Dynamical Creation of Channels for Particle Escape
in the Solar Corona

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ABSTRACT

It is shown that the connection of sufficiently fast flows with dynamical channels for particle escape in the Solar Corona is rather direct: it depends on their ability to deform (in specific cases to distort) the ambient magnetic field lines to temporarily stretch (shrink, destroy) the closed field lines so that the flow can escape the local region. Using a dissipative two-fluid code in which the flows are treated at par with the currents, we have demonstrated channel creation in a variety of closed-field line structures. This self-induced transparency constitutes the active mode for the formation of the solar wind.

Subject headings: Sun: atmosphere — Sun: chromosphere— Sun: corona — Sun: magnetic fields — Sun: prominences — Sun: solar wind
1. Introduction

The knowledge of the structure of the coronal magnetic field (see e.g. Lin, Penn and Tomczyk 2000) serves as the principal guide in the construction of all modern theories on the origin of the Solar Wind (SW), a stream of high speed charged particles that manages to escape the solar atmosphere. There are two possible modes of escape from the magnetic field: 1) the passive mode in which the particles find a region of open field lines and escape without affecting the ambient field, and 2) the active mode in which the particle flows are strong enough to distort/modify the local magnetic field to create their own escape channels. The former would have been a sufficient solution if the wind emergence was limited to the heliographic polar regions, especially at solar minima when the open field line structures are relatively stable lasting several years. The observational story, however, is very different. Habbal and Woo (2001), for example, have shown (by a careful and systematic comparison of the ULLYSES data with coronal measurements at $1.15 R_\odot$) that the fast solar wind detected by ULLYSES seems to arrive (mostly radially) from all latitudes of the so–called quiet Sun. The passive mode scenario, then, would imply regions of open magnetic flux over a large fraction of the solar surface — an implication that runs counter to observations.

From the most detailed coronal images available to date e.g., from TRACE (Schrijver et. al., 1999), the diffuse quiet Sun seems to be studded with a gamut of loop–like structures; no open magnetic field lines can be distinguished in these images. Even in the so called coronal holes (low temperature regions originally believed to have open field lines) there is no direct evidence for open magnetic field lines. For example, (Chertok et. al., 2002) recently reported the disappearance/eruption of a "reasonably large filament located within an extended trans–equatorial CH. The disappearance was accompanied by a number of large–scale dynamic phenomena such as a coronal mass ejection (CME), EUV–emitting
structures inside the CH, a soft X–ray arcade, and other effects. These features seem to mean that CH structures need not be so simple and quiet as previously assumed ... and can contain local areas of closed large–scale magnetic fields, at least at low altitudes”.

The authors also claim that ”consideration of the Yohkoh/SXT and SOHO/EIT data for other periods shows that similar but not so spectacular CH–interior filaments and extended accompanying activity can be found in some other events”. Indication of complicated magnetic topology and fine–scale structuring of corona including CH–s can be found in two–temperature coronal models from SOHO/EIT observations (see e.g. Zhang, White and Kundu (1999)).

Information about the magnetic field is hard to extract at chromospheric heights because of the low sensitivity and lack of high spatial resolution of the measurements coupled with the inhomogeneity and co–existence of small– and large–scale structures with different temperatures in nearby regions (Aschwanden et. al., 2001a). In Zhang, White and Kundu (1999) it was shown that: (i) while the raw EIT images are dominated by the spatial distribution of emission measure in the corona, the temperature maps often emphasize fine structure, which is less visible in the flux images; (ii) the emission measure of the hot component is always found to be at least as large as that of the cool component, meaning that single–temperature models miss most of the coronal plasma to which EIT is sensitive. Also, it was shown that blend of very cool Mg/Si lines with hot Fe xv lines in the EIT 284 Å bandpass induces a false solution for the hot component in CH-s. Thus, such models were found unsatisfactory in CH-s.

Observations seem to suggest, then, that the genesis of the solar wind may lie in the active mode of particle escape. If a given stream of particles were to punch out its own channels of escape in a short–lived, dynamic process, we could certainly explain the emergence of the wind from regions of the solar surface with no observable long–lived
(quasi–static) open–field line structures; the flow enters a closed field line region (preferably with weak fields), quickly distorts it, creates a channel, escapes and leaves the field lines to mend themselves. This kind of phenomenon will happen with statistical uniformity over the entire solar surface and the wind would appear to come from the regions permeated by primarily closed field line structures.

In this paper we report preliminary results demonstrating channel creation by sufficiently strong flows in regions of relatively weaker fields (Habbal, Woo and Arnaud 2001). We are motivated by the mounting evidence that strong flows are found everywhere — in the sub–coronal (chromosphere) as well as in the coronal regions (see e.g. Schrijver et. al., 1999, Winebarger, DeLuca and Golub 2001, Wilhelm 2001, Aschwanden et. al., 2001a, Aschwanden 2001b, Seaton et. al., 2001, Winebarger et. al., 2002, Choudhary, Shrivastava and Gosain 2002 and references therein), and by the growing belief and realization that the plasma flows may complement the abilities of the magnetic field in the creation of the amazing richness observed in the coronal phenomena (Mahajan et. al., 2001). In the latter paper, a short survey of the published data on flow evidence was given. We would repeat here the most representative specimens.

There is an abundance of short-lived (minutes) jets observed at the base of corona (Beckers, 1972, Beckers, 1979, Withbroe et. Al., 1976, Withbroe, 1983, Woo and Habbal, 1999) ; these jets can play a crucial role in the creation of Coronal structures (including CH-s). “When observed with high spatial resolution, the atmosphere at the base of the corona is found to be dynamic with a large fraction of the surface covered by chromospheric and transition region material moving up and down in structures with characteristic sized of $\sim 1000\, km$. Three types of jets (cold, with temperature $\sim 10^4\, K$) are observed: the ubiquitous spicules; macrospicules, large spicules best observed in CH-s and high speed jest with velocities of the order of $400\, km/s$”. It should be mentioned that at present
the knowledge of spicules is rather poor. "The upward mass flux provided by spicules is approximately 100 times that lost in the solar wind outflow. Hence, most of this mass, if heated to coronal temperatures, must cool and fall back into the chromosphere, with only a small fraction being carried out in SW. However, it is not known what fraction of the mass observed in spicules gets heated to coronal temperatures. There is no direct evidence that significant amounts of spicular material are heated to coronal temperatures, and some limited evidence that most of the mass in spicules remains at lower temperatures" (Withbroe, 1983). It is estimated that the energy flux carried by macrospicules is $\sim 2 \cdot 10^7 \text{erg/cm}^2\text{s}$ while the smaller spicules account for fluxes that are an order of magnitude smaller. Assuming that they appear spontaneously in time and space, and knowing from the latest observation that the corona is very diverse and dynamical (with continual appearance/disappearance of bright structures in specific regions, though the corona as a whole shines forever) one could certainly count the up-flows in the macrospicules and large spicules as possible energy and material sources for the coronal structures and the solar wind. At the end we quote from (Schrijver et. al., 1999) on the TRACE observations: "the EUV observations by TRACE reveal not only material at coronal temperatures moving upward from as low as a few thousand kilometers above the photosphere, but also cool material, no hotter than about 20000 K".

Detailed exploration of the mechanisms which generate the observed flows is beyond the scope of this paper. But, guided by phenomenology, we do give here a few examples: based on the estimates of energy fluxes required to heat the chromosphere and Corona, Goodman (2001) has shown that the mechanism that transports mechanical energy from the convection zone to the chromosphere (to sustain its heating rate) could also supply the energy to heat the corona and accelerate the Solar wind. The heating/acceleration problem is, thus, shifted to the problem of dynamic energization of the chromosphere for which the flows are found to be critical as warranted by the observations made by TRACE: the overdensity of
coronal loops, the chromospheric upflows of heated plasma, and the localization of heating function in the lower corona (Aschwanden et. al., 2001a, Aschwanden 2001b, Schrijver et. al., 1999 and references therein). Catastrophic models of flow production in which the magnetic energy is suddenly converted into bulk kinetic energy (and thermal energy) are rather well–known; various forms of magnetic reconnection (flares, micro and nanoflares) schemes permeate the literature (see e.g. Wilhelm 2001; Christopolou, Georgakilas and Koutchmy 2001 for chromosphere up–flow generations). A few other mechanism of this genre also exist: Uchida et. Al. (2001) proposed that the major part of the supply of energy and mass to the active regions of the corona may come from a dynamical leakage of magnetic twists produced in the sub-photospheric convection layer; Ohsaki, Shatashvili, Yoshida and Mahajan (2001,2002) have shown how a slowly evolving closed structure (modeled as a Double Beltrami two fluid equilibrium) may experience, under appropriate conditions, a sudden loss of equilibrium with the initial magnetic energy appearing as the mass flow energy. Another mechanism, based on loop interactions and fragmentations and explaining the formation of loop threads, was given in Sakai and Furusawa (2002). More steady mechanism of chromospheric flow generation was given in Mahajan et. al., 2002. The dynamic 2D modeling of the same mechanism constitute the subject of a future submission.

The magneto–fluid coupling that will be shown to lead to channel–creation has been the subject of intense theoretical study in the last few years. A simple two–fluid model with arbitrary flows has been explored to reveal the breadth of phenomena made possible by the combined actions of the flow–velocity and the magnetic fields. A remarkable evidence of the magnetofluid coupling “in action” is the recent demonstration that the hot coronal structures could be created from the evolution and re–organization of a relatively cold plasma flow (coming from the sub–coronal region) in the presence of the ambient magnetic field anchored inside the solar surface (Mahajan et. al., 1999, Mahajan et. al., 2001). The heating of the structures takes place due to the viscous dissipation of a part of the flow
kinetic energy during the process of particle trapping and accumulation; this happens in regions of relatively strong magnetic fields.

In this paper we wish to demonstrate that this very interaction between the flows and the magnetic fields provides the crucial ingredient in the physics of channel creation. What we need in this case are relatively stronger flows pushing their way through regions of relatively weaker fields. The detailed nature of a channel will depend on the initial, and the boundary conditions. Simultaneously with the creation of escape–channels, plasma heating takes place both in the created channels and in their neighborhood. Viscous dissipation, the primary heating mechanism in the model, preferentially heats ions — a feature essential to reproduce what is observed in the open field–line regions (see e.g. Bravo and Stewart 1997, Tu and Marsch 1997, Tu and Marsch 2001). Although primary heating is an integral part of the model, we will not dwell on it and limit this paper to elucidating the fundamentals of channel–creation. In fact, for simplicity, we will choose equal electron and ion temperatures.

2. Model

The physical model investigated for channel creation is a simplified two–fluid model. The results presented here are obtained from a 2 dimensional (2D) simulation code reported in (Mahajan et. al., 2001). We use quasi–neutrality — electron and proton number densities are nearly equal: 

\[ n_e \simeq n_i = n \quad (\nabla \cdot j = 0) \]

but allow the electron and the proton flow velocities to be different. Neglecting electron inertia, these are \( V_i \) and \( V_e = (V - j/en) \), respectively.

We assign equal temperatures to the electron and the protons so that the kinetic pressure \( p \) is given by: 

\[ p = p_i + p_e \simeq 2 nT, \quad T = T_i \simeq T_e. \]

The analysis can be readily extended later to the more realistic case of different temperatures for different species (see e.g. McKenzie, Sukhorukova and Axword 1998). We are aware of several studies of the solar wind problem.
using multi-fluid, multi-dimensional descriptions (see e.g. Tu and Marsch 1997, Tu and Marsch 2001, Hollweg 1999 and references therein) that even include the self-consistent effects of MHD waves on minority ions. We however, believe, that essential features of the primary flow-based physics of escape channels can be captured with our basic model.

The dimensionless two-fluid equations describing the flow-field interaction processes can be read from Mahajan et. al., 1999:

\[
\begin{align*}
\frac{\partial}{\partial t} \mathbf{V} + (\mathbf{V} \cdot \nabla) \mathbf{V} &= \frac{1}{n} \nabla \times \mathbf{b} \times \mathbf{b} - \beta \frac{1}{n} \nabla (nT) + \nabla \left( \frac{r_A}{r} \right) + \nu_i(n, T) \left( \nabla^2 \mathbf{V} + \frac{1}{3} \nabla (\nabla \cdot \mathbf{V}) \right), \\
\frac{\partial}{\partial t} \mathbf{b} - \nabla \times (\mathbf{V} - \alpha \frac{n}{n} \nabla \times \mathbf{b}) \times \mathbf{b} &= \alpha \beta \nabla \left( \frac{1}{n} \right) \times \nabla (nT), \\
\nabla \cdot \mathbf{b} &= 0, \\
\frac{\partial}{\partial t} n + \nabla \cdot n \mathbf{V} &= 0,
\end{align*}
\]

\[
\begin{align*}
3 \frac{d}{dt} (2T) + \nabla (q_e + q_i) &= -2nT \nabla \cdot \mathbf{V} + 2\beta^{-1} \nu_i(n, T) n \left[ \frac{1}{2} \left( \frac{\partial V_k}{\partial x_l} + \frac{\partial V_l}{\partial x_k} \right)^2 - \frac{2}{3} (\nabla \cdot \mathbf{V})^2 \right] + \frac{5}{2} \alpha (\nabla \times \mathbf{b}) \cdot \nabla T - \frac{\alpha}{n} (\nabla \times \mathbf{b}) \nabla (nT) + E_H - E_R.
\end{align*}
\]

where the notation is standard with the following normalizations: the density \( n \) to \( n_0 \) at some appropriate distance from the solar surface, the magnetic field to the ambient field strength at the same distance, and velocities to the Alfvén velocity \( V_{A0} \). The parameters \( r_{A0} = GM_{\odot}/V_{A0}^2 R_{\odot} \), \( \alpha_0 = \lambda_{i0}/R_{\odot} \), \( \beta_0 = c_{s0}^2/V_{A0}^2 \) are defined with \( n_0, T_0, B_0 \). Here \( c_{s0} \) is a sound speed, \( R_{\odot} \) is the solar radius, \( r_c = GM_{\odot}/2c_{s0}^2 R_{\odot} \), \( \lambda_{i0} = c/\omega_{i0} \) is the collisionless skin depth, \( \nu_i(n, T) \) is ion kinematic viscosity and \( q_e \) and \( q_i \) are electron and ion dimensionless heat flux densities, \( E_H \) is the local mechanical heating function and \( E_R \) is the total radiative loss. We note that the full viscosity tensor relevant to a magnetized plasma is rather cumbersome, and we do not display it here. Just to have a feel for the importance of spatial variation in viscous dissipation, we display its relatively simple symmetric form.

It is to be clearly understood that this version is meant only for theoretical elucidation and
not for detailed simulation. We notice that even for incompressible and currentless flows, heat can be generated from the viscous dissipation of the flow vorticity. For such a simple system, the rate of kinetic energy dissipation turns out to be

\[
\left[ \frac{d}{dt} \left( \frac{m_i V^2}{2} \right) \right]_{\text{visc}} = -m_i n \nu_i \left( \frac{1}{2} (\nabla \times \mathbf{V})^2 + \frac{2}{3} (\nabla \cdot \mathbf{V})^2 \right) .
\]  

(6)

What are the conditions for the dissipation rate to be large enough for effective plasma heating? This and the related question of the requirements on the radial energy fluxes for the flow-based mechanisms to be meaningful (for coronal heating and generation of the solar wind) were examined in Mahajan et. al., 2001. The flow requirements were found to be quite consistent with the latest observational data. It was, however, shown that in the absence of “anomalous viscosity”, the only way to enhance the dissipation rates (to the observed values) through viscosity is to create spatial gradients of the velocity field that are on a scale much shorter than that of the structure length (defined by the smooth part of the magnetic field). Thus, the viability of this two-fluid approach depends wholly on the existence of mechanisms that induce short-scale velocity fields. Theoretical foundations taking into account the fundamental role of Hall term and numerical simulations (without Hall term) showed that the short-scale velocity fields are, indeed, self-consistently generated in the two-fluid system.

3. Deformation of closed field lines

A high-speed flow in or near the transition region (TR) must overcome both gravity and the magnetic field to emerge as the solar wind. Overcoming gravity, by itself, imposes a stiff lower bound on the flow velocity. Negotiating the magnetic field is even harder; preliminary studies show that flows with reasonable TR densities and velocities \( \leq 400 \text{ km/sec} \) can not destroy or deform closed magnetic fields structures sufficiently to meet escaping conditions.
Estimates based on the observed magnetic field strengths show that even in weak field regions ($\sim (1 - 5) G$) flows must be rather strong to punch holes in the structure. If the up-flow creation and acceleration mechanisms were operative somewhere below the hot corona, the flow-magnetic field interaction could lead to conditions more favorable to particle-escape.

We want to remind the reader that there is an implicit assumption in this paper that the short-lived processes like flares, CME in inner corona (explained by catastrophe models) are characteristic for the active Sun and can not give continuous material and energy supply to relatively permanent particle escape process from all over the solar surface during its entire cycle (including quiescent period).

As mentioned earlier the creation of flows is a major subject beyond the scope of this paper. For some of the recent theoretical work on chromospheric-TR acceleration/flow-generation, the reader may consult: (Tu and Marsch 1997, Tu and Marsch 2001, Hollweg 1999, Ofman and Davila, 2001, Granmer, Field and Kohl 1999, Granmer et. al., 1998) for most promising SW acceleration and heating models based on high-frequency Alfvén waves, and (Ohsaki et. al., 2002, ) based on magneto-fluid coupling.

Some of the recent observational findings on the solar wind are also highly revealing. Doschek et,al, 2001, analyzing SUMER measurements (SOHO) on the polar CHs, found that the non-thermal motions sometimes, but not always, increase slightly with height above the limb. Based on the Doppler shift measurements of Warren, Mariska & Wilhelm, 1997 using SUMER coronal hole and quiet Sun Spectra, they speculate that this may be a manifestation of the fast Solar wind. They also report that ”Cooler plasma may be trapped in closed structures and not participate in the flow, or the flow may not begin in open structures until the temperature reaches values near $6 \cdot 10^5 K$”. At the same time IPS observation (EISCAT and VLBA systems of radio wave telescopes) carried out specifically
for measuring the fast SW speed as near to the Sun as possible deduced average speeds
\( \sim 800 \, \text{km/s} \) with very large scattering within heliocentric distances \( 2 - 10 \, r_\odot \) (Ofman et. al., 1997, Grall et. al., 1996)

In the light of the preceding discussion, we shall simply assume that high speed flows are already there below the coronal base where they begin to interact with the closed field regions; they provide the initial conditions in our numerical work. We shall also, justifiably, assume that the processes that generate the primary flows and the primary solar magnetic fields are independent (say at \( t = 0 \)). Simulation of two distinct representative problems will be presented: 1) the flow interacting with a single structure providing the simplest example of field–deformation, and 2) the flow passing through a multiple structure region creating escape–channels under specific conditions.

The numerical code to solve (1-5) was constructed in 2D flat geometry \((x,z)\) using the 2D version of Lax–Wendroff numerical scheme (Richtmyer and Morton 1967) alongwith applying the Flux–Corrected–Transport procedure (Richtmyer and Morton, 1967). Equation (2) was replaced with its equivalent for the \( y-\)component of the vector potential which automatically ensures the divergence-free property of the magnetic field. The equation of heat conduction was treated separately by Alternate Direction Implicit method with iterations (Zalesak, 1979). Transport coefficients for heat conduction and viscosity were taken from Braginski, 1965. We were quite careful in choosing the radiation loss term \( (E_{Br} \) denotes Bremsstrahlung radiation), \( E_R = 2 \cdot E_{Br} = 2 \cdot 1.69 \cdot 10^{-25} \cdot n^2 \cdot T^2 Z^3 \text{erg/cm}^3\text{s} \), with \( Z = 1 \); The choice was based on the results of Rosner, Tucker and Vaiana, 1978, Cox and Tucker, 1969, Potasch, 1965, Tucker and Koren, 1971, McWhirter, Thonemann and Wilson, 1975 (Mahajan et. al., 2001). And since we have a built–in heating mechanism no external heating source \( E_H \) was invoked though we believe that in the escaping channels one can later add secondary events like wave generation for additional acceleration mechanisms. A
numerical mesh of 200 × 150 points was used for computation.

The initial solar magnetic field, following Mahajan et. al., 2001, was modelled as a 2D arcade with circular field lines in the $x$–$z$ plane (see first plot of Fig. 1b for the contours of the vector potential, or the flux function). The field attains its maximum value $B_{\text{max}}(x_0, z = 0)$ at $x_0$ at the center of the arcade, and is a decreasing function of the height $z$ (radial direction).

Note that the 2D Cartesian nature of our code does not allow us to explore large distances from the surface due to interference with the boundaries. Although we present here only the symmetric cases, the simulation of asymmetric situations is straightforward.

3.1. Deformation of single closed field structure

We first study the dynamics of a spatially localized flow (taken to be initially a Gaussian as motivated by observations - e.g. jets, spicules) entering an arcade–like single closed field line structure. Two palpably distinct scenarios emerge:

1) When the flow is strong ($|V_0|_{\text{max}} \sim 600 \text{ km/sec}, \ n_0 \sim 10^8 \text{ cm}^{-3}$) and its peak is located in the central region of the arcade magnetic field structure, the original field ($B_{0\text{max}} = 5 \text{ G}$) shown in (Fig.1a) is seriously deformed (see Fig.1b representing the evolution of the arcade-like magnetic structure deformation process for three time–frames: $t = 0; \ 768, \ 1749 \text{ sec}$), and its central region is transformed to one with more or less parallel field lines. The local channel, however, does not go all the way but may extend to a respectable height. The resulting plasmoid–type configuration, though, may not lead to the particle escape. In all such cases one finds that narrower the flow pulse, the sharper the shear created, and stronger the flow, the faster is the deformation process.

2) When several flow pulses arrive simultaneously towards a single arcade structure,
they may create, in the central region, sheared narrow sub-regions with opposite polarity. The magnetic “well” displayed in Fig.2 (Fig.2b, again, displays the deformation process for three time–frames: \( t = 0; \ 768, 1749 \) sec), for instance, was formed by two identical pulses (see Fig.2a, \( |V_0|_{\text{max}} \sim 600 \text{km/sec}, \ n_0 \sim 10^8 \text{cm}^{-3} \)) located symmetrically on the opposite sides of the arcade-center with \( (B_{0\text{max}} = 5 \text{G}) \).

In carrying out the simulations an important assumption was made, namely, the diffusion time of magnetic field is longer than the duration of the interaction process (it would require the plasma temperature to be at least a few eV–s.)

In both of the above cases, the flows were not able to punch escape–channels although the ambient field was quite thoroughly deformed. This is true even when we put somewhat larger but realistic amount of energy in the flows; the flow cannot overcome the magnetic field in a direct “collision”.

Note that we are not discussing here a possible pathway for the creation of cold prominences; we believe that a 3D dynamical picture is essential for the study of such events. In addition, this paper deals only with relatively strong flows since the weaker flows are expected to be trapped in the structure and will, perhaps, create hot and bright areas near the TR–coronal interface without any serious deformation of field–lines Mahajan et. al., 2001.

### 3.2. Deformation of neighboring closed field structures – Channels for particle escape

We have just seen that the direct attempt by a relatively strong flow to force its way through a moderate–strength single magnetic field structure resulted in complete failure; the field is highly distorted but does not quite yield. We must, therefore, look for other
magnetic field configurations (prevalent in the corona) which might be more cooperative. Recent literature is extremely helpful in this quest. It has been suggested in Habbal, Woo and Arnaud 2001 that the coexistence of strong– and weak–field components observed in the quiet–Sun photospheric field (Lin (1995) and Lin & Rimmale (1999)), and supported by theoretical investigations of the solar dynamo (e.g., Cattaneo 1999), has a counterpart in the corona. Through this study it was shown that the observed predominance of the radial component of the quiet coronal magnetic field is defined, again, by the weak–field component.

Coupling these observations with the models of high–speed up–flow generation in the chromosphere and corona, it seems rather reasonable to study the passage of a strong flow through multi–arcade magnetic field structures. Although it is only the 3D simulations that can reproduce most of the observational features of the channel escape process, we believe that the current 2D code is sufficient to prove or disprove the principal point, that is, whether an escape–channel can be created.

We describe two representative case studies: 1) the flows interacting with two neighboring arcade–structures, and 2) the flows interacting with four neighboring arcades. For optimum effect we locate the maxima of the flow pulses in the weak–field region in between the neighboring arcades. For this study, the arcade structure is taken to be symmetric. It must be stressed that inhomogeneous initial conditions do lead to different evolutions, but channel creation remains a common feature.

The fate of the two–arcade structure when invaded in the middle (weak Field regions \(B_{0\text{max}} = 3 \, G\)) by a fast flow \(|V_{0\text{max}} \sim 900 \, km/sec, n_0 = 2 \cdot 10^7 \, cm^{-3}\) is shown in Fig.3. The flow is able to stretch and drastically deform the structure and, in a reasonably short time \((\sim 50 \, min)\), create a channel for escape (see the last time–frame of Fig.3b). The channel itself is practically cold for distances of a few \(R_\odot\). The neighboring regions
are comparably hotter: at the coronal base (created in this dynamical process), one can distinguish rather hot \( T \sim 10^6 \text{ K} \) areas where a part of the flow was trapped and thermalized (the heating source and process, described in Mahajan et al., 2001 and discussed in the introduction, is due to the effective viscous dissipation of the short scale shocks created in the velocity field). Note, that if the simulation were done in cylindrical \((r, \phi)\) geometry, we could see the widening of the channel with increasing \( r \). We would also add here that if the short scales created in the velocity fields due to Hall term and vorticity effects, and secondary processes like wave generation in the channel were also taken into account one could get hotter channels of escape. We are refining as well as modifying our model to incorporate these processes.

One of the more interesting consequences of the channel–creation dynamics is displayed in (Fig.4) —there is a sharp decrease in density (Fig.4(a)) along the channel (after the usual shock front area due to the interaction of flow with background plasma) with a clearly distinguishable ballistic deceleration of the flow (Fig.4(b)). At heights \( \geq 2 R_\odot \) from the Sun’s surface the flow speed \( \sim 800 \text{ km/sec} \) has only marginally decreased; the fast flow expends a negligible fraction of its energy in creating a channel for its escape; the escaping flow is almost as fast as the entering flow.

The response of a 4-arcade structure to the onslaught of the flow is rather inhomogeneous and complicated; several channels are created in the region of the flow (Fig.5). The central channel seems a bit pressed due to combined interactions (Fig.5(c))—but this could be just an artifact of the Cartesian geometry used here. In the dynamical evolution of this system, there is a ballistic deceleration of the flow in each one of the channels; the deceleration is faster in the central channel (see Fig.5(c)). One can also see that, at longer times, the three structures will be permeated by flows. This picture could be seen as a possible depiction of the complex and very diverse dynamical structure of the
recently observed Coronal Holes.

One word of caution is necessary: for all our runs, we assumed that the flows were, initially, constant in time. We understand that up-flows from the chromosphere or TR have finite life times; the channel creation process, therefore, will last only for the time dictated by the duration and other characteristics of the impinging flow-pulse.

We now list several other omissions of this preliminary study: Anisotropies of velocities and temperature (source of wave generation and instabilities), ionization, multi-species dynamics, flux emergence etc. are not included. Either of these could influence the channel-creation dynamics. We, however, believe that our simple model has adequately shown that sufficiently strong flows are capable of engineering their escape (self-induced transparency) from a variety of closed field line structures prevalent in the solar atmosphere.

4. Conclusions

By suggesting and investigating an active pathway by which strong flows can create temporary channels (with practically radial open field lines) through which they can escape the combination of gravity and ambient magnetic fields, this paper advances a possible resolution of the observational dilemma — that the Solar wind seems to originate (more or less uniformly) from the entire solar surface believed to be studded with closed field line structures. The intense re-arrangement of the magnetic field lines needed for the formation of escape channels is a consequence of the magneto-fluid coupling — the ability of a strong flow to deform and distort the field lines. During this highly dynamical phase, viscous dissipation leads to heating (preferentially of ions) of what would eventually become the solar wind.
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Fig. 1.— Magnetic field deformation caused by the strong flows: (a) Initial distribution of the flow kinetic energy, $|V_0|_{max}(x = 0) = 600 \text{ km/sec}$, $n_0 \sim 10^8 \text{ cm}^{-3}$, (b) The evolution of the arcade–like magnetic structure displayed for 3 distinct time–frames: $t = 0; 768; 1749 \text{ sec}$; the structure had initially $B_{0max}(0, Z = 0) = 5 \text{ G}$. It is shown that the strong shear is created in the central region of the structure resulting in the plasmoid–type configuration; this configuration may not lead to the particle escape. In this and later figures the heights are measured from the Sun’s surface.

Fig. 2.— Magnetic field deformation caused by interactions with the strong flow: (a) Initial distribution of flow kinetic energy, $|V_0|_{max}(x = 0) = 600 \text{ km/sec}$, $n_0 \sim 10^8 \text{ cm}^{-3}$; the structure had initially $B_{0max}(0, Z = 0) = 5 \text{ G}$, (b) The evolution of the arcade–like magnetic structure for 3 distinct time–frames: $t = 0; 768; 1749 \text{ sec}$. It is shown that the strong shear is created in the central region of the structure resulting in the well–type configuration; this configuration too may not lead to the particle escape and even to the cold prominence creation.

Fig. 3.— Dynamical Creation of a particle escape channel in a magnetic structure of 2 identical arcades by a strong flow: (a) For initial and boundary conditions : $B_{0max} = 3 \text{ G}$, flow $|V_0|_{max} = 920 \text{ km/sec}$, $n_0 = 2 \cdot 10^7 \text{ cm}^{-3}$, background plasma density $= 5 \cdot 10^6 \text{ cm}^{-3}$ at the height where the strong flows can be found, (b) Plots for the vector potential $A$; the density $n$, the temperature $T$, and the speed $|V|$ for 3 different time frames $t = 973 \text{ sec}; 1988 \text{ sec}; 3048 \text{ sec}$. The channel for particle escape may be clearly seen. Note: The shock seen at the leading edge is an artifact due to the interaction of the flow with the background plasma (necessary for the smooth working of the simulation code).

Fig. 4.— Evolution of (a) the density $n(x = 0, z)$; (b) the flow radial velocity $V_z(x = 0, z)$; and (c) the temperature $T(x = 0, z)$ in the center of the escape channel of Fig.(3) along the radial distance $z$. A sharp decrease in density and the accompanying ballistic deceleration
of the initial flow is revealed. It is also seen that flow is concentrated practically along the axis of the channel. $z$- projection of the shock explained in Fig.3 maybe be clearly seen.

Fig. 5.— Inhomogeneous and divergent boundary, temporary channel creation in a structure of four identical arcades: (a) Boundary conditions for the 3 pulse initial flow (spatially non-uniform), $|V_0|_{max} = 920 \text{ km/sec}$, $n_0 = 2 \cdot 10^7 \text{ cm}^{-3}$, background density $= 5 \cdot 10^6 \text{ cm}^{-3}$; (b) initial condition for $A$ (initial magnetic field $B_{0max}(x_0, Z = 0) = 4 \text{ G}$); (c) dynamical evolution results at $t = 2335 \text{ sec}$ for the potential $A$, the temperature $T$ and the speed $|V|$. It is seen that deceleration is ballistic and the flow occupies practically the entire region of the 4 initial arcades.
This figure "fig3b.gif" is available in "gif" format from:

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