Comments on ”The Coronal Heating Paradox”
by M.J. Aschwanden, A. Winebarger, D. Tsiklauri and H. Peter
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ABSTRACT

We point out the priority of our paper (Mahajan et al. 2001) over (Aschwanden et al. 2007) in introducing the term ”Formation and primary heating of the solar corona” working out explicit models (theory as well as simulation) for coronal structure formation and heating. On analyzing the (Aschwanden et al. 2007) scenario of coronal heating process (shifted to the chromospheric heating) we stress, that for efficient loop formation, the primary upflows of plasma in chromosphere/transition region should be relatively cold and fast (as opposed to hot). It is during trapping and accumulation in closed field structures, that the flows thermalize (due to the dissipation of the short scale flow energy) leading to a bright and hot coronal structure. The formation and primary heating of a closed coronal structure (loop at the end) are simultaneous and a process like the ”filling of the empty coronal loop by hot upflows” is purely speculative and totally unlikely.

Subject headings: Sun: atmosphere — Sun: chromosphere — Sun: corona — Sun: magnetic fields — Sun: transition region — Sun: coronal heating

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In a recently published paper, "The Coronal Heating Paradox" by M.J. Aschwanden, A. Winebarger, D. Tsiklauri and H. Peter [AWTP (2007)], it was pointed out:

A1) that observations show no evidence for local heating in the solar corona, but rather for heating below the corona in the transition region (TR) and upper chromosphere, with subsequent evaporation as known in flares,

A2) that the phrase "coronal heating problem" is therefore a paradoxical misnomer for what should rather be addressed as the "chromospheric heating problem" and "coronal loop filling process".

A3) that the hot temperature of the solar corona is generated by a primary heating process located in the solar transition region or upper chromosphere.

Before we present a critical analysis of the "proper" use of observational constraints that they invoke to arrive at their conclusions, we would like to draw the authors’ as well as the community’s attention to our paper "Formation and Primary Heating of the Solar Corona - Theory and Simulation", Mahajan et al., 2001, Phys. Plasmas, 8, 1340 (MMNS) published six years ago. A short summary of the substantive aspects of MMNS follows:

M1) MMNS first "invokes the term "primary heating of the solar corona”. In fact, it appears in the very title of the paper.

M2) discusses in great detail possible scenarios of closed coronal structure formation and heating.

M3) MMNS is based on an integrated Magneto–Fluid model that accords full treatment to the Velocity fields associated with the directed plasma motion; model was developed to investigate the dynamics of coronal structures formation.

M4) One of the principal objects of MMNS was to suggest and investigate the notion that the interaction of the fluid and the magnetic aspects of plasma may be a crucial element in creating so much diversity in the solar atmosphere.

M5) It was shown that the structures which comprise the solar corona can be created by plasma flows observed near the Sun’s surface — the primary heating of these structures is caused by the viscous dissipation of the flow kinetic energy. The structure formation and primary heating are simultaneous – when the coronal loop appears it is already hot.

M6) Some detail: we proposed that the high speed (≤ 300 km/sec) streaming of plasma up through the height of the so called base of the corona (observed by TRACE, and to some extent by earlier space observations of the Sun), is the primary source of hot material that makes up the corona. The primary plasma flow becomes heated to 10^6 K or more as it is
slowed down (up at the coronal base height) by passage through a shock front. 300 km/s is adequate to be thermalized to $(1 - 4) \cdot 10^6$ K in a shock transition. We also elaborated the model and suggested that there are at least two major stages in the "heating of the corona" (more accurately of a coronal structure): 1. A fast primary heating period (as observations show and simulations demonstrate) simultaneous with the creation of the hot coronal structure, and 2. An auxiliary or a supporting period needed to make up the losses and sustain the hot structure for a longer time.

M7) More detail: In the MMNS model, the first stage plasma "up-flows" (primary flows) are cold when entering the closed magnetic field regions but they provide the needed energy and material for the formation of the coronal structure. The second stage could be fuelled by a variety of mechanisms like magneto-fluid coupling (Mahajan et al. 1999; Mahajan et al. 2001), wave-dissipation, and reconnections. The TRACE observations, suggesting $\leq 300$ km/sec upward flows of plasma were the inspiration for the basic MMNS idea [see observational data in (Mahajan et al. 2001; Ohsaki et al. 2001; Ohsaki et al. 2002; Mahajan et al. 2002a; Mahajan et al. 2005; Mahajan et al. 2006) and references therein].

We stress that the exact value of the flow-velocity is not crucial; to explain the formation and primary heating era of the life of the hot closed coronal structure, the flow, however, must be supersonic for the chromospheric temperatures at the relevant heights. Very hot flows will not be, in general, supersonic and the shock formation could not dissipate their kinetic energy to heat. In this case we believe that the magneto-fluid mechanism may do the trick (Mahajan et al. 2001). If the flows are subsonic and cold then this very mechanism will be still operative but the end product (coronal loop) will be cooler than 1MK; then the additional heating mechanisms should be imposed to get the bright loop. Essential is, that in all cases plasma is accumulated and one gets an overdense loop with specific temperature different from that of primary flow.

M8) For the MMNS paper and our later work in the field, we have greatly benefitted from various papers (including observational) bearing the names from the AWTP list. We have learnt:

i) that the solar corona is a highly dynamic arena replete with multiple-scale spatiotemporal structures (Aschwanden et al. 2001a; Aschwanden 2001b) indicating a significant role for dynamical processes in coronal heating (Klimchuk 2006; Warren & Winebarger 2007). Observations suggest that there are strongly separated scales both in time and space in the solar atmosphere [see e.g. (Kjeldseth-Moe & Brekke 1998; Schrijver et al. 1999), also Lopez Fuentes & Klimchuk & Mandrini 2007 and references therein]. Loops at different temperatures exist in the same general region and may be co-located to within their measured diameters. The large line shifts, or high velocities ($\pm 50 - 100$ km/s, or even $200 - 300$ km/s),
are most common at transition region temperatures $T \leq 5 \cdot 10^5$ K, and seldom appear at 1 MK. Cool loops in active regions show temporal variability. Characteristic times for the changes may vary. A loop system may be quiescent for a long time with individual loops living for several hours (recall our 2nd era of quasi-equilibrium in the life of the closed coronal structure). Quiescent periods may be followed by rapid activity (loops are "turned on"/disappear in $\leq 10 - 40$ min). Flows are found within loops. The time variable emission over a full range in temperatures in a volume filled with transient loops points to a close connection between regions of various temperature structures, at least in the range from $10^4$ K to $1.5 \cdot 10^6$ K”.

ii) from the MMNs perspective, a major new advance is the discovery that strong flows are found everywhere — in the subcoronal (chromosphere/transition region) as well as in the coronal regions (see e.g. [Kjeldseth-Moe & Brekke 1998; Schrijver et al. 1999; Winebarger & DeLuca & Golub 2001; Wilhelm 2001; Aschwanden et al. 2001a; Aschwanden et al. 2001b; Seaton et al. 2001; Winebarger et al. 2002] and references therein). Equally important is 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 structures (Mahajan et al. 1999; Mahajan et al. 2001; Mahajan et al. 2002b; Mahajan et al. 2003).

iii) It stands to reason, then, that one should investigate the single hot closed coronal structure formation and primary heating process rather than the heating of the entire corona (see the next paragraph). Depending on the boundary and initial conditions taken for chromosphere/TR, one will find different dynamics of the formation and different final parameters of given loop. We cite here our conclusion from (Mahajan et al. 2002a). The coronal heating problem, ..., is shifted to the problem of the dynamic energization of the chromosphere. ... the coronal heating problem may only be solved by including processes (including the flow dynamics) in the chromosphere and the transition region. The challenge, therefore, was to develop a semi–steady state theory of flow generation in the chromosphere that we performed later based on the suggested and explored magneto-fluid coupling (Mahajan et al. 2002a; Mahajan et al. 2003; Mahajan et al. 2005; Mahajan et al. 2006). The correct theoretical model should explain the global dynamics of given solar atmosphere region.

M9) Thus, at any quasi-equilibrium stage of the accelerating plasma flow [the acceleration scenario could be one of many], the nascent intermittent flows will blend and interact with pre–existing closed field structures on varying scales. "New" flows could be trapped by other structures with strong/weak magnetic fields and participate in creating different dynamical scenarios (when dissipation is present) leading to:

1) Heating of a new structure of the finely structured atmosphere [see Mahajan et al. 1999; Mahajan et al. 2001]. 2) Explosive events/prominences/CME eruption [see Ohsaki et al. 2001;
3) Creation of a dynamic escape channel (providing important clues toward the creation of the solar wind [see Mahajan et al. 2002b; Mahajan et al. 2003]). 4) Instabilities, and wave-generation could also be triggered.

In this context we can now stress that our conjecture is rather general, and goes beyond just the heating issue (and even formation issue) for a specific coronal structure:

M10) Formation and primary heating of coronal structures as well as the more violent events (flares, erupting prominences and CMEs) are the expressions of different aspects of the same general global dynamics that operates in a given coronal region.

M11) The plasma flows, the source of both the particles and energy (part of which is converted to heat), interacting with the magnetic field, become determinants of a wide variety of plasma states comprising the observed coronal structures. The dissipation of short–scale component of the velocity field may provide a primary (during very formation) and a secondary (supporting) heating for the coronal structure (closed, open).

M12) We repeat: the formation and heating are contemporaneous – primary flows are trapped, accumulated and a part of their kinetic energy dissipates during their trapping period. It is the initial and boundary conditions that define the characteristics of a given structure (coronal structure $T_c \gg T_{flow} \geq 2eV$).

M13) When studying the formation dynamics of a closed coronal structure, one has to distinguish between, and model 2 distinct eras (Mahajan et al. 2001):  

i) A hectic dynamic period when it acquires particles and energy (accumulation + primary heating). Naturally the description must be time dependent.

ii) Quasistationary period when it ”shines” as a bright, high temperature object.

M14) In equilibrium each coronal structure has a nearly constant $T$, but different structures have different characteristic $T$-s, i.e., bright corona seen as a single entity will have considerable $T$–variation.

M15) The term: ”primary heating” can not be used separately from the term ”formation of the structure” when speaking of the heating of fineley structured dynamical solar atmosphere. Also the correct phrases for chromospheric heating should read as: ”primary heating of the chromospheric part of solar atmosphere loop”; ”creation of coronal base of the same loop” and ”formation of solar atmosphere loop”.

M16) The heating of Coronal holes (dynamical rather than given steady structures) is strictly linked to the bulk acceleration of plasma there, as well as to the dynamical magnetic field openings, and, thus, has to be treated differently. We would just stress that heating
mechanism that we suggest clearly explains the difference in the final temperatures of ions and electrons in CH – the viscous heating of ions is much stronger than electrons.

We are somewhat puzzled and highly disappointed that the authors of (Aschwanden et al. 2007) have chosen to completely ignore our considerable published work in this general field; a field that we have investigated over several years and in which we have even introduced some of the nomenclature and vocabulary they use. We have even communicated with at least two of the authors (sending our papers etc.) and two of our papers were cited by one of them earlier. This time, while using our terminology but for a different scenario, they do not show adequate respect to our rather encompassing and detailed investigations that produced, inter alia, a scenario for the formation and heating of the coronal structures.

We now go back and critique some of the arguments of AWTP (2007):

C1) They claim that "the observed overdensity of heated loops with respect to background corona need to be explained by every mechanism". And that "this fact can not be explained by local heating mechanisms (like wave-heating or magnetic reconnections)."

Here the authors believe that there can not exist cool solar atmosphere loops that are denser than background corona, though observations do show that such loops exist (see cited references above). We have clearly shown (points M6, M7, M11-14) that explanation of overdensity is rather straightforward, in fact, automatic, when one invokes primary upflows but follows a scenario different from AWTP (2007). At the same time heating is neither local nor external – it is due to the proper understanding of the magneto-fluid coupling when the primary flows (point M4) are introduced.

C2) According to AWTP (2007) (section 3.2) "the electron density in coronal loops can be only significantly enhanced by upflows of additional plasma from the loop footpoints, which requires a secondary heating process in the upper chromosphere or lower transition region".

We believe that here the terms primary heating and secondary heating are not being used carefully; both terms seem to refer to the same process of chromospheric heating of additional plasma (upflows). Everywhere before and after this statement, the authors use "primary heating" only for the chromospheric heating of the flows that will later fill the putative empty loops. One could imagine that they need to support the hot chromospheric upflows heating process for later times (to have continuous filling of loops) or for some other reason (e.g. chromospheric evaporation – see C6) below). If so, then, this supporting stage could be called the "secondary heating". Unfortunately there is no indication given in the AWTP (2007) about such supporting stage [we could only guess about such stage when
taking their statement presented in C6) – see excess heating term there). On the contrary, their conclusion given at the end of section 3.4 “this cycle of hot upflows and cool downflows clearly points to the transition region as primary heating source” explicitly says that they consider the chromospheric heating to be primary.

C3) AWTP (2007) implies that the loop footpoints are above the chromosphere/TR. Our calculations show explicitly that the magneto–fluid interaction starts to operate immediately as the flows enter the closed magnetic field region and interact with them. The loop footpoints lie far below the coronal base (due to the fact that the magnetic field emerges from the photosphere); the coronal base (CB) is the place where the temperature corresponding to the hot corona is reached; the CB and the ”loop footpoint” are, generally, quite apart. The loop is a composite atmospheric structure; it has several different parts (see point M15).

C4) AWTP (2007) states the following: ”every primary heating mechanism in the corona is not able to explain the observed overdensity or emission measure excess in hot coronal loops, unless chromospheric evaporation occurs”.

Postulating the chromospheric evaporation alone as responsible for overdensity without the benefit of an implicit theoretical model or a dynamical simulation is highly speculative and lacks content. To support their argument (for chromospheric heating with subsequent coronal filling) they give examples from observations of hot upflows from the chromosphere; this challenges the very idea of a closed coronal structure – this atmospheric structure, surely, has varying scale footpoints much below the hot CB and it is unlikely that there preexists some ”empty” vessel like a ”loop” which is waiting to be filled with hot plasma upflows.

C5) How does this filling take place? The authors do not explain this. They, of course, ignore the magneto–fluid coupling. We showed earlier (see discussion above and MMNS) that the given upflows are already thermalized (and hence slowed down) and accumulated at the so called ”coronal base” that is dynamically created and not given initially (!!) – when one observes the hot/bright coronal structure the job by chromospheric cold and relatively fast upflows is already done (reminding the reader that cooler overdense loops have the right to exist as well).

C6) The essence of the AWTP (2007) scenario is: ”the heat generated in the lower chromosphere is absorbed by strong radiative loss, some excess heating occurs in the upper chromosphere and lower transition region, which drives chromospheric evaporation and gives rise to filled coronal loops”.

This is an attempt by AWTP (2007) to provide a mechanism for the hot chromospheric evaporation. In this process they seem to forget about the upflows or, perhaps, for them the evaporation constitutes the upflow! Without paying due attention to the interaction of
the flows and the magnetic field, they seem to miss that when upflows (whatever their initial temperature) enter the closed magnetic field region, heating will always take place due to the dissipation of short-scale flow energy. The heating due to flow energy dissipation may, in addition, be augmented by secondary heating. The term ”secondary heating” in this case has a very different connotation – it bears no relation to the AWTP (2007) excess heating prior to filling (loop formation). In our model, the ”secondary heating” may occur to simply sustain (against, say, radiation losses) the hot bright loop. The emerging scenario, then, is not the filling of some hypothetical virtual loop with hot gas. The loop, in fact, is created by the interaction of the flow and the ambient filed; its formation and heating are simultaneous and the ”loop” has no ontological priority to the flow. [see (Mahajan et al. 2001) simulation results where the radiative losses are taken into account].

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