We have not used the most sunward NaI detectors to avoid these effects (see Table 2 for detector used in this analysis); however, taking data from detectors with larger offset angles reduces the count rates at high energies and also affects the detection of the small-scale pulsations. We note, however, that during some parts of SOL2014-02-25's time history, the impulsive energy signatures appear to change phase by 180°, becoming minima (at some energies) rather than maxima; this would have a natural explanation in terms of gain changes. Nevertheless, for this event we found similar results for different *Fermi*/GBM NaI detectors, suggesting that the lack of correlation between the SXR and HXR may not be an instrumental effect.

4. Discussion

We have found that most of the X-class flares in our sample show clear pulsation signatures in their time series, as would be expected from the presence of spikes in hard X-ray emission (*e.g.* Dennis and Zarro, 1993) and the operation of the Neupert effect on these time scales. These signatures appear strongly in the impulsive phase of the flare, but much less prominently in the gradual phase.

Our analysis typically covers a frequency range of about four octaves below the Nyquist frequency of the sampling, in the band $0.01 - 0.25$ Hz. Although the GOES peaks may have time scales down to our limit of 4 s, most of the variability is slower. The wavelet analysis for the most part does not show narrow features in spite of the presence of multiple peaks in the time series, and therefore need not be interpreted in terms of a resonant process. This seems reasonable, given the rapid structural changes of the emitting regions during the impulsive phase; one would not expect stable eigenfrequencies to dominate the time signatures. Later on and remote from the site of energy release, distinct signatures of damped oscillations appear commonly (Aschwanden *et al.*, 1999).

The QPP variability found here extends into the 0.1 Hz band, as discovered by Parks and Winckler (1969), but involves longer time scales ($8 - 112$ seconds) and agrees overall with the periods found in many QPP studies in different spectral ranges in the literature (*e.g.* Nakariakov, Melnikov, and Reznikova, 2003; Melnikov *et al.*, 2005; Reznikova *et al.*,
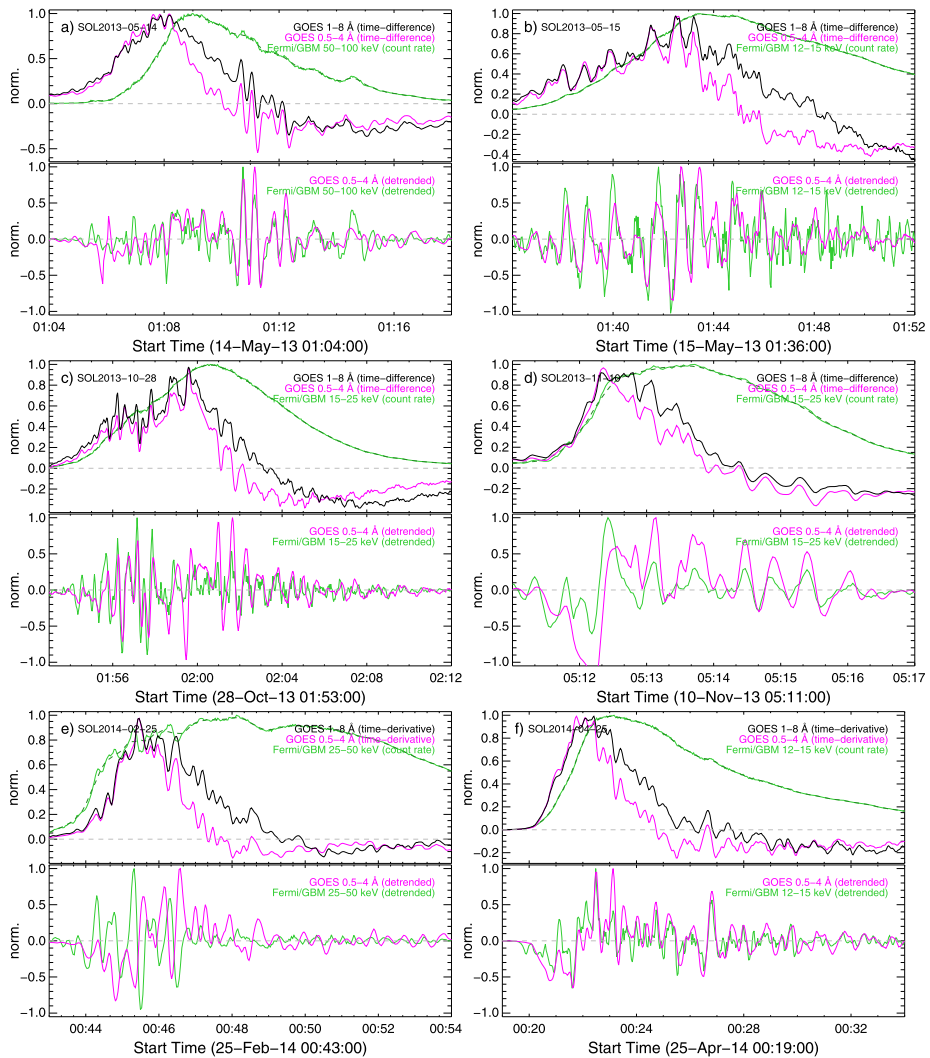
Figure 6 SXR (GOES) and HXR (*Fermi*/GBM) pulsations for a subset of our sample. Each panel shows the time derivative of time series of both GOES channels (for visualisation, as the detrended signals were used for comparison with the HXRs) and the *Fermi*/GBM energy band with the highest cross-correlation coefficient (see Table 2), and the detrended time series of *Fermi*/GBM and GOES 0.5 – 4 Å. The upper right panel (SOL2013-05-15) shows an excellent pulse-by-pulse match between GOES and the hard X-rays, limited by the decreasing S/N at late times. The only poor example is SOL2014-02-25 (lower left) in this set.

2007; Inglis, Nakariakov, and Melnikov, 2008; Inglis and Nakariakov, 2009; Kallunki and Pohjolainen, 2012). Parks and Winckler identified a specific time scale (16 s, or roughly 60 mHz), and we found a few cases in which there is a spectral peak in the range above about 80 mHz (or about 12 seconds). Curiously, one of the best-studied recent QPP events, SOL1998-05-08, shows almost exactly the same time scale (Asai *et al.*, 2001; Stepanov *et al.*, 2004; Inglis, Nakariakov, and Melnikov, 2008; Inglis, Ireland, and Dominique, 2015), and is one of the best examples of QPP that could arise from a true oscillation of some

Figure 7 Estimates of the Alfvén time scale for coronal or chromospheric structures for ion densities in the range 10^{8-11} cm^{-3} and for three plausible values of the magnetic field intensity, for a 10 Mm scale.
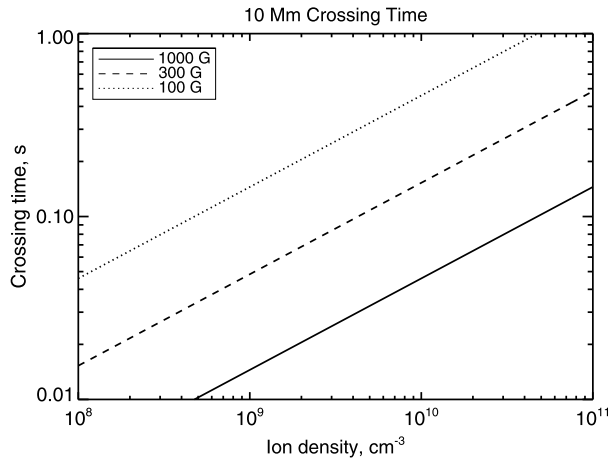
sort. Kupriyanova *et al.* (2010) investigated QPPs at 17 GHz using data from the *Nobeyama Radio Heliograph* and found periods in the range 5 – 60 seconds for ten events. In particular, in our analysis of SOL2011-02-15 (see Figure 4), we found a characteristic time scale of 12 – 24 seconds, in agreement with the results of Dolla *et al.* (2012). We note that the periodicity analysis of this event reported by Inglis, Ireland, and Dominique (2015), which used several HXR energy bands from *Fermi*/GBM and extreme ultraviolet (EUV) data from PROBA2/LYRA, did not find a periodic signal. We argue that analysing the global wavelet power or Fourier power (*e.g.* Inglis, Ireland, and Dominique, 2015) seems to reduce the chances of detecting any periodic power because the signal is averaged over the entire duration of the events. Any periodic signal would have to be persistently strong through the entire flare to appear. Moreover, the variability in the GOES SXR time series has a much smaller amplitude than the slowly varying component, thus a filter must be applied to retrieve it.

The observed time scales are therefore inconsistent with Alfvénic processes in the core of an active region, as reflected in Figure 7 (see also Fletcher and Hudson, 2008). In the impulsive phase of a flare, we expect low plasma densities since evaporation is just beginning to occur, and high magnetic fields since the events typically occur in active regions with sunspots. Thus the preferred domain in Figure 7 would be the lower right quadrant. This suggests that the chromospheric or photospheric regions of the flares may help to define the time scales of the flare development, or the travel times of the QPP disturbances, since the deep atmosphere has slower characteristic time scales.

The soft X-ray variability is highest at the very beginning (Figure 5), which we readily explain by the accumulation of hot material in the corona, which systematically tends to obscure new contributions.

5. Conclusions

We have surveyed the X-class flares of the current solar cycle (35 events from SOL2011-02-15 to SOL2014-09-10), as viewed by the standard soft X-ray irradiance measurements from the GOES satellites. Over this time interval, the GOES-15 detectors provided the data, and (as described in Section 2) its sampling precision greatly exceeds that of earlier members of the GOES series. This and the excellent signal-to-noise ratio of the observations allowed us to use the digital time derivative of the time series to study the variability in detail, up

to the Nyquist frequency of the sampling at 0.25 Hz. Our main conclusion is, therefore, to confirm the result reported by Dolla *et al.* (2012): the recent GOES measurements work very well in studies of QPP. By "recent" we mean GOES 13 – 15, with coverage from September 2010, and therefore the source of all of the data on X-class flares in Cycle 24 thus far. These data have a better precision than that of earlier GOES instruments, but still do not adequately sample the detector noise (Section 2).

Using the time derivative of time series, we found that 28 out of 35 X-class flares show QPP to some degree, especially during the impulsive phase of the event development. Here we defined the presence of QPP as the identification of power in the wavelet power spectrum (averaged over the impulsive phase) above the red-noise model, with a confidence level of 99.7 %. Overall, the characteristic time scale found is in the range 8 – 112 seconds (see Table 1). Because of the sampling problem we have discussed, the data are unable clearly to show QPP during the gradual phase of the flares. We find that most of the spectral power typically is at lower frequencies (between roughly 8 – 112 seconds) and is explicitly inconsistent with signal propagation at reasonable values of the Alfvén times for relevant scales in the active-region corona and upper chromosphere.

The QPP phenomenon in solar flares could be interpreted in several ways (*e.g.* Nakariakov and Melnikov, 2009). Nakariakov and Zimovets (2011), for example, described a scenario in which slow-mode MHD waves trigger episodes of magnetic reconnection at successive locations. We think this unlikely for the impulsive phase of a flare; the presence of non-steady evolution of the magnetic field, as required to release magnetic energy rapidly, would tend to destroy the identities of eigenmodes as the impulsive phase develops. Such an evolution is not typically considered in theoretical work in the area of coronal seismology, which is largely based on the structure of a fixed cylinder in the absence of non-steady flows (Nakariakov and Verwichte, 2005). The problem of time scales also remains: Nakariakov and Zimovets hypothesised that there might be slow coupling between arcade loops through perpendicular transport in the footpoint regions, but there would be no obvious source of resonant behaviour or periodicity in such a process.

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