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MHD simulations of quiescent prominence upflows in the Kippenhahn-Schlüter prominence model

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Abstract. Images from the Hinode satellite have led to the discovery of dark upflows that propagate from the base of prominences, developing highly turbulent profiles. The magnetic Rayleigh-Taylor instability has been hypothesized as the mechanism to create these plumes. To study the physics behind this phenomenon we use 3D magnetohydrodynamic simulations to investigate the nonlinear stability of the Kippenhahn-Shlüter prominence model to the magnetic Rayleigh-Taylor instability. The model simulates the rise of a buoyant tube inside a quiescent prominence, where the upper boundary between the tube and prominence model is perturbed to excite the interchange of magnetic field lines. We find upflows of constant velocity (maximum found $6\,\mathrm{km\,s^{-1}}$) and a maximum plume width $\approx 1500\,\mathrm{km}$ which propagate through a height of approximately 6 Mm, in general agreement with the Hinode observations.

Keywords : Sun: prominences – MHD – methods: numerical

1. Introduction

There is a long history of flows inside the cool (10000 K, Tandberg-Hanssen 1995), dense ($\sim 10^{11}\,\mathrm{cm^{-3}}$, Hirayama 1986) plasma of quiescent prominences. Observations of quiescent prominences have shown downflows (Engvold 1981), vortices of approximately 10^5 km $\times 10^5$ km in size (Liggett & Zirin 1984) and a bubble of size 2800 km forming a keyhole shape with a bright center (de Toma et al. 2008) with velocities of 10-30 km $\mathrm{s^{-1}}$. Using a characteristic gas pressure of $0.6\,\mathrm{dyn\,cm^{-2}}$ (Hirayama 1986) and magnetic field of $3 \sim 30$ G (Leroy 1989), gives a plasma $\beta \sim 0.01$-1. For a review

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of the current understanding of quiescent prominences see, for example, Tandberg-Hanssen (1995), Labrosse et al. (2010) and Mackay et al. (2010).

Observations by the Solar Optical Telescope (SOT) (Tsuneta et al. 2008) on the Hinode satellite (Kosugi et al. 2007) have shown that on a small scale quiescent prominences are highly dynamic and unstable phenomena. Berger et al. (2008) and Berger et al. (2010) reported dark plumes that propagated from large bubbles (approximately 10 Mm in size with column density less than 20 % of the prominence density, Heinzel et al. 2008) that form at the base of some quiescent prominences. The plumes flow through a height of approximately 10 Mm at a velocity of approximately 20 km s^{-1} before dispersing into the background prominence material (see Fig. 1). Berger et al. (2011) presented observations of prominence bubbles using the Atmospheric Imaging Assembly on the Solar Dynamics Observatory that show the temperature of the material inside the bubble to be $> 250,000$ K. The observed upflows are hypothesized to be created by the magnetic Rayleigh-Taylor instability.

The growth rate (ω) of the magnetic Rayleigh-Taylor instability for a uniform magnetic field parallel to the interface is $\omega^2 = kg/(\rho_+ + \rho_-)\left[(\rho_+ - \rho_-) - (B^2 k_{\|}^2)/(2\pi kg)\right]$ where B is the magnetic field strength and $k_{\|}$ is the perturbation in the direction of the magnetic field (Chandrasekhar 1961). Stone & Gardiner (2007) investigated the impact of shear in the magnetic field across the contact discontinuity, finding that this suppressed the small wavenumbers creating wider filamentary structures. Ryutova et al. (2010) described how the theoretical growth rate and behavior for the magnetic Rayleigh-Taylor instability well match the observations of the plumes.

The model that we use in this work is the Kippenhahn-Schlüter prominence model (Kippenhahn & Schlüter 1957; Priest 1982). This model describes the local structure of the prominence useing the Lorentz force of a curved magnetic field to support plasma against gravity (see Fig. 2). The model is uniform in the vertical direction and there is no corona. This model has been shown to be linearly stable to ideal MHD perturbations (Kippenhahn & Schlüter 1957; Anzer 1969). A full description of this study of the magnetic Rayleigh-Taylor instability in the Kippenhahn-Schlüter model is given in Hillier et al. (2011). A brief dscription of the results are given in this paper.

2. Numerical Method

In this study, we use the 3D conservative ideal MHD equations. Constant gravitational acceleration is assumed, but viscosity, diffusion, heat conduction and radiative cooling terms are neglected and we assume an ideal gas. The equations are non-dimentionalized using the sound speed ($C_s = 13.2$ km s^{-1}), the pressure scale height ($\Lambda = C_s/(\gamma g) = R_g T/(\mu g) = 6.1 \times 10^7$ cm), the density at the centre of the prominence ($\rho(x = 0) = 10^{-13}$ g cm^{-3}) and the temperature ($T_0 = 10^4$ K), giving a characteristic timescale of $\tau = \Lambda/C_s = 47$ s. We take $\gamma = 1.05$ and $\beta = 0.5$.

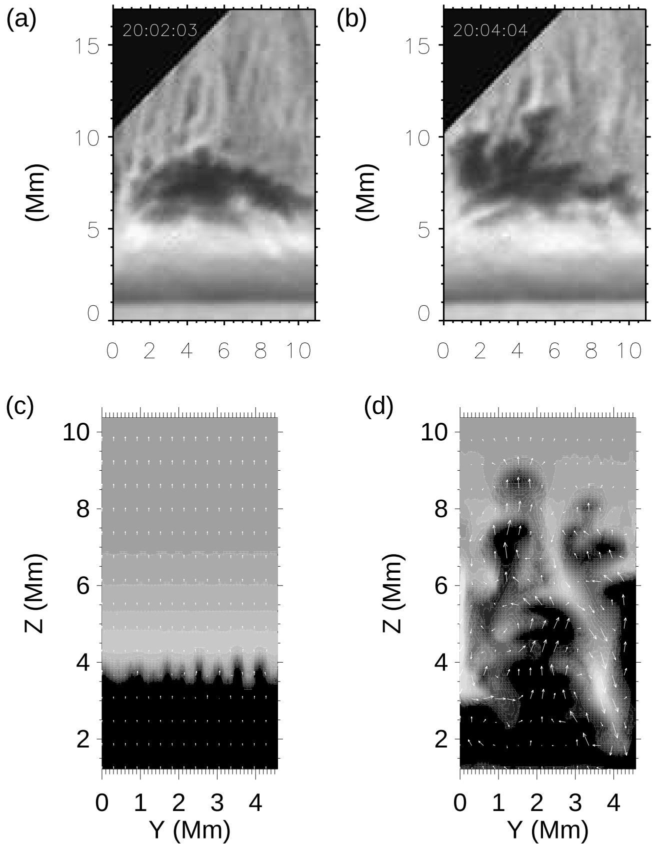

Figure 1. Panels a & b are observations showing the formation of dark plumes propagating from a bubble that forms below a quiescent prominence observed on 8 August 2007 20:01 UT taken in the 656.3 nm Hα spectral line. Panels c & d show the simulated evolution of upflows at t = 719 & 2453 s (normalized units t = 15.3 & 52.2) taken in the x = 0 plane.

The initial model is as follows $B_x(x) = B_{x0}$ and $B_z(x) = B_{z\infty} tanh\left[(B_{z\infty}x)/(2B_{x0}\Lambda)\right]$ where $p(x)$ and $\rho(x)$ are calculated from the horizontal and vertical hydrostactic equilibrium respectively. B_{x0} is the value of B_x at $x = 0$ and $B_{z\infty}$ is the value B_z as $x \to \infty$. A low density tube is placed in the centre of the model, at $x = z = 0$ with density of $0.3\rho(0)$ (temperature of $3.3T_0$) of width 2Λ and height 8Λ. The initial conditions are shown in Fig. 2. The grayscale represents the mass density, the lines represent the magnetic field lines. To excite the instability a velocity perturbation in v_y (given as a sum of sinusoidal curves) with maximum amplitude less than $0.01C_s$ is given.

We assume a reflective symmetry boundary at $x = 0$ and a free boundary at $x = L_x$ with a damping zone (damping time τ = 4.4) for the hydromagnetic variables and

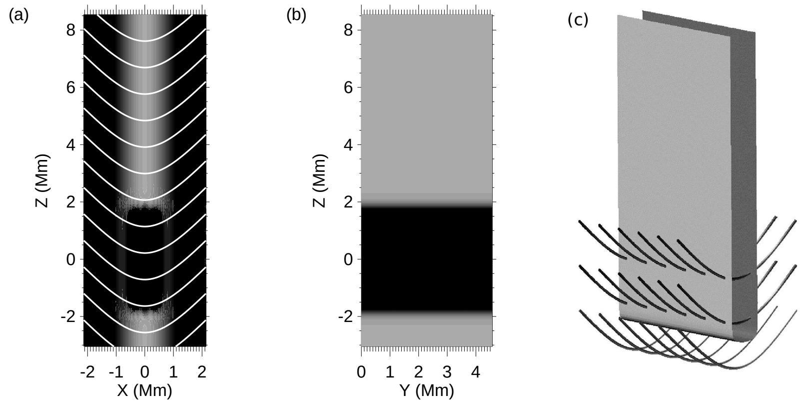

Figure 2. Contour plots of the initial density distribution for the standard model for (a) the $x-z$ plane at $y = 0$ (with magnetic field lines), (b) the $y-z$ plane at $x = 0$ & (c) the 3D visualisation. All physical quantities are initially constant in the y direction. The initial velocity perturbation is applied to the upper contact discontinuity in along the y direction.

B_z (to maintain the angle of the magnetic field at the boundary). For the top and bottom boundary, a periodic boundary is assumed and a reflective symmetry boundary is imposed at $y = 0, L_y$. The scheme used is a two step Lax-Wendroff scheme. In the y-direction there are 150 grid points with $dy = 0.05$, and in the x-z plane there are 75×400 grid points, giving an area of $3.5\Lambda \times 85\Lambda$ with a fine mesh in the area of the contact discontinuity to resolve the plumes.

3. Evolution of the upflows

Fig. 1 panels c and d show the evolution of the upflows for the simulation presented in this paper. Upflows of size $\sim 3\Lambda$ in width with velocities $\sim 0.39C_s$ can be seen in panel d of the figure. First the buoyant tube rises, then the interchange of magnetic field lines is excited by the small perturbation given at the start of the simulation.

As the upflows grow they interact with each other to create larger plumes. This interaction results from the slight difference in plume size created by the random perturbation. The result of this interaction is the formation of the large plumes. This is known as the inverse cascade process and is a common feature of the Rayleigh-Taylor instability (see, for example, Youngs 1984 or Isobe et al. 2006). In this case the density difference and magnetic field suppress the Kelvin-Helmhotz instability.

The 3D structure of the magnetic field evolution caused by the upflows and downflows is displayed in Fig. 3. The figure shows the density isosurface at $\rho = 0.85$ and the magnetic field lines at $t = 15.3$ & 52.2. The figure shows that the upflows form

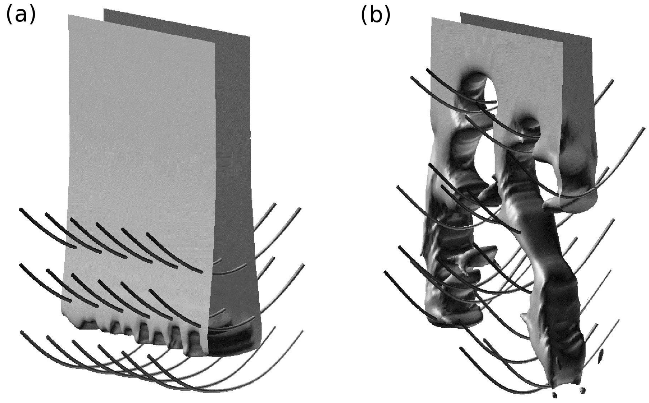

Figure 3. The 3D visualisation of the evolution of upflows for t = 719 & 2453 s (normalized units t = 15.3 & 52.2).

field aligned filamentary structures inside the prominence. The field lines move by gliding past each other in an interchange process.

4. Discussion

In this paper, results of the nonlinear evolution of the magnetic Rayleigh-Taylor instability in the Kippenhahn-Schlüter model are presented. We found that nonlinear mode coupling was important for forming large upflows. The plumes are field aligned structures created by the interchange of magentic field lines.

Fig. 1 is used for the comparison between the simulations and oservations (the magnetic field assumed to be along the line of sight). In both the simulation and the observations, the bubble-prominence boundary becomes unstable creating rising plumes that have similar morphology. The simulated plume temperature is determined by the initial conditions, in this case giving plumes of $T = 3.3 \times 10^4$ K. The observed upflows have a constant velocity of approximately 20 km s^{-1}, whereas the simulated plumes have an average velocity of 5.1 km s^{-1} which is a factor of 4 smaller than the upflows observed. The observed plumes propagate through a height of approximately 10 Mm and have a characteristic width of $\sim$ 300 km−2 Mm. The simulations produced upflows that have an initial width of $\sim$ 200km, but through nonlinear processes produced upflows of $\sim$ 600 km−1.8 Mm in width and, by the end of the simulation, had propagated through a height of 6 Mm.

The paper presents the first efforts to simulate the formation of upflows in a solar prominence. A wider parameter survey is required to fully understand the upflow dynamics in this model.

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