DYNAMIC PHENOMENA IN CORONAL FLUX TUBES

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INTRODUCTION

One of the major unsolved problems in the study of stellar atmospheres is the determination of specific physical mechanisms, geometries, and magnetic structures by which coronae are maintained. Ultraviolet and soft X-ray components observed in the radiative output of cool stars and the sun require counter-entropic temperature gradients for their explanation. The existence of a hot corona has long been recognized as resulting from mechanical or fluid dynamic effects and more recently the fact that the magnetic field plays an important role in this heating has come to be accepted. Thus magnetohydrodynamic energy release associated with the emergence of magnetic flux through the chromosphere and its dynamic readjustment in the corona are major counter-entropic phenomena which must be considered as primary candidates for coronal heating.

The medium in which these phenomena take place, a hot, magnetically-confined low-pressure plasma, has itself numerous non-intuitive properties which must be untangled and understood separately before observations of transient and spatially localized heating phenomena in this medium can be interpreted. It is the purpose of this paper to discuss results obtained using the recently-developed Dynamic Flux Tube Model to simulate and quantify some of these coronal plasma properties in magnetic flux tube configurations representing the chromospheric-coronal transition region, complete coronal loops, plasma jets, and flares. Results of these studies show that the strong dynamic interplay between thermal conduction and radiation gives the plasma a stressed, non-local behavior which makes non-monotonic and shocked profiles difficult to achieve. Nonlinear condensations can and do appear but their acceleration to sonic velocity and higher indicates magnetic forces. Numerical simulations show acceleration and flows generated by local heating to be a highly inefficient way of generating kinetic energy because enthalpy fluxes at flow rates of 5 - 10 km s\(^{-1}\) in coronal plasma are large enough to redirect energy being deposited at a rate adequate to maintain the corona.
DISCUSSION

To perform these calculations a new computational model has been developed to describe convective, wave, and heat transfer phenomena in the outer layers of the solar atmosphere. In this model a locally axisymmetric magnetic flux tube is represented by the complete nonlinear MHD equations fully resolved in the axial direction but integrated over an assumed but time varying similarity-like radial profile. To facilitate comparison with observations, a time-dependent description of the nonequilibrium ionization of oxygen has been included which is calculated along with the evolving MHD flow. Special techniques have been devised to permit accurate resolution of the dynamically important phenomena which take place in the thin transition region. Many aspects of the model have been described in previous publications (Oran, Mariska, and Boris 1982; Mariska et al. 1982). Here we concentrate on two aspects which have stimulated the most questions: our treatment of the chromosphere and our resolution of the transition region.

Although the coronal plasma has properties which make some aspects of its behavior difficult to understand, it is an open book compared to the complex interactions and processes in the chromosphere. Because of these complexities, there has been a natural tendency to solve problems which treat the transition region as a lower boundary to the corona (e.g., Kral and Antiochos 1980). We have found, time and again, that the chromosphere responds dynamically to changes in the coronal heat flux and pressure in a way which cannot be modeled as a boundary condition. The chromosphere behaves much like a loaded spring with the overlying layers providing most of the loading. Thus, changes in the pressure, such as might be caused by heating rate changes in the overlying layers, will cause the chromosphere and overlying transition region to rise and fall in response. This coupled system response requires inclusion of at least two scale heights of chromosphere within the computational region. A chromospheric region is also required in order to calculate evaporation of chromospheric material into the corona or condensation of coronal material back into the chromosphere.

Our computational treatment of the chromosphere avoids most of the usual radiation transport, opacity, and atomic physics difficulties by assuming the fluid to be an extension of the coronal plasma to higher density without large energy input from below or correspondingly large energy loss from radiation and transport. When the material exceeds $10^4$ K, it radiates the excess heat away according to the Cox-Tucker-Raymond optically thin plasma law. This radiation includes \textit{L}-alpha components from $1 - 3 \times 10^4$ K but this loss is zero when the plasma temperature drops below $10^4$ K. The "chromospheric material" in this approach moves, evaporates, condenses, compresses, etc. in a realistic way to properly support the transition region and corona. When compressed to temperatures above $10^4$ K, the dense chromosphere radiates the excess energy away. Thus, our chromosphere is essentially
isothermal and we do not have to be concerned with large energy depositions from below and corresponding large radiative losses from the chromosphere.

A number of calculations have been performed looking at the steady state transition region structure as a function of improving computational resolution. These calculations were designed to address two questions: the existence of a steady state and the necessary spatial grid size to resolve the transition region accurately. Another paper at this conference (Rosner 1982) has addressed the issue of whether or not the equilibrium transition region is hydrodynamically stable or unstable. The conclusion there, as in our papers, is that the combined corona-transition region-chromosphere system is stable. Reports of instability in earlier works are traced to improper boundary conditions and/or application of functionally unstable heating functions. This means that the observed fluctuations in the transition region plasma have to be attributed to external driving effects like changes in the heating rate or magnetic flux tube geometry. They appear not to result from any inherent turbulent tendency in the transition region structure itself. The uniformity and repeatability of laser-plasma experiments, where the thin ablation layer is closely analogous to the transition region, supports this theoretical conclusion indirectly.

In the transition region the temperature and hence the electron thermal conductivity decrease rapidly requiring very short temperature gradient scale lengths to maintain the downward directed heat flux. At the typical quiet sun coronal pressures of about 0.2 dynes cm$^{-2}$, temperature scale heights $h < 1$ km are required in the $1 - 5 \times 10^4$ K region. An important part of the downward directed heat flux high in the corona goes into the dense but thin transition region plasma at temperatures between $\sim 10^4$ K and $\sim 3 \times 10^4$ K which radiates L-alpha. Thus, our model automatically allows for this significant energy leakage from the corona.

The leakage also means the lower transition region is constantly "stressed" or connected by a significant heat flux well down into material normally considered chromospheric. The profiles of temperature, density, and hence radiation output in the hotter $3 - 15 \times 10^4$ K plasma just above are correspondingly altered to steeper gradients which transport the additional downward directed heat flux that is required to feed L-alpha. This already moving heat flux connects separated regions in the transition region and lower corona by a communication mechanism, electron thermal conduction, which moves faster than sound and therefore tends to stabilize purely fluid effects. The presence of steeper gradients also means that other models may underestimate the resolution required for convergence.

A number of calculations were performed of the same physical conditions for a typical quiet sun loop varying the spatial resolution from 20 km down to 1 km. While the structure of the low temperature transition region clearly reflects the resolution changes, the total
radiated power from the whole layer ~1 - ~5 $\times 10^4$ K was remarkably insensitive ( ~10 - 20% variations) to whether the temperature varies by a factor of two per computational cell or changes by only 10% per cell (Mariska et al. 1982).

When an excess of downward heat flux beyond that needed for the L-alpha radiation readjustment is supplied, the temperature rises in an energy conserving way until the heat flux to lower layers plus the increased radiation from higher temperatures can handle the increased input. This channeling of heat flux to lower layers and increased radiation in the vicinity of our L-alpha peak seems to be governed by integral conservation constraints of mass, momentum, and energy flow and hence is very insensitive to the local resolution. The success of the method with 5 - 10 km resolution can be traced to this relatively fortunate algorithm based insensitivity.

Several misconceptions exist in the literature concerning the systematic flow of plasma from one end of a coronal flux-tube to the other (e.g., Cargill and Priest 1980). Therefore, we have performed a number of detailed simulations to study these issues. We find that a pressure difference along the flux tube from the transition region at one end to the transition region at the other cannot be sustained by the complete chromosphere-corona-chromosphere system. The hot corona in a low-lying loop effectively equalizes the pressure when a continual source of coronal heat is present. Thus, the major flow is an expansion of the chromosphere at the high pressure end of the loop and a corresponding compression at the low pressure end until the two pressures have essentially equalized. The transition regions and corona readjust quickly and smoothly to follow the damped acoustic oscillations of the two chromospheres.

In the steady-state which eventually ensues (with or without systematic flow) there can be no net pressure difference without a corresponding acceleration of fluid from one end of the loop to the other. Since there is no net momentum increase in the overall system, the pressure difference at a given altitude can only arise from masses of overlying material. Since the coronal density is very low, the transition region pressures are essentially equal.

We do not see supersonic flows over the top of the loop at any time during these calculations, nor have we been able to generate standing shocks as postulated in the literature. The usual models for flow in closed loops generally also neglect the smoothing, stabilizing effects of thermal conduction. We have found, however, that systematic flows result quite naturally from asymmetric coronal heating. In general the flow direction is away from regions of excess heat deposition and in such a direction as to equalize radiative losses from the two transition regions.
These flows are saturated in the sense that the flow is as fast as it can be without actually over balancing the energy distribution in the opposite direction to the nonphysical case where more energy is being dissipated on the side of the loop farthest from the heat source. Once the asymmetry becomes appreciable the velocity saturates at about 5 km s\(^{-1}\). This is the velocity necessary to redistribute the energy evenly via the enthalpy flux.

CONCLUSIONS

The work summarized here for the cool stars meeting includes as well the efforts of our colleagues D. Book, C.-C. Cheng, G.A. Doschek, J. Karpen, E. Oran and T. Young. From these investigations, referenced below, the following conclusions, in the form of declarative sentences arose.

- The nonlinear evolution of the condensational instability leads in the presence of volumetric heating to a two-phase state in which a cool, dense plasma is surrounded by a hot, tenuous plasma.
- Once formed, these condensations will last a long time. In fact, such phenomena are observed.
- Once formed, a condensation may be accelerated by forces in the plasma such as those arising from gravity, differential heating, or magnetic fields.
- Shocks generated by transition region mass ejections are a possible coronal heating mechanism and these masses may be a possible source of coronal mass.
- The transition region is a dynamically stable structure which resembles the state resulting from the nonlinear evolution of the condensational instability.
- The thin laminar structure of the transition region is insensitive to changes in the heating function.
- The heating and cooling of small loops results in relative ionic abundances which can differ substantially from equilibrium values.
- Systematic flows in coronal flux tubes result from asymmetric heating.
- Doppler velocity measurements of downflows in the network suggest heating is concentrated elsewhere.
- Systematic flows can exist without substantial chromospheric pressure differences.
Dynamic chromospheric-coronal coupling is required for meaningful calculations of dynamic phenomena in coronal flux tubes.

REFERENCES


Rosner, R. 1982, these proceedings.