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NUMERICAL SIMULATIONS OF A SIPHON MECHANISM FOR QUIESCENT PROMINENCE FORMATION

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INTRODUCTION

Quiescent prominences represent a significant challenge to our understanding of the flow of mass and energy in the outer layers of the solar atmosphere. A small number of quiescent prominences contain as much mass as the entire corona (Athay, 1976). The problem then is how to get that much material into the relatively small volume of a prominence and maintain it at a temperature of 10,000 K in close proximity to material at one million K. The thermal insulation to conduction provided by the magnetic field explains the disparate temperatures. The mass source problem is less well understood.

One method for supplying mass to the prominence is to siphon it from the chromosphere. The siphon mechanism begins with a magnetic loop that evolves into a configuration with a gravitational well, such as that described by Kippenhahn and Schluter (1957). This could be formed, for example, by a twist in the magnetic field as shown in Figure 1a. A gravitational well could also be formed by a condensation induced sag in the field. This could further enhance the condensation process and lead to a geometry such as that shown in Figure 1b. Once this well has formed, or as it is forming, the material in the well area of the loop must cool and condense to the point where radiative losses exceed any heat input. Additional material must also flow into the well from the underlying chromosphere to supply the mass required to form the prominence. A number of authors have discussed this general scenario (e.g., An, 1985; Engvold and Jensen, 1977; Pickel'ner, 1971; Ribes and Unno, 1980).

In this contribution we present one example from a series of numerical simulations that we have performed to study the formation of quiescent prominences.

MODEL CALCULATIONS

The numerical model we use describes convective, wave, and heat transfer phenomena in magnetically confined plasmas under conditions typical of those in the outer layers of the solar atmosphere. In a specified magnetic geometry, we solve the time-dependent equations for mass, momentum, and energy conservation, including conduction, radiation, gravity, and heating. Details of the numerical model and the solution techniques are discussed in Poland and Mariska (1986), Mariska *et al.* (1982), and Mariska and Boris (1983).

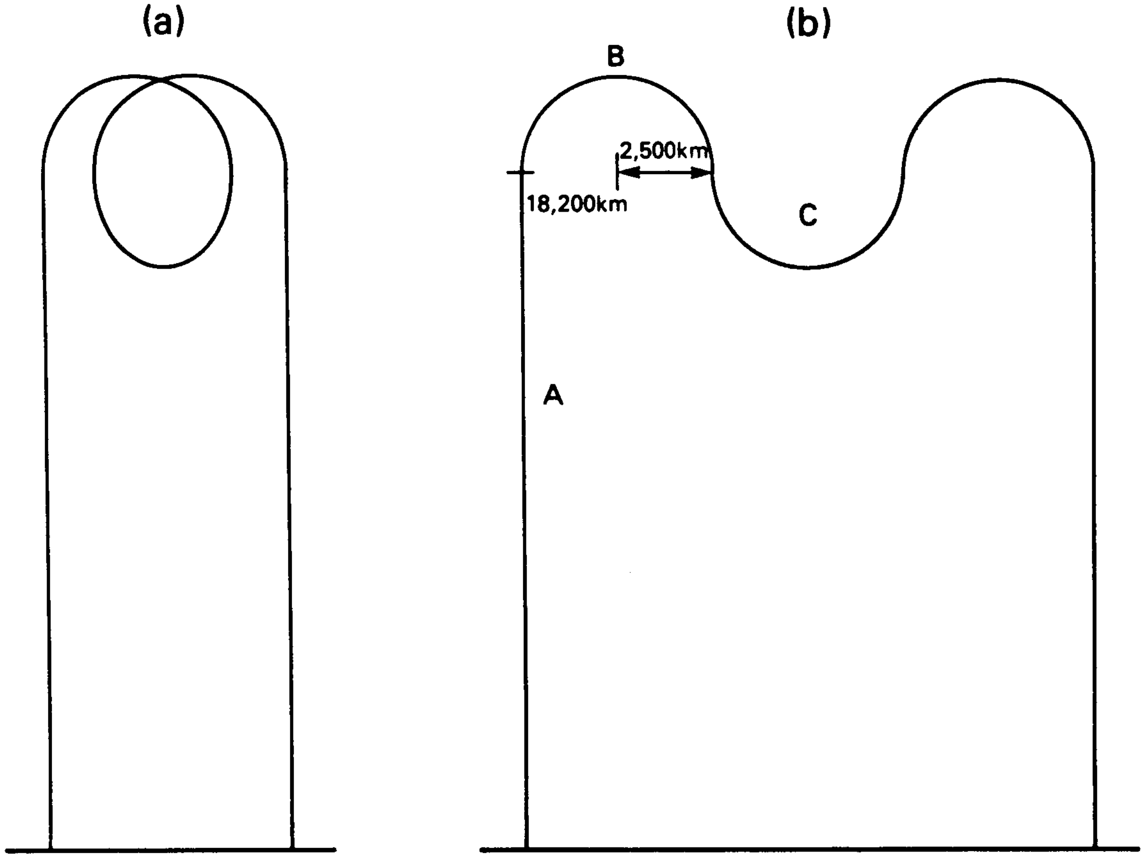

Figure 1

Figure 1b shows the geometry for the simulation. This is basically a very simple representation of a Kippenhahn-Schluter type geometry. Since the loop is symmetric about the top, we only compute half of it. The total length of the half-loop is 30,000 km, with 1100 km of that being chromospheric material at the base. Within this geometry we construct an initial static temperature-density distribution. This distribution is shown as the topmost of each pair of curves in Figure 2. The peak temperature is about 1.5 million K, and the pressure is about 2.5 dynes cm^{-2}.

From this initial model we attempt to form a prominence. It turns out that this is quite difficult without artificially injecting mass into the system. The model is stable against small perturbations. Our simulations to date suggest that the only way to form a prominence from this initial model is through a multistep process. The first step in the process is to reduce the heating to about 1% of the value required to maintain the initial loop. This produces a small cool region at the bottom of the gravitational well. Values of the heating larger than a few percent simply result in a slightly cooler coronal loop, but of essentially the same character as the initial model.

The result of this initial cooling is shown as the lower of each pair of curves in Figure 2. Here, along with the initial model, is the result of reducing the heating everywhere to 1% of the initial rate and letting the loop evolve for 4000 s, a little over one hour. The temperature structure now has a cool region in the well at the top, and the density in the loop legs has dropped dramatically. Note, however, that the density of the material in the well has not changed by much. It is still far below prominence densities.

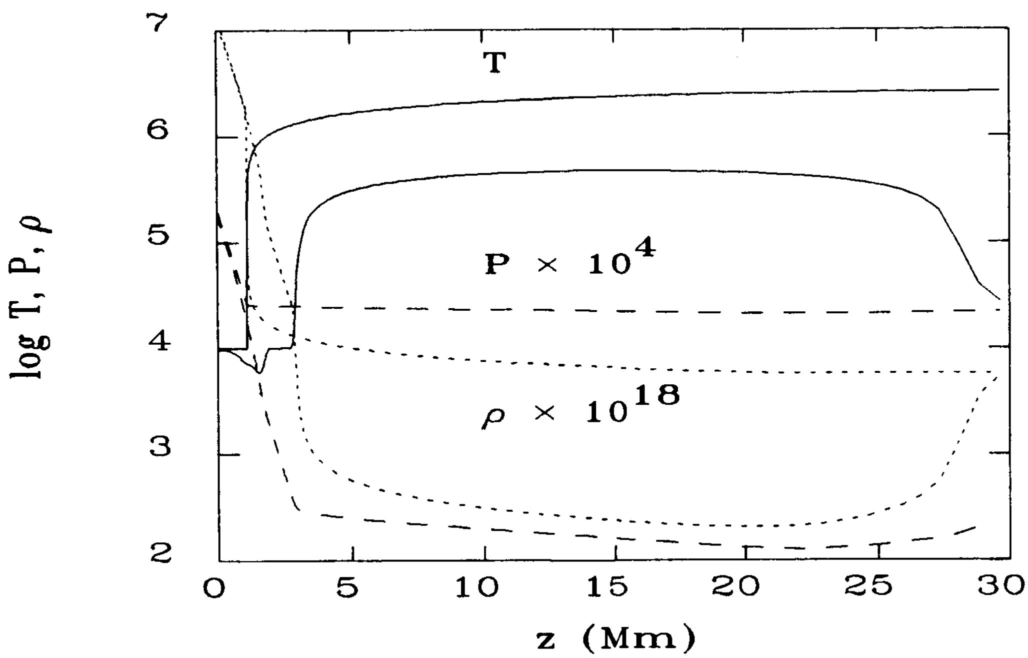

Figure 2

We have found that one way to go from this state to a high density prominence-like configuration is to drive mass upward into the well by heating only the loop legs. We do this in two phases. First, we heat only the legs at the same reduced heating rate that was used to produce the initial condensation. This slowly moves material from the chromosphere to the well. The flow velocity is only about 2 km s^{-1}, however. After about 21 hours at this rate, the electron density at the top has increased to about 10^{10} cm^{-3}, which is still somewhat low for most prominences (Hirayama, 1985; Bommier et al., 1986). It is high enough, however, that we can now increase the heating rate in the legs back toward the initial heating rate, say to 50%, and not destroy the condensation in the well. In just 5 more hours at this rate, the electron density in the well has reached 10^{11} cm^{-3}, which is typical of prominence conditions. Figure 3 shows the results of that reheating of the legs. The lower most of each pair of curves is the model at the end of the initial one hour cooling. The upper most of each pair of curves is the model after the reheating. The material in the well is clearly now more representative of prominence conditions.

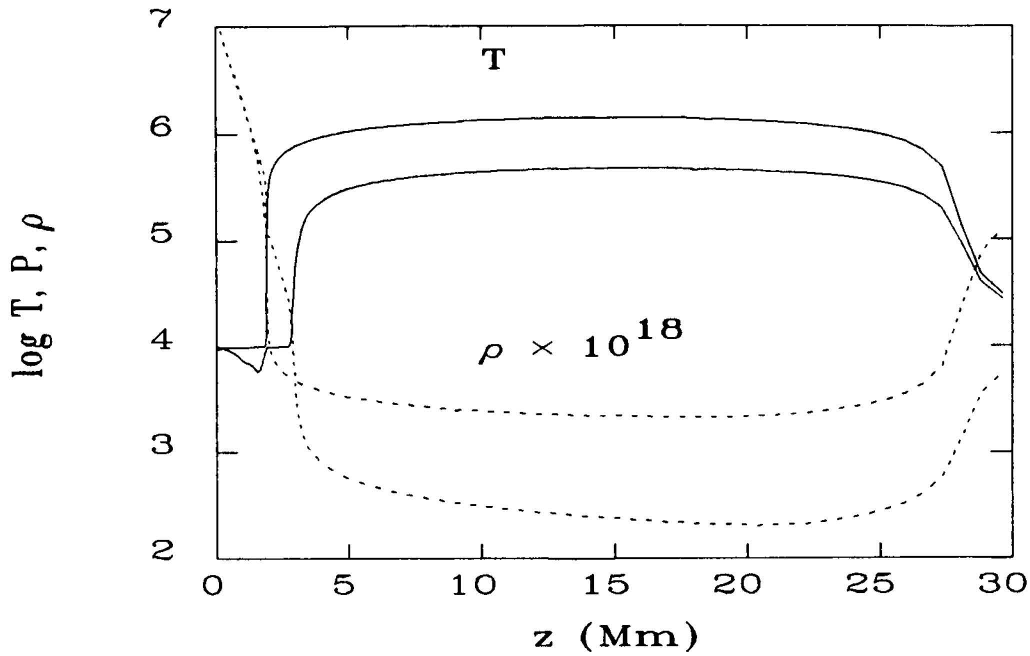

Figure 3

DISCUSSION

Our work indicates that forming a prominence from an active region loop is not as easy as some earlier studies would lead one to believe. It appears to require first a major disruption of the heating. This must then be followed by a gradual return of energy deposition, but only to the loop legs. One possible geometry in which this might occur is shown in Figure 1a. A loop with a twist in it might provide a natural way of forming a gravitational well at the top, while at the same time cutting off the heating to the region.

The necessity of the second phase, in which material is siphoned from the chromosphere through localized heating, is very significant. We have considered an alternate geometry of a low-lying loop with a very long and shallow gravitational well. Although there is ample material in the well initially to form a dense condensation at the bottom, we find that this does not occur. When the heating is first reduced, material is drawn up and out of the well, rather than settling to the bottom. This perhaps surprising result is apparently related to the extremely efficient cooling capacity of the lower transition region in the loop legs. There the radiation rates are at a maximum and cooling is most rapid. It would seem that a subhydrostatic pressure deficit is maintained which is able to suck material out of the well. We are presently exploring this scenario more closely.

A second significant discovery of our work is that once the prominence is formed it is very difficult to destroy. A large amount of heating is required to overcome radiative cooling in the condensed material. The exact amount needed depends, of course, on the prominence density. Once the heating rate does exceed the cooling rate, however, the prominence returns to a hot coronal loop configuration in only a few minutes.

While our calculations have shown that it is possible to produce a prominence by a siphon-like mechanism, they have not directly provided a basis for comparison with observations. We are currently developing more detailed calculations that will allow such a comparison. For example, we need a better resolved numerical grid in the vicinity of the transition to prominence temperatures and densities at the top of the loop. This would provide better estimates of observable velocities, emission measures, and UV line emissivities at this crucial interface. We are also examining the shocks that result from the condensation process to see how they might relate to the apparent motions observed in prominences. It is clear from time lapse photographs of prominences that they are dynamic phenomena. We hope to try to understand some of those observations in the context of our dynamic models.

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