Combined Magnetohydrodynamic and Radiative Transfer Modelling of Solar Prominences – Final Report Summary

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Solar prominences are among the most important objects found in the solar atmosphere. They are formed by cool dense regions of plasma which lie in near-equilibrium in a much hotter and rarer coronal environment. The existence of solar prominences is mainly due to coronal magnetic fields. These magnetic fields may sometimes become unstable and produce Coronal Mass Ejections - violent eruptions that may directly affect the Earth. These eruptions can compress the Earths Magnetosphere, leading to the damage of satellites or to the induction of electric currents and shorting of long-distance power grids. To answer many open questions on the fundamental nature of prominences we need to fully understand the relationship between the prominence magnetic fields and the emitting prominence plasma. To do this, two distinct areas of research need to be coupled together. The first is Magnetohydrodynamic (MHD) Simulations which describe the evolution and structure of prominence magnetic fields. The second is Radiative Transfer (RT) Modelling used to interpret the spectroscopic observations of the Sun and to understand the coupling between the prominence plasma and its radiation field.

Project objectives

This research project crosses the traditional boundaries of the research fields of MHD simulations and RT modelling and couples them together to achieve its principal aim – **the development of a new 3D modelling technique for Solar Prominences**. To accomplish this we have focused on two complementary goals: i) development of a model of whole prominences with their numerous fine structures that combines together the 3D prominence magnetic field configuration provided by MHD simulations with a realistic distribution of the prominence plasma and suitable radiative transfer methods; ii) application of the newly developed prominence model to more specific cases of real-life prominences, in order to study their magnetic field configuration and plasma properties of their fine-scale structures.

Work carried out and results of the project

We have fulfilled the principal aim of this project and developed a new innovative tool for studying the complex nature of Solar Prominences. By coupling together MHD simulations and RT modelling we have developed a new modelling technique that for the first time allows us to consistently study the complex relationship between the prominence magnetic field, prominence fine structure plasma and the radiation it produces.

To achieve this aim we have modified the 3D Non-Linear Force-free Field (NLFF) simulations of Mackay & van Ballegooijen (2009) and developed a randomization method for selection of individual dipped magnetic field lines from high-resolution MHD simulations. We have then adapted the method of Gunár et al. (2013) for filling the NLFF magnetic dips with realistic prominence plasma. This method produces numerous prominence plasma fine structures to form entire prominences. To effectively model the emerging radiation in such complex 3D plasma structures we have developed an innovative fast approximate radiative transfer method for the H-alpha line. This novel visualization method, allows us for the first time, to consistently study the structure of prominences at the solar limb and filaments on the solar disk using a single model. It also enables the first direct comparison of synthetic images of modelled prominences/filaments with high-resolution observations.
The newly developed 3D Whole-Prominence Fine Structure (WPFS) model and the techniques used in its development are discussed in detail in the paper **Gunár & Mackay (2015a, the Astrophysical**

Journal 803, 64). The radiative transfer method for H-alpha visualization is discussed in detail in the paper **Heinzel, Gunár & Anzer (2015, Astronomy & Astrophysics 519, A16)**.

We have also started to fully exploit the potential of the newly developed 3D WPFS model and broaden our understanding of solar prominences. To this end we have employed 3D MHD simulations with an evolving parasitic polarity and studied the evolution of the modeled prominences. We have produced 3D prominence magnetic field configurations from several prominence evolutionary steps which allow us to study the variations in the prominence magnetic field configuration caused by changes in the underlying photospheric magnetic flux distribution. We have then produced detailed representations of the prominence plasma for each evolution step and obtained a sequence of synthetic H-alpha images of the modeled prominence, both when viewed as a prominence on the solar limb and as a filament against the solar disk. This has allowed us for the first time to consistently study the link between evolving fine structures as viewed in both prominence and filament observations using a single model. We have also studied distributions of the magnetic field strength, its orientation and the distribution of plasma-beta values within modeled prominences. We have analyzed the implications of our findings on prominence magnetic field observations, the origin of prominence mass, and the stability of prominences. Moreover, we have studied the mass of the prominence plasma within the modeled prominences and its evolution due to the changes of the underlying photospheric magnetic field. We have related all our findings to the general conditions of real-life prominences.
The study of the prominence evolution based on the 3D WPFS modelling is discussed in detail in the paper **Gunár & Mackay (2015b, the Astrophysical Journal 812, 93)**. An investigation of the properties of the prominence magnetic field and plasma distributions obtained by 3D WPFS modelling is summarized in the paper **Gunár & Mackay (2016, Astronomy & Astrophysics, submitted)**.

In addition to these primary tasks we have also analyzed multi-instrument spectral and imaging observations of several observed prominences. These investigations were carried out in the framework of our long-standing international collaborations and their results were published in the papers **Gunár et al. (2014, Astronomy & Astrophysics 567, A123)**, **Schwartz, Gunár & Curdt (2015, Astronomy & Astrophysics 577, A92)**, and **Heinzel et al. (2015, the Astrophysical Journal 800, L13)**.

Conclusions

The unique nature of the combined MHD and RT technique for modelling of solar prominences allows us for the first time to study connections between the evolution of the photospheric magnetic flux distributions, prominence magnetic field configurations, prominence fine structure plasma, and its radiative output. The latter quantity is the only observable information about the real-life prominences. Understanding of these links will greatly enrich our knowledge of solar prominences and their influence on their local solar environment and the Earth.

The innovative 3D WPFS modelling and the individual techniques developed within this project can be applied also to different prominence magnetic field simulations and in other areas of solar physics research, thus benefiting the wider solar physics community. We have started to exploit this large potential by initiating several new long-term international collaborations. Within the framework of these collaborations we will apply the newly developed techniques to various studies of prominence fine structure dynamics. This will include the implementation of 3D MHD prominence magnetic field extrapolations from observed photospheric flux distributions, and the modelling of transfer of polarized radiation in prominence fine structures and the analysis of the spectro-polarimetric observations. These new collaborations will assure the dissemination of the results of this project into the wider solar physics community. They will also foster new fruitful connections between the leading scientific institutions from the “new” and “old” members of the European Research Area.