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# 3D Structure of the Outer Atmosphere: Combining Models and Observations

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**Abstract.** In this review, I focus on the structure and evolution of the coronal magnetic fields modelled from observations. The development of instruments measuring the photospheric and chromospheric magnetic fields with a high spatial and time resolutions allows us to improve the modeling of the coronal fields based on extrapolation and evolution techniques. In particular, I detail the advance modelling of quiet-Sun areas, active regions and full-disc evolution. I discuss the structure of coronal magnetic features such as filaments, sigmoids and coronal loops as well as their time evolution and instability. The complexity of the coronal field and the origin of open flux are also investigated in these different areas. Finally I discuss the future improvements in terms of instruments and models required to understand better the coronal field.

## 1. Introduction

The structure of the solar corona is organised by its magnetic field. The plasma $\beta$, the ratio of the plasma pressure to the magnetic pressure, is less than 1 from the bottom of the corona to about 2.5 solar radii (Gary 2001). Unfortunately to date, it is not possible to obtain a reliable measurement of the full magnetic vector in the corona, whilst it is routinely observed in the photosphere and chromosphere. Waiting for improved spectropolarimetric observations based on coronal lines, the coronal magnetic field has thus to be derived from physical assumptions relying on photospheric measurements.

The physical assumptions to model the coronal field depend on the areas of the Sun considered. Three different parts are often distinguished: (i) the active regions, (ii) the quiet Sun, and (iii) the full Sun. The active regions on the photosphere are regions of strong magnetic field which can form sunspots. The time evolution of active region is 10-15 min by considering an average Alfvén transit time along a loop of 200 Mm (except during flaring activity). The spatial scale is typically 300-500 Mm. Observations in a broad range of wavelengths show coronal structures such as filaments/prominences, sigmoids, loops. Active regions are the sources of eruptions such as flares and Coronal Mass Ejections (CMEs) due to the large amount of magnetic energy stored. The quiet Sun is the area outside active regions (including coronal holes). The typical spatial and time scales are imposed by the structure of granules (20 Mm and few minutes). The full Sun encompasses both the quiet Sun and active region areas. At the current spatial resolution, the time of evolution is imposed by the evolution of active regions for instantaneous magnetogram and by the differential rotation for synoptic magnetic maps. The models are imposed by the physical conditions of the different regions and constrained by the observations.

In this review, I only focus on the models developed to determine the different structures of the coronal magnetic field from photospheric observations with a special emphasize on nonlinear force-free models.

## 2. Force-Free Models

### 2.1. Magnetic Field Extrapolations

Magnetic field extrapolations consist in computing the coronal magnetic field assuming an equilibrium state and using the distribution of the magnetic field observed in the photosphere or chromosphere as boundary condition. This is a static model of the corona. In the corona, three main forces act on the plasma: the plasma pressure gradients, the gravitational force and the magnetic forces. The equation governing the equilibrium is then:

$$-\vec{\nabla} p + (\vec{\nabla} \wedge \vec{B}) \wedge \vec{B} + \rho \vec{g} = \vec{0}. \tag{1}$$

Several main assumptions are thus defined depending on the time and spatial scales to describe and, most importantly, on the magnetic field measurements available. It is worth noticing at this stage that none of these assumptions can describe the real physical nature of the corona as plasma flows have an important role. Nevertheless the study of magnetic equilibria remains a key to understand better the complexity of the coronal magnetic field and, to date, this is the most reliable method to access the 3D coronal field from observations.

Three main assumptions are currently in use to extrapolate the magnetic field into the corona: potential field for which no electric currents (or curl of magnetic field) are present in the configuration (Schmidt 1964; Semel & Rayrole 1968), the linear force-free field in which the electric currents are parallel to the magnetic field line and the coefficient of proportionnality is the same everywhere in the volume (Nakagawa & Raadu 1972; Chiu & Hilton 1977; Alissandrakis 1981; Semel 1988; Gary 1989), and the nonlinear force-free field in which the coefficient of proportionnality varies from one field line to an other (e.g., Woltjer 1958; Sakurai 1981; Aly 1984). The latter assumption is the most realistic and most advanced technique in use. Nonlinear force-free extrapolation techniques can be classified depending on the boundary conditions they use or their numerical schemes: optimisation (Wheatland et al. 2000; Wiegelmann 2004; Wiegelmann & Neukirch 2006; Wiegelmann et al. 2006, 2008; Tadesse et al. 2009), Grad & Rubin (Grad & Rubin 1958; Sakurai 1981; Aly 1989; Amari et al. 1997, 1999; Wheatland 2004; Amari et al. 2006; Inhester & Wiegelmann 2006; Wheatland 2006, 2007; Wheatland & Régnier 2009), evolutionnary techniques (Mikic & McClymont 1994), magneto-frictional (Yang et al. 1986; van Ballegooijen et al. 2000), vertical integration (Wu et al. 1990; Démoulin et al. 1992; Song et al. 2006), boundary integrals (Yan & Sakurai 2000; Yan & Li 2006; Valori et al. 2005). In recent reviews (Schrijver et al. 2006; Régnier 2007; Wiegelmann 2008), the pros and cons of the different numerical schemes are discussed and compared using semi-analytical models or observations. To determine nonlinear force-free configurations, the boundary conditions are the vertical or radial component of the magnetic field, and either the distribution of $\alpha$ in one polarity or the two transverse components of the magnetic field in both polarities. The first set of boundary conditions corresponds to a mathematically well-posed boundary value problem (Grad & Rubin 1958; Sakurai 1981).

Recently, more sophisticated assumptions have been developed to improve the physical content of the above models: the magnetohydrostatic model which takes into account the plasma pressure gradients and/or the gravitational force (Low 1985; Bogdan & Low 1986; Low 1991; Neukirch 1995; Wiegelmann et al. 2007; Ruan et al. 2008), and non force-free models (Hu & Dasgupta 2006, 2008; Hu et al. 2008; Gary 2009).

The force-free reconstruction is applied to an observed magnetogram at a given time and without a priori on the structure of the coronal field. Several other methods have been developed to construct force-free equilibria adding constraints from observations. In van Ballegooijen (2004), a weakly twisted flux rope is inserted into a potential field configuration and then relaxed to a nonlinear force-free state. The flux rope insertion model is constrained by chromospheric or coronal observations. Unlike the nonlinear force-free reconstructions mentioned above, the flux rope insertion model only requires the vertical or radial component of the magnetic field measured on the photosphere. In addition, a weakly magnetohydrostatic model based on Low (1991) has been developed by Aulanier et al. (1999) imposing an a priori external bipole allowing the existence of twisted flux bundle.

## 2.2. Magnetic Field Evolution

In order to follow the evolution of the solar corona, two approaches can be followed.

First, a time series of equilibria can be constructed from observed magnetograms assuming that the time of evolution of the coronal structures is slow enough compared to the reconnection time and the Alfvén transit time. The method does not consider the history of the region as the magnetograms are treated independently. Nevertheless, part of the history of the region is included in the electric currents for nonlinear force-free models. The technique of succesive force-free equilibria as been applied by Heyvaerts & Priest (1984) for linear force-free fields, by Régnier & Canfield (2006) for nonlinear force-free fields.

Second, the flux transport model is used to describe the long-term evolution of the solar corona during a magnetic cycle (Mackay & van Ballegooijen 2006a,b; Yeates et al. 2007, 2008a,b; Yeates & Mackay 2009). The flux transport model is twofold: (i) evolution of the photospheric magnetic field, (ii) magneto-frictional relaxation to a nonlinear force-free equilibrium. The photospheric boundary conditions (usually synoptic maps) are evolved in time by including in the induction equation the effects of differential rotation, meridional flow and surface diffusion. Those three effects have different characteristic times: 0.25 years for the differential rotation, 2 years for the meridional flow and 34 years for the surface diffusion. Once the photospheric field is determined, the coronal magnetic field is derived from the magneto-frictional relaxation method allowing the magnetic configuration to relax to a nonlinear force-free state. This method takes into account the history of the magnetic field during a cycle and also includes an automatic procedure of emerging magnetic bipoles based on the best match with coincident observations. The flux transport model is used to describe the large scale structure of the corona as a nonlinear force-free field, and thus gives physical insights different from the large-scale potential field commonly in use. As this review focuses on the nonlinear force-free modelling of the solar corona, I will omit the magnetohydrodynamic (MHD) models of coronal fields.

## 3. Structure of the Solar Corona

The above techniques to derive the force-free nature of solar corona have been applied to different magnetic regions: (i) the quiet Sun, (ii) the active regions, and (iii) the full Sun.

### 3.1. Quiet Sun

The quiet Sun is a misnomer. The evolution of the quiet Sun has a characteristic time of the granule evolution of few minutes. Consequently, lots of eruptive events are observed continuously. To model the magnetic field in observed quiet-Sun regions, the model used is the potential field because the magnetic field measurements are mostly provided by the line-of-sight component of the magnetic field. Nevertheless recent development in instrumentation shows the possibility to measure reliably the three components of the magnetic field with a great accuracy.

The quiet-Sun magnetic field, the so-called magnetic carpet, has been modeled as a potential field defining the polarities as point sources. This is the point charge method (Schrijver & Title 2002; Longcope et al. 2003; Close et al. 2003). These models are based on SOHO/MDI line-of-sight magnetograms as boundary conditions. SOHO/MDI has a moderate spatial resolution of 1.98 arcsecond and a time cadence of at most 1 min. Régnier et al. (2008) have computed the potential field of a quiet-Sun region observed by Hinode/SOT/NFI with a spatial resolution of 0.16 arcsecond. This model does consider a continuous distribution of the magnetic field on the photosphere. In addition, as revealed by previous work, the complexity of the quiet-Sun magnetic field lies near the photospheric surface (below 5 Mm), therefore Régnier et al. (2008) have implemented a stretch grid along the vertical axis with a very fine grid near the bottom boundary in order to resolve the nonlinearities of the magnetic field. The authors revealed that the complexity of the magnetic field (defined as the number of null points) is concentrated in the photosphere and the chromosphere (below 3.5 Mm) whilst the corona above a quiet-Sun region is not complex. By measuring the vector magnetic field, Hinode/SOT has successfully measured the magnetic field in coronal holes, and thus shows the almost unipolar nature of coronal hole: the small bipoles being connected at low height in the chromosphere or the bottom of the corona. Consequently, the open magnetic flux responsible for the fast solar wind has a strong latitudinal dependence as the quiet-Sun magnetic field becomes more and more unipolar from the equator to the poles.

The structure of the coronal field in the quiet Sun is complex and dynamic. The magnetic field evolves on the time scale of a granule.

### 3.2. Active Regions

The potential field is a minimum of magnetic energy for a given distribution of the vertical or radial magnetic field component on the photosphere. Therefore there is no free magnetic energy, no shear and/or twisted field lines in a potential field configuration. For these reasons, the nonlinear force-free field is more adequat to describe better the nature of the corona as it contains free magnetic energy and sheared and twisted flux bundles.

Regarding the magnetic energy, it has been found that an active region contains enough free magnetic energy to trigger flares (e.g., Régnier et al. 2002; Bleybel et al. 2002; Régnier & Priest 2007a). By studying the magnetic energy budget before and after a flare, it is difficult to conclude as often the magnetic energy released during the flare is in competition with the continuous injection of energy from the convection zone as well as the redistribution of the energy inside the volume considered (Bleybel et al. 2002; Régnier & Canfield 2006; Thalmann & Wiegelmann 2008; Su et al. 2009b).

The magnetic helicity of the magnetic field is a quantity more difficult to tackle as the knowledge of the vector potential is required inside the coronal volume. It has been shown that the magnetic helicity is not a conserved quantity in a volume above an active region as magnetic helicity is injected from the convection zone and ejected away from the corona.

In terms of the structure of the corona, the nonlinear force-free field based on vector magnetograms has revealed the existence of weakly and highly twisted flux bundles in active regions describing solar features such as:

- Filaments: filaments are magnetic structures containing cool and dense material compared to the coronal environment. In nonlinear force-free models, filaments are often identified as weakly twisted flux bundles with magnetic dips in which the plasma is stored (Aulanier et al. 1999; Yan & Sakurai 2000; Régnier & Amari 2004; Wiegelmann et al. 2005; Dudik et al. 2008; Yeates & Mackay 2009). Nevertheless observations have shown that active region filaments can be highly twisted as they are subject to kink instability;

- Sigmoids: sigmoids are observed in soft X-ray as S or inverse-S shaped structures of hot plasma. These structures have been often identified as weakly or highly twisted flux bundles with no magnetic dips (Régnier & Amari 2004; Canou et al. 2009; Su et al. 2009b; Savcheva & van Ballegooijen 2009). As shown by Régnier & Priest (2007b), highly twisted flux tubes are required to store magnetic energy high in the corona;

- Others: other twisted flux bundles are present in magnetic configurations with a different amount of twist and/or a different handedness (as both signs of currents are observed in a polarity) but which cannot be identified to observed features (Régnier & Amari 2004).

Coronal loops in the core of active regions (observed in soft X-rays) can carry a significant amount of current (Régnier & Amari 2004), whilst large loops on the edge of active regions (observed in EUV at 1-1.5 MK for instance) are close to potential magnetic field lines (DeRosa et al. 2009).

It is important to notice that the structure of the magnetic field strongly depends on the magnetic field model and on the nature of the active region, especially the total magnetic flux and the distribution of polarities on the photosphere (Régnier & Priest 2007b). In particular, Régnier & Priest (2007b) demonstrated that, statistically, the magnetic field lines are higher and longer in a nonlinear force-free configuration than in a potential field one.

### 3.3. Full Sun

The nonlinear force-free description of the whole corona is derived from the flux transport model. Starting from a potential field equilibrium, the photospheric magnetic distributions are evolved to match the observed synoptic maps and the 3D coronal field is thus given by a series of nonlinear force-free equilibria. Note that, compare to previous models, the flux transport model does not reset the coronal field to a potential field at each time step. As mentioned in the previous section, statistically speaking, the field lines in a nonlinear force-free model are longer and higher than in a potential field. The consequence is that the open magnetic flux contributing to the fast solar wind is larger in nonlinear force-free models than from potential models. The amount of open flux from the flux transport model is estimated to be one order of magnitude larger than for the potential field model (Mackay 2010). The potential models are useful for a qualitative description of the high corona but improved models are required to have a better quantitative description of the corona.

As shown by Cook et al. (2009), the complexity of coronal magnetic field is very low: only few null points (in average, 14 null points) are present in the whole 3D corona up to 2.5 solar radii. The time variation of the number of null points follows the magnetic cycle.

## 4. Discussion

The nonlinear force-free modelling of the solar corona has became a very attractive domain of research (Schrijver et al. 2006, 2008; Metcalf et al. 2008; DeRosa et al. 2009). This physical assumption corresponds to an important step in our understanding of the 3D structure of the solar corona. It corresponds currently to the state-of-the-art numerical techniques relying on magnetic observations. Nevertheless the force-free assumption is debatable especially at a time when the new space missions such as the Hinode satellite have significantly improved the spatial and time resolutions, and thus show that plasma flows play an important role in the nature of photospheric and chromospheric plasmas. The next step to improve this type of modelling based on observations is to consider the plasma parameter: the magnetohydrostatic model is a step forward to be implemented for future solar missions. As mentioned already, some tentatives to model the solar corona as a magnetohydrostatic equilibrium have attempted (Wiegelmann et al. 2007).

The nonlinear force-free models are constrained by the photospheric or chromospheric magnetic field. With the large amount of data from Hinode or Solar Dynamics Observatory (SDO), it is suggested that more constraints should be taken into account to retrieved a more realistic description of the coronal field. Attempts have been made in several papers mentioned above (e.g., van Ballegooijen 2004; DeRosa et al. 2009).

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