Dynamics and spectral properties of coronal funnels

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INTRODUCTION - MHD

The magnetic field in the quiet solar chromosphere is concentrated along the lanes of the super-granular network. From this chromospheric network magnetic funnels do emerge, and rapidly expand some 2–10 Mm above the photosphere and finally fill the whole corona. This causes the emission patterns of the chromospheric network to become wider with increasing temperature. When observed in lines formed in the corona the network will be no longer visible.

Based on these early observations a model was developed accounting for the magnetic expansion as well as for the energetics of the solar atmosphere (Gabriel, 1976). To study the properties of coronal funnels and their role in accelerating the solar wind close to the Sun we employed a new 2D MHD time dependant model including the solar atmosphere all the way from the chromosphere to the corona. We put special emphasis on the plasma flow out of the coronal funnel. The energetics of the plasma include radiative losses, thermal conduction and a prescribed heating term. In this poster we present 2D plasma properties (e.g. density, temperature, flow speed) within the funnel.

INTRODUCTION - Spectral code

We describe here how we used the properties from the MHD model to synthesize emission line spectra. From the results of the 2D MHD calculation we derive the resulting profiles of various emission lines formed in the transition region from the chromosphere to the corona. This allows us e.g. to study the Doppler shifts at various temperatures across the funnel and thus enables a detailed comparison of the model results with observations.

These results indicate a systematic variation of the Doppler shifts in lines formed in the low corona. The line shift above the magnetic field concentration in the network is stronger than in the inter-network, however, the maximum blue-shift is to be found *not* in the very center of the network but in the vicinity of the center.

This corresponds well to results of an analysis of SUMER observations of line shifts across the network and statistics from correlation between Ne VIII(770Å)intensity and Doppler shift (Aiouaz et al. poster, **"On the outflow at coronal heights"**).

MODEL

To solve the set of MHD equations, we used the Versatile Advection Code(VAC) (Tóth 1996) with the TVD Lax-Friedrich scheme, all being second order accurate in time and space.

ASSUMPTIONS:

- Area function $A = A_0 B_0 / B_z(z)$, where A_0 and B_0 is the area and magnetic field strengh at the upper end of the funnel (Hackenberg, 2000).
- Heat conduction along the magnetic field following Spitzer (1962).
- Radiative energy losses assumed as piecewise power laws for an optically thin medium (Rosner et al., 1978).
- Corona maintained against conductive, radiative, and solar wind losses by a specified a coronal heating function.

A standard one-fluid plasma model is considered. The density ρ, momentum $\rho\mathbf{v}$, total energy e and magnetic field $\mathbf{B}$ are the variables of the full MHD equations describing a two-dimensional conductive plasma flow in a coronal funnel, including the energy equation.

ENERGY EQUATION:

- $\partial_t e + \nabla \cdot \mathbf{F}[e] = S$ with $S = -\nabla \cdot q + \rho^2 Q(T) + H$
  where **S** is the energy function which includes all the sinks and sources of energy, i.e. thermal conduction, radiative losses and coronal heating.
- CORONAL HEATING FUNCTION: $H = \frac{F_0}{A \cdot \lambda} \exp\left(\frac{y - y_{chr}}{\lambda}\right)$
  where F_0 is the energy flux amplitude at the transition region, y_{chr} is the uppermost location of the chromosphere and λ is the damping length scale.

SPECTRAL CODE

In this section we described how we used the thermodynamic properties from the MHD model to see what could be measured or derived from spectrometer measurements.

ASSUMPTIONS:

- Considered lines are optically thin.
- Ionization equilibrium is assumed.

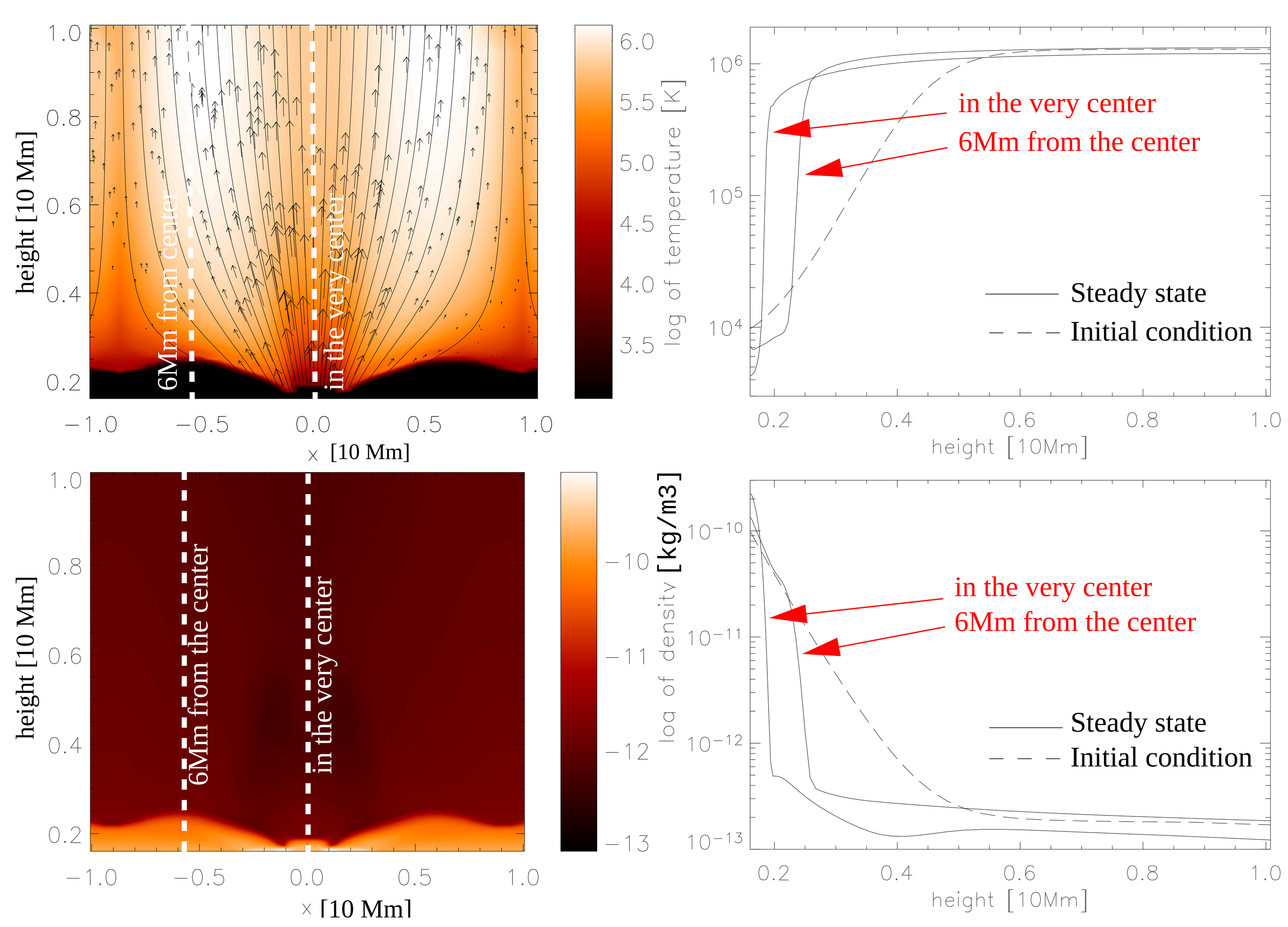
The transition region and corona are hot and low-density. If we know the temperature, density, and velocity of the plasma at each location then we can derive, at least to first order, the spectrocopic properties.

SYNTHETIC LINE PROFILE:

- Emissivity computed using the CHIANTI database (Young et al., 2003)
- Emissivity: $\epsilon_{ji} = \frac{h\nu_{ji}}{4\pi} A_{ji} n_j \; [ergs \cdot cm^{-3} \cdot s^{-1}]$
  where i, j are the lower and upper levels, A_{ji} is the spontaneous transition probability, n_j is the number density of the upper level j of the emitting ion.
- Synthetic line profile: $\epsilon_\nu = \epsilon_{ji} \frac{1}{\pi^{1/2} \Delta\nu_D} \exp\left[-\frac{(\nu - \nu_0)}{\Delta\nu_D^2}\right]$
  where the temperature is used to calculate the Doppler width, $\Delta\nu_D = \frac{\nu_0}{c}\left(\frac{2kT}{M}\right)^{1/2}$, and the velocity along the line of sight to calculate the Doppler shift, $(\nu - \nu_0) = \frac{v_y \nu_0}{c}$.
- The emissivities were integrated along a line-of-sight (y direction) to be able to compare the theoritical results to Spectrograph observations.

RESULTS

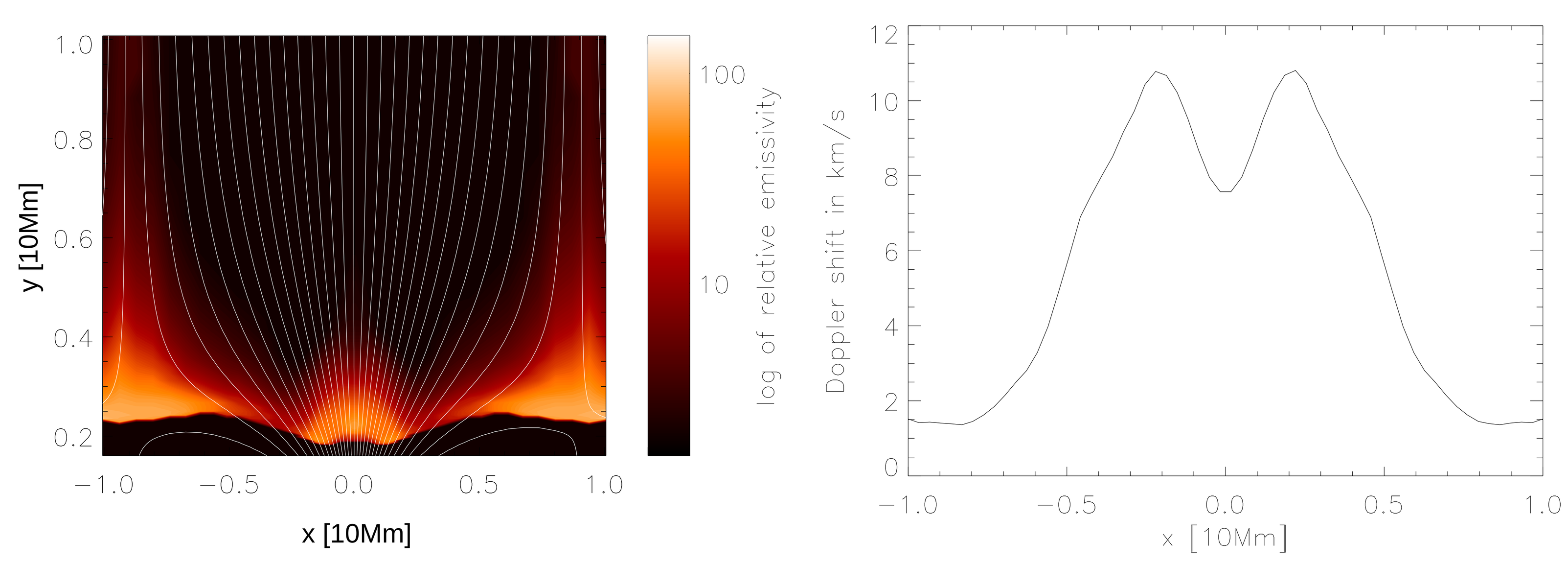
In this part, we present some typical results provided by the VAC code. The next pictures shows some 2-D plasma properties within the funnel:



The top panels show the evolution of temperature profile from the intial condition(dashed-line in right panel) uniform along the x-axis to the steady state (solid-lines in right panel) depending on the position in the x-axis. The bottom panels show similar evolution for the density.

RESULTS FOR Ne VIII 770.4 Å

Intensity and the line shift were extracted from integrated spectra along the line of sight (y-direction).



The left panel shows the relative emissivity of Ne VIII (770 Å), calculated from the MHD results using the CHIANTI database. Magnetic field lines are shown in white. The right panel shows the corresponding line shift across the funnel calculated for the resulting synthetic spectra integrated along the line of sight (y-direction).

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OUTLOOK

The model presented above is the first dynamic 2D-MHD model of funnels including calculation of spectral profiles for different ions. From the results of the MHD calculation we used the temperature, density and the velocity of the plamsa at each location of the computational domain to compute emissivities using the CHIANTI database.

We calculated then synthetic line profile using the thermodynamic properties and integrated it along the line-of-sight (y direction). This gives us total line profiles across the funnel (along x direction) that can be compared to spectroscopic observation with the slit placed across a network lane. This allowed us to study the Doppler shifts across the funnel and thus enables a detailed comparison of the model results with observations.

These results indicate a systematic variation of the Doppler shifts in lines formed in the low corona. The line shift above the magnetic field concentration in the network is stronger than in the inter-network, however, the maximum outflow is *not* found in the very center of the network but in the vicinity of the center.

This results shows that the variation of Doppler shifts across a funnel is non-trivial. This study motivates further work on coronal funnel modeling as well as on our understanding of the acceleration of the solar wind and the structure of the solar atmosphere.

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