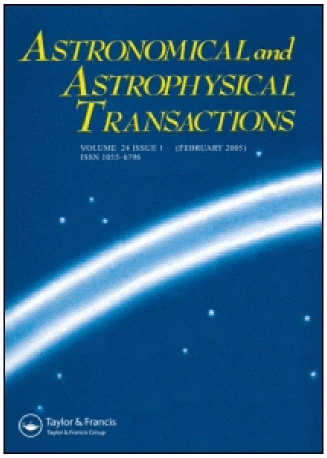

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THE CORONA AND THE SOLAR WIND AS A MANIFESTATION OF THE SOLAR HIGH SPEED MASS EMANATION

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A concept of the solar corona and the solar wind resulting from the interaction between the solar primary high speed mass emanation and over-photospheric magnetic fields is outlined and developed. The model arises from the recent view of the solar corona spatial structure and Ulysses solar wind measurement data. The initial solar fast outflow is found out to be able to provide the energy and mass transfer from the Sun into the corona and the solar wind. Number density and velocity of the primary plasma outflows are estimated on the basis of the solar wind data and the corona energy balance requirement.

KEY WORDS Corona, coronal heating, solar wind, solar mass emanation

1 INTRODUCTION

Over nearly 40 years the solar mass emanation known as the solar wind (SW) has been interpreted as the expanding corona (Chapman, 1957; Parker, 1958). Within such an approach the solar wind can originate only through the acceleration of the hot coronal plasma from a velocity of < 10 km s^{-1} to 750 km s^{-1}. Therefore the problem of SW formation is reduced to the search for coronal plasma acceleration mechanisms. However in spite of a large number of studies up to now this search has failed. The expanding corona theory (ECT) proposed by Parker (1958) meets many difficulties mainly connected with additional energy sources for the fast SW fluxes (Axford and McKenzie, 1992). Chamberlain (1960), followed by Shklovsky (1962), called in to question the ability of the ECT to explain even slow SW outflows. Actually, the expanding corona theory is invalid as it is based on the erroneous solar corona model that treats the corona as a hot homogeneous hydrostatic plasma shell around the Sun. Magnetic fields were neglected.

For the first time the coronal magnetic fields were introduced into consideration was by Shklovsky (1951), six years before Parker's ECT publication. Analysing the coronal observations available Shklovsky (1951) concluded that the spatial structure of the solar corona as well as the coronal plasma temperature inhomogeneity can be explained only by magnetic field effects: without magnetic fields all the coronal plasma inhomogeneities would be smoothed within several minutes by fast thermal motions of the coronal ions. Shklovsky (1951) was the first to calculate the coronal magnetic field strength sufficient to control the coronal plasma spatial distribution: 10^{-5}–10^{-7} G. Ten years later Shklovsky (1962) discussed the problem of the solar corona magnetic fields again. He interpreted the solar magnetic fields as a hard framework for the corona rooted deep in the photospheric layers and rotating rigidly together with the Sun. In 1962 Shklovsky defined the coronal structures as magnetic traps isolating the temperature inhomogeneities of the coronal plasma from each other and confining the coronal plasma near the Sun.

All these ideas ignored by SW theories were completely confirmed during the next two and half decades by different spacecraft and ground-based observations of the corona. According to recent knowledge *the solar corona is a composition of high temperature plasma structures formed by closed magnetic fields of different types and scales.*

The large-scale corona is extremely fragmentary and in the global view strongly flattened toward the solar magnetic equatorial plane (Gulyaev, 1994). All the bright features of the white-light and monochromatic corona are found to be connected with three types of bipolar (closed) magnetic field topologies:

(1) *Coronal streamers* associated with the solar magnetic equator; their extension over the solar limb is $h_{\rm str} \geq 1.5R_{\odot}$, electron density $N_e \simeq 10^9$ cm^{-3} and magnetic field strength $H \simeq 10$ G;

(2) *Active region coronal loops*: $h \simeq 0.5R_{\odot}$, $N_e \simeq 10^{10}$ cm^{-3}, $H \simeq 100$ G;

(3) *Arches of the inner corona* seem to be connected with bipolar (closed) substructures of large-scale magnetic fields: $h \simeq 0.3R_{\odot}$, $N_e \simeq 10^9$ cm^{-3} and $H \simeq 10$ G.

All these features are responsible for the numerous high temperature emission lines of the quiescent Sun within visible and XUV spectral ranges as well as for the white-light corona. New observations have shown the coronal plasma to be highly structured in respect of both temperature and density. It has been found that all the coronal material is concentrated in the finest (down to 1 arc second in diameter) quasi-isothermal arch-like features of different temperature and density situated side by side (Rosner *et al.*, 1978; Nikolskaya, 1986 and 1991; Habbal, 1994; Neupert *et al.*, 1995). The plasma density in small-scale coronal features differs from that in between by one or more orders of magnitude. The temperature of quiet small-scale coronal loops ranges within $10^6 < T_e < 4 \times 10^6$ K. The magnetic pressure within the coronal structures is by a factor of fifty larger than that of the plasma.

So, the closed magnetic fields confine the coronal plasma near the Sun. Therefore, the hot coronal material cannot escape without destruction of the magnetic traps. This means that *the generation of regular plasma outflows from the quiescent corona structure is impossible.* That is why an adequate acceleration mechanism for the solar wind has not been found up to now. For this reason Parker (1992) sets the coronal plasma acceleration processes into unipolar magnetic field regions where coronal holes are situated. But as with the previous model of the SW acceleration (Parker, 1958) this one runs into difficulties connected with the same problems of coronal heating and additional energy sources (Axford and McKenzie, 1992). Besides, let us note that no observational data are available which would verify undoubtedly the solar wind acceleration within the corona.

The coronal heating problem continues to remain a task of principal importance for solar physics. The Sun is the only possible source of plasma and energy for the creation and heating of the coronal structures (Shklovsky, 1962). The problem of coronal heating is reduced to the study of the mass and energy transport mechanisms into the corona. In spite of multiple studies devoted to the coronal heating problem (see Mechanisms of Chromospheric and Coronal Heating, 1991) no sufficient heating mechanism for the corona has yet been found. The question on mass contribution for the corona as well as for the solar wind has been ignored until now.

In this paper we discuss a concept of the formation of the solar corona and the solar wind as a consequence of the interaction of primary solar high speed mass outflow with over-photospheric magnetic fields. Our consideration concerns only the quiescent non-flaring corona.

2 THE CONCEPT OF THE CORONA AND SOLAR WIND: WORDING AND ARGUMENTATION

The concept suggested was born as a result of the analysis of Ulysses data on the solar wind flow distribution within the heliosphere along with the global 3D coronal structure. Unlike spacecraft on geocentric orbits which observed only ecliptic SW, the Ulysses mission (Phillips *et al.*, 1994; Phillips *et al.*, 1995; Smith *et al.*, 1995) involved solar wind measurements in the whole heliosphere. The Ulysses experiment has shown the solar wind to penetrate the heliosphere rather homogeneously from the ecliptic plane up to the poles. According to the Ulysses data, the SW velocity increases from values of 300–400 km s^{-1} near the ecliptic plane to $\sim$ 800 km s^{-1} over the polar zones of the Sun. The solar wind becomes a purely high speed wind ($V > 500$ km s^{-1}) when heliographic latitudes exceed 30° (see Figure 1). High speed outflows predominate within the heliosphere, occupying more than 2/3 of its volume. The slow SW fluxes are recorded in the smaller part of the heliosphere over the coronal regions with bipolar magnetic fields. The SW velocity distribution within the heliosphere looks as though it is the negative image of the global 3D corona and certainly cannot be explained in terms of the EC concept. The next conclusion can be made from Ulysses SW data analysis: *high velocity plasma outflows are primary events and come directly from the solar surface. the solar corona and slow solar wind both arise from these initial mass outflows under the influence of the solar magnetic field.*

All this leads us to an alternative understanding of the Sun–corona–heliosphere relation: *the corona and sw can both be understood as resulting from the interac-*

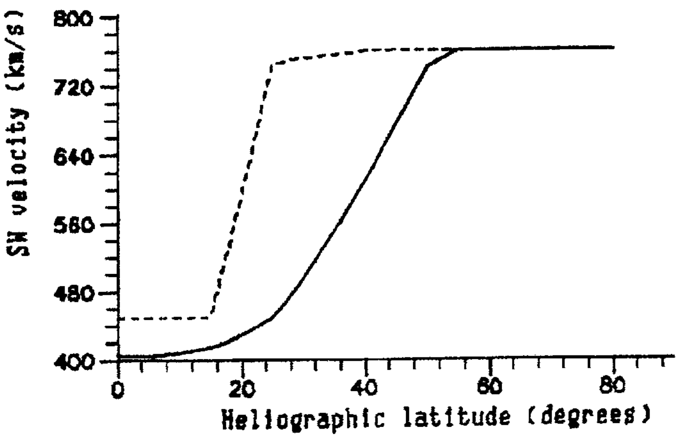

Figure 1 SW velocity versus heliographic latitude in any generalized quasi-meridional section of the outer heliosphere, extracted by the authors from Ulysses measurements (Phillips *et al.*, 1994 and 1995): solid line, SW velocity on Ulysses pass from Jupiter to over the solar south pole; dashed line, the same between two solar poles.

tion of the solar primary high speed mass emanation with the solar magnetic and gravitational fields.

Here is a possible coarse sketch of the formation of the corona and solar wind. Solar high velocity primary streams ejected from the Sun flow away radially through the corona. Being of low density these streams are optically thin and therefore invisible as radiance events. This primary outflow has to contain some plasma component to begin interaction with the magnetic fields. Closed magnetic configurations capture the high speed plasma, stop it quickly and accumulate it up to visible densities. Energy transfer for coronal heating is provided by the same initial solar mass outflows as their kinetic energy which is converted into heat through plasma halting in magnetic traps. So bright coronal features are formed contoured by magnetic trap bounds. Now solar high velocity mass emanation dissipating in the coronal structures provides a regular energy input into the corona. Obviously, all these processes have to be calculated in terms of magnetohydrodynamics.

Within open magnetic fields, primary plasma ejections recede nearly free along the strength lines under the influence of the solar gravitational field. So coronal holes as well as the high speed solar wind arise. Thus high speed SW streams, measured at 1 AU and farther, carry information on the primary outflow properties, which allows us to infer the SW velocity at the base of the corona, $V_{1R\odot}$, using the value $V_{1\mathrm{AU}} = 750$ km s^{-1} and two equations of particle motion in the gravitational field:

$$V_{1R\odot} = V_{1\mathrm{AU}} + g(r)t \quad \text{and} \quad S(t) = V_{1\mathrm{AU}}t + \frac{1}{2}g(r)t^2,$$

where $g(r)$ is the gravitational acceleration and r is the heliocentric distance. The resulting value $V_{1R\odot} \approx 1000$ km s^{-1} can be accepted as a lower bound on the initial SW plasma outflow velocity.

The total number density of the primary outflow at the base of the corona $N_{\rm tot}$ can be expressed as the sum of two components:

$$N_{\rm tot} = N_{\rm pc} + N_{\rm SW},$$

where $N_{\rm pc}$ and $N_{\rm SW}$ denote the number density of the plasma outflow fractions responsible for the formation of the corona and the solar wind, respectively. To evaluate $N_{\rm pc}$ we can use the requirements of the coronal energy budget. According to our concept, energy for coronal heating is transferred from below by the plasma flows as their kinetic energy is converted into heat by abrupt plasma halting the magnetic traps. To maintain the coronal energy balance, the energy input Φ provided by the initial mass outflow has to compensate the total energy losses of the quiescent corona $F : \Phi = F$. The kinetic energy flux carried by high speed plasma fluxes can be expressed in the following way:

$$\Phi = \frac{1}{2} m_p N_{\rm pc} V_{1R\odot}^3.$$

Here m_p is the proton mass, and $N_{\rm pc}$ is the proton number density of the primary plasma outflow fraction responsible for the corona formation. Using $V_{1R\odot} =$ 1000 km s^{-1} and $F = 10^5$–10^6 ergs cm^{-2} s^{-1} for a non-flaring corona (Foukal, 1990) we infer the proton number density needed for corona formation and heating as:

$$N_{\rm pc} \simeq N_e = 1.2 \times 10^5\text{–}1.2 \times 10^6 \ {\rm cm}^{-3}.$$

A value of $N_{\rm SW}$ deduced from the solar wind density and velocity data at $r = 1$ AU, using the expression for the total mass flux conservation

$$N_{\rm SW} V r^2 = \text{constant}$$

is $N_{\rm SW} \approx 2 \times 10^5$ cm^{-3}. This value is close to that at the bottom of the coronal holes obtained from the empirical model of the averaged white-light corona (Allen, 1977): $N_{\rm SW} \approx 5 \times 10^5$ cm^{-3}. The total number density of the primary mass outflow at the base of the corona can be estimated therefore as

$$N_{\rm tot} = 3.0 \times 10^5\text{–}1.4 \times 10^6 \ {\rm cm}^{-3}.$$

The scheme of the corona and solar wind formation considered above can be generalized as the following concept of the corona–solar wind relation which is alternative to the conventional view:
both the solar corona and the solar wind are a result of the interaction between the primary solar high velocity mass emanation with over-photospheric magnetic fields, under the influence of the solar gravitation field.

Let us note that both the velocity and the density of the estimated primary plasma flows appear to be quite realistic. Plasma outflows with a density $\sim 10^6$ cm^{-3} cannot be detectable by the removed optical technique as it takes place in the coronal holes.

3 DISCUSSION

The principal point of the corona and SW concept presented here is the thesis on the initial high velocity mass emanation from the solar surface. This thesis is not an arbitrary postulate but follows from the comparative analysis of the Ulysses SW data and the 3D global corona structure. One can object in at least two points: firstly, high speed mass emanation is unaccountable in terms of the classic stellar atmosphere theory (SAT) and secondly, such a fast plasma outflow is not observed in the corona. As for the former point, SAT is also incapable of explaining the existence of the hot solar corona. The theory of stellar atmospheres has to be improved in accordance with the modern observational data both inside and outside the photospheres. In the meanwhile, we leave the question of the mechanisms of the primary solar high velocity plasma ejections beyond these considerations, as an independent fundamental problem concerning the processes deep under the solar surface. We can say only that these primary fast plasma ejections have to be of non-thermal origin.

In respect of the second point, such a high speed outflow cannot be detected in both the corona and the heliosphere by methods of removed observations of different radiation effects. The question of whether the fast plasma outflows are situated at the coronal bottom can be answered only by in situ plasma measurements within the corona at $r < 10R_{\odot}$. Such an experiment is planed for the *Fire and Ice* mission in the first decade of the next century. The high altitude outflow velocity calculated in terms of our corona-SW concept has to be $V > 750$ km s^{-1} at $r \leq 10R_{\odot}$, whereas the velocity derived on the basis of the ECT (Parker, 1992; Sandbaek and Leer, 1995) must not exceed 500–600 km s^{-1} at the same heliocentric distance. If $V < 650$ km s^{-1} is measured at $r \leq 10R_{\odot}$, our concept is invalid. So far there are certainly no observational arguments against this concept. Moreover, the authors' point of view has been confirmed by the detection of the high speed plasma flows with mean velocity $V \approx 750$ km s^{-1} on heliocentric distances $r \approx 10R_{\odot}$ by the technique of the interplanetary scintillation observations (Grall *et al.*, 1996).

According to the concept presented, the solar corona inevitably arises when two conditions are fulfilled, which are the high velocity plasma flows at the bottom of the corona and the bipolar magnetic fields in the coronal space. As far as such coronal magnetic fields exist *the solar corona can be considered as a manifestation of the high speed mass emanation from the solar surface. Magnetic fields reveal this invisible high velocity optically thin plasma outflow as bright coronal structures.* Some portion of the primary plasma outflow recede through the open magnetic fields or dissipate due to leaks in the magnetic traps forming the fast or the slow solar wind. As shown by Nikolskaya and Valchuk (1997) the initial plasma outflow splits into the slow and fast solar wind within $r \leq 3R_{\odot}$ under gravitation and magnetic field influence.

Here we do not detail the plasma capture mechanism within the magnetic traps. Of course, corona formation processes have to be described in terms of magnetohydrodynamics.

We note here that the idea of high energetic particles ejected from the Sun was suggested by N. A. Yakovkin in the early 1950s in connection with his concept of the cold corona. Beams of high velocity particles were introduced by him to provide the high ionization degree of cold coronal material. Following the development of coronal physics Yakovkin's nonorthodox approach was not confirmed.

4 CONCLUSION

A concept is presented of the formation of the solar corona and the solar wind through the interaction of solar primary high speed mass outflow with over-photospheric magnetic field configurations of different types. Within this concept the corona and the solar wind are exhibited as two different manifestations of the same event, such as the solar high speed mass emanation providing the plasma and energy transfer from the Sun to the corona and the solar wind. The velocity and density of the primary outflow are estimated as

$$V_{1R\odot} \approx 1000 \text{ km s}^{-1} \quad \text{and} \quad N = 3 \times 10^5\text{–}1.4 \times 10^6 \text{ cm}^{-3}.$$

Because of the low density the primary plasma flows are invisible in the coronal space. The closed magnetic fields reveal these flows as coronal structures. Thus the corona can be considered as evidence of the existence of high speed mass emanation from the Sun.

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