

Modeling the scattering polarization of the hydrogen Ly- α line observed by CLASP in a filament channel

J. Štěpán (AIAS), J. Trujillo Bueno (IAC), S. Gunár (AIAS), T. del Pino Aleman (UCAR), P. Heinzel (AIAS), R. Kano (NAOJ), R. Ishikawa (NAOJ), N. Narukage (NAOJ), T. Bando (NAOJ), A. Winebarger (NASA-MSFC), K. Kobayashi (NASA-MSFC), F. Auchere (IAS)

ABSTRACT: The 400 arcsec spectrograph slit of CLASP crossed predominantly quiet regions of the solar chromosphere, from the limb towards the solar disk center. Interestingly, in the CLASP slit-jaw images and in the SDO images of the He I line at 304 Å, we can identify a filament channel (FC) extending over more than 60 arcsec crossing the spectrograph slit. In order to interpret the peculiar spatial variation of the Q/I and U/I signals observed by CLASP in the hydrogen Ly α line (1216 Å) and in the Si III line (1206 Å) in such a filament channel, it is necessary to perform multi-dimensional radiative transfer modeling. In this contribution, we show the first results of the two-dimensional calculations we are carrying out in given filament models, with the aim of determining the filament thermal and magnetic structure by comparing the theoretical and the observed polarization signals.

1. THE CLASP OBSERVATIONS

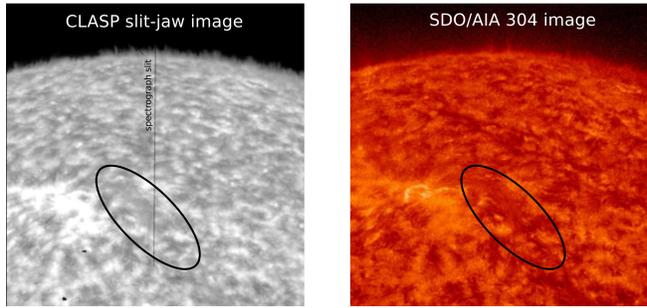


Figure 1 The spectrograph slit of CLASP (Kobayashi et al. 2012) crossed a plasma structure at the cosine of the heliocentric angle $\mu \approx 0.7$ that appears to be a filament channel (FC; indicated by an ellipse in the panels). While the structure can be seen in the Ly α line and in the He II 304 Å line of SDO/AIA, it is not clearly visible in the IRIS Mg II k line nor in H α .

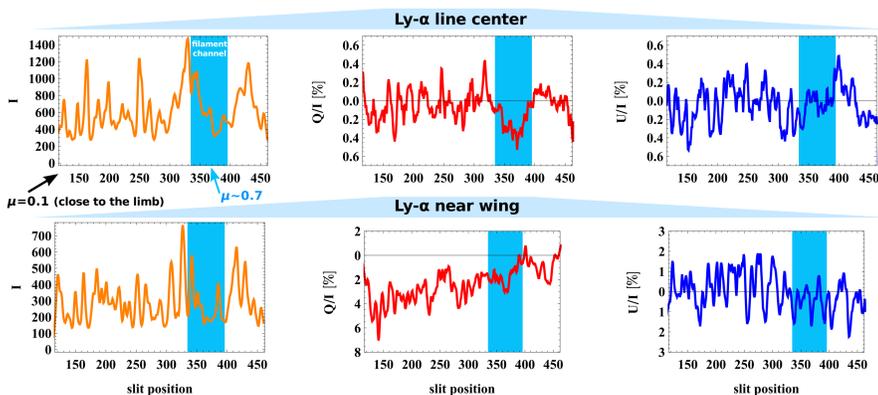


Figure 2 Intensity and fractional linear polarization along the CLASP spectrograph slit. The FC (the blue zone in the panels) produces the most interesting signals in the linear polarization: The Ly α line-center Q/I signal (top panels) is negative with maximum amplitude in the center of the FC. In the near wings of Ly α (0.55 Å off the line center), the signal seems to follow the chromospheric center-to-limb variation (CLV) which indicates the FC may be optically thin at this wavelength (bottom panels). The U/I signal does not show any large-scale variation. The positive Q direction is defined as being perpendicular to the spectrograph slit.

4. MULTI-THREAD SOLUTION

It has been demonstrated that multi-thread models of filaments provide better agreement with the spectroscopic observations of SOHO/SUMER (e.g., Gunár et al. 2007). Instead of a single thread, we can model the FC as a collection of small-scale threads with qualitatively similar thermal structure as shown in Fig. 3. In Fig. 6, we plot the synthetic Q/I and U/I signals along a single thread with significantly smaller dimensions.

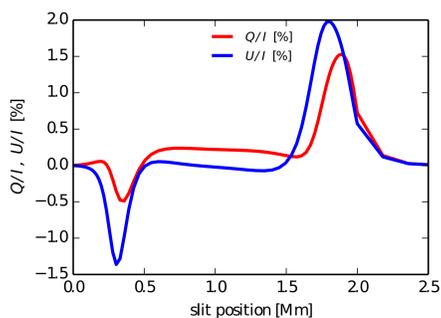
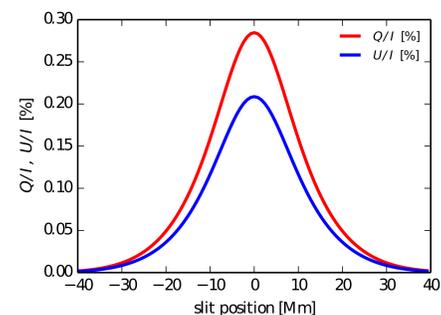


Figure 6 Same as Fig. 5 but here for a FC thread with dimensions of about 2 Mm x 0.5 Mm. We note that the qualitative behavior of Q/I and U/I is very similar to that of Fig. 5.



We model the FC spectrum as a superposition of the small-scale threads contributions. In this work, we neglect the mutual radiative interaction between the threads and we assume that the average density of threads decreases as

$$D(x, z) \propto e^{-\frac{x^2}{D_x^2}} e^{-\frac{z^2}{D_z^2}} \quad (2)$$

where the coordinates are measured from the center of the FC. The total optical thickness of the FC decreases accordingly to Eq. (2) from much larger than one in the central parts of the FC to zero at the FC edges. For the overall effect of the multi-thread solution, see Fig. 7. The large-scale variation of Q/I now resembles the CLASP data up to the sign. The U/I signals show even larger discrepancy.

Figure 7 The Q/I and U/I line-center signals across the FC calculated as a cumulative effect of multiple fine-structure threads. The total signal results from partial cancellation of the positive and negative Stokes parameters across the individual threads and from the partial transmission of the unpolarized radiation of the underlying chromosphere which plays the most important role at the edges of the FC.

5. DISCUSSION

The physical properties of our model are based on the standard ad-hoc parametrization of temperature that has been previously successfully used for modeling of the intensity spectra of the hydrogen Lyman series (Gunár et al. 2007). The CLASP observations now revealed that the PCTR layer in which the center of Ly α is formed is probably not well approximated by these models.

The positive Q/I signals originate in the regions of negative J_0^2 radiation field tensor (cf. Landi Degl'Innocenti & Landolfi 2004). The gradient of the line source function S in the *chromosphere-corona* transition region in the semi-empirical model atmospheres determines the sign of J_0^2 : One finds $J_0^2 < 0$ if the line source function gradient is positive (i.e., S increases with height) and for a certain interval of negative values (see Fig. 6; for more details see Trujillo Bueno et al. 2012). The source-function gradient is closely related to the temperature gradients: To obtain positive J_0^2 in the PCTR, the temperature gradient should be *much steeper* than in the present models. We have tested models with various values of γ but none of the models was able to qualitatively reproduce the observed signals. The likely explanation is that the simple parametrization by Eq. (1), which is otherwise quite successful in explaining intensities of some spectral lines, does not describe the real PCTR of the observed FC.

2. A SINGLE-THREAD MODEL OF THE FC

Our goal is to use the models of a filament to understand, at least qualitatively, the behavior of the Q/I and U/I signals of Ly α along the slit. To this end, we use 2D non-LTE radiative transfer calculations. Our model of choice is an isobaric ($\rho_{\text{gas}} = 0.015 \text{ dyn cm}^{-2}$) 2D filament structure with the plasma temperature given analytically (Anzer & Heinzel 2001):

$$T(x, z) = t(z) + (T_{\text{tr}} - T(z)) \left(1 - 4 \frac{x}{D_x} \left(1 - \frac{x}{D_x}\right)\right)^{\gamma_x} \quad (1)$$

where

$$t(z) = T_0 + (T_{\text{tr}} - T_0) \left(1 - 4 \frac{z}{D_z} \left(1 - \frac{z}{D_z}\right)\right)^{\gamma_z}$$

The Ly α core forms in the *prominence-corona transition region* (PCTR; see Fig. 3) where the temperature rapidly increases from about 10,000 K to coronal temperatures. Assuming that the FC is composed of a single thread, we choose the plasma parameters following the previous successful investigations of the SOHO/SUMER line intensities (e.g., Gunár et al. 2007). In Fig. 3, we show the spatial variation of temperature and density in the FC model.

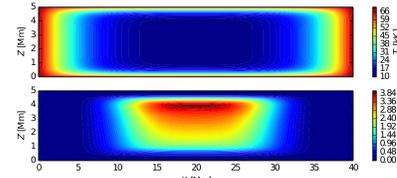


Figure 3 Vertical slice of the model FC defined by Eq. (1). Top panel: temperature; bottom panel: neutral hydrogen density. The thread is infinite in the Y direction. The geometry of the PCTR depend strongly on location in the FC and the parameters γ_x and γ_z , here $\gamma_x = 2$ and $\gamma_z = 5$.

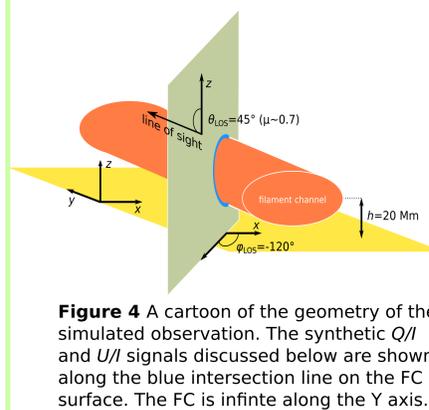


Figure 4 A cartoon of the geometry of the simulated observation. The synthetic Q/I and U/I signals discussed below are shown along the blue intersection line on the FC surface. The FC is infinite along the Y axis.

3. THE RESULTING Q/I AND U/I

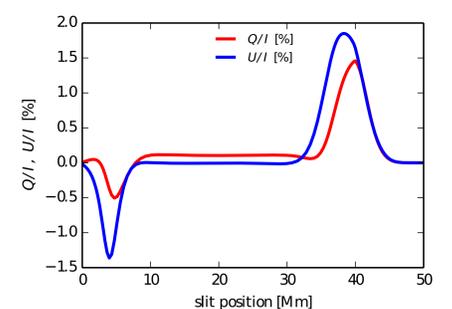


Figure 5 The spatial dependence of Q/I and U/I across the FC. The discrepancies between the CLASP and the model are obvious: Q/I has the opposite sign, and the largest signals are found at the edges of model FC, and U/I peaks strongly at the FC edges (cf. Fig. 2).

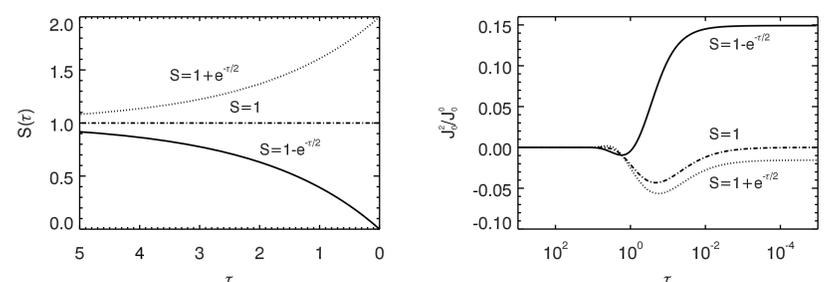


Figure 6 Illustration of the sensitivity of the fractional anisotropy of the local radiation field (right panel) to the gradient (with respect to the optical depth) of the source function (left panel) in an academid 1D plane-parallel model. From Trujillo Bueno et al. (2012).

Nevertheless, the multi-thread model similar to that introduced in Sect. 4 seems to be necessary for explanation of the large-scale variation of the polarization signals across the filament. In the near future, it will also be necessary to include the mutual radiative interactions among the threads. This mutual illumination can significantly affect the anisotropy of radiation and, consequently, the emergent scattering polarization signals.

We have found that introduction of sufficiently strong magnetic fields ($B > 50$ G) can significantly reduce the U/I signals, hence the results are in better agreement with the observations. On the other hand, magnetic fields are only capable of reducing Q/I but not changing its sign the value comparable to the CLASP data.

6. CONCLUSIONS

- The present models fail to explain the CLASP observation: The Q/I signal in all our models has opposite sign than in the observations of the FC.
- Multi-thread approach may be necessary for explanation of the large-scale variation of Q/I
- Assuming that the observed structure is representative of a quiescent solar filament, we need to significantly reassess the current filament/prominence models: CLASP data suggest that the temperature gradients in PCTR are much larger than usually expected.
- Incorporation of the magnetic field along the model Y axis cannot change the sign of Q/I in the current geometry but it can remove the U/I signal, consistently with the CLASP observations.
- Fully consistent 2D/3D solution including mutual radiative interaction among the threads needs to be calculated in the future.
- CLASP provides unprecedented constraints for the near-future models of filaments/prominences.

REFERENCES

- Gunár, S., Heinzel, P., Schmieder, B., Schwartz, P., Anzer, U. 2007, *A&A*, 472, 929
 Heinzel, P. & Anzer, U. 2001, *A&A*, 375, 1082
 Kobayashi, K. 2012, *ASPC*, Vol. 456, 233
 Landi Degl'Innocenti, E. & Landolfi M. 2004, *Polarization in Spectral Lines*, Kluwer
 Štěpán, J. & Trujillo Bueno, J. 2013, *A&A*, 557, 143
 Trujillo Bueno, J., Štěpán, J., Belluzzi, L. 2012, *ApJ*, 746, L9