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Simulation of the observed coronal kink instability and its implications for the SDO/AIA

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Abstract

Srivastava et al. (2010) have observed a highly twisted coronal loop, which was anchored in AR10960 during the period 04:43 UT-04:52 UT on 4 June 2007. The loop length and radius are approximately 80 Mm and 4 Mm, with a twist of 11.5 π. These observations are used as initial conditions in a three dimensional nonlinear magnetohydrodynamic simulation with parallel thermal conduction included. The initial unstable equilibrium evolves into the kink instability, from which synthetic observables are generated for various high-temperature filters of SDO/AIA. These observables include temporal and spatial averaging to account for the resolution and exposure times of SDO/AIA images. Using the simulation results, we describe the implications of coronal kink instability as observables in SDO/AIA filters.

Keywords: Magnetohydrodynamics (MHD); Magnetic reconnection; Corona

1. Introduction

The active region magnetic field exhibits complex topology due to the emergence of new large-scale magnetic flux from the sub-photospheric layers of the Sun. Such complexity some times generates various types of magnetic instabilities that are well observed in the solar active regions as a trigger of flares and associated dynamical processes (Srivastava et al., 2010; Kumar et al., 2010; Foullon et al., 2011; Innes et al., 2012; Srivastava et al., 2013). Among the various types of magnetic instabilities, the kink instability is most commonly observed in the solar atmosphere, and evolved in the large-scale magnetic flux-tubes due to their azimuthal twist. However, the twist must cross the minimum threshold value of $\Phi > 2.5\,\pi$ to trigger the kink instability in the magnetic flux-tubes in the solar corona (Hood and Priest, 1979). The kink instability is well observed in active region loops (Srivastava et al., 2010), eruptive filaments (Liu et al., 2008), eruptive coronal cavities (Liu et al., 2007), and it can eventually trigger flares and CMEs (Kliem and Török, 2006; Cho et al., 2009). Recently, Zaqarashvili et al. (2010) have given an important conclusion that the axial mass flow in the magnetic flux-tubes reduces the threshold of kink instability, and can easily lead to solar flares and CMEs. The kink instability does not only liberate the flare energy, it can also cause the excitation of MHD wave modes (Haynes et al., 2008). The kink instabilities observed in the astrophysical plasma are also reproduced in a laboratory experiment (Moser and Bellan, 2012), which shows the confinement of kink unstable twisted plasma structures due to multi-stage cascade reconnection at laboratory scales.

In addition to the observations the coronal kink instability is studied using analytical and numerical modelling (Mikić et al., 1990; Baty and Heyvaerts, 1996; Arber et al., 1999; Gerrard et al., 2002). The ideal MHD kink instability has been inferred as a trigger for reconnection

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in the flaring loops (Browning et al., 2008; Hood et al., 2009). Botha et al. (2011) initialised the kink instability with a twisted magnetic field and reported that the inclusion of thermal conduction along magnetic field lines can reduce the maximum reconnection generated temperature by an order of magnitude. This changes the range of spectral lines as observables of the kink instability when compared to simulations without conduction. Botha et al. (2012) have also reported the observational signatures of the MHD kink instability with the inclusion of thermal conduction. A kink-unstable cylindrical loop is evolved by using the initial conditions of a highly twisted loop as observed by TRACE (Srivastava et al., 2010). The numerical results are synthesized through TRACE temperature response function filtering, and through spatial and temporal averaged line of sight intensity measurements (Haynes and Arber, 2007).

In the present paper, we extend the work of Botha et al. (2012) and study the evolution of the kink unstable loop as observed by Srivastava et al. (2010) in the high-temperature filters of SDO/AIA. In Section 2 we present a brief description of the numerical model and initial conditions. In Section 3 we describe the results related to the synthesis of a kink unstable loop in various SDO/AIA channels. The discussion and conclusions form the last section.

2. Numerical simulation of the observed coronal kink instability

The nonlinear three-dimensional simulation is executed by implementing the MHD Lagrangian-remap code (Lare3d) of Arber et al. (2001). The numerical code solves the resistive MHD equations for the fully ionised plasma with a heat flux included in the energy equation (Botha et al., 2011; Botha et al., 2012). Thermal conduction is considered to be included along the magnetic field lines in the form of a classical Spitzer and Härm (1953) or Braginskii conductivity with $\log \Lambda = 18.4$ that corresponds to the standard thermal conductivity parallel to the magnetic field of $\kappa_{\parallel} = 10^{-11} T^{5/2}\ \mathrm{W\,m^{-1}\,K^{-1}}$ (Priest, 2000; Botha et al., 2012). The numerical code consists of an artificial resistivity that is activated only when the electric current exceeds a critical value, which is set in the present case to $j_c = 2$ mA (Botha et al., 2012). This resistivity is considered in the form given as follows

$$\eta = \begin{cases} \eta_0, & |j| \geqslant j_c, \\ 0, & |j| < j_c, \end{cases} \tag{1}$$

where η_0 is the anomalous resistivity. η_0 is switched on when the kink instability occurs and thereafter it remains active for the duration of the simulation (Botha et al., 2011; Botha et al., 2012). The coronal loop is initialised as a straight twisted cylinder in a uniform background temperature and density (Fig. 1) as previously performed by Botha et al. (2012).

The initial conditions of the numerical simulation of the coronal loop is taken from observations of a highly twisted loop (Srivastava et al., 2010). Using the multi-wavelength observations of SOHO/MDI, SOT-Hinode/blue-continuum (4504 Å), G band (4305 Å), Ca II H (3968 Å), and TRACE 171 Å, they observed a highly twisted magnetic loop in AR 10960 during the period 04:43 UT-04:52 UT on 2007 June 4. SOT-Hinode/blue-continuum (4504 Å) observations show that the penumbral filaments of a positive polarity sunspot have counterclockwise twist that may be caused by the clockwise rotation of the spot umbrae and can activate a right-handed helical twist in the loop system. This loop whose one footpoint is anchored in this sunspot, shows strong right-handed twist in chromospheric SOT-Hinode/Ca II H (3968 Å) and coronal TRACE 171 Å images, which was consistent with the Hemisphere Helicity Rule (HHR). The length and the radius of the loop are estimated as L≈80 Mm and a≈4 Mm, respectively. The distance between neighbouring turns of magnetic field lines is estimated as ≈10 Mm, which further gives the total twist angle Φ=11.5 π as estimated for a homogeneous distribution of the twist along the loop. This observed twist is much larger than the Kruskal–Shafranov instability criterion(Φ>2 π) for the kink instability and later triggers a B5.0 class solar flare that occurred between 04:40 UT and 04:51 UT in this active region. The details of these observational finding are given in Srivastava et al. (2010).

The observed curved loop is straightened to perform numerical simulations (Fig. 1, left-panel). One of the footpoints of the active region loop is anchored in a positive polarity spot (Srivastava et al., 2010) and it is estimated that the minimum value of the magnetic field at this location is 470 G (Botha et al., 2012). From this photospheric value of the magnetic field, the chromospheric field is calculated approximately as 80 G, as well as near the loop apex in the corona as 20 G (Petrie and Patrikeeva, 2009; Botha et al., 2012). The numerical simulation is initialised for the loop with a maximum internal field of 20 G, while the outside background magnetic field is considered as a uniform value of 15 G parallel to the cylindrical axis of the simulated loop structure. In the numerical simulations the coronal loop is initialised as a uniform cylinder in force-free equilibrium and set unstable to an ideal MHD kink instability (Hood et al., 2009; Botha et al., 2012). The axial twist is given by the following equation

$$\Phi = \frac{LB_\theta}{rB_z} \quad \text{with} \quad \max(\Phi) = 11.5\pi, \tag{2}$$

where L is the loop length and r is the radial distance from the central axis of the loop. The axial and azimuthal magnetic fields are given respectively by B_z and B_θ as a function of r. The maximum twist is considered at position $r = 1$ Mm, which exceeds the stability threshold, therefore, the loop becomes kink unstable (Mikić et al., 1990). The details of the magnetic field configuration is outlined in Botha et al. (2011, 2012). Gravity is not included in the simulations. The initial temperature and mass density are taken as uniform and constant, with typical values of $1.67 \times 10^{-12}\ \mathrm{kg\,m^{-3}}$ (Young et al., 2009) and 0.125 MK respectively. This temperature is selected to make the