## The Solar Corona: Why It Is Interesting for Us

Abstract. Strong magnetic fields are of vital importance to the physics of the solar corona. They easily move a rarefied coronal plasma. Physical origin of the main structural element of the corona, the so-called coronal streamers, is discussed. It is shown that the reconnecting current layers inside streamers determine their large-scale structure and evolution, including creation, disruption and recovery. Small-scale (fine) magnetic fields in the photosphere experience random motion. Their reconnection appears to be an important source of energy flux for quiet-corona heating. For active-corona heating, the peculiarities of entropy and magnetoacoustic waves, related to radiative cooling, are significant and should be taken into account in the coronal heating theory.

Perhaps the most amazing aspect of the corona of the Sun is its intricate beauty. Thousands of people move through thousands of km (even from Moscow to Australia) to achieve a place of the best seeing a solar eclipse. They move heaven and earth in order to observe this nice natural phenomenon. Recall that the corona, consisting mainly of ionized plasma, becomes visible to the naked eye during a total eclipse (Fig. 1).

Figure 1: Composite using the White-Light total eclipse image of 11 July 2010 taken in French Polynesia and the simultaneous AIA (SDO) image of the disk put inside. The shape of the corona reveals the structure of the solar magnetic field with open field lines at the poles of the Sun and closed field lines above which the distribution of plasma takes the form of *coronal rays* or *coronal streamers* shaped like medieval helmets. These formations are connected with the large-scale magnetic fields on the surface of the Sun. Courtesy of Jean Mouette and Serge Koutchmy, CNRS France and AIA (SDO) from NASA
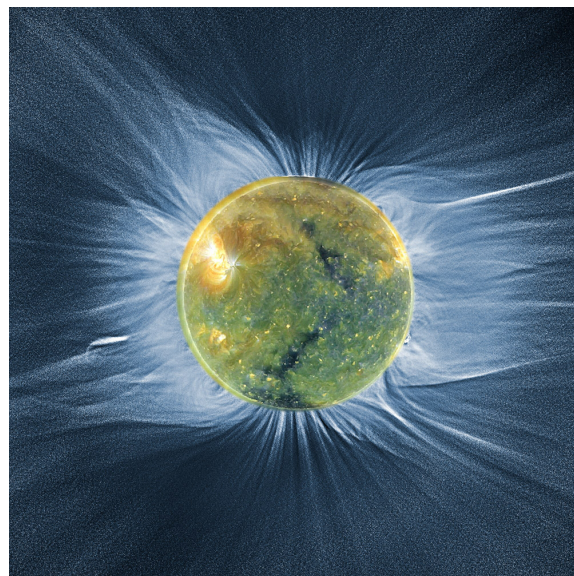
Parker (Parker E.N., ApJ, 1958, **128**, 677) suggested that outer parts of the corona must be expanding in the form of a *solar wind*. The first calculations of the magnetic field in the corona were based on two main premises: the magnetic field over the photosphere is potential up to a certain height, at which the field becomes purely radial owing to drawing-out by the solar wind. The magnetic fields calculated under these simplified assumptions exhibited a reasonable correlation with the optical structure of the chromosphere and corona, as well as with the radio- and soft X-ray pictures of the Sun.

The coronal magnetic field constructed by this method contains neutral points where in the presence of plasma the current layers appear (Syrovatskii S.I., Sov. Astron. - AJ, 1962, **6**, 768). They change geometry of magnetic field. A current layer with quasi-radial fields of opposite direction on either side of it appear inside a coronal streamer similar to the current layer in the magnetosphere tail. In both cases the dipole magnetic field is drawn out by the stream of the solar wind plasma: in the corona it is the dipole magnetic field of an extended active region, and in the magnetosphere it is the Earth magnetic field. The simple 2D problem of stretching out of a dipole field by a plasma flow was formulated assuming that the field is frozen in the flow which is accelerated similar to the solar wind (Somov B.V. and Syrovatskii S.I., Sov. Phys. - JETP, 1972, **34**, 992).

The capture of the magnetic field by the solar wind occurs from the interior of the field itself. The plasma slowly flows along the field lines in the strong-field region, near the dipole. However, as the magnetic field becomes weaker with a height in the corona, the plasma flow becomes stronger and is smoothly transformed into a radial solar wind that carries an external part of the field away. As a result, a quasi-stationary picture of magnetic field can be established for a long-lived active region as illustrated by Fig. 2.

Figure 2: Magnetic field lines corresponding to the first analytical 2D model for coronal streamer: (a) the general solution with a reverse current in the region RC; (b) the particular (stationary) solution without a reverse current.
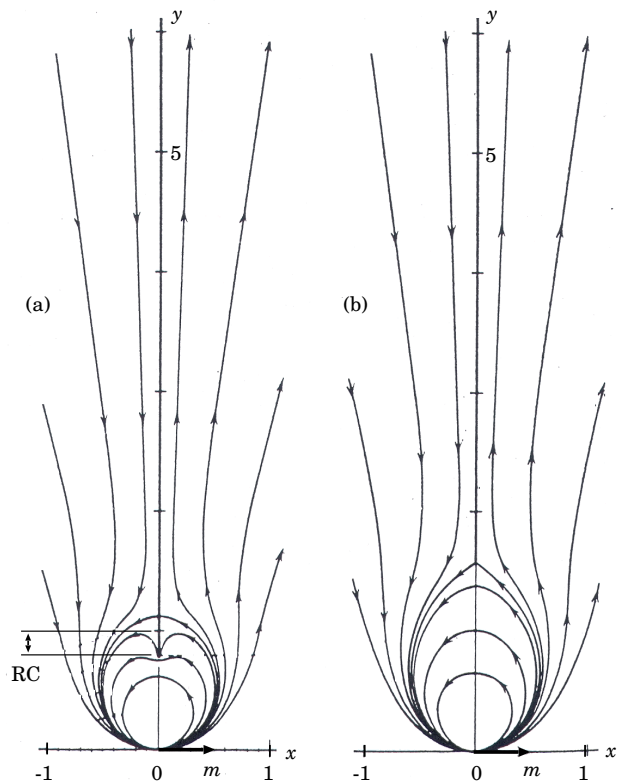
We see that the MHD approximation of a strong magnetic field can be very good in reproducing the large-scale structures in the corona. Moreover, varying with time according to boundary conditions, the magnetic field easily sets the highly conducting coronal plasma in motion. Its kinematics is uniquely defined by two equations. The first of them follows from the momentum conservation law and means that the acceleration is orthogonal to the magnetic field lines. The second equation is a corollary of the freezing-in condition. For example, the set of 2D ideal MHD equations describing the plasma flows can be rewritten as the following set of equations (e.g., Somov B.V., Plasma Astrophysics, Part II, Reconnection and Flares, New York, Springer SBM, 2013, Ch. 2):

$$\Delta A = 0, \quad \frac{d\mathbf{v}}{dt} \times \nabla A = 0, \quad \frac{dA}{dt} = 0, \quad \frac{\partial \rho}{\partial t} + \operatorname{div} \rho \mathbf{v} = 0. \tag{1}$$

Here the scalar function $A(x, y, t)$ is commonly called a vector potential because of definition the vector potential $\mathbf{A} = \{0, 0, A(x, y, t)\}$ for the magnetic field $\mathbf{B} = \operatorname{rot} \mathbf{A}$. A complete

solution of the set of equations (1), including the velocity field and the plasma density distribution, was obtained in a vicinity of a reconnecting current layer at a hyperbolic zeroth point of magnetic field (Somov B.V. and Syrovatskii S.I., in *Neutral Current Sheets in Plasma*, New York and London, Consultants Bureau, 1976, p. 13).

In the corona, more complicated models are required in order to describe the coronal streamer behavior in the periods of high solar activity. A generalization of the model illustrated by Fig. 2 is needed because the current layer inside a streamer can be disrupted into parallel current filaments or ribbons (Wagner S.A. and Somov B.V., in *Cosmicheskie Issledovania*, Sankt-Peterburg, FTI, 1991, p. 79, in Russian).

Fig. 3a demonstrates such a model which assumes that a rupture (a gap between points h_D and h_U) of the reconnecting current layer (RCL, two thick vertical segments) emerges in a region of high electric resistivity, for example, anomalous resistivity due to the excitation of plasma turbulence. Fast magnetic reconnection takes place in the vicinity of the X-type zeroth point h_X of a strong magnetic field. The reconnection process is driven by the uncompensated magnetic forces $\mathbf{F}_{mag}$, acting on the edges of the gap, h_D and h_U, and having a disruptive influence on the RCL. A simple analytical model of a disrupting RCL (Somov B.V. and Syrovatskii S.I., Bull. Acad. Sci. USSR, Phys. Ser., 1975, **39**, No. 2, 109) shows that the magnetic tension forces $\mathbf{F}_{mag}$ are proportional the the size of the gap, $h_U - h_D$, and are tending to increase it.

Figure 3: Magnetic field lines corresponding to the generalized 2D model for a coronal streamer with non-equilibrium RCL. The effective magnetic 'charges' e_n and e_s at the points $x = \pm a$ model the photospheric (or under-photospheric) sources of magnetic field. (a) Disruption of the RCL due to magnetic reconnection at the point h_X. At the point h_Y the magnetic force equals zero, but at the points h_D and h_U it is not equal to zero and is directed downwards and upwards respectively. Therefore, fast reconnection is driven by the magnetic forces $\mathbf{F}_{mag}$, acting on the edges of the gap. (b) The non-stationary process of recovery of the RCL via a secondary reconnecting current layer (h_{Y1}, h_{Y2}). Thick empty arrows show the plasma flows in the vicinity of this new RCL. $\mathbf{V}_{rec}$ is the velocity corresponding to the reconnection rate in the secondary RCL.
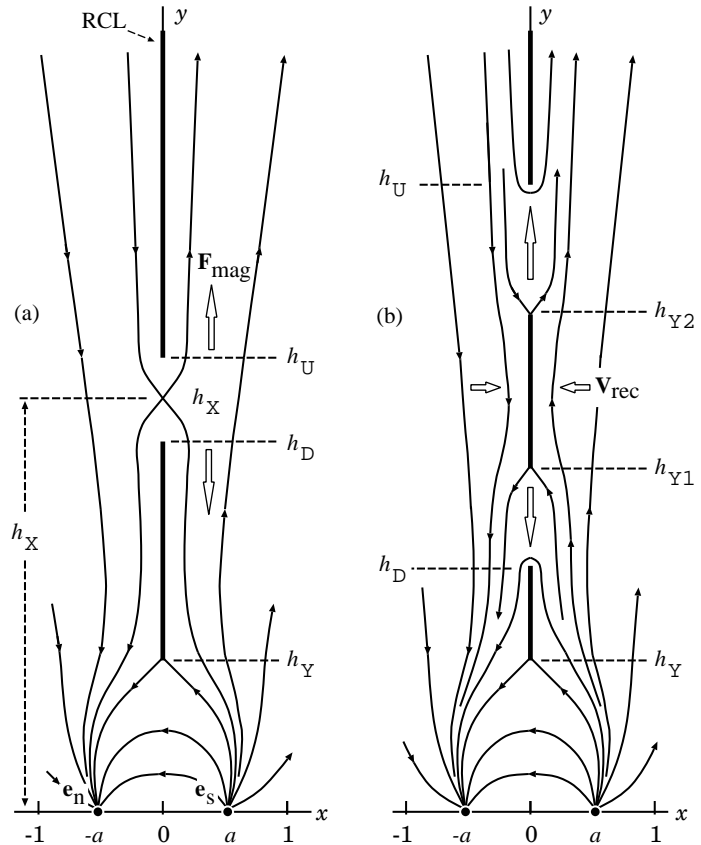
While considering the (x, y) plane as a complex plane $z = x + \mathrm{i}y$, we relate an analytic function F to the vector potential A as follows $F(z, t) = A(x, y, t) + \mathrm{i}\,A^{+}(x, y, t)$. Then

$$\mathbf{B} = B_x + \mathrm{i}\,B_y = -\,\mathrm{i}\,(dF/dz)^{*},$$

where the asterisk denotes the complex conjugation. Define $\mathbf{B}^{*} = B_x - \mathrm{i}\,B_y \equiv B(z)$. The magnetic field of non-equilibrium disruptive streamer shown in Fig. 3a is given by formula

$$B(z) = c_1(a^2 - z^2)^{-1}(z^2 + h_{\mathrm{X}}^2)(z^2 + h_{\mathrm{Y}}^2)^{1/2}(z^2 + h_{\mathrm{D}}^2)^{-1/2}(z^2 + h_{\mathrm{U}}^2)^{-1/2}. \tag{2}$$

The X-type point h_{X} at the center of the reconnection region has a special status. If the plasma density near this point does not drop too much in the reconnection process (see, however, Somov B.V. and Syrovatskii S.I., in *Neutral Current Sheets in Plasma*, New York and London, Consultants Bureau, 1976, Ch. 3, Sect. 2), then a secondary current layer (the thick vertical segment between points h_{Y1} and h_{Y2} in Fig. 3b) will appear. Otherwise, the plasma is not enough to produce the secondary current layer capable of suppressing the current layer disruption. In other words, the primary reconnecting current layer (RCL) can be completely disrupted or, alternatively, recreated in the non-stationary process shown in Fig. 3b. The streamer will make a full recovery from the rupture (Fig. 3a) to its original shape (Fig. 2). The magnetic field of a recovering streamer (Fig. 3b) is

$$B(z) = c_2(a^2 - z^2)^{-1}(z^2 + h_{\mathrm{Y}}^2)^{1/2}(z^2 + h_{\mathrm{Y1}}^2)^{1/2}(z^2 + h_{\mathrm{Y2}}^2)^{1/2}(z^2 + h_{\mathrm{D}}^2)^{-1/2}(z^2 + h_{\mathrm{U}}^2)^{-1/2}. \tag{3}$$

So, the basic idea articulated above is that coronal streamer formation is a twofold magnetic process. First, the magnetic field plays a passive role in shaping streamers by some processes involving the stretching-out the field by the solar wind acceleration and motion. Second, the magnetic field plays an active role in providing dynamic behavior of a streamer by magnetic reconnection. The non-stationary dynamics of a coronal streamer combines two opposite processes: (a) the disruption of a reconnecting current layer inside a streamer and (b) its recreation, which we call recovery.

As a consequence, depending on physical conditions, a streamer can be completely disrupted and disappears or be recovered once or several times after being disrupted. That is why a streamer can exist a very long time even as long as an underlying active region exists. Moreover, its large-scale external structure looks like the same stationary configuration. Non-stationary plasma flows inside a streamer related to magnetic reconnection in a recovering streamer (Fig. 3b) are always present but not always they are well observable. Because of conservation of the global configuration, a coronal streamer may be compared with a river: one cannot come in the same river twice.

The orientation of coronal streamers, the change of shape of the corona with the solar activity cycle, etc., all these observational facts tell us about the existence of coronal magnetic fields. However it is quite difficult to measure them because the coronal emission is exceedingly faint. Until the present, observations are scarce and our knowledge about the coronal magnetic field comes mainly from the theoretical extrapolation of photospheric fields and from comparison of the theoretical model predictions with the observed large-scale structures of the corona.

<p style="text-align:center">*   *   *</p>

Fine structure of solar magnetic fields presumably has properties of complex field configurations containing many places (points or lines) where reconnection occurs. Such a situation frequently appears in astrophysical plasmas, for example in a set of closely packed flux tubes

suggested by Parker (Parker E.N., ApJ, 1972, **174**, 499). The tubes tend to form many reconnecting current layers (RCLs) at their interfaces. This may be the case of active regions when the field-line footpoint motions are slow enough to consider the evolution of the coronal magnetic field as a series of equilibria, but fast enough to explain *coronal heating*.

Magnetic flux tubes in the photosphere are subject to constant buffeting by convective motions, and as a result, flux tubes experience random walk through the photosphere. From time to time, these motions will have the effect that a flux tube will come into contact with another tube of opposite polarity. We refer to this process as reconnection in weakly-ionized plasma (Litvinenko Yu.E. and Somov B.V., Solar Phys., 1994, **151**, 265). Another possibility is the photospheric dynamo effect (Hénoux J.C. and Somov B.V., A&A, 1997, **318**, 947) which, in an initially weak field, generates thin flux tubes of strong magnetic fields. Such tubes extend high into the chromosphere and contribute to the mass and energy balance of the quiet corona.

SOHO's MDI observations have shown that the magnetic field in the quiet network of the photosphere is organized into relatively small 'concentrations' (magnetic elements, small loops etc.) with fluxes in the range of 10^{18} Mx up to a few times 10^{19} Mx, and an intrinsic field strength of the order of a kilogauss. These concentrations are embedded in a superposion of flows, including the granulation and supergranulation. They *fragment* in response to sheared flows, *merge* when they collide with others of the same polarity, or *cancel* against concentrations of opposite polarity. Newly emerging fluxes replace the canceled ones.

Direct evidence that the so-called '*magnetic carpet*' (Day C., Physics Today, 1998, March issue, 19), an ensemble of magnetic concentrations in the photosphere, really can heat the corona comes from the two other *SOHO* instruments: CDS and EIT. Both have recorded local brightenings of hot plasma that coincide with disappearances of the carpet's elements. This indicates that just about all the elements reconnect and cancel, thereby releasing magnetic energy.

The transition region and chromospheric lines observed by *SOHO* together with radio emission of the quiet Sun simultaneously observed by VLA show that the corona above the magnetic network has a higher pressure and is more variable than that above the interior of supergranular cells. Comparison of multiwavelength observations of quiet Sun emission shows good spatial correlations between enhanced radiations originating from the chromosphere to the corona. Furthermore the coronal heating events follow the basic properties of regular solar flares and thus may be well interpreted as *microflares* and *nanoflares*. The differences is mainly quantitative (Krucker S. and Benz A.O., Solar Phys., 2000, **191**, 341).

What do we really need to replenish the entire magnetic carpet quickly, say 1-3 days? – A rapid replenishment, including the entire cancelation of magnetic fluxes, requires the fundamental assumption of a *two-level* reconnection in the solar atmosphere (Somov B.V., Bull. Russ. Acad. Sci., 1999, **63**, 1157). First, we apply the concept of fast reconnection of electric currents as the source of energy for microflares to explain coronal heating in quiet regions (Somov B.V. and Hénoux J.-C., in *Magnetic Fields and Solar Processes*, 9th Eur. Meet. on Solar Phys., ESA SP-448, 1999, 659). Second, in addition to coronal reconnection, we need an efficient mechanism of magnetic field and current dissipation in the photosphere. The presence of a huge amount of neutrals in the weakly ionized plasma in the temperature minimum region makes its properties very different from an ideal MHD medium. Dissipative *collisional* reconnection is very efficient here (Litvinenko and Somov, 1994).

<center>* * *</center>

While the corona is evidently heated everywhere, there is no question that it is heated most intensively within active regions where the magnetic field is the strongest. Detailed models of coronal heating in active regions typically invoke mechanisms belonging to one of the two broadly defined categories: wave (AC) or stress (DC) heating. In the AC heating, the large-scale magnetic field serves essentially as a conductor for small-scale MHD waves propagating into the corona. Thus the properties of these waves are of principal importance.

In the corona, the low-frequency MHD oscillations can be studied comprehensively. They are observed almost at all wavelengths (see Aschwanden M.J., Physics of the Solar Corona, Berlin, Springer,2004). Most of these oscillations are commonly interpreted as standing oscillations of various types in coronal magnetic loops. Meanwhile the oscillations of coronal loops observed from *TRACE* satellite in EUV are, as a rule, damped rapidly. The ratio of the characteristic damping time τ_d to the oscillation period τ_ω is $\tau_d/\tau_\omega = 1.8 \pm 0.8$ in the range of periods $\tau_\omega = 317 \pm 114$ s. Such *rapid damping* of the MHD oscillations seemed difficult to explain.

Why rapidly damped oscillations are seen best in a small group of loops precisely in EUV radiation is a key question. Contrary to popular belief, the answer is simple. Where the rate of energy losses via optically thin plasma radiation has a maximum (i.e. at $T \sim 10^5$ K), the brightness of the oscillating loops also has a maximum (i.e. in EUV) and, as a consequence, the MHD oscillations are damped more rapidly than in other places. This is the case of *slow* magnetoacoustic waves (Somov B.V., Dzhalilov N.S., and Staude J., Astron. Lett., 2007, **33**, 309). The significant advantage of slow magnetoacoustic waves over *fast* ones is that the regions of reduced magnetic field in the former coincide with the regions of enhanced plasma density. Here the rapid radiative losses manifest themselves. Meanwhile, as calculations show, fast magnetoacoustic waves radiate little and, therefore, are damped too slowly.

Another feature of small MHD perturbations in an optically thin, perfectly conducting plasma with a cosmic abundance of elements is an instability of entropy waves. The instability mechanism is simple. In the temperature regions of a rapid decrease in the radiative loss function with temperature, a small decrease in temperature causes a large increase in the rate of radiative energy losses. Conversely a small increase in temperature is accompanied by a decrease in the rate of radiative plasma cooling. As a result, small perturbations grow rapidly. The growth time for the entropy waves in the corona can vary over a wide range: from tenths of a second to tens minutes.

The fact that the instability condition for entropy waves is almost independent of the magnetic field strength and configuration is fundamentally important for the theory of coronal heating. This means that among the various physical processes involved in the coronal heating, the growth of entropy waves can manifest itself everywhere. The peculiarities of entropy and magnetoacoustic waves, related to radiative losses of energy, should be taken into account in general theory of evolutionarity of MHD discontinuities (see Ch. 17 in Somov B.V., Plasma Astrophysics, Part I, Fundamentals and Practice, New York, Springer SBM, 2013).

Sternberg Astron. Inst.
13 Universitetskij prosp.   Boris V. Somov
Moscow, 119234 Russia
somov@sai.msu.ru
Received January 31, 2013