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Study of multi-periodic coronal pulsations during an X-class solar flare

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Abstract

We investigate quasi-periodic coronal pulsations during the decay phase of an X 3.2 class flare on 14 May 2013, using soft X-ray data from the RHESSI satellite. Periodogram analyses of soft X-ray light curves show that ~53 s and ~72 s periods co-exist in the 3–6 keV, 6–12 keV and 12–25 keV energy bands. Considering the typical length of the flaring loop system and observed periodicities, we find that they are associated with multiple (first two harmonics) of fast magnetoacoustic sausage waves. The phase relationship of soft X-ray emissions in different energy bands using cross-correlation technique show that these modes are standing in nature as we do not find the phase lag. Considering the period ratio, we diagnose the local plasma conditions of the flaring region by invoking MHD seismology. The period ratio $P_1/2P_2$ is found to be ~0.65, which indicates that such oscillations are most likely excited in longitudinal density stratified loops.

Keywords: Flares; Oscillations; Waves; Corona; Magnetohydrodynamics (MHD)

1. Introduction

Solar flares are sudden release of magnetic energy occurring in the solar atmosphere, and lasting from a few tens of seconds (impulsive) to a few tens of minutes (gradual). Flare emissions are detected in the entire electromagnetic spectrum, ranging from radio, microwave, visible, ultraviolet, X-rays, hard X-rays, and even to Gamma-rays. The effect of these flares are also detected in the variations of the flux density of solar energetic particles approaching towards the Earth. The electromagnetic radiation generated in solar flares often exhibits oscillatory patterns in the light curves. They are periodic in nature, operating in the flare magneto-plasma, and having typical periods ranging from a few milliseconds to several minutes (Nakariakov and Verwichte, 2005; Nakariakov and Melnikov, 2009; Kim et al., 2012; Kupriyanova et al., 2013; Huang et al., 2014, and references cited therein). These oscillations are referred to as quasi-periodic pulsations (QPPs). In some cases, they have inharmonic shape with apparent amplitude and period modulation (Nakariakov and Melnikov, 2009).

QPPs are classified mainly as short QPPs (sub-second), medium QPPs (seconds to several minutes), and long QPPs (from several minutes to tens of minutes) according to the possible physical mechanisms associated with them (Nakariakov and Melnikov, 2009; Kupriyanova et al., 2010). According to Aschwanden (1987), the short QPPs are probably connected with the interaction of electromagnetic, plasma, or whistler waves with accelerated particles detected in the radio emission. Medium QPPs are likely associated with magnetohydrodynamic (MHD) processes in the solar flaring loops as detected in radio, microwave, white light, and X-ray emissions (Inglis et al., 2008, 2009; Jakimiec and Tomczak, 2008; Asai et al., 2001; Melnikov

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et al., 2005; Reznikova et al., 2007; McAteer et al., 2005; Reznikova and Shibasaki, 2011, and references cited therein). On the other hand, the long ones are usually relevant to active region (AR) dynamics (Sych et al., 2009, 2015) and global oscillations of the Sun (Tan et al., 2010; Srivastava and Dwivedi, 2010).

QPPs in solar flares are one of the major diagnostic tools to study the physical conditions in flaring sites, and triggering mechanisms. These studies can also be extended to stellar flares, which exhibit QPPs in their radio, optical, and soft X-ray emissions (Mathioudakis et al., 2003; Mitra-Kraev et al., 2005; Pandey and Srivastava, 2009; Anfinogentov et al., 2013; Srivastava et al., 2013). Understanding QPPs during the flare eruption is still an open question. The fundamental physical processes of these oscillations in solar flares are relevant to understanding magnetic reconnection, magnetohydrodynamic (MHD) waves in coronal structures, particle acceleration, thermodynamics, and other kinetic effects. Although the properties of QPPs in solar hard X-ray (HXR) emissions have been widely studied by different researchers, their nature in solar soft X-ray emissions (SXRs) in different energy bands simultaneously remains to be extensively investigated. This calls for more observational information from samples with oscillatory behavior in low-energy X-rays.

The ratio of the statistically significant QPPs of the simultaneously existing spectral components is important for determining the nature and mechanisms of the pulsations both in observations and theory (Van Doorsselaere et al., 2007; Srivastava et al., 2008; Inglis and Nakariakov, 2009; Srivastava and Dwivedi, 2010; Macnamara and Roberts, 2011; Orza and Ballai, 2013; Luna-Cardozo et al., 2012; Erdélyi et al., 2014; Guo et al., 2015, and references cited there). Different periods of QPPs may be associated either with different MHD modes simultaneously present in a flaring loop or with different harmonics of the same MHD mode (Melnikov et al., 2005; Van Doorsselaere et al., 2007; Srivastava et al., 2008; Andries et al., 2009; Inglis and Nakariakov, 2009; Srivastava and Dwivedi, 2010, e.g.).

In this paper, we use the RHESSI data to study the intensity of the co-existing QPPs at 3–6 keV, 6–12 keV and 12–25 keV multiple energy bands during the decay phase of an X-class solar flare on 14 May 2013. In Section 2, we briefly present the observations and power spectral analysis methods for detecting QPPs. Section 3 describes the results of the QPPs observed in different energy bands of the flaring loop. Exploration of various harmonics of appropriate MHD modes leaving their imprints on selected SXR while excited in the flaring loop system is discussed along with conclusions in Section 4.

2. Observations and analysis methods

The X 3.2 class solar flare on 14 May 2013 is investigated in the present study. It started at 00:42:39 UT, reached its maximum at 01:07:41 UT, gradually decayed and ended at 03:14:40 UT in GOES SXR observations. Its coordinate at the Sun is N11E74 in an active region NOAA 11748. The flare region is detected by both RHESSI and Nobeyama Radioheliograph (NoRH) in an integrated mode providing flaring light curves in its decay phase in X-rays and radio respectively. Figs. 1(a)–(c) represent some features of this solar flare and related emissions.

Fig. 1(a) shows time profiles of the flare in soft X-rays taken with GOES satellite 1.0–8.0 Đchannel and microwave emission during this flare at 17 and 34 GHz observed by NoRH. NoRH provides intensity (Stokes parameter $I = R + L$) and circular polarization (Stokes parameter $V = R - L$) images at 17 GHz with a temporal resolution of 1.0 s (Nakajima et al., 1994). The fluxes (Fig. 1(a), middle panel) and correlation curves (Fig. 1(a), bottom panel) at 17 GHz and 34 GHz obtained from NoRH vary with the same pattern during the flare process. However, for the flare peak, the 17 GHz flux is larger than the 34 GHz and afterwards both fluxes become comparable with each other. The radio emission is probably generated by gyro-synchrotron motion of accelerated electrons during the flare peak phase, while in the long decay phase the thermal free-free emissions dominate. The full Sun image obtained from NoRH at 17 GHz (Stokes parameter $I = R + L$) and the corresponding flaring region of the day under study is shown in Fig. 1(b).

Fig. 1(c) shows this localized temporal span of the light curve during the decay phase of the flare detected by RHESSI. In these data sets of 3–6 keV, 6–12 keV and 12–25 keV energy bands, best-fit exponential functions of the form $I = I_0 \times e^{-bt}$ are fitted for the time period between 01:23:40 UT and 01:51:56 UT to remove the long-term background flare variations and corresponding graphs are shown in Fig. 2. For 3–6 keV energy band, the values I_0 and b are 349.9 and -0.003996; for 6–12 keV data set, these values are 4265 and -0.004179; and for 12–25 keV energy band, the corresponding values are 1960 and -0.005061 respectively.

We have studied the QPPs present in the de-trended signal during the decay phase of the flare by conventional Fast Fourier Technique (FFT), Maximum Entropy Method (MEM) and Lomb–Scargle (LS) periodogram analysis method. The MEM is an alternative method to FFT which avoids the limited resolution and power 'leaking', due to the windowing of data, present in the FFT, and it belongs to the class of methods which fit a satisfied model to the data. The parameters of a maximum entropy spectral estimation are equivalent to the 'ones' in the auto-regressive (AR) model of a random process in real domain (Burg, 1972).

On the other hand, the Scargle periodogram (Scargle, 1982; Horne and Baliunas, 1986) is an important algorithm for time series analysis of unevenly sampled data. Being quite powerful for finding and testing, the significance of weak periodic signals through false alarm-probability