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Excitation of flare-induced waves in coronal loops and the effects of radiative cooling

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Abstract

EUV imaging observations from several space missions (SOHO/EIT, TRACE, and SDO/AIA) have revealed a presence of propagating intensity disturbances in solar coronal loops. These disturbances are typically interpreted as slow magnetoacoustic waves. However, recent spectroscopic observations with Hinode/EIS of active region loops revealed that the propagating intensity disturbances are associated with intermittent plasma upflows (or jets) at the footpoints which are presumably generated by magnetic reconnection. For this reason, whether these disturbances are waves or periodic flows is still being studied. This study is aimed at understanding the physical properties of observed disturbances by investigating the excitation of waves by hot plasma injections from below and the evolution of flows and wave propagation along the loop. We expand our previous studies based on isothermal 3D MHD models of an active region to a more realistic model that includes full energy equation accounting for the effects of radiative losses. Computations are initialized with an equilibrium state of a model active region using potential (dipole) magnetic field, gravitationally stratified density and temperature obtained from the polytropic equation of state. We model an impulsive injection of hot plasma into the steady plasma outflow along the loops of different temperatures, warm (~1 MK) and hot (~6 MK). The simulations show that hot jets launched at the coronal base excite slow magnetoacoustic waves that propagate to high altitudes along the loops, while the injected hot flows decelerate rapidly with heights. Our results support that propagating disturbances observed in EUV are mainly the wave features. We also find that the effect of radiative cooling on the damping of slow-mode waves in 1–6 MK coronal loops is small, in agreement with the previous conclusion based on 1D MHD models.

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

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1. Introduction

Waves are found to be ubiquitous in the solar atmosphere thanks to the high resolution, high cadence multi-wavelength EUV observations by SDO/AIA. Various MHD oscillations and waves present in coronal loops (such as slow modes, fast kink, sausage and torsional modes) have been spatially resolved with EUV imaging and spectroscopic observations (see recent reviews by Liu and Ofman (2014), Wang (2016) and Nakariakov et al. (2016)). A phenomenon of propagating EUV intensity disturbances (PDs) along magnetic structures is commonly detected in plumes (first observation reported in Ofman et al. (1997); recent review by Banerjee and Krishna

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Prasad (2016)) and in large, quiescent coronal loops by different space instruments including SOHO/EIT (DeForest and Gurman, 1998), TRACE (De Moortel et al., 2000), Hinode/EIS (Wang et al., 2009; Kitagawa et al., 2010), SDO/AIA (KrishnaPrasad et al., 2012a,b; Uritsky et al., 2013). PDs often appear in the loops near the edge of active regions and seen as small, by few percent, amplitude changes in EUV intensity, and were found to propagate at approximately the local sound speed. PDs observed in coronal loops are generally quasi-periodic with periods of the order of a few minutes ranging in 2.5–9 min (De Moortel, 2009). The phenomena of PDs observed both in coronal plumes and in large fan-like coronal loops were interpreted as slow magnetosonic waves (Ofman et al., 1999; Robbrecht et al., 1999; Nakariakov et al., 2000). In addition, Doppler shift oscillations observed with SOHO/SUMER in hot (>6 MK) flaring loops (Wang et al., 2002) were interpreted as standing slow-mode waves (Ofman and Wang, 2002). The trigger of oscillations in hot loops was found to be associated with high-speed (200–300 km/s) flow pulses, which were likely produced by small (or micro-) flares at the footpoints (Wang et al., 2005). Later Srivastava and Dwivedi (2010) reported first observations from EIS/Hinode of multiple harmonics of slow acoustic oscillations in non-flaring (cooler) coronal loops. They also detected a bright blob of the plasma propagating with the subsonic speed along the loop. The blob was interpreted as a signature of a pulse of plasma flow which could excite observed slow magnetoacoustic oscillations.

Observations of coronal waves and loop oscillations are important for a new rapidly developing research area, coronal seismology (see the review by Nakariakov et al., 2016, and references therein), which aims to infer physical parameters of the solar atmosphere from observations of coronal waves. Methods of coronal seismology may provide information on the corona magnetic field e.g., Nakariakov and Ofman (2001, 2005) and dissipation coefficients in coronal plasma (e.g., Wang et al., 2015). Slow magnetoacoustic waves can provide a significant contribution to the heating of coronal loops (Tsiklauri and Nakariakov, 2001). In particular, PDs are believed to be driven below the corona making this phenomenon important for studies of the connection between the corona and chromosphere/transition region (De Moortel et al., 2002). Recently, the origin of magnetoacoustic waves observed above sunspots was identified from p-mode helioseismic waves traveling upward through different atmospheric levels (Zhao et al., 2016). By using seismology techniques, the sunspot waves have been applied to determine the coronal magnetic field strength (Jess et al., 2016).

The interpretation of PDs in non-sunspot loops is still controversial. The main reason is that these PDs were discovered to be associated with high-speed (~50 km/s) outflows with the quasi-periodic features. A typical observation, demonstrating PDs along the active region loops in EUV from SDO/AIA 193 Å and upflows in Doppler shift map of Hinode/EIS in AR 11106, is presented in our previous related paper Wang et al. (2013). Several authors (De Pontieu and McIntosh, 2010; Tian et al., 2011) alternatively interpreted PDs as periodic upflows (or jets). Recognition of the true nature of PDs is crucial to their seismological application and to understand their role in coronal heating and mass supplies. Some 3D MHD simulations have shown that quasi-periodic outflows injected at the footpoints of coronal loops inevitably generate slow magnetoacoustic waves propagating upwards along the loop (Ofman et al., 2012; Wang et al., 2013). The simulated flows decelerate with height rapidly, suggesting that the observed PDs at higher corona ($r \gtrsim 1.2R_S$) are due to slow magnetosonic waves.

Despite of numerous works on observations and theory of propagating slow magnetoacoustic waves in coronal loops, it is still not completely understood what are the driving mechanisms and what processes cause a rapid damping of slow waves in the corona. Amplitudes of waves rapidly decay as they travel outward along the loop with the decay time of the order of minutes. Recent studies indicate that observed wave damping is frequency-dependent (KrishnaPrasad et al., 2014; Mandal et al., 2016). Also, the observed propagation velocities and damping lengths of slow waves are temperature-dependent (KrishnaPrasad et al., 2012b; Uritsky et al., 2013). Several theoretical studies showed that thermal conduction, compressive viscosity, radiative cooling and effect of magnetic field divergence can lead to a decay of amplitude of propagating slow magnetoacoustic waves. High thermal conduction in hot coronal loops with temperature ~6 MK results in rapid damping of slow waves on timescales on the order of a wave period (Ofman and Wang, 2002). Other studies by Porter et al. (1994), Nakariakov et al. (2000), De Moortel and Hood (2003), and Klimchuk et al. (2004) also found that thermal conduction is the dominant damping mechanism for slow waves in coronal loops while other processes and effects have smaller contribution. However, thermal conduction process alone does not account for the observed damping (Sigalotti et al., 2007).

Coronal radiative losses are small compared to the energy losses due to thermal conduction. For typical quiescent corona ($T = 1$ MK, $n = 10^9$ cm^{-3}) characteristic time of radiative cooling is about 30 min, while for thermal conduction the timescale is in the order of a few seconds. De Moortel and Hood (2004) showed that in 1 MK corona the effect of optically thin radiation on slow magnetosonic waves is almost negligible causing wave damping by only few percent. Recent study by Kuźma et al. (2017) that modeled a spicule as a localized velocity pulse at the upper chromosphere into the corona also showed that radiation only slightly affects the dynamics of a spicule and a generated shock wave. Other studies showed that in certain plasma parameters cooling can significantly affect propagation of magnetoacoustic waves in coronal loops. Al-Ghafri

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