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Quasi-periodic pulsations in solar and stellar flares

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Abstract. Light curves of thermal and non-thermal emission associated with solar flares usually contain statistically significant quasi-periodic pulsations (QPP). Typical periods range from a fraction of a second to several tens of minutes. Physical mechanisms responsible for QPP can be attributed to three main, while non-exclusive, groups: modulation of the emitting plasma parameters and kinematics of non-thermal electrons by coronal magnetohydrodynamic oscillations, spontaneous periodic magnetic reconnection, and magnetic reconnection periodically induced by magnetohydrodynamic oscillations. Similar QPP are also detected in stellar flares, including those hosted by Sun-like stars. Recently, a number of stellar flare QPP events were detected in white light with Kepler. In several cases, the characteristic time signatures of stellar flare QPP are very similar to those detected in solar flares, suggesting that they may be created by the same mechanisms. This report summarises the invited review talk given by V.M. Nakariakov at the workshop "Superflares on solar-type stars and solar flares, and their impacts on exoplanets and the Earth" at Kyoto University in March 2016.

Keywords: Solar flares, Stellar flares, MHD waves, Magnetic reconnection

1. Quasi-periodic pulsations in solar flares

The time resolution of modern instrumentation observing the Sun in microwave, EUV, soft and hard X-ray and gamma-ray bands provides us with an excellent opportunity to study the fine structure of flaring light curves. In a number of cases we can also obtain information about the spatial structure of the emission sources and their evolution. Often light curves of solar flares contain well-pronounced quasi-periodic variations of the brightness, called quasi-periodic pulsations (QPP). QPP are detected in all observational bands associated with both thermal and non-thermal emissions, and with both ground-based and spaceborne instruments. QPP are seen in flares of all GOES classes. Moreover, the emissions recorded in different bands associated with non-thermal electrons, e.g. hard X-rays, gyrosynchrotron microwave and in some cases gamma rays, are seen to have well-correlated QPP. Furthermore, application of different data analysis techniques usually results in the robust detection of the same QPP pattern in the light curve. This indicates that QPP are a natural phenomenon, not an artefact of a specific instrument or a specific data analysis method. The detected periods range from a fraction of a second to several tens of minutes, see (Nakariakov, 2009) for a comprehensive review.

Figure 1 shows a histogram of QPP periods detected in solar flares, based upon the compilation of published results obtained by different authors in different observational bands. It is evident that the vast majority of the events have relatively short periods, shorter than one minute. However, we must stress that this figure should be taken as an illustration only, as it does not present results of any systematic study. We would also like to mention that the detection of QPP is a non-trivial task that should not be based on the use of Fourier or wavelet analyses only, as usually QPP are short trains of a small number of nearly periodic variation of the emission, localised in some part of the light curve. Moreover, in a number of cases QPP, have well-pronounced modulation of the period (e.g. a drift) and the amplitude (e.g. an exponential or Gaussian decay). On the other hand, the modulation depth, or the relative amplitude of QPP can reach 100% with the highest amplitudes usually seen in the non-thermal emission. Some case studies showed the simultaneous presence of two or more statistically significant periodicities in light curves. In some cases, QPP are found not to have a harmonic shape, but rather the oscillatory signal is triangular with symmetric front and back slopes. It makes the QPP detection an interesting data analysis challenge that possibly requires the application of techniques specifically designed for non-stationary and nonlinear signals, e.g. the Hilbert-Huang transform based upon the empirical mode decomposition (Kolotkov, 2015). There is no apparent correlation between QPP periods and the flare energy and duration, and other observables.

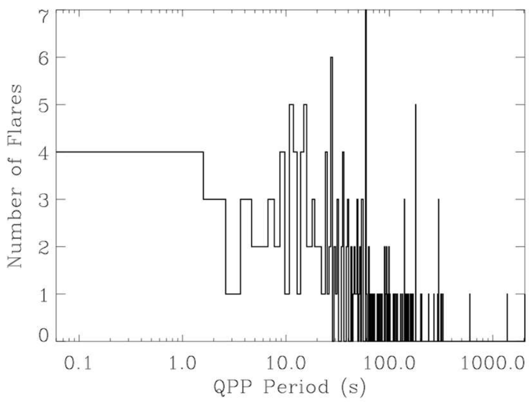

Figure 1. QPP periods in solar flares, constructed using the online catalogue of published QPP events (Nakariakov, 2016).

Analysis of the microwave emission produced in twelve consecutive flares associated with spatially-resolved single coronal microwave loops, observed simultaneously with both the Nobeyama Radioheliograph and Radio Polarimeters, revealed the common presence of statistically-significant QPPs (Kupriyanova, 2010). In ten out of twelve analysed events at least one significant spectral component was detected, and periods were found to range from 5 to 60s. Only those QPPs that were confidently detected in the data of both these instruments were counted. Very recently, a similar study of QPP in thermal, soft X-ray emission, showed that in 80% of X-class flares observed in solar cycle 24 with GOES-15 there were statistically significant QPP in the impulsive phase (Simoes, 2015). These findings clearly indicate that QPP are a common, and possibly even intrinsic, feature of solar flares.

2. Mechanisms for QPP

The variety of QPP properties, such as broad ranges of periods and amplitudes, different time-signatures, and their appearance in different phases of flares, suggests that QPP are most likely produced by several different mechanisms. Revealing these mechanisms provides us with the possibility to use QPP for diagnostics of physical parameters in flaring sites and the processes operating there.

2.1. Magnetohydrodynamic oscillations

Recently commissioned high spatial and time resolution observational facilities, mainly operating in the EUV band, show the omnipresence of various wave and oscillatory phenomena in the hot plasma of the solar corona. Typically, these oscillations are associated with distinct plasma non-uniformities, such as loops in coronal active regions, plume structures in coronal holes, prominences, and various transients, e.g. jets. Typical periods range from several seconds (or even shorter, in the radio band) to several tens of minutes. Thus, by the order of magnitude these oscillation periods coincide with those of QPP. Coronal oscillatory phenomena are commonly interpreted in terms of magnetohydrodynamic (MHD) oscillations. Hence, the periods are determined by the fast and slow magnetoacoustic transit times across and along the plasma non-uniformity that hosts the oscillation.

The theory of coronal MHD oscillations, based on magnetoacoustic modes of a plasma cylinder stretched along the magnetic field, predicts the presence of several distinct kinds of oscillations. Among them are: sausage oscillations, which are peristaltic variations of the cross-sectional area of the waveguiding plasma cylinder, accompanied by radial plasma flows and variations of the plasma density and the magnetic field strength; kink oscillations, which are transverse displacements of the cylinder's axis (they must not be confused with the Alfvén waves that are essentially incompressive transverse perturbations of individual magnetic surfaces); and acoustic oscillations, which are compressive plasma motions along the field. Different modes have very different observational signatures that allow for their unequivocal identification. All these modes are observationally detected in the solar corona. There are several possibilities for MHD oscillations to produce QPP. In particular, it can be done by either direct modulation of physical parameters of the emitting plasma (e.g. thermal emission and gyrosynchrotron emission), or by periodically changing the kinematics of non-thermal electrons (e.g. by periodic variation of the magnetic mirror ratio near footpoints of flaring loops, causing periodic precipitation of non-thermal particles producing hard X-ray and white light emission).

2.2. Periodic regimes of spontaneous magnetic reconnection

The process of magnetic reconnection that is believed to be responsible for the liberation of magnetic energy in flaring regions is known to be non-stationary. Numerical simulations show that it may occur in a quasi-periodic regime, e.g. periodically shedding the magnetic islands (Kliem, 2000). This would result in the periodic injection of non-thermal particles and possibly in periodic thermalisation of the plasma. This process could be referred to as "magnetic dripping", with the periodicity essentially not connected with any kinds of oscillations, but determined by the physical parameters in the reconnecting current sheet only. In nonlinear dynamics such processes are referred to as "self-oscillations". Investigation of this regime is an interesting theoretical problem.

2.3. Periodically induced magnetic reconnection

Physical parameters in the reconnecting current sheet could also be periodically modulated by an MHD oscillation, resulting in periodic triggering of the reconnection or variation of its rate. Thus, this process would result in the periodic acceleration of charged particles and thermalisation of the plasma, and hence QPP. Possible scenarios are based upon the periodic production of strong spikes of the electric current density in the current sheet or a magnetic x-point. Further study of this effect and assessment of its possible manifestation in flares is of great interest.

3. QPP in stellar flares

QPP in stellar flares have been sporadically detected for long time. For example, a long-period oscillation (220 s) was observed in the white light emission during the peak of a flare on the active RS Canum Venaticorum binary (RS CVn) II Pegasi (Mathioudakis, 2003). Short-period QPP (0.5-5 s) were detected in the radio band during a flare on AD Leonis (Stepanov, 2001). In soft X-ray band, (Mitra-Kraev, 2005) detected a 750 s oscillation with an exponential damping time of 33 min during the peak of a flare on AT Microscopium. A similar, rapidly-decaying long-period QPP with period of 32 min and a decay time about 46 min was found in the white light emission produced by a powerful "megaflare" on the dM4.5e flare star YZ CMi (Anfinogentov, 2015).

A systematic study of QPP in stellar superflares began only recently, with the use of Kepler data (Balona, 2015). White light curves of some superflares were found to have clean QPP. In several cases these QPP are almost harmonic QPP with an exponentially decaying amplitude, suggesting their possible association with MHD oscillations. Moreover, analysis of a superflare on a K-type eclipsing binary KIC 9655129 revealed the simultaneous presence of two statistically significant periodicities, of about 78 min and 32 min (Pugh, 2015). This finding further supports the interpretation of QPP as MHD oscillations, and indicates possible similarity of solar and stellar flare QPP.

4. Future work

QPP are a common, possibly even intrinsic, feature of solar flares. This result puts additional constraints on any model of the flaring energy release. There are several possible mechanisms that can be responsible for the QPP production, and their theoretical modelling is an interesting and timely challenge. In particular, one needs to search for and investigate quasi-periodic, self-oscillatory regimes of magnetic reconnection, and the possible periodic triggering of reconnection or modulation of its rate by MHD oscillations.

The detection of QPP in the light curves of stellar superflares, and the similarity of these QPP with those detected in solar flares, suggests that solar flares and stellar superflares could be produced by a similar mechanism. It indicates that there are no principal differences between flares and superflares, and hence the Sun could possibly produce a devastating superflare.

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