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A MAGNETOHYDRODYNAMIC MODEL FOCUSED ON THE CONFIGURATION OF MAGNETIC FIELD RESPONSIBLE FOR A SOLAR PENUMBRAL MICROJET

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ABSTRACT

In order to understand the configuration of magnetic field producing a solar penumbral microjet that was recently discovered by *Hinode*, we performed a magnetohydrodynamic simulation reproducing a dynamic process of how that configuration is formed in a modeled solar penumbral region. A horizontal magnetic flux tube representing a penumbral filament is placed in a stratified atmosphere containing the background magnetic field that is directed in a relatively vertical direction. Between the flux tube and the background field there forms the intermediate region in which the magnetic field has a transitional configuration, and the simulation shows that in the intermediate region magnetic reconnection occurs to produce a clear jet-like structure as suggested by observations. The result that a continuous distribution of magnetic field in three-dimensional space gives birth to the intermediate region producing a jet presents a new view about the mechanism of a penumbral microjet, compared to a simplistic view that two field lines, one of which represents a penumbral filament and the other the background field, interact together to produce a jet. We also discuss the role of the intermediate region in protecting the structure of a penumbral filament subject to microjets.

Key words: magnetohydrodynamics (MHD) – methods: numerical – Sun: magnetic topology – sunspots

Online-only material: animation, color figures

1. INTRODUCTION

The solar observing satellite *Hinode* was launched in 2006 September, and since then it has revealed various hidden aspects of solar activity. The sunspot is one of the important targets of observations by *Hinode*, and many new findings on sunspot activity have been reported, such as penumbral structure and dynamics (Bellot Rubio et al. 2007; Jurčák et al. 2007; Katsukawa et al. 2007a; Ichimoto et al. 2007; Borrero & Solanki 2008; Sainz Dalda & Bellot Rubio 2008; Zakharov et al. 2008; Ning et al. 2009; Franz & Schlichenmaier 2009), fine structure of umbrae (Bharti et al. 2007; Kitai et al. 2007; Riethmüller et al. 2008; Watanabe et al. 2009; Sobotka & Jurčák 2009), light bridges (Katsukawa et al. 2007b; Louis et al. 2009; Shimizu et al. 2009), and moving magnetic features (Kubo et al. 2007; Zuccarello et al. 2009; Li et al. 2009).

Among them, a new kind of sunspot activity has been discovered by *Hinode*, named penumbral microjets. This jet-like activity was first reported in Katsukawa et al. (2007a), where the basic properties of penumbral microjets were derived. They are associated with transient brightenings, observed at the boundary of a penumbral filament. Their spatial size is typically 1000–4000 km in length and 400 km in width, while the apparent speed of jet-like motion is about 100 km s^{-1} and the lifetime is about 1 minute. Katsukawa et al. (2007a) found penumbral microjets in the Ca II H line that observes the lower chromosphere with the temperature below 10^4 K. Later, Jurčák & Katsukawa (2008) reported that a penumbral microjet tends to be aligned with the background magnetic field emanating from a sunspot in a relatively vertical direction.

The physical mechanism for producing a penumbral microjet has also been investigated. Some observational works have suggested that a penumbral filament is composed of horizontal magnetic field lines with some twist (Ichimoto et al. 2007) and is surrounded by relatively vertical field lines (Langhans et al. 2005), so the magnetic field is supposed to change direction abruptly near the boundary of a penumbral filament. Magnetic reconnection might occur at that location to produce a jet-like phenomenon (Katsukawa et al. 2007a). Ryutova et al. (2008) present a model where magnetic reconnection and associated shock waves reproduce several observed properties of a penumbral microjet. Sakai & Smith (2008) performed two-fluid simulation in an idealized configuration where vertical and horizontal magnetic flux tubes interact together to produce a jet-like phenomenon. They derived the speed and temperature of a jet.

Following these previous studies, we here investigate a dynamic process of how the configuration of magnetic field responsible for a penumbral microjet is formed in a local penumbral region. We basically follow a model of a penumbra presented by Solanki & Montavon (1993) where a nearly horizontal magnetic flux tube representing a penumbral filament is placed in a stratified atmosphere containing relatively vertical magnetic field (background field). Our result gives a new view that a continuous distribution of magnetic field in three-dimensional space gives birth to the intermediate region where the magnetic field has a transitional configuration between a penumbral flux tube and the background field, and magnetic reconnection occurs in the intermediate region to produce a jet-like structure aligned with the background field, just as the observations indicate. The fact that magnetic reconnection does not involve a penumbral flux tube itself may explain why a penumbral filament can maintain its shape and dynamic state even though a number of microjets occur in the vicinity of that penumbral filament.

2. MODEL DESCRIPTION

We solved a set of magnetohydrodynamic (MHD) equations with uniform gravity in the three-dimensional Cartesian co-