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MHD seismology as a tool to diagnose the coronae of X-ray active sun-like flaring stars

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Abstract. It is now well accepted that the detection of impulsively generated multiple MHD modes are potentially used in diagnosing the local plasma conditions of the solar corona. Analogously, such analyses can also be significantly used in diagnosing the coronae of X-ray active Sun-like stars. In the present paper, we briefly review the detection of MHD modes in coronae of some X-ray active Sun-like stars, e.g. Proxima Centauri, ξ-Boo etc using XMM-Newton observations, and discuss the implications in deriving physical information about their localized magnetic atmosphere. We conclude that the refinement in the MHD seismology of solar corona is also providing the best analogy to develop the stellar seismology of magnetically active and flaring Sun-like stars to deduce the local physical conditions of their coronae.

Keywords : magnetohydrodyamics (MHD) – magnetic reconnection – flares – coronae

1. Introduction

The mega-Kelvin plasma coupled with the magnetic field generates variety of magnetohydrodynamic wave modes in the solar corona that are one of the important candidates in its heating and plasma dynamics (cf., Nakariakov & Verwichte 2005). The magnetic field activity generated in the sub-photospheric layers and fanning out in

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the outer atmosphere of the Sun, leads other variety of plasma processes (e.g., jets, surges, spicules, hot plasma flows etc) as well as transient phenomena (e.g., solar flares, eruptive filaments, CMEs etc) at diverse spatio-temporal scales, which are crucial to transport mass and energy (e.g., De Pontieu et al. 2004; Gopalswamy et al. 2012; De Pontieu et al. 2011; Srivastava & Murawski 2011; Shibata & Magara 2011; Joshi et al. 2012a,b; Kayshap et al. 2013a,b, and references cited therein). Along with these transient plasma processes, the solar coronal magnetic fields play important role in yielding high energy particles, emissions over the whole electromagnetic spectrum from Gamma-rays, X-rays to the Radio waves, and infer about variety of physical processes of coronal magneto-plasma (e.g., Vilmer 2012, and references cited therein). These transients also trigger the tube-waves (e.g., kink, sausage, torsional, and slow modes), which are very important candidates to derive the local plasma conditions (e.g., magnetic field) of the solar corona (e.g., Nakariakov & Ofman 2001; Nakariakov & Verwichte 2005; Srivastava et al. 2008; Andries et al. 2009; Srivastava & Dwivedi 2010; Kumar et al. 2011; Luna-Cardozo et al. 2012, and references cited therein).

The Sun-like stars, especially the cool sub-dwarfs, having sufficiently thick convection zone in their sub-surface layers, can transport the magnetic fields in their coronae, and exhibit the transients with high energy emissions (e.g., X-rays), coronal heating, as well as some signature of the MHD waves and oscillations (e.g., Mitra-Kraev et al. 2005; Pandey & Srivastava, 2009). The solar MHD seismology is now in very advanced state with the detection of various tubular MHD modes in the variety of magnetized structures at diverse spatio-temporal scales, and being very useful on deducing the local plasma conditions (e.g., O'Shea et al. 2007; Srivastava et al. 2008; Verwichte et al. 2010; Srivastava et al. 2010; Kumar et al., 2011; Kim et al. 2012; Srivastava et al. 2013, and references cited therein). However, the detection of transients (e.g., flares) induced MHD waves and oscillations are very few in the case of the stellar coronae of Sun-like stars (e.g., Mitra-Kraev et al., 2005; Pandey & Srivastava 2009; Anfinogentov et al. 2013, and references cited there). Moreover, the determination of local plasma structuring and magnetic field conditions are mostly unknown in the case of stellar coronae, and the solar analogy of the MHD seismology can be useful in deducing such conditions to know more about the physical properties of the stellar coronae (e.g., Nakariakov & Ofman 2001). In the present paper, we briefly review the detection of MHD waves and oscillations in the X-ray active coronae of Sun-like flaring stars, as well as discuss their significance in the framework of MHD seismology.

2. X-ray active sun-like flaring stars

The energy in stellar flares is originated from the interaction/reconnection of magnetic fields that are permeating the coronae of such flaring stars and originally formed in their interior. The magnetic fields fan-out through their convection zone into photosphere and finally into their coronae to form the stellar magnetic loops. The flares

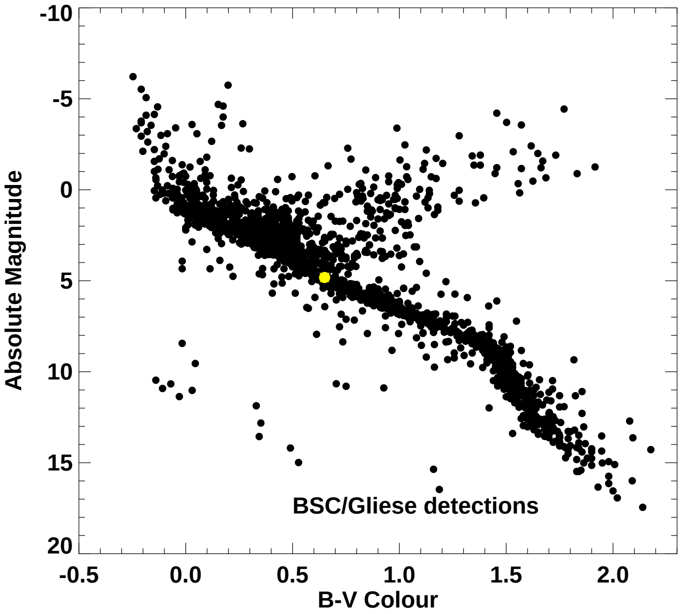
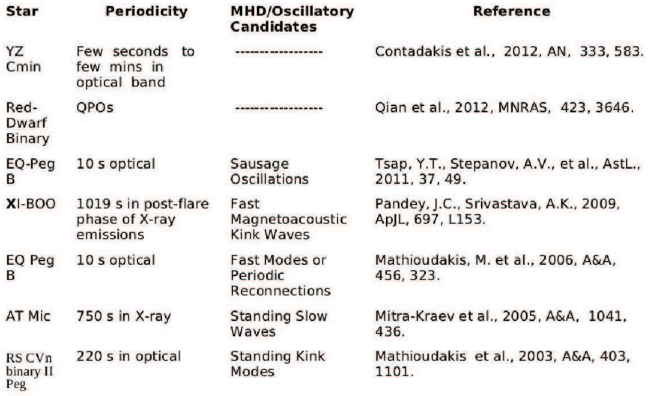


Figure 1. H-R diagram showing the Sun-like stars having X-ray activities and lying around the Sun (yellow circle). The cool stars around the Sun possessing the Sun-like magnetic coronae may have typical transient phenomena (e.g., flares) as well as MHD processes (Credit : Data from Huensch et al. 1997, 1998; Ph.D Thesis of S. Lalitha).

occur due to the magnetic field line reconnection in the coronae leading to the heating and particle acceleration in the reconnection region as per the analogy of the occurrence of solar flares (e.g., see the reviews by Benz 2008; Shibata & Magara 2011, and references cited therein). Particles are accelerated downwards into the chromosphere to heat the denser ambient plasma, which further expands and evaporates into the corona during the solar and stellar flaring processes. The stellar loops are filled with denser and hot plasma that is observed in form of soft X-ray stellar flares during the transient plasma processes in the stellar coronae (e.g., Pandey & Singh 2008). Fig. 1 shows the X-ray active stars detected along the H-R diagram (Huensch et al. 1997, 1998; Lalitha 2013) based on ROSAT observations. The yellow circle represents the Sun that is also having X-ray active corona.

If we consider between the F-M spectral classes of the main-sequence stars, then there are significant detection of the cool and magnetically active stars which are having their X-ray active coronae associated with various transient activities (cf., Fig. 1), e.g., flares and associated plasma processes. The magnetic field generation in the stars from F to mid-M spectral classes may be due to Parker type dynamo (1955) that generates the seed magnetic field further fanning out into their coronae to make them

Table 1. Summary of detected stellar oscillations in last one decade.



Star	**Periodicity**	**MHD/Oscillatory Candidates**	**Reference**
YZ Cmin	Few seconds to few mins in optical band	-----------------	Contadakis et al., 2012, AN, 333, 583.
Red-Dwarf Binary	QPOs	-----------------	Qian et al., 2012, MNRAS, 423, 3646.
EQ-Peg B	10 s optical	Sausage Oscillations	Tsap, Y.T., Stepanov, A.V., et al., AstL., 2011, 37, 49.
XI-BOO	1019 s in post-flare phase of X-ray emissions	Fast Magnetoacoustic Kink Waves	Pandey, J.C., Srivastava, A.K., 2009, ApJL, 697, L153.
EQ Peg B	10 s optical	Fast Modes or Periodic Reconnections	Mathioudakis, M. et al., 2006, A&A, 456, 323.
AT Mic	750 s in X-ray	Standing Slow Waves	Mitra-Kraev et al., 2005, A&A, 1041, 436.
RS CVn binary II Peg	220 s in optical	Standing Kink Modes	Mathioudakis et al., 2003, A&A, 403, 1101.

magnetically active. However, stars of spectral type M3 and others in the decreasing temperature down the main sequence in H-R diagram may be fully convective (Chabrier & Baraffe 1997). These cool dwarfs may not undergo the same dynamo process (Browning 2008), therefore, they can be low X-ray luminous and active (Robrade & Schmitt 2005) stars during the typical transient activities. These stars can also produce strong impulsive flares of short duration as well as long duration gradual flares in their coronae very similar to the typical solar flares (Benz 2008; Fuhrmeister et al., 2008, 2011; Robrade et al., 2010). Therefore, there must be some physical processes (e.g., typical reconnection process) in such stellar coronae of mid- to late-M type stars to build-up and release of the large amount of magnetic energy stored in their coronal magnetic fields (e.g., Reiners & Basri 2010). Above mentioned properties of the cool dwarfs are summarized in Fuhrmeister et al. (2011). In conclusion, these Sun-like stars have seed magnetic field generation in their interior, which transport outward to permeate their chromosphere and coronae in leading to the formation of transients (e.g., flares) as well as some form of MHD wave activity (e.g., Pandey & Srivastava 2009) similar to the transients and waves of the solar corona. As said above, these MHD wave modes are worth to diagnose the stellar coronae in the context of their localized physical properties.

3. Detection of MHD waves and oscillations in some X-ray active sun-like flaring stars

Few potential cases of the detection of stellar oscillations in magnetized stars are reported in optical as well as X-ray emissions as outlined in Table 1 since last one decade . However, there are only very few detection of the MHD waves and oscillations in the coronae of X-ray active Sun-like stars. Based on the solar analogy, the detection of such quasi-periodic oscillations can be a useful tool to determine the local plasma conditions of the stellar coronae (e.g., Nakariakov & Verwichte 2005; Nakariakov & Melnikov 2009; Srivastava 2010, and references cited there). Some of these potential findings in the context of stellar oscillations are summarized as follows:

Detection of slow magnetoacoustic waves in AT Mic by Mitra-Kraev et al. (2005): This is the first X-ray observation of an oscillation during a stellar flare in the corona of an active M-type dwarf AT Mic as observed by XMM-Newton on 16 October 2000. The soft X-ray light curve (0.2-12 keV) is investigated that exhibits an evidence for a damped oscillation with a period of around 750 s with a damping time of 2000 s. It was claimed that the oscillation is a first evidence of standing magneto-acoustic waves generated by the impulsive loop heating during the flare. The mode was detected as a longitudinal, slow-mode standing wave, with a resulting loop length of $(2.5 \pm 0.2)\times10^{10}$10 cm. The local magnetic field strength is estimated as 105 G in the flaring loops.

Detection of fast magnetoacoustic kink waves in ξ-BOO by Pandey & Srivastava (2009): The observations of X-ray oscillations during the flare in a cool active star ξ-Boo is reported for the first time as observed by EPIC/MOS of the XMM-Newton satellite during the epoch on 19 January 2001. The X-ray light curve is investigated with wavelet and periodogram analyses, which show oscillations of the period of 1019 s interpreted as a fundamental fast-kink mode of magnetoacoustic waves. These oscillations can be highly dispersive and can be a useful candidate for the localized heating of the corona of ξ-Boo. It should be noted that it is a binary K-Dwarf with the magnetized atmosphere and flaring activities.

Observations of the decaying long period oscillation of a stellar megaflare by Anfinogentov et al. (2013): In the decay phase of the U-band light curve of a stellar megaflare observed on 2009 January 16 in the corona of dM4.5e star YZ CMi, the long-period oscillations of 32 min with a decay time of 46 minutes is observed with its most likely interpretation as the impulsive generation of slow magnetoacoustic oscillations in the stellar loop system.

Detection of multiple slow magnetoacoustic oscillations in Proxima Centauri by Srivastava et al. (2013): The first observational evidence of multiple slow acoustic oscillations in flaring loops in the corona of Proxima Centauri using the XMM/Newton observations of 14 March 2009 has been detected. The oscillations in the decay phase of the flare in its soft X-ray emissions (cf., Fig. 3) are found with the detection of multiple periodicities of 1261 s and 687 s respectively with the probability of >99 % and for > 4 cycles. The appearance of such oscillations are bursty during flare energy release, and exhibit strong decaying nature similar to the slow acoustic oscillations observed in the solar corona (e.g., Wang et al. 2002). Thermal conduction may also play a significant role in the dissipation of observed slow waves in the stellar corona of Proxima Centauri. The period ratio P_1/P_2 is found to be below than 2.0, i.e., 1.83, which may be the signature of the longitudinal density stratification of the stellar loops in which such oscillations are excited. Using the half loop length of 7.5×10^9 cm, and period ratio, the density scale height of the stellar loop system is estimated as 23

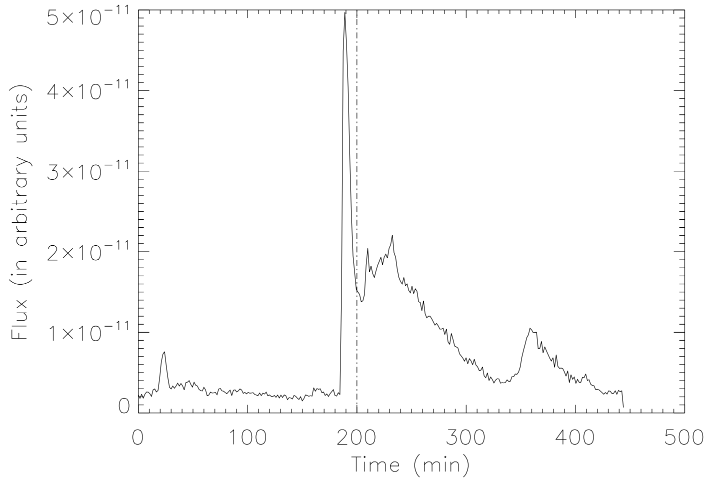


Figure 2. XMM-Newton light curve of a flaring epoch in the corona of Proxima Centauri on 14 March 2009. The vertical dotted line shows the time when quasi-periodic oscillations trigger-on in the decay phase of the flare. The oscillatory light curve in the decay phase of the flare has been chosen for the detection of the significant periodicities in the soft X-ray emissions. The periodicities have been detected using the wavelet analyses on the de-trended light curve after the removal of long-term variation.

Mm based on the analogy of solar corona (e.g., McEwan et al. 2006; Srivastava et al. 2010; Macnmara & Roberts 2010; Kumar et al. 2011; Luna-Cardozo et al. 2012, and references cited therein). The density scale height is well below the hydrostatic scale height of such loops assuming the few mega-Kelvin temperature, which indicates the existence of non-equilibrium conditions there, e.g., flows and mass structuring. First clues of the excitation of multiple slow acoustic oscillations in the hot stellar loops in the corona of Proxima Centauri are obtained and its MHD seismology is performed to diagnose the local plasma conditions (Srivastava et al. 2013). We outline the summary of this new important detection published in the Astrophysical Journal Letters in 2013.

Discussions and conclusions

The heightened and integrated X-ray emissions from the un-resolved coronae of the distant Sun-like stars during the flaring activity give some episodic quasi-periodic pulsations especially in the post-flare phases (e.g., Pandey & Srivastava 2009). The reconnection in the formed current-sheets in the stellar coronae may dissipate the magnetic energy and generate the heating, energetic particles, as well as shocks (e.g., Nakariakov & Melnikov 2009; Shibata & Magara 2011). The flare generated disturbances may also trigger the fast magnetoacoustic waves (e.g., kink, sausage) in the nearby stellar loops similar to the oscillations of coronal loops (e.g., Srivastava et al. 2008; Aschwanden & Schrijver 2011, and references cited therein). The longitudinal sausage oscillations can directly modify the density and thus the intensity, which may generate the X-ray QPOs emitted from the stellar coronae (e.g., Antolin & Van Doorsselaere 2013). While, the kink oscillations in the tangled stellar loops w.r.t. L.O.S. can also cause the variation in the plasma column depth, and thus can generate the weak density perturbations as well as intensity oscillations in the stellar flare emissions (Cooper et al. 2003). The strong energy release can also trigger the non-linear kink oscillations that can perturb the density and can generate the weak intensity oscillations (Andries et al. 2009). Therefore, the quasi-periodic oscillations can be triggered as a proxy of these fast wave modes in various emissions from the stellar loops during the flare epoch. Apart from the fast mode waves, the impulsive foot-point heating in the stellar loops during the flare energy release may generate the slow-acoustic oscillations similar to the slow modes of the solar coronal loops (e.g., Wang 2010, and references cited therein).

In conclusion, the strong flares that are being frequently observed in the Sun-like flaring stars (Maehara et al. 2012), may be enough energetic to trigger the various magnetohydrodynamic (MHD) wave modes. The detection of such wave modes in the stellar coronae may give potential information on the physical processes that generate such waves, as well as can be utilized to understand the local plasma conditions there (e.g., Mitra-Kraev et al. 2005; Pandey & Srivastava 2009; Srivastava & Lalitha 2013, and references cited therein). The future space-borne observational campaign should be planned for observing more samples of the flaring epoch of Sun-like stars to achieve significant statistics about the detection of the MHD oscillations in their coronae, and therefore, the diagnostics of local plasma properties in the framework of MHD seismology can be performed more convincingly keeping the view of solar analogy.

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