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STABILITY AND DYNAMICS OF A FLUX ROPE FORMED VIA FLUX EMERGENCE INTO THE SOLAR ATMOSPHERE

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ABSTRACT

We study the stability and dynamics of a flux rope formed through the emergence of a twisted magnetic flux tube into the solar atmosphere. A three-dimensional magnetohydrodynamic simulation has been performed to investigate several key factors affecting the dynamics of the flux rope. The stability of the flux rope is examined by deriving the decay index of the coronal magnetic field surrounding the flux rope. We investigate a transition between the quasi-static and dynamic states of the flux rope through an analysis of the curvature and scale height of emerging magnetic field. A practical application of this analysis for global eruptions is also considered.

Key words: magnetohydrodynamics (MHD) – Sun: corona – Sun: coronal mass ejections (CMEs) – Sun: magnetic topology

Online-only material: color figures

1. INTRODUCTION

Emergence of magnetic field from the solar interior into the solar atmosphere, called flux emergence, is regarded as a key process for forming structures of magnetic field in the solar atmosphere where various kinds of active phenomena such as solar flares, jets, and coronal mass ejections (CMEs) are occasionally observed (Svestka & Cliver 1992; Low 1996; Golub & Pasachoff 1997; Priest & Forbes 2002; Aschwanden 2004; Forbes et al. 2006). The helioseismology suggests that magnetic fields producing these active phenomena are amplified in the tachocline between the radiative zone and convective zone (Miesch 2005). After traveling through the convective zone (Fan 2009), these magnetic fields eventually emerge to the solar surface via magnetic buoyancy (Parker 1955). They then expand rapidly due to the abrupt decrease of the surrounding gas pressure, thereby forming magnetic structures in the solar atmosphere where free magnetic energy is stored (Shibata & Magara 2011).

Among those active phenomena mentioned above, solar flares are one of the typical phenomena caused by the dissipation of the coronal electric currents that supply the free energy. There is another group of phenomena known as global eruptions, which are caused by the imbalance among forces acting on magnetic structures. CMEs are one of these phenomena driven by the upward Lorentz force dominating other forces. An intensive effort has been made toward understanding the physical mechanism of those magnetically driven global eruptions. Low & Hundhausen (1995) explain the destabilizing effect of mass drain on a magnetic structure. Increasing the shear and/or twist of magnetic field at the solar surface is another possible driver of global eruptions (Mikic et al. 1988; Biskamp & Welter 1989; Chen 1989; Steinolfson 1991; Inhester et al. 1992; Mikic & Linker 1994; Choe & Lee 1996; Török et al. 2004). The cancellation of magnetic flux at the solar surface causes the imbalance between the magnetic pressure force and magnetic tension force, leading to the global eruption (van Ballegooijen & Martens 1989; Forbes & Isenberg 1991; Amari et al. 2000; Linker et al. 2003; Roussev et al. 2003; Lin 2004). Ideal MHD instabilities such as the kink instability (Sturrock et al. 2001; Fan & Gibson 2004) and torus instability (Kliem & Török 2006) could also drive global eruptions. The tether-cutting model proposed by Moore et al. (2001) explains that the weakening of the line-tying effect via magnetic reconnection produces global eruptions. Furthermore, in several multi-polar flux systems the magnetic reconnection between different flux domains leads to the global eruption (Antiochos et al. 1999; Chen & Shibata 2000; Kusano et al. 2004).

These works mentioned above nicely explain the eruptive process of magnetic structures on the Sun, although they mostly prescribe particular magnetic configurations for pre-eruptive structures, so the origin of these pre-eruptive structures, that is, how they are self-consistently formed in the solar atmosphere before the global eruption, is not clear. In this respect, studies based on flux emergence have demonstrated the self-consistent formation of pre-eruptive structures on the Sun. Matsumoto et al. (1998) and Magara & Longcope (2001) explain the formation of sigmoidal structures on the Sun. Manchester et al. (2004) show how a flux rope is formed in the corona via flux emergence. Archontis & Török (2008) and Archontis & Hood (2012) discuss the evolution of a flux rope interacting with some particular pre-existing coronal magnetic fields.

The present paper aims at shedding some light on the stability and dynamics of a flux rope formed via flux emergence. Toward this end, we have performed a three-dimensional MHD simulation for the emergence of an isolated magnetic flux tube from a subsurface region into the solar atmosphere. Our particular interest is to investigate several key factors affecting the dynamics of a flux rope formed through the emergence of the flux tube. We discuss a transition between the quasi-static and dynamic states of the flux rope through an analysis of the curvature and scale height of emerging magnetic field.

The stability of the flux rope is discussed especially from the viewpoint of the torus instability (Kliem & Török 2006). Kliem & Török (2006) and several following works (Török & Kliem 2007; Fan & Gibson 2007; Schrijver et al. 2008; Liu 2008; Guo et al. 2010; Xu et al. 2012; Kumar et al. 2012) focus on the decay index of the coronal magnetic field surrounding a flux