Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research xxx (2017) xxx–xxx
ELSEVIER
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
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An analytical model of prominence dynamics

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Received 30 January 2017; received in revised form 18 October 2017; accepted 22 October 2017

Abstract

Solar prominences are magnetic structures incarcerating cool and dense gas in an otherwise hot solar corona. Prominences can be categorized as quiescent and active. Their origin and the presence of cool gas ($\sim 10^4$ K) within the hot ($\sim 10^6$ K) solar corona remains poorly understood. The structure and dynamics of solar prominences was investigated in a large number of observational and theoretical (both analytical and numerical) studies. In this paper, an analytic model of quiescent solar prominence is developed and used to demonstrate that the prominence velocity increases exponentially, which means that some gas falls downward towards the solar surface, and that Alfvén waves are naturally present in the solar prominences. These theoretical predictions are consistent with the current observational data of solar quiescent prominences.

Keywords: Solar physics; Sun; Solar prominence; MHD waves

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1. Introduction

It is a well known fact that solar prominences are cool, dense plasma clouds composed of small-scale ever-changing threads of fibrils, embedded in the hot solar corona (Anderson and Athay, 1989; Berger and Ricca, 1996). The prominence plasma is in nearly equilibrium state supported by the magnetic field against gravity (Kippenhahn and Schluter, 1957; Raadu and Kuperus, 1973).

Quiescent prominences are large and appear as thin vertical sheets endowed with fine filamentary structure. These prominences display minor changes over a period of time (days) (Webb et al., 1998). Irrespective of the “quiescent” phrase, these prominences display remarkable mass motion when observed in high resolution Hα movies. These filaments possess the solar material concentrated as rope-like structures with diameter less than 300 km.

Primarily, two types of topology have been suggested for supporting prominences that are related to magnetic fields. The first one was put forward by Kipppenhahn and Schluter in 1957 (Kippenhahn and Schluter, 1957). Kuperus and Tandberg-Hanssen proposed the latter in 1967 (Kuperus and Tandberg-Hanssen, 1967). This was developed further by Kuperus and Raadu (K-R) in 1973 (Raadu and Kuperus, 1973). In the Kuperus-Schlitter (K-S) model, the prominence material sits on top of the field lines supported by the normal polarity field. The K-R model suggests that the prominence is embedded in an inverse polarity field. Simply stated, a prominence is considered as a sheet of plasma, erected in the corona, above a magnetic neutral line.

Prominences are highly dynamical structures exhibiting flows in Hα, UV and EUV lines. The study of these flows improve our understanding of prominence formation and stability, the mass supply and the magnetic field structure of the prominence imparting great interest to these topics.

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https://doi.org/10.1016/j.asr.2017.10.035

Please cite this article in press as: Routh, S., et al. An analytical model of prominence dynamics. Adv. Space Res. (2017), https://doi.org/10.1016/j.asr.2017.10.035

A complex dynamics with vertical down flows, up flows and horizontal flows is observed in the Hα lines and quiescent limb prominences (Chae et al., 2008; Engvold et al., 1985; Kubota and and Uesugi, 1986; Lin et al., 2003; Zirker et al., 1998). The velocity of these flows lies between a range of 2 and 35 km/s, while in EUV lines, these flows seem to be of slightly higher velocity. The pertinent aspect of these observations correspond to various temperatures indicating the speed of flow corresponding to different parts of the prominence. These flows seem to be field aligned due to the filament plasma.Vertical filamentary downflows often have been observed in vertically striated or ‘hedgerow’ prominences (Engvold, 1976; Martres et al., 1981) as well as vortices (Liggett and Zirin, 1984). Explaining these observations of vertical and rotational flows with existing theoretical MHD models is one of the major goals of prominence’s investigations.

In more recent numerical studies performed by Terradas et al. (2015), the MHD equations have been solved and time evolution of solar quiescent prominences embedded in sheared magnetic arcades has been investigated. Moreover, Terradas et al. (2016) have studied solar active prominences embedded in magnetic flux ropes. The authors have shown that prominences may originate in the solar photosphere and presented their evolution through the solar atmosphere. The physical properties of the solar prominences and the existence of oscillations associated with such prominences resulting from numerical simulations have also been presented and discussed.

In this paper, we develop an analytical approach to investigate the dynamics of solar quiescent prominences by considering a simple model that is suitable for such an analytical treatment. The main theoretical results obtained from the model are:

- an exponential increase of the prominence velocity within very short time (few minutes) and then resuming the motion with a uniform velocity;
- the downfall of cool gas and neutral material toward the solar surface, which is consistent with the observational data;
- the theoretical evidence for the existence of Alfvén waves responsible for driving oscillations observed in solar quiescent prominences

The paper is organized as follows: Section 2 presents the model of the prominence, based on the MHD equations; this is followed by the obtained results and conclusion in Sections 3 and 4 respectively.

2. MHD equations

Hα photographs of quiescent solar prominences above the solar limb often show evidence of the prominence plasma assuming the form of vertically oriented, narrow filaments (Tandberg-Hanssen, 1995). Vector magnetic fields, using the Hanle effect, have been used to observe the prominence plasmas. Such observations have helped establishing the fact that the magnetic fields inside the prominences are horizontal, binding across slab like macroscopic prominence while the principal field component remains parallel to the horizontal length of the prominence (Leroy, 1989). The narrow vertical filaments are composed of pieces of plasma lined up vertically. Hα observations also demonstrate that the filamentary structures of a quiescent prominence are not truly static Tandberg-Hanssen (1995) and Zirin (1988). Here, we attempt to analyze the dynamics of such a prominence using the MHD equations (Fig. 1).

Suppose there exists a one dimensional infinite vertical rigid sheet of perfectly conducting massive material sitting in a perfectly conducting incompressible static fluid. Let the sheet be threaded by a uniform magnetic field that is perpendicular to the sheet. Gravity is assumed to be uniform and acts vertically to the prominence sheet. Gravity is neglected for the medium (assuming the medium’s density to be significantly less compared to the sheet’s density) but considered to be acting on the prominence thread. Let $\overrightarrow{B}(y,t)\hat{z}$ and $\overrightarrow{v} = v(y,t)\hat{z}$ be the perturbations in the magnetic field and velocity of the medium respectively. The magnetic field acting on the prominence is described as $\overrightarrow{B} = [0, B_0, \overrightarrow{B}(y,t)]$, where $\overrightarrow{B}(y,t)\hat{z}$ is perturbation in magnetic field, and B_0 is constant magnetic field in the y direction, perpendicular to the sheet.

The z-component of the MHD momentum equation for the medium outside the prominence sheet can be written in the following form,

$$\rho_0 \frac{\partial v}{\partial t} = \frac{B_0}{4\pi}\frac{\partial B}{\partial y}. \tag{1}$$

and the z-component of MHD induction equation becomes,

$$\frac{\partial B}{\partial t} = B_0 \frac{\partial v}{\partial y}. \tag{2}$$

It must be pointed out that we have not used any small amplitude approximation to linearize the MHD equations in order to obtain the above equations.

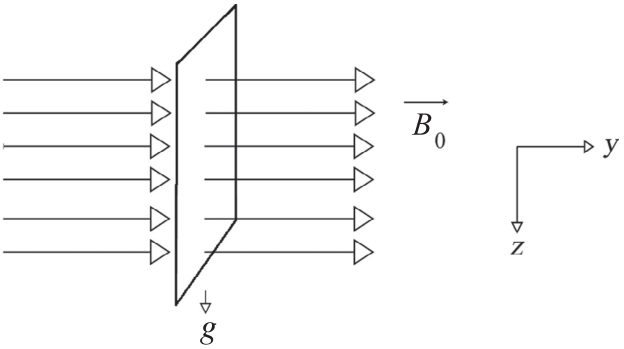

Fig. 1. Schematic representation of prominence sheet along with conditions.