Solar Phys (2007) 246: 145–164
DOI 10.1007/s11207-007-9011-9

Damped Oscillations of Coronal Loops

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Received: 31 January 2007 / Accepted: 26 July 2007 / Published online: 3 November 2007

Abstract A mechanism of damped oscillations of a coronal loop is investigated. The loop is treated as a thin toroidal flux rope with two stationary photospheric footpoints, carrying both toroidal and poloidal currents. The forces and the flux-rope dynamics are described within the framework of ideal magnetohydrodynamics (MHD). The main features of the theory are the following: *i*) Oscillatory motions are determined by the Lorentz force that acts on curved current-carrying plasma structures and *ii*) damping is caused by drag that provides the momentum coupling between the flux rope and the ambient coronal plasma. The oscillation is restricted to the vertical plane of the flux rope. The initial equilibrium flux rope is set into oscillation by a pulse of upflow of the ambient plasma. The theory is applied to two events of oscillating loops observed by the *Transition Region and Coronal Explorer* (TRACE). It is shown that the Lorentz force and drag with a reasonable value of the coupling coefficient (c_d) and without anomalous dissipation are able to accurately account for the observed damped oscillations. The analysis shows that the variations in the observed intensity can be explained by the minor radial expansion and contraction. For the two events, the values of the drag coefficient consistent with the observed damping times are in the range $c_d \approx 2-5$, with specific values being dependent on parameters such as the loop density, ambient magnetic field, and the loop geometry. This range is consistent with a previous MHD simulation study and with values used to reproduce the observed trajectories of coronal mass ejections (CMEs).

Keywords Sun: magnetic field · Sun: corona · Sun: coronal loops · Sun: oscillations · Sun: flux ropes

1. Introduction

Oscillations of coronal structures have been reported in connection with solar flares and other eruptive phenomena. Examples include oscillations of quiescent prominences (the so-called "winking filaments") induced by nearby flares (*e.g.*, Ramsey and Smith, 1966; Hyder,

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1966) and oscillations of flare emission regions (Seely and Feldman, 1984). Typically, these motions have periods of several to tens of minutes and are damped in several oscillation periods. Recently, oscillations of coronal loops have been observed with high resolution in space and time by the *Transition Region and Coronal Explorer* (TRACE) (*e.g.*, Schrijver *et al.*, 1999; Aschwanden *et al.*, 1999, 2002; Schrijver and Brown, 2000; Nakariakov *et al.*, 1999; Wang and Solanki, 2004). Theoretical calculations have shown that oscillations of flux ropes depend primarily on magnetic field strength, geometry, and mass (*e.g.*, Kleczek and Kuperus, 1969; Chen, 1989, 1990; Vršnak *et al.*, 1990; Cargill, Chen, and Garren, 1994; Roberts, 2000; Nakariakov and Ofman, 2001; Brady and Arber, 2005). Thus, an accurate understanding of oscillations may allow one to estimate these coronal quantities, and the observed damping rate can shed light on coronal dissipation. For example, Hyder (1966) estimated the viscosity in the corona surrounding prominences, and Nakariakov *et al.* (1999) inferred shear viscosity and Ohmic resistivity in coronal loops.

The coronal loop oscillations observed by TRACE are interpreted as the horizontal polarization (Aschwanden *et al.*, 1999, 2002; Nakariakov *et al.*, 1999; Schrijver and Brown, 2000) or the vertical polarization (Wang and Solanki, 2004) of the global "kink" oscillation in which an entire loop oscillates with its stationary footpoints anchored in the photosphere. Theoretically, coronal loops have been simplified and treated as either straight bundles or slabs of field "lines" (*e.g.*, Nakariakov *et al.*, 1999; Roberts, 2000; Ruderman and Roberts, 2002; Uralov, 2003; Brady, Verwichte, and Arber, 2006) or untwisted and unsheared curved field lines (*e.g.*, Van Doorsselaere *et al.*, 2004a; Brady and Arber, 2005; Selwa *et al.*, 2006; Terradas, Oliver, and Ballester, 2006; Verwichte, Foullon, and Nakariakov, 2006). The loops are defined by field-line bundles or slabs with higher density and slower Alfvén speed and carry no electric currents. The oscillations are envisioned as magnetohydrodynamic (MHD) waves trapped on the field lines with slower Alfvén speed (Roberts, Edwin, and Benz, 1984). An arcade of loops is modeled as a periodic array of density enhancements trapping transverse waves (Uralov, 2003). The trapped waves may be set up by the motions of magnetic field lines threading the boundary surfaces or by transverse waves impinging on the loops. The loop oscillation (*i.e.*, trapped waves) may be damped by viscosity and Ohmic resistivity inside the loops via resonant absorption (Nakariakov *et al.*, 1999), resonant absorption in dissipative layers (*e.g.*, Goossens, Ruderman, and Hollweg, 1995; Ruderman and Roberts, 2002; Goossens, Andries, and Aschwanden, 2002; Aschwanden *et al.*, 2003; Van Doorsselaere *et al.*, 2004b; Terradas, Oliver, and Ballester, 2006; Arregui *et al.*, 2007), or lateral wave leakage resulting from mode coupling or tunneling without anomalous dissipation (Uralov, 2003; Brady and Arber, 2005; Brady, Verwichte, and Arber, 2006; Verwichte, Foullon, and Nakariakov, 2006).

In a quantitative work, Nakariakov *et al.* (1999) modeled the event of 14 July 1998 in which a set of bright coronal loops in TRACE 171 Å data were observed to oscillate in response to a nearby flare, an event discussed by Aschwanden *et al.* (1999). Focusing on one of the loops, Nakariakov *et al.* interpreted the motion as a horizontal oscillation and found a period of $\approx$4.3 minutes and a decay time of $\approx$12.1 minutes. They found that if viscosity is assumed to dominate in the damping of the oscillation, the observed decay time suggests a shear viscosity Reynolds number of $\mathrm{Re} \approx 10^{5.3} - 10^{6.1}$, which is eight to nine orders of magnitude smaller than the classical value of $\mathrm{Re} \approx 10^{14}$. If the coronal plasma resistivity is assumed to dominate, a Lundquist number of $S \approx 10^5 - 10^{5.8}$ is implied, which is seven to eight orders of magnitude smaller than the classical value of $S = 10^{13}$. They concluded that coronal plasmas may have large anomalous viscosity and resistivity under certain conditions (Ofman, Davila, and Steinolfson, 1994).

Wang and Solanki (2004) described a loop oscillation observed on 17 April 2002 by TRACE in 195 Å. They interpreted the observed loop motion as a vertical oscillation, with