QUIESCENT PROMINENCES

(Invited Review)

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Abstract. This review surveys recent research on quiescent solar prominences. The main topics considered are magnetic structure, thermal structure, and formation. Sub-arc sec fine-structures undoubtedly play a crucial role in all three topics. Current attempts to model the magnetic and thermal structure are hampered, in part, by the lack of observations with sufficient spatial resolution. The process of formation is quite complicated, but is yielding slowly to detailed numerical simulations. Unfortunately, observations of prominence 'condensation' from the corona (the favored hypothesis) are lacking. Some suggestions for future work are offered.

1. Introduction

“Prominences are fascinating objects, abundant in variety, beautiful and above all mysterious.” I cannot improve on this opening line from Hirayama’s (1985) recent review, nor in many respects can I improve on much of his treatment of the subject. During the past three or four years, however, there has been a visible upsurge in interest in solar prominences, sparked in part by the very successful NASA Workshops on Coronal and Prominence Plasmas (Poland, 1986), and in part by the culmination of a decade of effort to measure vector magnetic fields in prominences. Given the accelerated pace of research, it seemed appropriate to take stock once again of what we know and wish we knew. A monograph on the subject is being written by E. R. Priest and his associates (1988). This review, then, will focus on very recent research, although reference is given to some earlier key results. Moreover, only research on quiescent prominences will be mentioned; the more difficult questions of filament activation, eruption and association with coronal transients will be ignored.

Even so, the organization of this paper may seem somewhat arbitrary. The reason for this is the logical difficulty of separating such topics as energy and mass balance from magnetic topology, or thermal structure from magnetic and velocity fine-structure. We find all these topics heavily coupled in the real prominence. This is especially true in the matter of prominence formation, where the magnetic, thermal and dynamic phenomena are intimately entwined. As a result, the following account will have some unavoidable repetitions. The major sections are: Magnetic Structure, Thermal Structure, Formation, and a final Summary.

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2. Magnetic Structure

Prominences are essentially magnetic structures. The field supports the dense plasma against the force of gravity, and channels thermal energy and fluid flow. Twisting fields induce electrical currents that may, in turn, heat the plasma. Moreover, a preferred field configuration may be required to form a stable prominence.

Until recently, we had no reliable vector field measurements in quiescent prominences, and had to rely on supplementary observational clues such as H α, X-ray, and white-light images. Before summarizing the new measurements, let us recall the older observations and the schematic models they stimulated.

2.1. Clues to the Field Structure

Quiescent prominences, as seen in H α, are long flat sheets of cool gas that lie on the neutral line of the longitudinal magnetic field, and separate large unipolar magnetic regions. These few facts were sufficient to suggest that a prominence lies in a current sheet and is supported by the Lorentz force in bowed coronal field lines (Kippenhahn and Schluter, 1957). Further consideration suggested that such a current sheet may be unstable to the tearing mode instability (Furth, Killeen, and Rosenbluth, 1963), and may break up into closed magnetic ‘islands’ that shield the cool gas from the hot corona (Kuperus and Tandberg-Hanssen, 1967). In three dimensions such islands could imply a helical field. Occasional H α observations of helical structure in erupting prominences (Malville, 1965; Anzer and Tandberg-Hanssen, 1970; Tandberg-Hanssen and Anzer, 1970) have been quoted in support of such a model, although helical structure is rarely, if ever, seen in stable prominences.

A prominence is a part of a much larger structure, a coronal streamer. Eclipse photographs in white-light often show a prominence at the limb surrounded by a faint ‘cavity’ and sometimes by high arches, all contained within the base of a streamer (Saito and Tandberg-Hanssen, 1972; Koutchmy, Picat, and Dantel, 1977; Koutchmy et al., 1978). Pneuman (1972) has stressed that the formation of quiescent prominences is a natural evolution of a streamer system.

The large-scale field in the vicinity of the prominence sheet is too weak to measure directly. If, as seems plausible, the plasma outlines the field lines, then monochromatic or narrow-band images can suggest the field configuration. Coronal loops have been observed in the red (6374 Å) and green (5303 Å) lines in good spatial correspondence to quiescent prominences at the limb (Fort and Martres, 1974; Smartt and Zhang, 1984). X-ray loops seem to form an arcade over the magnetic neutral line, and over the faint channel in which a filament lies (Vaiana et al., 1973; Vaiana, Krieger, and Timothy, 1973; McIntosh et al., 1976). These X-ray loops are apparently nested and extend to great heights (< 0.8 R ⊙) above the neutral line. The feet of the loops are sheared in a ‘herring-bone’ pattern about the filament channel, reminiscent of the H α chromospheric fibrils that behave similarly (Foukal, 1971). EUV images from Skylab (Schmahl et al., 1982) show similar arcades at plasma temperatures between 2 and 4 × 10^5 K. These observations suggest the magnetic field pattern may be fairly simple on a scale large compared to the prominence width.
The field inside the cool prominence sheet may be extremely complicated, however. At high resolution, a typical hedgerow prominence is seen as a fibrous structure composed of sub-arcsecond vertical threads and knots (Dunn, 1960). When seen from above, as a filament, the prominence sheet resolves into a tangle of fine threads with no obvious large-scale organization (Simon et al., 1986). EUV images show that the emission structure at all transition temperatures \(10^5 < T < 6 \times 10^5\) is cospatial at a resolution of 5 arc sec (Orrall and Schmahl, 1976). The fine structure of prominences poses extraordinarily difficult problems. We shall return to these further on. Let us turn next to the recent magnetic observations.

2.2. Measurements of the Vector Magnetic Field

Independent observations of the Hanle or Zeeman effects in prominences by three groups (Athay et al., 1983; Leroy, Bommier, and Sahal-Brechot, 1984; Nikolsky et al., 1984) have yielded fairly consistent results on the vector field, with one important exception. This work represents a tremendous achievement against formidable instrumental and theoretical difficulties. Leroy (1987) has reviewed these results and we summarize his conclusions:

(a) Quiescent (polar crown) prominences have field strengths that lie in the range 2–30 G. Active region prominences have slightly stronger fields: 10–40 G.

(b) The field vector in quiescents is nearly horizontal (within 30°) and lies at a small angle \(\alpha \sim 25°\) to the long axis of the prominence.

(c) The height gradients of the field strength and azimuth angle \(\alpha\) are small and positive. The field seems remarkably uniform over the prominence.

(d) The direction of the field through the prominence, in relation to the polarities in the neighboring bipolar photospheric field, is a crucial issue in deciding between the two principal classes of MHD models (Kuperus–Raadu (KR) or Kippenhahn–Schlütter (KS)). Unfortunately, the Hanle effect contains a fundamental ambiguity in this respect. The French group has used two methods to try to resolve this issue. They observed a few prominences edge-on (i.e., along the long axis) and, in addition, applied a statistical test to a large sample (256) of prominences. They concluded that the field in high (polar crown) prominences has the opposite direction to the photospheric field (as in a KR configuration), while that in low prominences has the same direction (as in the KS model). Most of their large sample prefers the KR model, but their sample may be biased toward prominences of low height (Anzer and Priest, 1985; Athay et al., 1983). The U.S. group (Athay et al., 1983) concluded that no firm conclusion on this question is possible with the available evidence. They offer the following possibilities, however, consistent with their data: If the prominence field has the same polarity as the photosphere, the field vector is nearly perpendicular to the prominence axis. If opposite in polarity, the vector is nearly parallel to the axis.

(e) The spatial resolution achieved by either group (2–10 arc sec) was insufficient to give conclusive results in the vertical Hα threads. Leroy states, however, that in this data the field strength dispersion is smaller than the emission intensity dispersion, which suggests a rather uniform field. This stands in conflict with his earlier conclusion

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(Engvold and Leroy, 1979), that field and emission threads are predominantly coaligned.

(f) Within the noise limit, the field parameters are time-independent over at least tens of minutes, while the Hα fine-structure varies significantly within a few minutes.

While these results give us a consistent picture of the magnetic field, it is a puzzling picture: The vector field is apparently horizontal, uniform, and static over an object that is riddled with transient, vertical, fine structures. How are we to reconcile these contrasting views of the prominence? The spatial resolution of the field measurements is typically 2–5 arc sec. Is this simply insufficient to detect smaller scales? Are the threads and knots we see in Hα images unaligned with the field? This would imply that the plasma and field are not ‘frozen’ together.

We might hope that observations of the spatial scale and direction of vertical motions in a filament could help to clarify the relation between the emission threads and the magnetic field. The velocity field might also distinguish between a KS or KR topology. Let us turn next to velocity observations of prominences and filaments.

2.3. The velocity field

Two methods have been used to determine motions in a prominence: tracing the apparent displacements of knots in Hα movies, and mapping Doppler shifts. In 1976, Engvold published a study of Dunn’s high-resolution Hα movies. He found predominately downward motions in the vertical threads, with speeds of 15–35 km s⁻¹. The coarser knots toward the tops of prominences move more slowly: \( v \sim 0.5 \) km s⁻¹.

Since these vertical motions may only be apparent, arising from some sort of excitation or condensation wave, most subsequent investigations have mapped Doppler velocities in filaments in such lines as Hα and Ca II K. Malherbe, Schmieder and their associates have published a long series of such investigations. Their results may be summarized as follows:

(a) Doppler velocities in filaments are generally small (1–3 km s⁻¹), steady, and mainly upward, except at the ‘feet’ of a hedgerow, where speeds may reach 10 km s⁻¹ and may be directed either up or down (Malherbe, Schmieder, and Mein, 1981; Malherbe et al., 1983b).

(b) Although good spatial resolution (1–2 arc sec) has been claimed (e.g., Schmieder et al., 1985), the velocity structures are generally coarser (5–10″), with no suggestion of fine vertical threads.

(c) Simultaneous observations in Hα and CIV (Schmieder et al., 1984, 1985; Simon et al., 1986; Malherbe et al., 1987) show larger speeds in CIV and larger velocity dispersions, but with no correlation between intensity and velocity in either line, and little correspondence between lines.

Engvold and Keil (1986) thought that Hα might be a poor line in which to measure filament velocities, because of possible distortions by the scattered chromospheric line. They chose He I 10830 instead, but found similar results: small velocities, directed mostly upward, and no sign of vertical threads.

Athay et al. (1983) studies CIV Doppler velocities in an active region, and found a velocity neutral line coincident with the magnetic neutral line. While their results may
not apply to quiescent prominences, they do suggest a large-scale systematic flow (in loops, perhaps), associated with a magnetic arcade.

These results suggest two possibilities:

1. The large vertical thread speeds seen in H\(\alpha\) movies are associated with some sort of excitation wave or,

2. They indicate real plasma motions, but the H\(\alpha\) threads are too transparent to appear on the disk – i.e., they are undetectable in filament Doppler observations. This would not be surprising: Heasley and Milkey (1978) found that a uniform slab (\(T = 7500\), \(P = 0.01\) dynes cm\(^{-2}\)) 240 km thick has an optical thickness of only 0.04 in H\(\alpha\).

In either case, the thread motions seem to be directed primarily perpendicular to the horizontal magnetic field observed in prominences.

2.4. Magneto-hydrodynamic models

Several authors have constructed MHD models of prominences, usually in two dimensions, in order to explain their primary characteristics: they are cool, dense sheets, suspended in a hot, tenuous corona. Most of these models are static, and assume ideal MHD, i.e., infinite plasma conductivity, with perfect ‘freezing-in’ of the field lines.

As we noted above, the early models have been very influential. The original Kippenhahn–Schlüter model pictured the prominence as an infinitely thin current sheet, suspended on bowed, coronal arches. The Kuperus–Raadu model (Kuperus and Tandberg-Hanssen, 1967; Raadu and Kuperus, 1973, 1974) differs from the KS in several important respects. The KS prominence is supported by the tension in curved field lines, while the KR prominence is supported by the repulsion of two current systems, one in the prominence, and the other (its mirror image) induced in the photosphere. Secondly the KR is basically a steady-state model in which a steady flux of field and plasma is directed toward the prominence sheet, and a steady reconnection of field-lines occurs at a neutral point. And, as we have seen, that KR model implies a field polarity in the prominence that is opposite to that in the photosphere.

Both classes of MHD models have been examined critically for their stability against arbitrary perturbations. Anzer (1969) gave two necessary and sufficient conditions for the stability of a KS model to MHD instabilities: (a) the horizontal field strength must increase, and (b) the jump in the vertical field component across the current sheet must decrease, with increasing height. Zweibel (1982) and Galindo-Trejo and Schindler (1984) have recently confirmed the stability of the KS model to arbitrary MHD perturbations.

Malherbe and Priest (1983) have generated a number of variations of the basic KS, KR topologies, using analytic functions of a complex variable. Their main purpose was to show that steady photospheric flows under a prominence can account for their slow rising motions. They also suggested a ‘quasi-static’ evolution of topology, due to the photospheric flows, for both the KS and KR classes of models. The KS model, originally an arcade of arches, develops a closed loop or helix at the top of the arches. The KR model, initially with field lines that open upwards to infinity, collapses into a
figure eight. A steady influx of coronal plasma \((v = 10 \text{ km s}^{-1})\), just above the reconnection point, was predicted for the figure-eight model.

Anzer (1985) expressed doubts about the stability of such a figure-eight model. He derived a necessary stability condition and showed that the upper part of the KR model will be pulled downward. In a later paper Anzer and Priest (1985) modified these conclusions. A KR model can be stable, but only if it extends to heights that are too low to agree with observations. Moreover, the evolution in form of KR models that Malherbe and Priest proposed cannot occur unless both the total current and the photospheric large-scale field change. Finally, a KR prominence is self-pinching and would collapse into a cylindrical plasma tube, rather than remain as a flat sheet. Thus these authors concluded that the simple current sheet KR models that have been proposed cannot account for the observed height and shape of quiescent prominences, although the polarity of the field, with respect to the photospheric field, agrees with Leroy's observations.

B. C. Low has constructed a variety of analytic two-dimensional KS models. In his early papers (Low, 1975, 1981) he found solutions to the complete momentum equation (including pressure, magnetic forces and gravity), but ignored the energy equation. However, his solutions included a free function that can simulate thermal conductivity along magnetic field lines. Thus, he could examine the energy balance, under simplified assumptions, within precisely-defined magnetic configurations. His results showed that a simple KS model, with a loop at the top of an arch, has much too broad a temperature distribution to mimic the observed flat sheet. The reason, as Orrall and Zirker (1961) pointed out is that uninhibited heat conduction along field lines is much too efficient to permit steep temperature gradients, except very close to the cool sheet.

In a later paper Low and Wu (1981) used a complete energy equation in a solution for a sheared KS model. The shear of the field lines steepens the temperature gradients considerably, but not enough to accord with observations: the model prominence is still much too thick.

Thus, both the KS and KR models appear to pass the stability test, but fail to satisfy other energy-related constraints, at least in their simplest forms. Low has offered some interesting ideas for the origin of long vertical emission threads. Low (1981a) suggested that the threads are composed of a series of 'beads', hung on the low points of different field lines in a helix. Each bead may only extend for a (small) pressure scale height, but the string appears to be much longer. He constructed a magnetostatic model (Low, 1982) of a horizontal row of vertical threads, hanging in bowed field lines. This model is admittedly artificial, but it demonstrates mechanical equilibrium and suggests that the thread diameter is fixed by the pressure scale height. Reality may be much more complex, as we shall see.

3. Thermal Structure

Optical and EUV spectra have provided the most detailed information we have on the thermodynamic properties of prominences. The trend in recent studies has all been in
the direction of incorporating the fine structure, or at least underlining its crucial role. Uniform slab models suffice to explain, with remarkable precision, some aspects of the prominence optical line spectrum. Heasley and Milkey (1976, 1978) calculated the emergent radiation from isobaric, isothermal slabs that depart from thermodynamic equilibrium, in order to interpret the photoelectric line flux observations (Landman and Illing, 1976, 1977). They aimed at predicting the observed line flux ratios, such as Ca II 8542/Hβ or D3/Hβ, since such ratios are less sensitive to photospheric calibration errors. They found that slabs at 7500 K with a pressure of 0.01 dynes, and with different mass column densities, could reproduce the range of observed ratios to within a few percent. Such models fail to predict the observed absolute line fluxes, however, unless the slabs are unacceptably thick.

Engvold (1980) proposed that such inconsistencies might be removed by invoking fine structure. He measured the intensity of Hα in threads of different sizes on Dunn’s (1960) films, and compared these to the predictions of Heasley and Milkey. The best fit requires a pressure near 0.1, not 0.01 dynes cm\(^{-2}\). Engvold suggested that Landman’s aperture (5 × 20 arc sec) was spasrly filled with small emitting structures, so that his derived intensities are too small. The discrepancy between theory and observation is by a factor of 20, however, and it seems unlikely that Landman’s aperture was only 5\% full. No final resolution of this controversy has been reached.

Hirayama’s study of the Stark broadening of hydrogen lines (1986) yields some useful limits on the size and spatial density of unresolved threads. He derived the electron density from the Stark profile of Hα at 57 positions in five hedgerow prominences. The density averages 10\(^{11}\) cm\(^{-3}\), with a range from 10\(^{10.2}\) to 10\(^{11.4}\). The line flux at each position yields an emission measure, \(N_e^2L\), and when combined with the electron density, \(N_e\), the effective thickness \(L\) of a 10-arc sec slice. The average \(L\) is only 80 km. Assuming a typical diameter of 300 km for each thread (Dunn, 1960) and \(L = 80\), Hirayama finds an average \(N = L \times 7300/\pi(300/2)^2 = 8\) threads within a 10\(^\circ\) sampling aperture. Smaller derived values of \(L\) imply diameters less than 300 km; e.g., \(L = 2.4\) km implies \(d < 150\) km.

The hotter portions of a prominence (\(T > 10^4\)) produce the EUV spectra. As mentioned previously, monochromatic images from Skylab show that all temperature regimes below about 3 \(\times\) 10\(^5\) or 6 \(\times\) 10\(^5\) K are cospatial, within the 5 arc sec resolution (Orrall and Schmahl, 1976). This result suggests fine structure with steep temperature gradients in the line of sight. Orrall and Schmahl (1980) tested two models for the fine structure: unresolved cylinders and thin resolved slabs, both with cool uniform cores and hot uniform sheaths. The test relies on the observed attenuation by the hydrogen Lyman continuum of lines with wavelengths below 912 Å (Schmahl and Orrall, 1979). The net attenuation factor (which ranges from 0.05 to 0.155 in nine prominences) depends upon the distribution of absorbing and emitting structures in the line-of-sight. If several identical threads are aligned in the line-of-sight, each thread absorbs the line radiation emitted behind it and emits radiation to threads in front of it. Orrall and Schmahl derived expressions for the attenuation factor (\(\alpha\)) as a function of the total opacity at the head of the Lyman continuum (\(N_\tau\)) and the number of threads or slabs
(N) in the line-of-sight. The mathematical form of the attenuation factor \( \alpha(N\tau) \) establishes a lower bound of \( N \) for a given \( \alpha \). On average there were \textit{five or more aligned} structures within the \( 5'' \times 5'' \) entrance aperture of the HCO Skylab spectrometer.

In a later paper, Orrall and Schmahl (1986) re-analyzed the differential emission measures observed from Skylab in one prominence. They allowed for a \textit{random} distribution of unresolved vertical threads within the entrance aperture and also considered two additional structures: many isothermal threads, and threads with longitudinal temperature gradients along the magnetic field. Random threads with cool cores and hot sheaths can explain the \textit{run} of the emission measure with temperature, but only if the pressure increases radially outward by two orders of magnitude, an improbable situation. Isothermal threads fail to reproduce the observed decrease of Lyman continuum absorption with increasing temperature. The third geometry (\( VT \parallel B \)) is attractive because it allows radiation losses to be balanced by conductive flux. However, several threads or sheets must lie in the line-of-sight to provide sufficient absorption, and these cannot lie on the same field lines, since then the conductive flux will be insufficient. The net result of this investigation seems to be that no obvious geometry of threads or slabs can explain all aspects of the EUV spectra.

Rabin (1986) offers a new idea. He suggests that heat conduction, across and along field lines, can account for the observed differential emission measures at all temperatures (\( 10^4 < T < 10^6 \)). His idea would work in flat plasma sheets, but only if the cross-field area exposed to the corona were \( \sim 10^4 \) as large as the longitudinal area. We are led then to a picture of very thin ribbons for the fine-structure. The idea needs further development. In particular, can a multiple ribbon geometry account for the observed Lyman absorption? How is all this structure organized into some object we recognize as a prominence?

The reader will have realized at this point that we are still far from even a preliminary model for prominence fine structure. The work done to date emphasizes how helpful measurements at higher spatial resolution would be.

Without some definite ideas of the geometry of the fine structure, it is pointless to attempt detailed energy balance models, and in fact none has appeared in the past five years. It is curious, however, that with all the present discussion about fine structure, there has been so little attention paid to the possible role of electric current dissipation as a heating mechanism. Rabin's ideas on cross-field apparently originated in connection with a model of chromospheric heating (Rabin and Moore, 1984) by ohmic dissipation. Electric currents lead naturally to extreme filamentation, provide an energy source and are essential for prominence support. Malherbe \textit{et al.} (1983) dismissed Joule heating as negligible for their KR models, but another hard look may be warranted.

\section*{4. Prominence Formation}

The basic ideas for explaining prominence formation were published two, or even three decades ago. Since then massive efforts have been expended to clarify, elaborate, and confirm these ideas. We are still some distance from detailed understanding of the complex processes that are involved.
In 1953 Kiepenheuer (1953) noted that the free-bound radiation from a pure hydrogen plasma increases as the square of the density and decreases as an inverse power of the temperature. Thus a hydrogen corona would be thermally unstable, and could form prominences from cool, dense inclusions. Parker (1953) showed that free-free radiation, which increases with temperature, would stabilize a hydrogen corona at a sufficiently high temperature. Below that temperature, heat conduction can ensure stability. However, if the mechanical heating which balances coronal energy losses is temperature-insensitive, a critical scale length exists, beyond which heat conduction fails to smooth out temperature fluctuations. The inclusion of radiation from all the coronal constituents (Cox and Tucker, 1969) does not radically change these conclusions.

In 1967 Kuperus and Tandberg-Hanssen (1967) added the final ingredients to our present conceptual model. They proposed the following sequence: (a) the appearance of a helmet streamer magnetic configuration with field lines nearly parallel above a closed arcade, (b) formation of a neutral sheet where the gas density is enhanced for lateral pressure balance, (c) thermal instability which further enhances the density and sets up lateral pressure gradients that propel an influx of coronal gas, (d) formation of closed loops (or helices) by the tearing mode instability. The loops thermally insulate the plasma and promote further cooling.

This basic picture has been elaborated, and to some extent, quantified since 1967. Although it still seems to be the most likely sequence of events, we must bear in mind that observational confirmation is entirely lacking. We have no observations of the coronal plasma in the proto-prominence, not any of the thermal collapse. When we finally detect the prominence in Hα, most of the cooling process must be over. Thus Martin’s (1973, 1986) descriptions of the changes in the chromospheric fibril structure and magnetic knots near a filament channel, while interesting intrinsically, do not test the main features of the formation scenario. The ‘main event’ probably occurs higher and in hotter plasma (10⁸ K?) than we can see in Hα.

It is unfortunate that the Skylab instruments, which were well-suited to follow the thermal collapse of a prominence from coronal through transition zone temperatures, never provided an example in nine months of observations. This null result may indicate that the final collapse occurs very quickly.

For lack of new pertinent observations, recent research has been entirely theoretical. The details of formation are very complicated, so it is not surprising that no single calculation has followed the complete process in full detail, although this goal is now within view. Instead, different authors have tried to clarify limited aspects of the problem. We summarize this work in the following categories: thermal instability in a magnetic field, condensation without field reconnection, and condensation with field reconnection.

4.1. THERMAL INSTABILITY IN A MAGNETIC FIELD

Field (1965) showed that a uniform field has no effect on stability parallel to the field lines, but enhances instability across the field because of the drastic reduction of the cross-field heat conduction. In an isobaric condensation, the instability is finally limited by the build-up of magnetic pressure.
Hildner (1974) was the first to investigate the nonlinear development of a two-dimensional coronal condensation, including the effects of fluid flow, mechanical heating, a horizontal magnetic field and gravity. He ignored heat conduction, however, on the assumption that an axial magnetic field effectively suppresses it. Hildner found that fluid inflow enhances the condensation process significantly, that the growth rate accelerates rapidly, and that the density increases by an order of magnitude in $3 \times 10^4$ s. Unfortunately, his models do not reach a final equilibrium.

Recent work examines the role of the magnetic field in more detail. For example, Van Hoven and co-workers have considered thermal stability in a particular two-dimensional field, which reverses polarity smoothly near an axial plane. Van Hoven and Mok (1984) concluded that the magnitude of cross-field heat conductivity is critical, though it is orders of magnitude smaller than parallel conductivity, because condensation starts at the axial plane, where the field is exactly perpendicular to the temperature gradient. The growth rate is approximately equal to that for a field-free plasma at constant density, not (as one might think) at constant pressure. Subsequent papers (Van Hoven et al., 1985; Van Hoven, 1986; Van Hoven, Sparks, and Tachi, 1986) showed that the initial thickness of a condensation in this sheared field is not fixed by a balance of radiation and parallel conduction, nor by the precise value of the cross-conductivity.

Many authors have investigated the thermal stability of coronal loops (see Hood and Anzer, 1988, for a summary), and some of this work bears on the formation of prominences. Hood and Priest (1979, 1980) showed that a uniform loop is thermally unstable to perturbations in the heating function, or the pressure or the temperature (if the loop length exceeds a critical value). Oran, Mariska, and Boris (1982), carried out numerical calculations of the thermal evolution of a rigid, sealed flux tube, and found a stable final state that might resemble a prominence. These results are all expected on the basis of the elementary thermal instability theory, but were criticized (Antiochos, 1979; Craig, Robb, and Rollo, 1982) because of incorrect boundary conditions. Since a loop can exchange heat and mass with the chromosphere, these processes must be included in any discussion of loop stability. Different authors have proposed different boundary conditions and have reached different conclusions as a result. Thus, Antiochos (1979) found that all loops with zero heat flux at their feet are unstable. Craig, Robb, and Rollo (1982) allow chromospheric evaporation, but either fix the chromospheric temperature or force the heat flux to vanish at the chromosphere during a perturbation of the loop. They found that such loops are stable. McClymont and Craig (1985) set conditions on the mechanical heating (which may depend on density, temperature, field strength or position) for loop stability. The controversy on proper boundary conditions persists (e.g., Mok and Van Hoven, 1988). Hood and Anzer (1988) avoid the boundary condition issue altogether by using a ‘phase plane’ approach. They investigated a variety of perturbations and found, for example, that a reduction in heating or in the heat flux (due to a divergence of field lines) can produce condensations. However, their method only indicates the existence of a condensation process: a numerical integration (with specified geometry and boundary conditions) would be needed to find a complete solution.
If the source of mechanical heating (which is presently unknown) were somehow to fluctuate in a coronal loop, then clearly a possibility arises for thermal instability. Davis and Krieger (1982) and Poland and Mariska (1987) have recently looked into his idea. Evidently some rather special sequences and locations of excess (or deficit) heating must occur for this mechanism to work.

In summary, the conditions for thermal stability of a coronal loop have been explored extensively, but (a) no final consensus has yet appeared, and (b) the further development of such an instability into a prominence has not been demonstrated.

4.2. Condensation in a Current Sheet

Malherbe et al. (1983) have presented an unusually complete treatment of the formation of a Kuperus–Raadu prominence. Their order-of-magnitude calculations are a necessary preliminary to a complex numerical study, and attempt to isolate the important physical effects.

The authors assume that the K–R magnetic configuration has somehow formed in the hot corona, and examine its thermal stability with the energy equation. They found four possible destabilizing factors:

(a) the scale length for parallel conduction may exceed a critical value (Smith and Priest, 1977);

(b) the magnetic field may be sheared beyond a critical angle, again reducing the effective conductivity;

(c) the initial compression at the axial current sheet (which is required to balance the lateral pressure) may exceed a critical value; and

(d) coronal heating by MHD waves may be reduced sufficiently near the current sheet. The argument here is that Alfvén and slow mode waves will follow the diverging field lines, avoiding the mid-plane, while magnetosonic waves (which do propagate across field lines) may dissipate far from the sheet. Incidentally, ohmic heating is estimated to be negligible compared to conduction.

The authors calculate the cooling time, the final prominence temperature for thermal equilibrium, and the coronal mass flux toward a (postulated) reconnection point. Their estimates agree well with observations, where these are available, but the agreement is unconvincing because of their approximations. For example, they identify the parallel conduction scale length with the cool prominence density scale height (much too small a value; see Orrall and Zirker, 1961; and Low, 1981), and ignore the effect on cooling time of the increase in density during collapse.

In order to follow the condensation of coronal material with any degree of realism, time-dependent numerical simulations are required, and several authors have attempted these recently. For example, Van Hoven, Sparks, and Schnack (1987) have studied nonlinear radiative condensation in their favorite two-dimensional sheared field. This calculation still employs the ideal MHD equations; i.e., does not include the possibility of reconnection. As in their previous stability calculations, the sheared field suppresses parallel heat conduction near the axial plane, and this is where condensation begins. Their results show that the magnetic pressure rises in the condensation, but more slowly
than the gas temperature falls. Starting at an initial value of \(2 \times 10^6\) K, the temperature falls below the peak of the Cox–Tucker radiative loss curve and reaches \(T = 12000\) K in 730 Alfvénic times – i.e., \(T = 730 a/V_a\), where \(a\) is the shear scale length. With \(a = 10^8\) cm, \(B = 1\) G and \(n = 10^{10}\) cm\(^{-3}\), \(t = 9.2\) hours. However, because the magnetic pressure in the condensation is unrelieved by reconnection, the gas density can rise only by 50\%, rather than the factor of 10\(^2\) that is observed. Thus a realistic treatment of condensation should include a specific mechanism (e.g., the tearing mode) for field reconnection. We turn next to such models.

4.3. Condensation with reconnection

The tearing instability (Furth, Killeen, and Rosenbluth, 1963; Furth, 1969) arises in a plane current sheet from the tendency of individual parallel current elements to attract each other. X-type neutral points form, creating a series of isolated magnetic islands. The fastest growing modes have wavenumbers \(k\) smaller than a critical \(k_c = 1/a\), where \(a\) is the scale over which the field reverses polarity.

This simple picture must be modified in two ways to apply to prominence formation: (a) the sheet is finite, so that stability in at least two dimensions must be considered, and (b) the tearing mode may be accompanied by a tearing (e.g., converging) flow normal to the sheet (see Spicer, Mariska, and Boris, 1986).

Moreover, to be relevant, the tearing mode must proceed sufficiently rapidly. Otherwise, magnetic islands (or helices) will not form in time to accelerate cooling. In a one-dimensional current sheet the tearing mode has a growth time of \((\tau_d/\tau_a)^{1/2}\), where \(\tau_d\) and \(\tau_a\) are, respectively, the resistive diffusion time and the Alfvénic time. For coronal conditions, with a magnetic shear scale of \(10^8\) cm, the tearing time can reach 70 days, which seems too long for prominence formation.

However, Steinolfson and Van Hoven (1984) show a way out of this difficulty. They studied the coupling of the tearing and thermal instabilities in Van Hoven’s favorite two-dimensional sheared field model.

They found two hybrid modes. A condensation mode (with tearing) proceeds roughly a hundred times faster than the other, a tearing mode with condensation, at magnetic Reynolds numbers \((\tau_d/\tau_a \sim 10^{11})\) that are appropriate to the corona. Thus it appears that condensation with tearing can occur in times as short as a few days.

Malherbe, Forbes, and Priest (1984) have attempted to calculate the nonlinear development of a current sheet, including the effects of reconnection. They start with a vertical two-dimensional sheet (in mechanical, but not radiative equilibrium) whose field lines are tied in the photosphere. They then solve the resistive MHD equations, neglecting gravity and heat conduction, but including Joule and mechanical heating and optically-thin radiative losses. To accelerate the numerical simulation, they were forced to adopt an unrealistically small magnetic Reynolds number (120), but their results are interesting anyway. They find that the sheet develops a KR prominence above a KS prominence. The KR portion possesses an X-type neutral point, but no magnetic islands and, without gravity, erupts vertically. The KS portion is stable, but rather low. The plasma density in both portions rises (and the temperature falls) by a factor of ten.
during the simulation. In later papers Malherbe and Forbes (1986) extended this work by investigating the role of shocks in compressing the plasma.

These initial attempts show that, as expected, the condensation process is exceedingly complicated. Considerably more numerical modelling will be required to clarify the sequence of events and to determine which of the several possible tearing modes is crucial. A complete simulation, even in 2-D, is some distance off, but not beyond the limits of large-scale computers.

5. Summary

I do not exaggerate when I say that no characteristic of quiescent prominences is thoroughly understood. Even the support of the dense plasma by magnetic forces, which has been repeatedly demonstrated with magnetostatic models, and which has been made plausible by vector field measurements, is open to question. The slow downward motions in Hα threads, if real and not apparent, may indicate that the plasma is not fully frozen to the field and dribbles through it. Sturrock and Coppi (1966) have considered a gravitational resistive instability, in connection with a flare model, that might induce such ‘dribbling’.

The large-scale magnetic field around a prominence has not been observed; we can only guess its form from proxies. Within the prominence sheet, the magnetic field seems too uniform and steady to account for all the fine structure we see. This may only result from insufficient time and space resolution for the magnetic observations.

We have reasonably detailed observations of the optical and EUV emission of prominences, but no structural thermodynamic model that explains all the facts. Any plausible description of the energy balance and the mass balance must await such a structural model. The fine-structure is undoubtedly critical. Once again, we need higher spatial resolution.

The Kuperus–Tandberg-Hanssen scenario for the formation of a prominence remains the best available working hypothesis. Here I think the theorists are gaining insight with their detailed numerical simulations that incorporate an increasing amount of the relevant physics. Unfortunately, unless I am very mistaken, we still lack observations of the birth of a quiescent prominence, if in fact it condenses from the corona. Even the time-scale for formation is uncertain: does the drop from 10⁶ K to 10⁴ K take several hours or several days?

How can we progress? Clearly, we need better observations to guide theory and model-building. The fine structure is the great unknown at present, and as usual, we must strive for better spatial resolution. High-resolution imaging at optical wavelengths would help. HRSO will eventually be launched and should provide some answers. Alternatively, THEMIS may offer new opportunities for spectroscopy and magnetometry. LEST is another possibility, although a rather distant one at present. Meanwhile, we should explore modern techniques of image reconstruction (e.g., speckle interferometry) and imaging interferometry, to resolve prominence fine structure in selected emission lines.
The real challenge lies in resolving the fine-scale magnetic field. Leroy (1988) estimates that a gain in photon flux of at least 20 would be needed. This might be satisfied by a new large-aperture (2-m class) reflecting coronagraph (Koutchmy, Private communication, 1988) at a good site.

We surely need better EUV and XUV imaging spectroscopy with at least 1" resolution, to follow the early phases of prominence formation and to model the equilibrium transition zone structure. Recent advances in normal incidence multi-layer mirrors for the XUV (Golub et al., 1985; Lindblom, Walker, and Barbee, 1986; Walker et al., 1988) suggest that a spectrometer of radically new design could be built. The prospects for flying such an instrument on the shuttle or on a space station are remote, but as both of these groups have shown, we could gain some very valuable information from a short rocket flight.

Solar prominences will continue to challenge the ingenuity of astronomers for some time to come. In my opinion, they deserve our best efforts, if only because they represent the best example of thermal-magnetic field coupling, which is a fundamental process in astrophysics.

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