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Modelling of quiescent prominence fine structures

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Abstract. We review here the current status and the latest results of the modelling of quiescent prominence fine structures. We begin with the simulations of the prominence magnetic field configurations, through an overview of the modelling of the fine structure formation and dynamics, and with the emphasis on the radiative transfer modelling of the realistic prominence fine structures. We also illuminate the future directions of the field that lie in the combining of the existing approaches into more complex multi-disciplinary models.

Keywords. Sun: prominences, Sun: filaments, magnetic fields, radiative transfer

1. Introduction

In this paper we review the state-of-the-art of the modelling of the prominence fine structures. We focus solely on the quiescent solar prominences and we consider only the simulations and models that include individual or multiple small-scale prominence structures.

Quiescent solar prominences are cool dense regions of plasma which lie in a near-equilibrium in a much hotter and rarer coronal environment. Their large-scale structure remains stable for days or weeks while their fine structures with dimensions as small as 100 km exhibit rather dynamical behaviour on time scales of a few minutes. The cool core of prominence fine structures have a temperature below 10,000 K, while the surrounding corona is over 1MK. The nature of the transition region between cool prominence plasma and hot corona (the prominence-corona transition region - PCTR) has a significant impact on the formation, energy equilibrium, and stability of prominences. Many of their important characteristics are given in the monograph by Tandberg-Hanssen (1995). The existence of prominences is mainly due to the coronal magnetic fields. Firstly, the magnetic fields define the framework configuration of prominences and support the dense prominence plasma against gravity. Secondly, they insulate the cool prominence fine structure material from the hot coronal plasma. Prominences, even the quiescent, may also become unstable, producing Coronal Mass Ejections - violent eruptions that may directly affect the Earth.

The exceptionally large amount of observations with ever-increasing spatial and temporal resolution, obtained by space-borne missions like SOHO, Stereo, Hinode, and SDO, together with a plethora of ground-based observatories facilitated a rapid advancement in our understanding of prominences in the last decade. Indeed, the synergy between the wealth of observations and the prominence modelling is still the main driving force of the prominence research. The contribution of these observations to the prominence research was reviewed by Patsourakos & Vial (2002) and Schmieder & Aulanier (2012). The fine structure of the solar prominences was comprehensively reviewed by Heinzel (2007) and the state-of-the-art of prominence physics was reviewed by Labrosse *et al.* (2010) and Mackay *et al.* (2010).

The modelling of the prominence fine structures relies on three main components. These are the simulations of the prominence magnetic field configurations, models of the prominence plasma and its dynamics, and the modelling of the radiative transfer in the prominence plasma. In the following sections we review the current status and the latest results of these approaches, beginning with the whole-prominence magnetic field simulations (Sect. 2). In Sections 3 and 4 we give a brief overview of the fine structure formation and oscillations, respectively. In Sect. 5 we describe the state-of-the-art of the radiative transfer modelling of prominence fine structures and in Sect. 6 we give our conclusions.

2. Whole-prominence magnetic field simulations

It is generally assumed that the majority of the dense cool plasma of the prominence fine structures lies in dips of the predominantly horizontal magnetic field (see e.g. observational findings of Schmieder *et al.* 2010 and López Ariste *et al.*2006). These dips can be either strongly affected or indeed be caused by the weight of the prominence fine-structure plasma or they can occur as the result of for example the force-free nature of the magnetic field configurations. For discussion of the force-free assumption validity in prominences see Anzer & Heinzel (2007).

In this section, we briefly review the whole-prominence magnetic field simulations under the assumption of the force-free field. This means that neither the whole magnetic field configuration nor the shape of the individual dipped magnetic field lines are affected by the prominence plasma weight (low plasma β conditions). These simulations do not assume any representation of the prominence fine structure plasma (except for visualization purposes) and therefore also do not treat the radiative transfer. A comprehensive review of the prominence magnetic field simulations and the details of the techniques and methods used to construct them are presented by van Ballegooijen (2013) in this volume (see also the review by Mackay *et al.* 2010). In this review we place the emphasis on the connection between the prominence fine structures and recent prominence magnetic field simulations based on either the assumption of the sheared magnetic arcade or the magnetic flux rope forming the structure accommodating the magnetic dips. The **sheared arcade models** such as those of Antiochos, Dalhburg & Klimchuk (1994), DeVore & Antiochos (2000), and Aulanier, DeVore & Antiochos (2002) incorporate a magnetic arcade formed by shearing photospheric footpoint motions. More recently, Aulanier, DeVore & Antiochos (2006) simulated the interaction and merging of two sheared magnetic arcades. On the other hand the **flux rope models** contain a weakly twisted flux ropes overlying the polarity-inversion line and are based on the extrapolation of the photospheric magnetic flux distribution into the corona. Such models were constructed by Aulanier & Démoulin (1998) assuming the *linear force-free fields* and by Aulanier *et al.* (1998, 1999), Aulanier, Srivastava & Martin (2000), Aulanier & Démoulin (2003), and Dudík *et al.* (2008, 2012) assuming the *linear magneto-hydrostatic fields*. Another successful prominence magnetic field extrapolation models, assuming the *non-linear force-free fields*, were developed by van Ballegooijen (2004) and by Mackay & van Ballegooijen (2009) who considered the evolution of the structure of the magnetic dips caused by the advection of a single parasitic polarity bipole.

The common feature of all these magnetic field simulations is the existence of the dipped field lines lying above the polarity-inversion line that can accommodate the prominence fine structure plasma but are not caused or affected by its weight. The spatial variation of the simulated magnetic field along these dipped field lines is comparable with the largest geometrical dimensions of the observed prominence fine structures, especially with the length of the filament fibrils (several thousand km) that are probably aligned with the field lines. However, the scale on which the simulated magnetic field varies in the plane perpendicular to the field lines is much larger than the smallest observed dimensions of the prominence fine structures that can be as small as 100 km. In other words, the localized, small-scale 3D magnetic field elements, such as 3D magnetic dips, that could constrain the prominence fine structure plasma in the 3D space do not exist in these simulations. Rather, one can imagine the spatial magnetic field configuration produced by these simulations as a set of larger-scale nearly identical 2D valleys lying one above the other. On the other hand, the small-scale 3D magnetic field dips are produced by the tangled field models of van Ballegooijen & Cranmer (2010) that, however, assume a relatively simple cylindrical geometry and are not able to reproduce the larger-scale configurations of the prominence magnetic field.

Position of the magnetic dips within a 3D prominence magnetic field configuration produced by simulations can be visualized by commonly used techniques based on the drawing of portions of the dipped field lines. These are usually drawn to the geometrical extend that represents the dip height equivalent to one pressure scale-height (approximately 300 km if assuming an isothermal plasma with a temperature of 10,000 K). Such visualization shows that the force-free magnetic field simulations are highly successful in reproducing the appearance of the global features of prominences and filaments. For example, Dudík *et al.* (2008) performed a linear magneto-hydrostatic field extrapolation based on the observed photospheric flux distribution and compared the resulting magnetic field configuration with the corresponding Hα observation of filament obtained by THEMIS on Oct 6 2004. The position of dips in the magnetic field configuration produced by simulations is in a remarkable agreement with the general structure of this filament (see Fig. 3, therein). Another striking example of the agreement between the magnetic field simulations (in this case the non-linear force-free fields) of the prominence observed by the SDO/AIA on Dec 6, 2010 is presented by Su & van Ballegooijen (2012) (see Fig. 13, therein). To show the position of the magnetic dips in these cases, precisely those dipped field lines are drawn that pass through the grid-points in the given simulation box. Such a technique is suitable for indication of position of dips in the particular simulation, but introduces several arbitrary effects into the visualization of the individual prominence fine structures. The apparent clusters of the drawn magnetic dips (see e.g. Fig. 13 in Su & van Ballegooijen 2012) are a product of the filling factor dependent on a number of grid-points in the simulation box and also on the boldness of the lines used for drawing of the dipped portions of the magnetic field lines. Moreover, the use of the non-transparent color bars as representations of the prominence fine structures is in fact equivalent to the observation in a spectral line with an infinitely large optical thickness, which is in contrast with the optical thickness of the Hα line commonly used for prominence observations that is typically around unity in the whole prominence. This leads to the disregarding of any effects of integration of radiation along the line of sight that might play a significant role in the appearance of the observed prominence and filament fine structures. Thus, in the absence of a realistic visualization of the magnetic dips produced by current prominence magnetic field simulations these cannot be truly compared with the high-resolution observations of the prominence fine structures.

3. Fine-structure formation modelling

In this section we give a brief overview of the quiescent prominence formation modelling with focus only on the models that allow for the formation of the individual prominence fine structures. More thorough reviews of prominence formation modelling can be found in review by Mackay *et al.* (2010).

Presently the most developed and successful prominence fine structure formation models are the *thermal non-equilibrium models* of Karpen *et al.* (2006), see also Luna *et al.* (2012). The mechanism of lifting of the chromospheric plasma upwards along the field lines used in these **evaporation-condensation models** is based on the heating near the footpoints of the magnetic flux tubes extended into the corona that leads to an increase of the density in the flux tube. Subsequent cooling of the plasma located inside the flux tube in the corona leads to the condensation and thus to creation of the cool prominence structures. Luna *et al.* (2012) successfully demonstrated the ability of such models to predict observable signatures such as the thermal properties, speed, and mass of moving fine structures and showing that these models are consistent in many ways with the SDO/AIA observations. Thse models are based on the detailed 3D whole-prominence magnetic field structure provided by the double sheared arcade simulations of DeVore, Antiochos & Aulanier (2005). The asymmetrical heating is applied at the footpoints of the selected flux tubes leading to the chromospheric evaporation and thus increase of the plasma density. The thermal non-equilibrium processes govern the evolution of the prominence plasma modeled individually along each selected flux tube in the 1D geometry. They are shaped as elongated threads or compact blobs, depending on the geometry of the individual flux tubes and the location of a condensation along each flux tube. At the dipped flux tubes, inside the magnetic dip, plasma condensations tend to form rather massive cool elongated threads which remain in the dips for long time. On the other hand, condensations that form outside the dipped portions of the flux tubes tend to be compact and rapidly fall to the chromosphere. The dynamical behaviour of these two populations of the cool prominence fine structures is in a good agreement with the prominence observations. The drawback of these present thermal non-equilibrium prominence formation models is their inability to adequately simulate the plasma cooling below temperatures of 30,000 K, where the optically thick radiative transfer effects (radiative losses) start to play a significant role (see also the study of the prominence radiative equilibrium by Heinzel & Anzer 2012).

A novel idea of the plasma transport into the prominences is the **magneto-thermal convection** in which hot mass moves upwards (in essence perpendicularly to the field lines) in the form of fine structure plumes and returns to the photosphere in the form of cool fine structure plasma blobs. Such dynamical behaviour of the prominence fine structures often seen in the Hinode/SOT high-resolution observations (see Berger 2013 in this volume) seems to be caused by the magnetic Rayleigh-Taylor instability modeled by Hillier *et al.* (2012a,b). These authors used a 3D ideal MHD simulation of the isothermal prominence plasma with the pressure balance governed by the Kippenhahn-Schlüter-type equilibrium forming the magnetic dips. Fragmentation of the initially uniform plasma distribution creating numerous prominence fine structures and their dynamical motions are consequences of the Rayleigh-Taylor instability, caused by the introduction of a low-density region into the simulation. However, these simulations might be strongly affected by the stabilizing effect of the field line tying or by the radiative cooling/heating effects, that are not considered in the present simulations.

Low *et al.* (2012) recently suggested a mechanism that might lead to the formation of the vertically aligned sets of the prominence fine structures, due to a chain of successive break-downs of the frozen-in-magnetic-field conditions of the cold prominence plasma located in the dipped field lines. Such an approach relies on a radiative collapse of the 1D prominence plasma sheet into an infinitely narrow layer with near zero temperature due to the radiative losses. However, as was shown by several authors (e.g. Heinzel & Anzer

2012), at sufficiently low temperatures (around 4500 – 8000 K) net radiative losses can be significantly diminished, or even equal to zero when the prominence plasma reaches the radiative equilibrium (radiative losses are balanced by the radiative heating effect of the incident radiation). The radiative equilibrium temperatures are well above those needed for the breaking of the frozen-in-magnetic-field conditions, rendering this mechanism unrealistic in the quiescent prominence conditions.

An unconventional mechanism of support of the prominence fine structures against the gravity (but not their formation) in the predominantly vertical magnetic field (that might exist e.g. in the prominence feet) is the **plasma levitation** due to the weakly damped MHD waves modeled by Pécseli & Engvold (2000).

4. Fine-structure oscillations modelling

Recent models of the prominence oscillations successfully develop the theory of the prominence seismology utilizing the observations of the oscillations of the prominence fine structures for the diagnostics of their physical conditions. These models generally assume simplified geometry of the magnetic field and often 1D models of the prominence plasma including a simplified representation of the magnetic field but without any radiative transfer treatment. Modelling of the prominence oscillations is covered in depth in Ballester (2013) in this volume and was reviewed also by Mackay *et al.* (2010). Here we briefly mention only models explicitly dealing with the prominence fine structures.

Luna & Karpen (2012) (see also Luna 2013 in this volume) constructed a prominence fine structure model for investigation of the **large-amplitude longitudinal oscillations**. It is based on the prominence formation model described in the above section (Luna *et al.* 2012) and utilizes the geometrical shape of selected dipped flux tubes produced by the double sheared arcade magnetic field simulations (DeVore, Antiochos & Aulanier 2005). The 1D model is used to describe the prominence fine structure plasma located in the magnetic dips. These authors selected an ensemble of flux tubes representing the whole prominence volume. The prominence fine structures located in these flux tubes respond to an outside trigger (e.g. a nearby flare) by a collective oscillation along the flux tubes. After several periods the initially coherent oscillations of individual fine structures become increasingly out-of-phase, which is in agreement with observations. The damping of these longitudinal oscillations caused by the force of gravity is dependent on the curvature of the dipped magnetic field. This might allow us to indirectly investigate the internal structure of the prominence magnetic field.

Another type of prominence fine structure oscillations was studied by Arregui *et al.* (2008) who used a simplified model with a straight magnetic flux tube and a 1D cylindrical fine-structure plasma representation for the investigation of the **small-amplitude transverse oscillations** of filament fine structures (see also contribution by Soler 2013 in this volume). These authors identified the resonance absorption due to the inhomogeneities of the fine structure plasma as the most likely source of the damping of these transverse (perpendicular to the magnetic field) oscillations of the plasma structures embedded in the horizontal magnetic field. This might allow us to investigate the internal plasma properties of the prominence fine structures.

Although the results of the prominence fine structure oscillations modelling are promising, the full utilization of the prominence seismology potential requires an inclusion of the realistic magnetic field simulations and realistic models of the prominence fine structure plasma including the radiative transfer calculations. Only recently Heinzel *et al.* (2013) attempted for the first time to model the time-dependent synthetic spectra of the hydrogen Balmer lines arising from the oscillating prominence. However, these authors used the 1D whole prominence slab model and did not consider the fine structures.

5. Fine-structure radiative transfer modelling

The main topic of this review are models of the prominence fine structures employing the radiative transfer computations to obtain the synthetic spectra emerging from the plasma structure that realistically describes the physical conditions of prominences. This topic was recently reviewed in Labrosse *et al.* (2010), here we present the most recent developments and results.

The non-LTE (i.e. departures from local thermodynamic equilibrium) radiative transfer modelling of the prominence fine structures was considered already several decades ago when Morozhenko (1978) developed a multi-thread fine structure model composed of 1D plane-parallel isothermal and isobaric slabs and solved the radiative transfer for a two-level hydrogen atom to obtain the synthetic Hα line spectra. Later, Fontenla & Rovira (1983) used the two-level hydrogen atom to obtain the Lyman-α synthetic spectra from individual 1D plane-parallel isobaric slabs with the temperature structure determined by the energy balance equation considering the conductive heat flux and radiative losses. This was further improved by Fontenla & Rovira (1985) who used the three-level plus continuum hydrogen atom to obtain the synthetic Lyman-α, Lyman-β, and Hα lines and the Lyman continuum. These authors assumed a similar energy balance equation. These early efforts were reviewed by Heinzel (1989) who also studied the mutual radiative interaction between individual 1D prominence fine structures. Later, Gouttebroze, Heinzel & Vial (1993) used a sophisticated 20 level plus continuum hydrogen atom and a large grid of 1D isothermal isobaric slab models. The partial frequency redistribution (Heinzel, Gouttebroze & Vial 1987) was considered for the Lyman-α and Lyman-β lines. Fontenla *et al.* (1996) used the five-level plus continuum hydrogen atom and a collection of 1D isobaric plane-parallel models in the energy balance, including the effects of the ambipolar diffusion. Energy balance of the prominence fine structures was also studied by Anzer & Heinzel (1999) using a 1D slab model in magneto-hydrostatic equilibrium including the empirically prescribed temperature structure of the prominence-corona transition region (PCTR). Labrosse & Gouttebroze (2001) used the 1D isobaric isothermal slab models and a complex 33-level plus continuum helium atom to synthesize the He I and He II spectra. Later, Labrosse *et al.* (2002) used 1D slab models in the magneto-hydrostatic equilibrium (including the PCTR) to calculate the synthetic spectra of hydrogen, helium and calcium.

Although such 1D models still represent a useful and a computationally efficient approach for a number of situations, proper understanding of the prominence fine structures requires the use of a more general 2D or 3D models. The 2D vertically infinite models with the cylindrical cross-section were used by Gouttebroze (2006). The plasma parameters and the radiation field in these models varies with the cylinder radius and with the azimuth which allows for the inclusion of the anisotropic incident radiation. Gouttebroze (2007) used these models to study the temperature relaxation of the prominence fine structure plasma.

The first self-consistent 2D radiative-magneto-hydrostatic model of the prominence fine structures was developed by Heinzel & Anzer (2001). These authors generalized previously 1D prominence model of Anzer & Heinzel (1999) that is based on the work of Heasley & Mihalas (1976). The model of Heinzel & Anzer (2001) represents the quasi-vertical fine structure threads in a 2D vertically infinite geometry with a cross-section parallel to the solar surface. This means that all quantities vary in the x-y plane parallel to the solar surface but are uniform along the vertical z-axis. The prominence plasma is suspended in the magnetic dips which are the product of the local 2D magnetohydrostatic (MHS) equilibrium of the Kippenhan-Schlüter type. These gravity-induced dips are caused by the weight of the prominence mass acting on the initially horizontal magnetic field lines, as opposed to the force-free magnetic dips occurring in the whole-prominence magnetic field simulations (see Sect. 2). Temperature structure is prescribed semi-empirically and accommodates two different forms of the PCTR. In the direction perpendicular to the magnetic field temperature steeply rises from the central cool part within a very narrow layer (typically few tens of km), while along the field lines the temperature gradient is shallow and the PCTR layer is much more extended. The gas pressure variation and the extension of the thread along the x-axis results from the MHS equilibrium. The multi-level non-LTE radiative transfer is solved in this 2D plasma structure assuming a 5-level plus continuum hydrogen atom and the partial frequency redistribution for the Lyman-α and Lyman-β lines. The details of the method used for the radiative transfer computations are given in Heinzel & Anzer (2001), along with an example of the resulting synthetic spectra. These are consistent with the typically observed Lyman spectra obtained by the SOHO/SUMER and also with the Hα line observations. An adaptive MHS grid was introduced into these 2D models by Heinzel & Anzer (2003). Further, Heinzel, Anzer & Gunár (2005) introduced the 12-level plus continuum hydrogen atom and analyzed a set of different models with focus on the dependence of the resulting synthetic Lyman spectra on the choice of the model input parameters and on the orientation of the magnetic field with respect to the line-of-sight. These authors also used the 2D contribution functions to indicate the place of formation of individual spectral lines inside the fine-structure threads. This work was complemented by Gunár, Heinzel & Anzer (2007), who studied the formation of the Lyman continuum. Later, Gunár *et al.* (2007) implemented a multi-thread model where a set of identical 2D threads (without mutual radiative interaction) is stochastically distributed with a given line-of-sight intersecting multiple threads. These authors then compared the resulting synthetic Lyman spectra with the observations. Such direct profile-to-profile analysis showed that the 2D multi-thread fine-structure models produce the synthetic spectra in a very good agreement with the observed spectra. Gunár *et al.* (2008) further improved the 2D multi-thread prominence fine structure models by introduction of randomly distributed line-of-sight velocities of individual threads. This allowed for investigation of the asymmetries of the hydrogen Lyman line profiles observed by the SOHO/SUMER (see also Vial, Ebadi & Ajabshirizadeh (2007)). The observed Lyman line profiles exhibit rather large asymmetries which, if attributed simply to a Doppler shift, would indicate velocities of the order of 100 km s^{-1}. However, the prevailing velocities in the quiescent prominences are only around 10 km s^{-1} or below. In addition, the asymmetries of the neighbouring spectral lines, especially Lyman-α and Lyman-β (observed nearly simultaneously) often show an opposite character at the same place in the prominence. The synthetic Lyman line profiles obtained by the 2D multi-thread model exhibit similar substantial asymmetries as the observed ones, even though the LOS velocities of individual threads are between $\pm$ 10 km s^{-1}. The synthetic Lyman line profiles also exhibit the same opposite character of asymmetries as the observed profiles. The ability of these 2D multi-thread prominence fine structure models to reproduce the observed spectra was further demonstrated by Gunár *et al.* (2010). These authors performed an extensive statistical comparison of a large data-set of observed Lyman lines obtained by the SOHO/SUMER and the synthetic Lyman spectra obtained by 2D modelling. The synthetic spectra resulting from a model with a realistic set of input parameters showed a very good agreement with the observations for most of the studied statistical parameters, including the asymmetries of the line profiles. This was further complemented by Gunár *et al.* (2012), who used the statistical comparison of the synthetic and observed Hα line profiles (obtained by the Meudon/MSDP instrument) to analyze the prominence velocity fields. The aforementioned works use the 2D multi-thread models without the mutual radiative interaction between individual threads. An illustrative study of the effects of the mutual radiative interaction on the synthetic Lyman line profiles was done by Heinzel, Anzer & Gunár (2010) using a simple configuration of three identical fine structure threads.

To study the plasma structure produced by the 2D MHS equilibrium used in the 2D fine-structure thread models, Gunár, Heinzel & Anzer (2011) developed a method for obtaining the synthetic differential emission (DEM) measure curves from 2D multi-thread models. These were compared with the DEM curves derived from the SOHO/SUMER observations of a prominence by Gunár *et al.* (2011) and proved to be in a very good agreement with the observed prominence DEM curves within the temperature range covered by the model (up to 100,000 K).

6. Models combining whole-prominence magnetic field simulations and radiative transfer modelling

Present 3D whole-prominence magnetic field simulations (summarized in Sect. 2) provide realistic large-scale configurations of the prominence magnetic field containing regions of magnetic dips that correspond to the general structure of the observed prominences/filaments. However, details of the localized prominence fine structures cannot be fully determined from such simulations, as these do not assume any representation of the prominence fine structure plasma. Neither can the visualizations of these configurations (by drawing portions of the dipped field lines as color bars) be directly compared with the high-resolution observations such as those obtained by the Hinode/SOT. On the other hand, 2D radiative transfer models of individual prominence fine structures (see Sect. 5) are able to reproduce the observed prominence spectra with a high degree of accuracy, but their localized nature does not allow us to study a large-scale configurations of fine structures. To overcome these limitations we have to, in the future, combine models by integrating the 3D magnetic field simulations with a realistic description of the prominence fine structure plasma and self-consistent treatment of the radiation transfer.

The first step in this direction was taken by Gunár *et al.* (2013a). These authors use the whole-prominence magnetic field configurations produced by the 3D non-linear force-free simulations of Mackay & van Ballegooijen (2009) and extract the resulting force-free magnetic dips. These are then filled with the realistic 2D representation of the prominence fine-structure plasma by a newly developed technique. The 2D non-LTE radiative transfer is self-consistently solved in the resulting plasma structure using the method of Heinzel & Anzer (2001). The synthetic spectrum produced by these force-free dip models is in a qualitative agreement with a range of typical quiescent prominence observations. Moreover, their plasma structure is similar to that of the gravity-induced 2D models of Heinzel & Anzer (2001).

The availability of realistic models of individual prominence fine structures located in the 3D whole-prominence magnetic field configuration will allow us in the future to consistently visualize entire sets of prominence/filament fine structures with any given line of sight, either as a prominence in emission above the solar limb, or as a dark filament seen in absorption against the solar disk. This might help us to understand the hitherto puzzling relation between the quasi-vertical fine structures often seen in quiescent prominences observed on the solar limb and the horizontally aligned dark fibrils representing the fine structures observed in absorption against the solar disk. This topic was recently discussed by Gunár *et al.* (2013b).

7. Concluding remarks

Presently, the research on the quiescent solar prominences approaches a point, where most of the basic blocks of our understanding of these spectacular solar features are sufficiently well developed. In the near future the upcoming space-borne missions and ground-based telescopes will provide even wider range of prominence observations with very high spatial, temporal, spectral, and polarimetric resolution compared to what we have now. These include the IRIS, CLASP, Proba-3, Solar Orbiter, and Solar-C missions, and the large ground-based solar telescopes such as Gregor, ATST, EST, and even the radio-interferometer ALMA. This unprecedented amount of detailed observations of the prominence fine structures will bring further significant challenges for the prominence modelling. Such a situation, however, creates also new opportunities in enabling us to combine the existing approaches of prominence fine structure modelling into more complex models, such as those of Gunár *et al.* (2013a). The combined multi-disciplinary fine structure models will help us to accelerate our understanding of the quiescent prominences and solve some of the still open questions about their true nature.

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References

Antiochos, S. K., Dahlburg, R. B., & Klimchuk, J. A. 1994, *Astrophys. J.* 420, 41
Anzer, U. & Heinzel, P. 1999, *Astronomy & Astrophysics* 349, 974
Anzer, U. & Heinzel, P. 2007, *Astronomy & Astrophysics* 467, 1285
Arregui, I., Terradas, J., Oliver, R., & Ballester, J. L. 2008, *Astrophys. J.* 682, 141
Aulanier, G. & Démoulin, P. 1998, *Astronomy & Astrophysics* 329, 1125
Aulanier, G., Demoulin, P., van Driel-Gesztelyi, L., Mein, P., & Deforest, C. 1998, *Astronomy & Astrophysics* 335, 309
Aulanier, G., Demoulin, P., Mein, N., van Driel-Gesztelyi, L., Mein, P., & Schmieder, B. 1999, *Astronomy & Astrophysics* 342, 867
Aulanier, G., Srivastava, N., & Martin, S. F. 2000, *Astrophys. J.* 543, 447
Aulanier, G., DeVore, C. R., & Antiochos, S. K. 2002, *Astrophys. J.* 567, 97
Aulanier, G. & Démoulin, P. 2003, *Astronomy & Astrophysics* 402, 769
Aulanier, G., DeVore, C. R., & Antiochos, S. K. 2006, *Astrophys. J.* 646, 1349
Ballester, J. L. 2013, *The IAU Symposium 300 Proceedings* (this volume)
Berger, T. 2013, *The IAU Symposium 300 Proceedings* (this volume)
DeVore, C. R. & Antiochos, S. K. 2000, *Astrophys. J.* 539, 954
DeVore, C. R., Antiochos, S. K., & Aulanier, G. 2005, *Astrophys. J.* 629, 1122
Dudík, J., Aulanier, G., Schmieder, B., Bommier, V., & Roudier, T. 2008, *Solar Phys.* 248, 29
Dudík, J., Aulanier, G., Schmieder, B., Zapiór, M., & Heinzel, P. 2012, *Astrophys. J.* 761, 9
Fontenla, J. M. & Rovira, M. 1983, *Solar Phys.* 85, 141
Fontenla, J. M. & Rovira, M. 1985, *Solar Phys.* 96, 53
Fontenla, J. M., Rovira, M., Vial, J.-C., & Gouttebroze, P. 1996, *Astrophys. J.* 466, 496

Gouttebroze, P., Heinzel, P., & Vial, J. C. 1993, *Astronomy & Astrophysics Suppl.* 99, 513
Gouttebroze, P. 2006, *Astronomy & Astrophysics* 448, 367
Gouttebroze, P. 2007, *Astronomy & Astrophysics* 465, 1041
Gunár, S., Heinzel, P., & Anzer, U. 2007, *Astronomy & Astrophysics* 463, 737
Gunár, S., Heinzel, P., Schmieder, B., Schwartz, P., & Anzer, U. 2007, *Astronomy & Astrophysics* 472, 929
Gunár, S., Heinzel, P., Anzer, U., & Schmieder, B. 2008, *Astronomy & Astrophysics* 490, 307
Gunár, S., Schwartz, P., Schmieder, B., Heinzel, P., & Anzer, U. 2010, *Astronomy & Astrophysics* 514, A43
Gunár, S., Heinzel, P., & Anzer, U. 2011, *Astronomy & Astrophysics* 528, A47
Gunár, S., Parenti, S., Anzer, U., Heinzel, P., & Vial, J.-C. 2011, *Astronomy & Astrophysics* 535, A122
Gunár, S., Mein, P., Schmieder, B., Heinzel, P., & Mein, N. 2012, *Astronomy & Astrophysics* 543, 93
Gunár, S., Mackay, D. H., Anzer, U., & Heinzel, P. 2013a, *Astronomy & Astrophysics* 551, A3
Gunár, S., Heinzel, P., Anzer, U., & Mackay, D. H. 2013b, *J. Phys.: Conf. Ser.* 440, 012035
Heasley, J. N. & Mihalas, D. 1976, *Astrophys. J.* 205, 273
Heinzel, P. 1989, *Hvar Observatory Bulletin* 13, 317
Heinzel, P. 2007, in *The Physics of Chromospheric Plasmas*, *ASPC* 368, 27
Heinzel, P. & Anzer, U. 2001, *Astronomy & Astrophysics* 375, 1082
Heinzel, P. & Anzer, U. 2003, in *Stellar Atmosphere Modeling*, *ASPC* 288, 441
Heinzel, P. & Anzer, U. 2012, *Astronomy & Astrophysics* 539, 49
Heinzel, P., Gouttebroze, P., & Vial, J.-C. 1987, *Astronomy & Astrophysics* 183, 351
Heinzel, P., Anzer, U., & Gunár, S. 2005, *Astronomy & Astrophysics* 442, 331
Heinzel, P., Anzer, U., & Gunár, S. 2010, *Mem. S.A.It.* 81, 654
Heinzel, P., Zapior, M., Oliver, R., & Ballester, J. L. 2013, *Astronomy & Astrophysics*, submitted.
Hillier, A., Berger, T., Isobe, H., & Shibata, K 2012, *Astrophys. J.* 746, 120
Hillier, A., Isobe, H., Shibata, K., & Berger, T. 2012, *Astrophys. J.* 756, 110
Karpen, J. T., Antiochos, S. K., & Klimchuk, J. A. 2006, *Astrophys. J.* 637, 531
Labrosse, N. & Gouttebroze, P. 2001, *Astronomy & Astrophysics* 380, 323
Labrosse, N., Gouttebroze, P., Heinzel, P., & Vial, J.-C. 2002, in *Solar Variability: From Core to Outer Frontiers*, *ESA SP* 506, 451
Labrosse, N., Heinzel, P., Vial, J.-C., Kucera, T., Parenti, S., Gunár, S., Schmieder, B., & Kilper, G. 2010, *Space Sciences Reviews*, 151, 243
López Ariste, A., Aulanier, G., Schmieder, B., & Sainz Dalda, A. 2006, *Astronomy & Astrophysics* 456, 725
Low, B. C., Berger, T., Casini, R., & Liu, W. 2012, *Astrophys. J.* 755, 34
Luna, M. & Karpen, J. *Astrophys. J.* 750, 1
Luna, M., Karpen, J. T., & DeVore, C. R. 2012, *Astrophys. J.* 746, 30
Luna, M. 2013, *The IAU Symposium 300 Proceedings* (this volume)
Mackay, D. H., Karpen, J. T., Ballester, J. L., Schmieder, B., & Aulanier, G. 2010, *Space Sciences Reviews*, 151, 333
Mackay, D. H. & van Ballegooijen, A. A. 2009, *Solar Phys.* 260, 321
Morozhenko, N. N. 1978, *Solar Phys.* 58, 47
Patsourakos, S. & Vial, J.-C. 2002, *Solar Phys.* 208, 253
Pécseli, H. & Engvold, O. 2000, *Solar Phys.* 194, 73
Schmieder, B., Chandra, R., Berlicki, A., & Mein, P. 2010, *Astronomy & Astrophysics* 514, A68
Schmieder, B. & Aulanier, G. 2012, *EAS Publications Series* 55, 149
Soler, R. 2013, *The IAU Symposium 300 Proceedings* (this volume)
Tandberg-Hanssen, E. 1995, *The nature of solar prominences*, Kluwer, Dordrecht
van Ballegooijen, A. A. 2004, *Astrophys. J.* 612, 519
van Ballegooijen, A. A. & Cranmer, S. R. 2010, *Astrophys. J.* 711, 164
van Ballegooijen, A. A. 2013, *The IAU Symposium 300 Proceedings* (this volume)
Vial, J.-C., Ebadi, H., & Ajabshirizadeh, A. 2007, *Solar Phys.* 246, 327
Su, Y. & van Ballegooijen, A. 2012, *Astrophys. J.* 757, 168