Magnetism of Solar Flares and Prominences

P. Heinzel\textsuperscript{1} and H. S. Hudson\textsuperscript{2}

\textit{Astronomical Institute, Academy of Sciences, Ondřejov, Czech Republic}

\textit{Space Sciences Laboratory, University of California, Berkeley, California, USA}

Abstract. We give an overview of magnetic fields in solar flares and prominences. Magnetic fields related to flares play a crucial role in the process of energy release and transport to the lower atmosphere, and thus magnetometry under the coronal and chromospheric conditions is extremely challenging. Magnetic fields in prominences are supposed to keep the prominence plasma at coronal heights against the gravity. Their measurements have been numerous, but high-resolution mapping is still missing. We discuss various flare and prominence models in connection to current and future high-resolution observations.

1. Introduction

Solar flares and prominences are related through the global magnetic topology, as sketched (in 2D) in Figure 1, a version of the well-known cartoon of the standard reconnection model. Initially a prominence (or filament as seen on the disk) forms in the magnetic arcade as a dense and cool plasma structure kept by the magnetic field against the gravity. At a certain stage of evolution, the whole structure is destabilized and the magnetic arcade erupts. Nowadays we can see this frequently on excellent EUV images from SDO/AIA, i.e. we observe an abrupt lifting of the whole filament into the corona. Later on the field lines start to reconnect and we have the scenario of eruptive flares. The hot and cool flare loops manifest themselves in different spectral lines and continua observed from X-rays up to radio. They are rooted in flare ribbons well visible in the transition-region and chromospheric lines. Moreover, during the initial (impulsive) phase of a flare, the hard X-ray kernels are detected in the chromosphere.

In this paper we discuss some aspects of the magnetism of prominences and flares, namely in connection to future high-resolution (polarimetric) observations with both ATST (Advanced Technology Solar Telescope) and EST (European Solar Telescope) – some examples of science cases for EST have been given in Sobotka et al. (2009). For the eruptive flares that follow the sketch of Figure 1, we argue that the prominence material may provide the detectability of the field needed for understanding both the quiescent and eruptive structures involved.
2. Prominences

2.1. Global structure

Observing quiescent prominences on the limb with low spatial resolution (e.g., in the Hα line), we can approximate them as simple 1D plasma slabs vertically standing above the solar surface. The first physically relevant model of their support against the gravity was that of Kippenhahn & Schlüter (1957), which used the Lorentz force to balance gravity. Later on, various scenarios of the force-free (i.e. low plasma β) magnetic support were considered by different authors – see the reviews by López Ariste & Aulanier (2007) or Heinzel (2007). Recent force-free extrapolations of the photospheric magnetic field lead to rather complex magnetic configurations which, at least partially, resemble the fine-structure of solar quiescent prominences. The most striking feature of polar-crown quiescent prominences is that, on the limb, they exhibit quasi-vertical plasma threads (Figure 2a) while on the disk they are composed of many compact horizontal threads (Figure 2b).

The question of field orientation was raised already by J.-L. Leroy and his collaborators (Leroy 1989; Bommier & Leroy 1998). They assumed the magnetic field in such prominences to be predominantly horizontal, following their early polarimetric measurements. The vertical threads were modeled as a pile-up of magnetic dips (Heinzel & Anzer 2001) and such structures can be also inferred from linear magnetohydrostatic modeling of Dudík et al. (2008) (our Figure 3). Heinzel & Anzer (2006) made an approximate projection of such dips on the solar disk and found that they appeared as elongated fibrils similar to those observed with extremely high spatial resolution. But other authors (e.g., Lin et al. 2008) interpret these filament fibrils as parts of cool loops.
in which the plasma flows horizontally. The questions remain as to how this plasma is kept on tops of such loops against gravity, and why we don’t see flows also at more distant sections of the loop. The so-called ‘counter-flows,’ first reported by Zirker et al. (1998), can be interpreted also as oscillatory motions of the hedgerow magnetic pattern often seen, e.g., on EUV movies from TRACE, or now from SDO/AIA. Dark prominence structures on the limb are due to the absorption of EUV coronal line radiation by hydrogen and helium resonance continua (Heinzel et al. 2008). Currently we are unable to measure the magnetic fields in prominence fine structures with such high resolution and thus the answer to the above questions represents a challenge for future observations with ATST and EST. On the other hand, the global extrapolations lead to a magnetic pattern which is consistent with that of an Hα filament, even including details such as barbs. This was nicely proven in a ‘blind test’ by Aulanier et al. (2000b) who first used the longitudinal magnetogram to perform the linear force-free field ex-
trapolation around a flux rope and then looked at the shape of the Hα filament which was present at that magnetic region. To visualize the filament, the force-free dips were marked by dark bars which represent the dip width (corresponding to one hydrostatic scale height) as in Figure 3.

Another critical question relates to the actual magnetic intensity of the prominence field. Again, the early studies by Leroy and his collaborators led to more-or-less horizontal fields with a typical value of $B \approx 3 – 8$ Gauss for quiescent prominences. This was confirmed by the force-free extrapolations of Aulanier & Démoulin (2003) who found higher values, above 10 or up to a few tens of Gauss, only in active-region prominences. However, recent measurements and their analyses point to much larger fields in some prominences, reaching values of a few tens of Gauss – see the magnetic-field mapping by Casini et al. (2003) (our Figure 4) and the review by López Ariste and Aulanier (2007). The question is how such small flux concentrations reaching 80 Gauss can be confined within a rather uniform field of say 20 Gauss.

2.2. Fine structure and dynamics

Assuming that typical gas pressures in quiescent prominences are (much) lower than 1 dyne cm$^{-2}$ (see Labrosse et al. 2010), the configurations must be predominantly force-free. Thus the shape of a magnetic dip will only be marginally affected by the gravity. On the other hand, gravity-induced fine-structure dips have been extensively modeled as magnetostatic 2D configurations (Heinzel & Anzer 2001; Gunár et al. 2008). In Figure 5 we show a random distribution of such magnetic dips which leads, with optimum adjustment of plasma and magnetic parameters, to a radiation output consistent with UV spectra from SOHO/SUMER. In this context a question arises regarding the meaning of the inversion of Stokes profiles based on a simple 1D slab magnetic model (see e.g. Asensio Ramos et al. 2008). Work is in progress on forward syntheses of Stokes
Figure 5. Multithread model consisting of randomly distributed 2D magnetic dips aligned to the magnetic field \( \mathbf{B} \). The shape of dips follows the magnetostatic equilibrium in this \( x - y \) plane, while vertically the dips form long (infinite in 2D models) threads often visible on high-resolution prominence images like Figure 2a. The gray scale shows temperatures from coolest central parts to PCTR, isocontours indicate the density decreasing towards the boundary of the dip. From Gunár et al. (2008).

profiles using such 2D multithread dip structures. Note that force-free dips with low \( \beta \) (e.g., Mackay et al. 2010) will also form similar structures and thus this technique of spectrum synthesis seems to be generally applicable. A problem closely related to these dips is the structure of the prominence-corona transition region (PCTR). It has been assumed that a PCTR along the field lines (i.e., along the dip) is much shallower than the one across the dip, where the temperature gradient is very steep. This should result from the anisotropy of thermal conduction with respect to the direction of the magnetic field. Therefore the spectral synthesis strongly depends on the orientation of the field direction with respect to the line of sight. Another example of the fine-structure magnetic fields are the so-called ‘tangled fields’ which have been recently suggested by van Ballegooijen & Cranmer (2010).

To achieve a reasonable signal-to-noise ratio in today’s polarimetric measurements, one has to integrate rather large portions of the prominence structures and thus cannot be sure about the fine-structure magnetic fields. Again, this is a challenge for extremely large telescopes which are capable of collecting enough polarization signal even in faint prominences and their fine structures.

So far we have considered only the static models, although some of them use prescribed velocity fields to reproduce the asymmetric shape of spectral line profiles (e.g., Gunár et al. 2008). On the other hand, high-resolution prominence and filament movies show a large variety of fine-structure motions – see, e.g., the well-known movie from which our Figure 2a was extracted, or Berger et al. (2008). While the global prominence structure is relatively well described by magnetostatic configurations, the fine-structure dynamics has been simulated numerically only very recently. Hinode/SOT movies show all kinds of fine-structure motions with predominant dark upflows (plumes) that propagate through quiescent prominences and bright downflows (Berger et al. 2011). Dark plumes originate from large dark bubbles often present at the bottom of a prominence (see our Figure 2a). This appears to be an observational
Figure 6. 3D simulations of the magnetic Rayleigh-Taylor instability in the Kippenhahn-Schlüter model (Hillier et al. 2011). The left panel (a) shows the initial condition, and the right (b) a later stage in the evolution of the Rayleigh-Taylor instability.

Figure 7. Two-ribbon proton flare with overlying cool loops observed in the Ca II H line by Hinode/SOT. Note that the flare occurs above a sunspot.

signature of the Rayleigh-Taylor instability in prominences. 3D MHD simulations have been used to study the response of the Kippenhahn-Schlüter prominence configuration to such instability (Hillier et al. 2011). We show an example of these simulations in Figure 6. The instability takes place at the boundary between dense cool prominence and underlying hotter and rarified medium. Figure 6a shows the initial situation, while Figure 6b demonstrates the later stage of evolution of such instability. However, this is a first rather schematic attempt which suffers from several ad hoc assumptions. Further more realistic radiation-MHD simulations are needed to understand the fine structure and dynamics of the magnetized prominence plasma.
3. Flares

3.1. Global structure

From the cartoon in Figure 1 we see that important processes in eruptive flares take place in association with magnetic reconnection in the corona. In this ill-understood region the magnetic field releases energy, which is then transported to the lower solar atmosphere in association with intense fluxes of non-thermal particles. The reconnection cartoon is aimed at describing also the gradual phase of eruptive flares. However, we have no clear consensus yet on such a cartoon description of the impulsive phase of a flare, or of a ‘confined’ flare. Nevertheless, even for flares without eruptions, we can speculate that a filament-channel configuration may be involved. In such a case the pre-flare magnetic configuration that is decisive might be a twisted flux rope, whether detectable via emission signatures or not. The filament itself may provide the detectability needed for characterizing the field in the cavity.

In either an eruptive or a confined flare, coronal magnetic energy suddenly reappears in other forms, specifically as electrons accelerated to 10-100 keV, but also sometimes with comparable energy in MeV ions. The part of this released energy transported downwards leads to the heating of lower atmospheric layers, from which the plasma evaporates back into hot coronal loops. These gradually cool down, after their impulsive energization, and finally appear as the cool loops typically seen in Hα. Figure 7 shows such late-phase loops forming (in emission) between the ribbons. In reality the whole process is three-dimensional and the magnetic topology of the flaring active region can be very complex (e.g., Deng 2007). The direct measurement of the coronal magnetic field, and in particular its variations during a flare, is a challenging task which ATST or EST should be capable to undertake even when the line-of-sight integration is an important issue. We note also the relevance of microwave imaging spectroscopy (e.g., by FASR, the Frequency-Agile Solar Radiotelescope) for the characterization of coronal fields in active regions (e.g., Lee et al. 1999).

The magnetometry of the photospheric field is more-or-less a routine observation, and the ever-improving spatial resolution discloses more and more complexity. The detection and characterization of photospheric field changes during flares has now become commonplace. Such changes were first detected by Wang (1992); for the most recent work see, e.g., Petrie & Sudol (2010), who found the median value of the change in the longitudinal field to be about 70 G. That such changes must occur, as a matter of energy conservation in the restructuring of the coronal field, was noted by Hudson (2000); furthermore the sense of variation found by Petrie and Sudol matches the expectation (Hudson et al. 2008) that a flare should generally result in an inward tilt of the field, as shown in Figure 8.

The Lorentz force associated with sudden changes of the photospheric field may play a role in powering the seismic waves in the solar interior, originally discovered by Kosovichev & Zharkova (1998). These waves uniquely represent an actual perturbation of the solar interior by a coronal restructuring, but there are other mechanisms than the Lorentz force under current discussion. During a flare, the various radiation signatures that appear correspond to different heights of the energy deposition, as disclosed by simple 1D radiation-hydrodynamic modeling (e.g., Allred et al. 2005; Kašparová et al. 2009). Such models ignore the 3D magnetic structuring of the plasma but may also help to identify the sources of the seismic waves. We anticipate that the new large-aperture
3.2. Diagnostics

Chromospheric magnetic fields in flaring active regions are much more difficult to measure than the photospheric fields, and coronal fields still more difficult (e.g., Lin et al. 2004; Tomczyk et al. 2008). The flare shown in Figure 7 shows why we need to study the chromospheric field: the elongated, nearly linear ribbon structure appears to ignore the configuration of the strong sunspot fields in the nearby photosphere. In addition, the loop arcade between the ribbons does not show the azimuthal variation that one might expect from a round sunspot.

Polarimetric methods for studying the field properties as a function of height are also becoming available. An interesting possibility is to use magnetically-sensitive iron lines normally formed in the photosphere. During flares, the cores of such lines may go to emission, being formed higher in the atmosphere as compared to the pre-flare situation (see Figure 9). This opens the possibility of measuring the magnetic fields around the temperature-minimum region or even in the lower chromosphere and determine a structure of the flux-tube canopies. The vector magnetograms taken in the chromosphere will need much better spatial resolution (Lagg 2007) which represents a challenge for ATST and EST. We note also that the white-light continuum may veil the line emission signatures during the impulsive phase (Martínez Oliveros et al. 2011). Non-thermal particle propagation, as revealed by hard X-ray bremsstrahlung, may also provide a means of probing the flaring field structure (Kontar et al. 2008).

Coronal structures such as flare loops can guide us directly or indirectly to the coronal magnetic field above an active region. The flare loops are rooted in the ribbons, and the different spectroscopic signatures of these objects may help us to understand...
their connection in the chromosphere and transition region. The cool loops (seen, e.g., in the Hα or Ca ii lines) appear in emission or absorption when projected against the disk, and with inferior spatial resolution they may be merged with flare ribbons to which they are attached. This then causes serious problems for spectral diagnostics because the projected loops (with penetrating background radiation) and true ribbons have quite different geometry and also their physics is different. High-resolution observations such as those in Figure 7, or better, can distinguish the magnetic flare loops clearly from the ribbons. This aspect of flare observations was discussed by Berlicki et al. (2008).

Cool loops seen on the limb during flares are spectacular events, and many studies have been devoted to them (e.g., Schmieder et al. 1996). They may appear during both impulsive (initial) and gradual phases of solar flares (e.g., Švestka 1976) and have often been inappropriately called ‘post-flare’ loops. Their magnetic field is nearly potential (Schmieder et al. 1997; Aulanier et al. 2000a) or evolves from sheared to potential (Su et al. 2006; Warren et al. 2011), while the field intensity decreases with height. Measurements can determine the degree of non-potentiality left after the reconnection and thus contribute significantly to our understanding of the basic flare processes. These loops resemble the prominences; at lower densities they may appear dark against the disk in the Hα line, as do filaments (Heinzel & Karlický 1987). Both Hanle and Zeeman techniques can be used in the same manner as with prominences or filaments.

Finally, we want to mention one aspect of the flare polarimetry which is not primarily related to determination of the magnetic field. Electron or proton beams could propagate through the chromosphere and collisionally excite hydrogen or other atoms which then emit linearly-polarized radiation. A net polarization would result from a strongly anisotropic beam. This mechanism is analogous to scattering polarization in prominences or the chromosphere and is termed impact polarization. Note that non-thermal collisional excitation competes with ordinary thermal excitation by ambient plasma electrons and may significantly contribute to the line radiation under consideration (Kašparová et al. 2009). There have been many attempts to measure such a linear polarization during flares, but the results are rather controversial. For example Xu et al. (2005) or Firstova et al. (2008) reported significant polarization signals using large-aperture telescopes, but Bianda et al. (2005) found no significant polarization with the ZIMPOL polarimeter at Locarno Observatory. The reason for such a discrepancy is not completely clear, but could reflect the different instrumental setups and spatial resolutions of the instruments used, or, in case of the absence of polarization, an isotropization of energetic protons by collisions in the chromosphere, or through defocusing of the beam by converging magnetic fields. Note that the theoretical studies have predicted significant degrees of polarization for plausible flare models, but later on Štepán et al. (2007) reconsidered such modeling and found much lower polarization degrees. However, all these studies have neglected the potential effect of the magnetic field on the degree of linear polarization, an aspect related to the flare magnetism. It will be extremely interesting to use large-aperture telescopes with polarimetry capabilities for solving this problem.

4. Conclusions

This paper has considered the behavior of magnetism detected in flares and prominences. Both of these phenomena depend on the structure of the coronal filament cavity, arguably a fundamental building block of solar activity. The eruption of a filament cav-
ity often causes the (usually temporary) disappearance of all or part of the prominence it supported, and also may lead to the flare and CME effects sketched in Figure 1.

Diagnosing these structures presents formidable observational problems, partly because the coronal cavity itself – at low plasma beta – contains insufficient plasma to compete, at most wavelengths, with the solar radiation. The structures may become more visible on the limb, but then they present additional difficulties from projection effects. One promising technique to diagnose the magnetic fields in prominences is the so-called ‘prominence seismology.’ By detecting prominence oscillations, which appear in various modes, one can estimate the strength of the supporting field – see, e.g., the review by J.-L. Ballester in Mackay et al. (2010). Filament cavities outside active regions may persist for several solar rotations (e.g., Tandberg-Hanssen 1995; Hudson et al. 1999), and their structure can be studied both by forward (e.g., Gibson et al. 2010) and inverse (e.g., Vásquez et al. 2009) techniques.

The new telescopes can make dramatic improvements in the observational situation, as a result of higher resolution, better polarization capabilities, and improved cadence. The fine structures of the prominence material become much more visible with the improved resolution, and the higher signal-to-noise ratios will give these observations better diagnostic potential. These advantages will also apply in active regions, where the pre-flare and post-flare states can be studied more quantitatively. We anticipate the description of the highly inhomogeneous structures of the visible filament material in terms of their full Stokes profiles to result from these new observations. In particular, chromospheric magnetography may allow us to escape from the uncertainties involved in propagating photospheric vector magnetic measurements through the photosphere and chromosphere, for which force-free approximations to the field are not really correct (e.g., De Rosa et al. 2009).

Flares themselves are problematic, since these involve major disruptions of the atmosphere on temporal and spatial scales that are not presently known. We do know that these convulsions of the coronal field have lasting consequences for the photospheric field, in the sense that major flares produce clearly detectable stepwise changes in the line-of-sight field (Petrie & Sudol 2010). On the other hand, prominences themselves involve highly dynamical flows, and so they present similar problems for the new telescopes as regards actually following the restructuring as it happens.

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Magnetism of Solar Flares and Prominences


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Heinzel and Hudson

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