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# ON THE FORMATION OF CORONAL CAVITIES

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## ABSTRACT

We present a theoretical study of the formation of a coronal cavity and its relation to a quiescent prominence. We argue that the formation of a cavity is initiated by the condensation of plasma which is trapped by the coronal magnetic field in a closed streamer and which then flows down to the chromosphere along the field lines due to lack of stable magnetic support against gravity. The existence of a coronal cavity depends on the coronal magnetic field strength; with low strength, the plasma density is not high enough for condensation to occur. Furthermore, we suggest that prominence and cavity material is supplied from the chromospheric level. Whether a coronal cavity and a prominence coexist depends on the magnetic field configuration; a prominence requires stable magnetic support.

## I. INTRODUCTION

The coronal cavity is a dark region whose density is lower than in the surrounding streamer. The close association of coronal cavities with prominences has led to the suggestion that the coronal cavities are a manifestation of prominence formation by condensation of coronal plasma (Pneuman, 1983). However, Saito and Tandberg-Hanssen (1973) found that the formation of a prominence requires much more material than available in the cavity before depletion. They concluded that prominence material must be supplied from below (e.g., in the form of spicules), not from the adjacent corona. Here, we investigate further how and when a coronal cavity forms, and suggest what the relation is between a coronal cavity and a prominence. It is believed that the global steady corona is a consequence of the interaction between outward flowing solar wind plasma and the cornal global magnetic field (Pneuman and Kopp, 1971; Steinolfson, Suess, and Wu, 1982). When interacting with the magnetic field, the plasma adjusts itself for energy as well as force balance. We believe that the coronal cavity is formed in the process of the dynamic adjustment. In this paper we study the stability of the streamer model of Steinolfson, Suess, and Wu (1982) (henceforth referred to as SSW) to the condensation mode. SSW calculated the dynamic interaction between outward flowing solar wind plasma and a global coronal magnetic field using a 2-D, time-dependent, ideal MHD computer simulation. In the final steady state, they found a density enhancement in the closed field region with the enhancement increasing with increasing strength of the magnetic field. Our stability calculation shows that if density enhancement is higher than a critical value, the plasma is unstable to condensation modes. We describe how, depending on the magnetic field configuration, the condensation may produce a coronal cavity and/or initiate the formation of a prominence.

## II. CONDENSATION AS A CAUSE OF CORONAL CAVITIES

The initial plasma density from the steady hydrodynamic solar wind equations and the two final states with $\beta = 0.5$ and 4 are shown in Figure 1. For $\beta = 4$ the density is enhanced about 1.4 times the initial value, while for $\beta = 0.5$ the maximum enhancement is 4.3 times the initial value at $r = 1.3\ R_\odot$. Figure 2(a) shows the magnetic field configuration and plasma velocity in the nearly steady-state for $\beta = 0.5$. Note that velocity is zero in the closed region. An expanded view of the closed field region of the figure is shown in Figure 2(b), with the condensation mode growth rate $\omega$ for $\beta = 0.5$ and 4 shown on the right side of the vertical axis (s implies stability).

For evaluation of the stability, we neglect the temperature and density variation along field lines but consider the variation on each field line of different equatorial height. Heat conduction perpendicular to the magnetic field was neglected – only a parallel component was considered. The ambient heating rate was assumed to be constant in time and is balanced to the radiation in a steady-state. An (1985) found that the plasma is stable against condensation modes if the local growth rate $\omega = -\rho_o\Phi/\gamma P_o$ is positive on all the field lines, but unstable if $\omega$ is negative on any field line. Here,

$$\Phi = \frac{(\gamma-1)\,T_o}{\rho_o}\left[\left(\frac{\partial R}{\partial T}\right)_P + \frac{T_o^{5/2}}{B_o^2}\,\frac{t_r}{t_c}\,(\bar{k}\cdot\bar{B}_o)^2\right]$$

and R, $T_o$, $\rho_o$, $B_o$, and $P_o$ are dimensionless radiative energy loss rate, temperature, density, magnetic field, and pressure, and $\bar{k}$ is a wave vector. The quantities $t_r$ and $t_c$ are radiative and heat conduction timescales defined as $t_r = 3P_o/2R$ and $t_c = L^2P_o/\kappa_o T_o^{7/2}$. Because of the local nature of the stability we evaluate $\omega$ on each field line of the closed field region. Figure 2(b) shows that the stability of the final states for $\beta = 0.5$ and 4 is significantly different. For $\beta = 4$, all the field lines are stable – mainly because the density enhancement over the initial value is small as seen in Figure 1. For $\beta = 0.5$ all the field lines of equatorial height less than $r = 2.05\ R_\odot$ are unstable. The local growth rate $\omega$ is maximum at the field line nearest to $r = R_\odot$ and decreases with height. If we include the gravity in the calculation, the height above which the plasma is stable is far less than $r = 2.05\ R_\odot$ due to the stabilizing effect of the gravity (Wragg and Priest, 1982; Antiochos and An, 1985).

Next, let us discuss how, depending on the magnetic field configuration, the thermal instability initiates a coronal cavity or prominence formation. As plasma density increases above a critical value the plasma becomes unstable to condensation modes. The condensed plasma accumulates on or falls along the field lines depending on whether or not the field lines provide stable support against gravity. If the condensed plasma accumulates, the radiative loss rate continues to increase until the plasma cools to $T = 10^5$ K (An et al., 1983). The plasma keeps cooling to $T_c$ ($\sim 10^4$ K) after the temperature reaches $T = 10^5$ K because the radiative energy loss rate exceeds heat conduction and ambient heating rate. As the temperature approaches $T_c$, the ambient heating rate is approximately equal to the radiative energy loss rate and heat conduction is negligible in the overall energy balance. The temperature $T_c$ ($< 10^4$ K) and corresponding density $N_c$ are typical of prominence temperature and density.

If the condensed plasma falls down along field lines, runaway condensation is not possible. During initial condensation, the temperature decreases, density increases, and the radiative energy loss rate increases. If condensed plasma slips down faster than the radiative energy loss rate

($t_r$ = 2 x $10^4$ s for the $\beta$ = 0.5 streamer at r = 0.1 $R_\odot$) the radiative energy loss rate decreases until it reaches an energy balance and the condensation and slippage cease. However, because the plasma cools during the initial condensation and the temperature change is negligible during the slippage, energy balance can be reached only after the density is depleted below the initial value (assuming the ambient heating rate is constant in time). The density depletion causes the plasma to become stable to the thermal instability. Since SSW considered a simple dipole field which may not provide stable support, the thermal instability for $\beta$ = 0.5 will lead to a cavity. On the other hand, for $\beta$ = 4, the streamer is thermally stable and cannot have a cavity. Saito and Hyder (1968) argue that the difference between prominences with and without clearly defined coronal cavities could be explained by geometry. Our stability calculation suggests that the existence of the cavity also depends on the coronal field strength.

Saito and Tandberg-Hanssen (1973) and Saito and Hyder (1968) found that plasma mass in a cavity is not sufficient to account for the mass of the prominence. The other possibility is that the material comes from below (Saito and Tandberg-Hanssen, 1973), possibly in the form of spicules. For a newly formed prominence with height $10^4$ km, it takes about one day for a spicule material of average flux density F = 1.2 x $10^{15}$ $cm^{-2}$ $s^{-1}$ (Athay and Holzer, 1982) to fill the prominence. The time is about equal to the timescale of a quiescent prominence formation (Zirin, 1978). The spicule plasma which is thermalized in the corona and flowing outward will be trapped by and accumulated on the closed field. If the accumulation is sufficiently high to initiate condensation and the magnetic field gives stable support at the base but no such support above, we will find a prominence at the base below a coronal cavity. In other words, a prominence below a coronal cavity is formed by the material supplied from below as Saito and Tandberg-Hanseen (1973) suggested and is a consequence of condensation of the plasmas. The main difference is that prominences require magnetic support and continuous consideration of coronal material supplied by spicules for fully developed prominences. We schematically summarize our results in Figure 3, showing four different regions; region 1 is an open field region and source of solar wind plasma. In region 2 the plasma has reached a steady-state with energy and force balance. In region 3 condensed plasma flows down along the field lines, leaving a cavity behind. Region 4 is the local field region in which the condensation initiates prominence formation. The local sheared magnetic field provides stable support against gravity.

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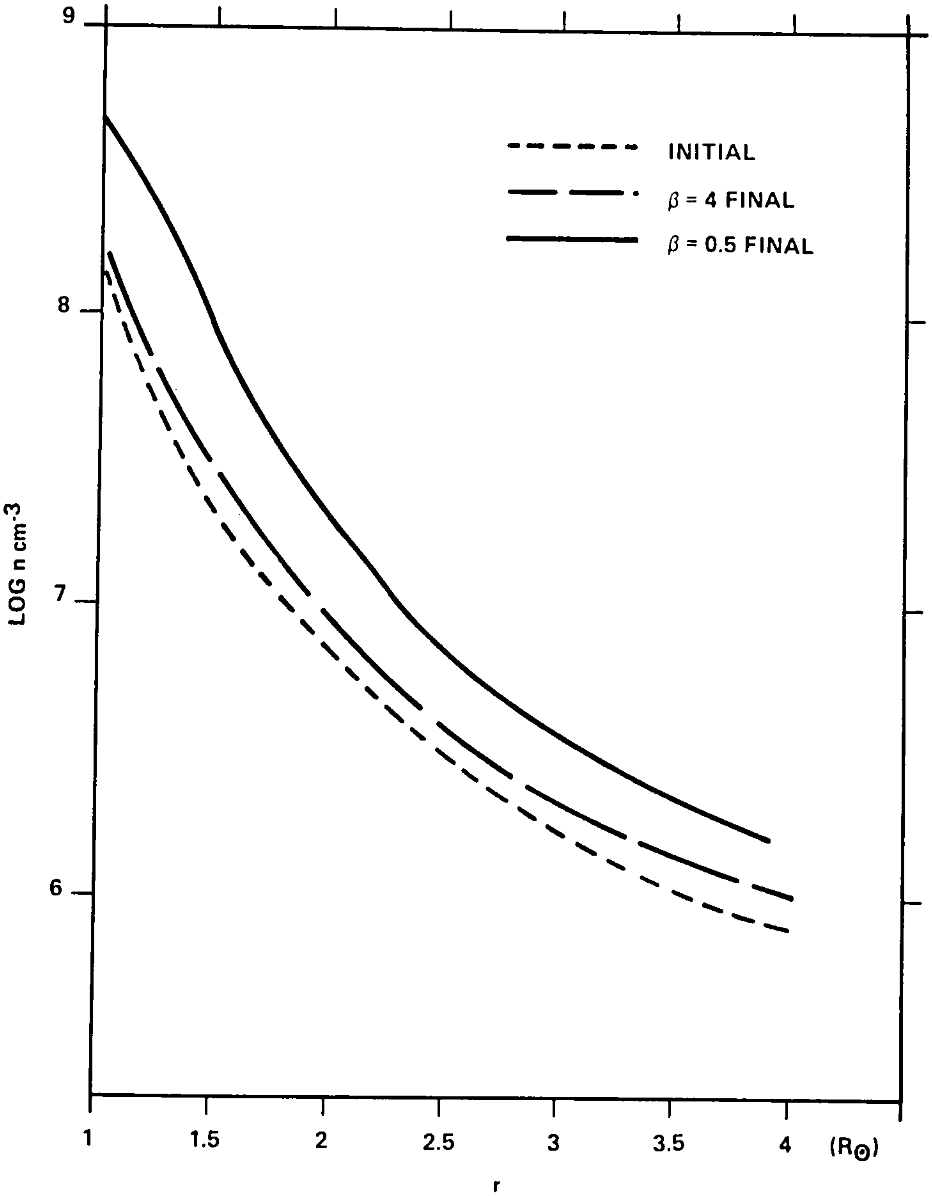


Figure 1. Density profiles in the initial and final states.

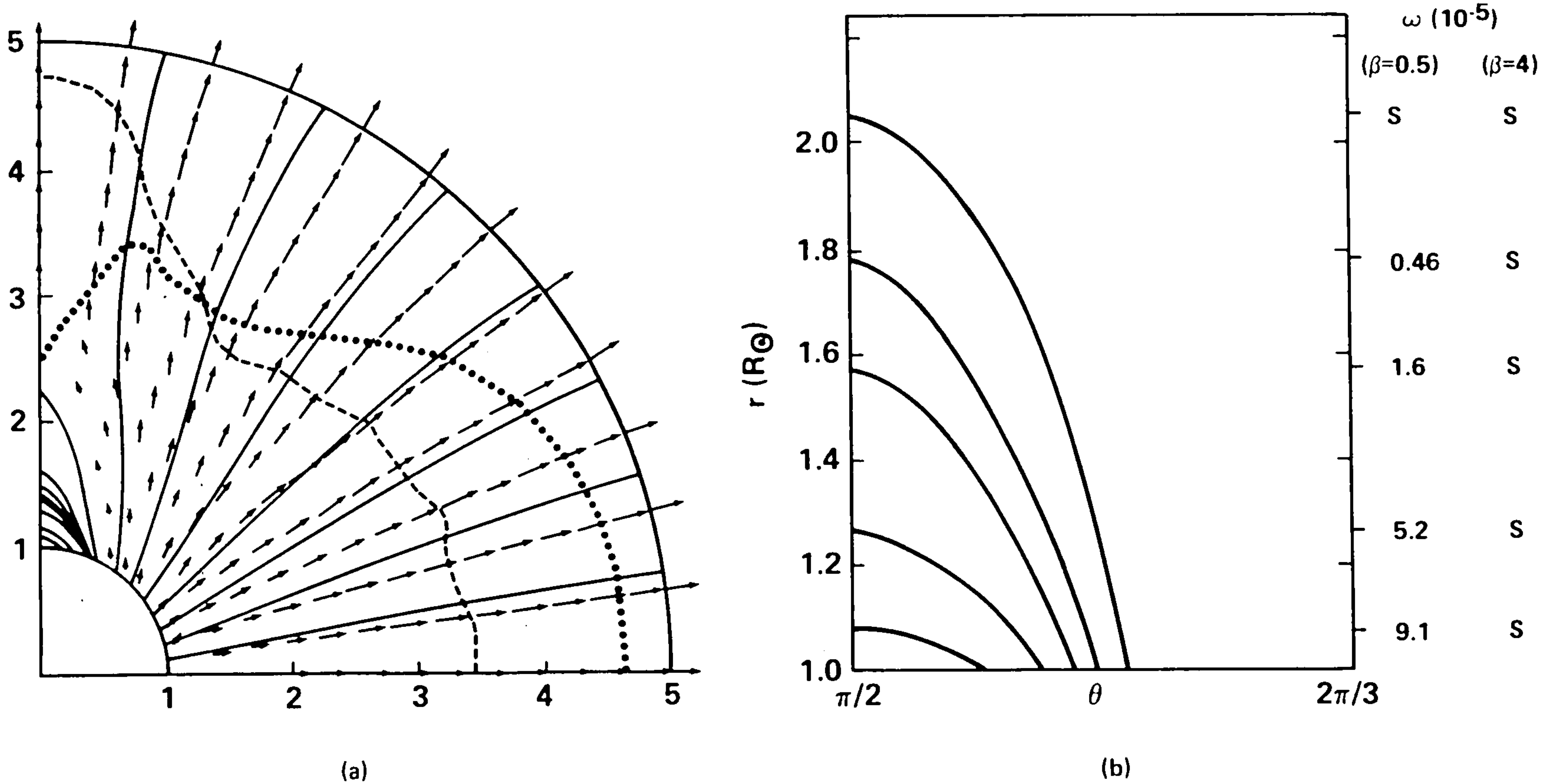


Figure 2. (a) The magnetic field configuration and plasma velocity in the nearly steady-state for $\beta$ = 0.5 (from Steinolfson, Suess, and Wu, 1982). The dotted-line is the Alfvén and the dashed-line is the sonic curve. (b) The expanded closed field region of (a) with the instability growth rate $\omega$ for $\beta = 0.5$ and 4 on the right side of the vertical axis (s = stability).

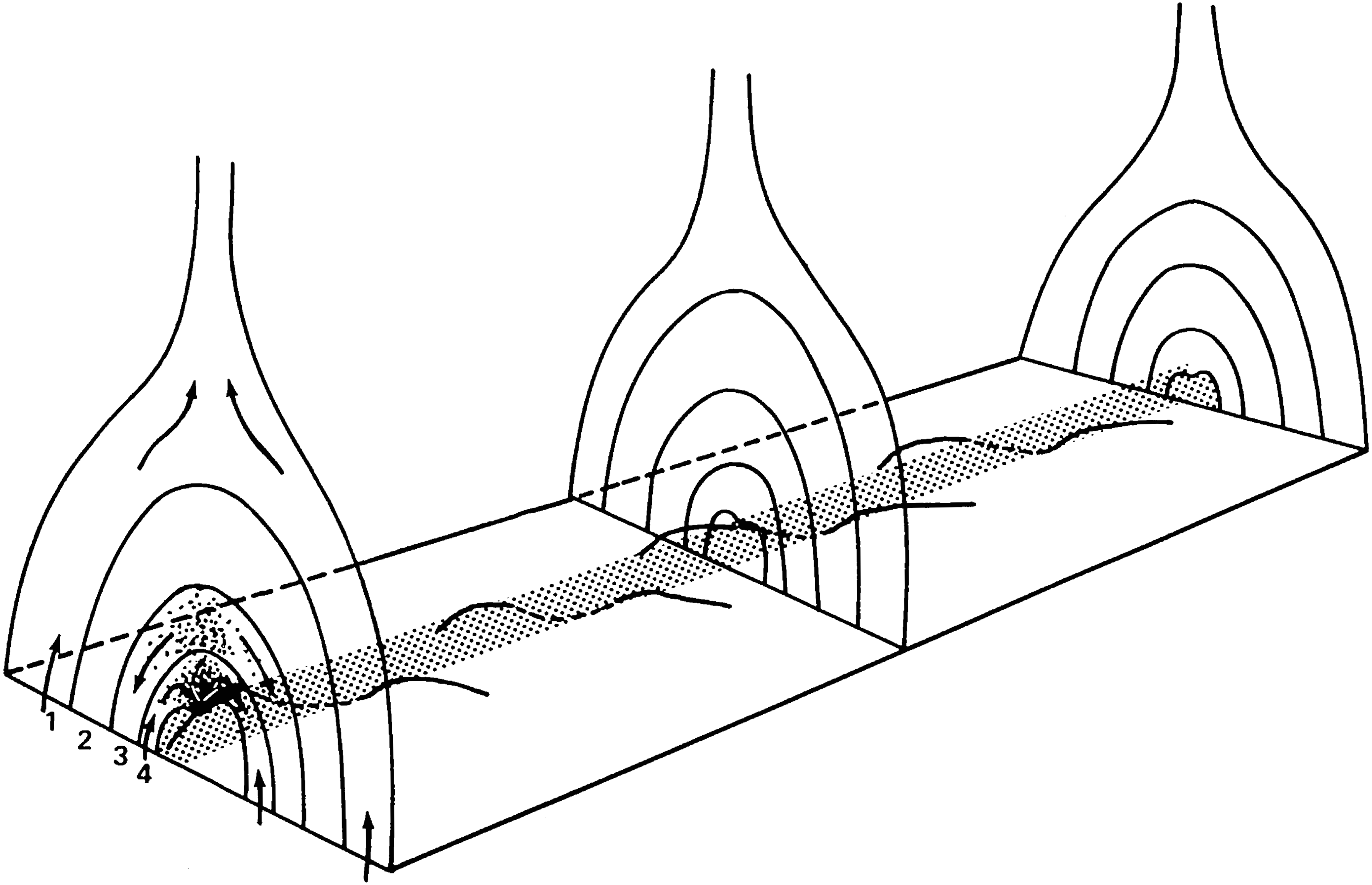


Figure 3. A three-dimensional sketch for a coronal streamer and its fine structures. The arrows represent the plasma flows.