Puzzling nature of the fine structure of quiescent prominences and filaments

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Abstract. Even after more than 160 years of observations and modelling of solar prominences their true nature contains many open questions. In this work we argue that current 2D prominence fine structure models can help us to understand the puzzling connection between quasi-vertical fine structures often seen in quiescent prominences observed above the solar limb and horizontally aligned dark fibrils representing the fine structures of prominences often seen in absorption against the solar disk (filaments).

1. Introduction
Some of the most striking features visible during total solar eclipses, of course besides the beautiful renderings of the coronal structures, are solar prominences. Indeed, these were first observed during total solar eclipses and studied since. In the last decades prominences were observed by powerful instruments and extensively modeled but their nature still puzzles solar physicists, even after more than 160 years. One of the most puzzling problems in current prominence physics is the presence of quasi-vertical fine-structure threads often seen in quiescent prominences observed in emission above the solar limb (see e.g. [1] and their Fig. 1). How can such vertically aligned structures be embedded in the predominantly horizontal magnetic field [2]? How can they be related to fine densely-packed horizontal dark fibrils usually observed in filaments in absorption against the solar disk (see e.g. [3] and Figs. 1 and 2 therein)? Are these the same structures?

Our contribution to answering the above questions is based on a detailed 2D modelling of the prominence fine structures using either gravity-induced Kippenhahn-Schlüter type (KS-type) models of [4] or newly developed non-linear force-free (NLFF) magnetic dip models of [5]. The 2D KS-type models represent the magnetic dips in initially horizontal field caused entirely by the weight of the prominence mass. Such dipped regions could propagate vertically and might lead to formation of quasi-vertical structures. Gunár et al. (in [6], [7], [8], [1], and [9]) showed that these models can produce synthetic hydrogen spectra in very good agreement with optical
and UV observations, especially in case of multi-thread configurations. On the other hand, the NLFF magnetic dips result from large-scale 3D NLFF modelling of the whole prominence magnetic field [10]. They can be then filled with the realistic prominence plasma for example by the technique described in [5]. We demonstrate here that such prominence fine structure models, either gravity-induced or NLFF, can be also consistent with observations of fine structures of both prominences and filaments.

### 2. Prominence fine structure models

Both types of prominence fine structure models used in this work assume 2D vertically infinite geometry with all quantities uniform along the vertical axis and varying within the horizontal $x$-$y$ plane (see Fig. 1). Such an approach is valid for modelling of quasi-vertical prominence fine structures observed above the solar limb, because the dominant incident radiation from the disk penetrates the prominence body along the horizontal plane. In this plane we solve, in both cases, the 2D multi-level non-LTE (i.e. departures from Local Thermodynamic Equilibrium) radiative transfer problem to obtain the synthetic hydrogen spectra, including the Hα spectral line.

In order to model fine structures of filaments observed against the solar disk we have to artificially cut our 2D vertical threads at an arbitrary height and use resulting 3D structures to compute the radiation output along the line of sight pointing vertically. To this end we use the plasma properties and source function variation obtained by 2D radiative transfer modelling in the $x$-$y$ plane distributed uniformly in the vertical direction. While this approach does not conserve the magneto-hydrostatic (MHS) equilibrium of the KS-type models and is not suitable to model the spectral lines with significant optical thickness, such as Lyman lines, it is useful for obtaining synthetic Hα line profiles. Thus we can produce synthetic narrow-band observations in the Hα centre for both cases, prominences on the limb and filaments against the disk.

The above idea of projection of 2D vertical threads produced by KS-type models against the disk was presented by [11], who computed the Hα line contrast of dark fibrils. Here we use a multi-thread model consisting of identical 2D prominence fine-structure threads, without any mutual radiative interaction. We arrange this set of threads in a way that qualitatively corresponds to the observed prominence/filament structure, however, we do not attempt to reproduce any particular prominence or filament. Individual threads are arranged so that when viewed from the top they resemble the main body of a filament with dark fibrils aligned along a sheared magnetic field. Each thread is shifted by a randomly selected distance with respect to its central position along the spine of the filament (see Fig. 2). The width of individual threads is 1000 km and the gap between threads is also 1000 km wide. These dimension can be too large in comparison with the observed widths of the prominence/filament fine structures that may be as small as 100 km.

![Figure 1](image_url). Scheme of a 2D vertically infinite fine structure thread with indicated lines of sight for prominence and filament observations. Drawn magnetic field lines approximate the shape of the magnetic dips. Note that we assume $B_y = 0$. 

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Journal of Physics: Conference Series 440 (2013) 012035 doi:10.1088/1742-6596/440/1/012035
km [3]. However, with this multi-thread set-up (Fig. 2) we aim to demonstrate that our models can consistently simulate the prominence and filament fine structure observations. For that we use the 2D model (MODEL1) from [8] that produces synthetic hydrogen Lyman spectra in very good agreement with SOHO/SUMER [12] observations. The width of the thread (1000 km) is an arbitrarily chosen input parameter of the model, and the length of the thread (approximately 28000 km) is determined by the MHS equilibrium computations. We have artificially cut the 2D vertical threads of the model to obtain height of 10000 km. Figure 2 shows, in the bottom panel, the synthetic Hα line centre image of fine-structure threads as dark fibrils in projection against the solar disk. The panel on the top shows the same multi-thread set-up as seen with the LOS along the $y$-axis (see Fig. 1). This produces a synthetic Hα line centre image of the vertical prominence fine structures seen above the solar limb. Here we see relatively narrow vertical structures even though the LOS is perpendicular to the longer of the thread dimensions. This is due to the fact, that the most intense (and thus easily observable) Hα line emission is produced in the relatively confined region in the middle of each thread. On the other hand, an observable absorption producing the dark fibrils in the projection against the solar disk occurs in more extended volume, which produces significantly elongated fibrils. Their length depends on the assumed height of the threads (i.e. vertically aligned dips), however, [11] showed that this dependence is not very strong (see also Fig. 3, bottom).

In the next step we employ the NLFF magnetic dip model (the DEEP_DIP from [5]) not in a multi-thread configuration but to demonstrate the properties of the synthetic Hα line centre observations of a single fine structure. This model, produced by insertion of the prominence plasma into dipped magnetic field created by large-scale 3D NLFF modelling of the whole prominence magnetic field [10], can be restricted in height naturally, without the loss of the plasma hydrostatic equilibrium.

The top panel of Fig. 3 shows, as a synthetic Hα line centre prominence image, a single fine structure viewed with three different orientations of the LOS, all lying in x-y plane (Fig. 1).

![Figure 2](image2.png)

**Figure 2.** Multi-thread configuration of the 2D KS-type model. The top panel shows the synthetic on-the-limb image in the Hα line centre. The bottom panel shows the Hα line-centre projection against the disk. The dashed line represent the filament spine.
Figure 3. NLFF magnetic dip model observed as a single fine structure. The top panel shows the synthetic on-the-limb image in the \( \text{H} \alpha \) line centre. Over-plotted contours represent the optical thickness in the \( \text{H} \alpha \) centre. The bottom panel shows the \( \text{H} \alpha \) line-centre projection against the disk in dependence on the height of the fine structure. Over-plotted contours represent the optical thickness in the \( \text{H} \alpha \) centre. The maximum \( \tau_{\text{H} \alpha \text{ centre}} \) in case of LOS along \( y \)-axis (0°) and with 45° inclination is well below unity. This would, in case of randomly arranged multiple fine structures along the given LOS, lead to occurrence of smaller-scale regions with highest intensities where emission from more fine structures would add up. Note that the synthetic intensities are plotted in the same intensity scale for all three LOS orientations. The bottom panel shows the synthetic \( \text{H} \alpha \) line centre images of the same NLFF magnetic dip model against the solar disk. Here we show the geometrical extension of such produced dark fibrils in dependence on the height of the fine structure.

3. Conclusions
In this work we show that current 2D prominence fine structure models, either gravity-induced or NLFF, can be adapted to consistently produce synthetic narrow-band images (e.g. in the \( \text{H} \alpha \) line centre) of prominence and filament fine structures resembling the real observations. However, the limitations of currently used 2D geometry don’t allow us to look for models consisting of multiple fine structures that will be able to explain all observed characteristics of prominences. To this end we will have to concentrate on development of truly 3D fine-structure models with well described structure of supporting magnetic field and with detailed treatment of the 3D radiative transfer. Such models will for the first time allow us to consistently visualize the fine structures of prominences observed on the limb and against the disk. This will help us to understand the true nature of these fascinating solar features.
Acknowledgments

S.G. and P.H. acknowledge the support from grant P209/12/0906 of the Grant Agency of the Czech Republic. P.H. acknowledges the support from grant P209/10/1680 of the Grant Agency of the Czech Republic. S.G. and P.H. acknowledge the support from the MPA Garching; U.A. thanks for support from the Ondrejov Observatory. S.G. acknowledges the support from St Andrews University. Work of S.G. and P.H. was supported by the project RVO: 67985815. DHM acknowledges financial support from the STFC and the Leverhulme Trust. This research has also received funding from the European Commission’s Seventh Framework Programme (FP7/2007-2013) under the grant agreement SWIFF (project n 263340, www.swiff.eu).

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