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The effect of a current free double layer below the photosphere on the acceleration of the solar wind

Running head: A sub-photospheric CFDL and the acceleration of the solar wind

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Abstract

Neither the collisional hydrodynamic nor the collisionless kinetic models have yet been able to fully explain the acceleration of the fast solar wind without *ad hoc* assumptions of additional energy input or suprathermal electron populations at the base of the models in the lower corona. Separate research has shown that plasma naturally forms a Current Free Double Layer when expanding into a lower-density region, the effect of which is to generate a suprathermal electron population and beams of fast ions on the low potential side. It is suggested that the expansion of the dense plasma in the body of the Sun will form a stationary Current Free Double Layer below the photosphere and thus provide initial ion acceleration together with the type of electron velocity distribution function that kinetic models require as boundary conditions. The turbulence generated by the outflowing particle beams colliding with the low-density plasma in and above the upper chromosphere may contribute to the additional wave energy which the hydrodynamic models require. The implications of the present model for the coronal heating problem are also explored.

Introduction

The purpose of this paper is to suggest firstly that the behaviour of a plasma Double Layer (DL) may offer an answer to the question of the origin of the additional energy and suprathermal electron population which are required respectively by hydrodynamic and kinetic models of the acceleration of the fast solar wind; and secondly that the mechanism whereby a DL forms in an expanding plasma makes it likely that a DL will form as the Sun's dense internal plasma expands into the lower density corona. This paper is therefore structured in three main parts. The first section will outline the present models of the solar wind; the second will outline the research into plasma Double Layers, concentrating on those features of relevance to the solar wind models; and the third will explore the implications of the postulate that a Current Free Double Layer exists immediately below the Sun's photosphere. Section IV contains a summary and conclusions.

I. Acceleration of the Solar Wind

Introduction to section I

The phenomenon of the solar wind remains an enigma. "*After four decades of extensive observations, the origin and acceleration of the solar wind are still not fully understood*." (Issautier 2006 p26). More recently, Tokumaru (2013) confirmed *"there is no established theory which fully accounts for the formation of the solar wind."* (ibid. p67). Reviews by Lemaire (2010), Echim *et al* (2011) and Cranmer (2012) confirm that it has so far proved impossible to model the acceleration of the fast solar wind without incorporating *ad hoc* assumptions or postulating additional sources of energy. The present state of research will be summarised briefly below.

Modelling the acceleration of the solar wind

Existing models of the acceleration of the solar wind fall into two main classes at opposite ends of the possible range of the Knudsen number (K_n) defining the relative importance of collisions and the density scale height (Maksimovitch *et al* 1997). The collisional hydrodynamic models with $K_n << 1$ originated with the work of Parker (1958) whilst the collisionless or exospheric type of kinetic models with $K_n \rightarrow \infty$ arose from that of Chamberlain (1960, 1961). However, *"Because of the semicollisional nature of the solar wind, the collisionless or exospheric approach and the hydrodynamic one are both inaccurate."* (Zouganelis *et al* 2004 p542). Nevertheless, both approaches can provide insights into the basic mechanisms involved (ibid.).

It is recognised that hydrodynamic models cannot explain the existence of the fastest solar wind speeds observed at 1 AU without some form of additional energy input (Echim *et al* 2011). The extra heating is required to generate up to 50% of the total acceleration in magnetic flux tubes connected to polar coronal holes in which the fast solar wind originates (Cranmer 2012). Recent investigations have concentrated on the role of wave-particle interactions as a means of supplying the extra heating required. The principal alternative mechanisms for delivering the additional energy from the photosphere to the lower corona are either wave/turbulence-driven (WTD) models or reconnection/loop-opening (RLO) models. WTD models rely on mechanical collisions between magnetic flux tubes in the photosphere to generate waves; RLO models assume that the flux tubes derive their energy from magnetic reconnection events in the lower atmosphere (Cranmer 2009).

Despite recent advances, the hydrodynamic models still fall short of a complete description of the fast solar wind from coronal holes. Firstly, ".. *the macroscopic parameters do not fit well with the observations."* (Issautier 2006 p45). Secondly, based on estimates of the energy fluxes released in reconnection events that involve the opening up of closed flux tubes, Cranmer (2012) concluded that RLO processes on supergranular scales in unipolar coronal holes are *"probably not responsible for the majority of the bulk solar wind acceleration."* (Cranmer 2012 p153). More recently, Thurgood *et al* (2014) have concluded that SDO/AIA data shows that transverse Alfvénic waves, the preferred mechanism of WTD models, *"cannot be the dominant energy source for fast solar wind acceleration in the open-field corona."* (ibid. p8). Thus both the alternative mechanisms for providing the additional heating in the hydrodynamic models have been shown to be insufficient. Whilst this does not rule out the possibility of other wave-driven heating such as torsional Alfvénic waves (Thurgood *et al* 2014), the search continues for a possible means of delivering the additional energy.

In contrast to the hydrodynamic models, the exospheric kinetic models recognize the role of an electrostatic potential in accelerating the protons beyond the model exobase, defined as the surface at which the particles can be described as collisionless, i.e. the radius at which $K_n = 1$ (Maksimovitch *et al* 1997). As Lemaire (2010) stated: *".. it is this electric potential that accelerates the protons to* [the] *supersonic bulk velocity."* (ibid. p3)

Chamberlain's (1961) model adopted the Pannekoek-Rosseland value of 150 Volts for the gravitationally-induced potential drop (Pannekoek 1922; Rosseland 1924; see also Lemaire 2010) but this resulted in solar wind speeds well below those observed. Later, it was realised separately by Lemaire and Scherer (1969) and Jockers (1970) that the electron flux would be 43 times as large as the proton flux leaving the corona because the ratio of the fluxes is inversely proportional to the square root of the particle masses. As a result, the corona would become positively charged, thereby further restraining the electron flux by development of a larger potential than that derived by Pannekoek-Rosseland. At equilibrium, the particle fluxes must be equal; in the second generation kinetic model of Lemaire and Scherer (1971) the resulting potential difference was calculated to be ~670 Volts. The kinetic models could now explain the 320 km/s average speed of the slow solar wind at 1AU reasonably well (see Lemaire 2010 Fig 2) but the models still could not explain the fast solar wind speeds.

Both the first and second generation kinetic models had assumed that the velocity distribution function (VDF) of the particles at the exobase was Maxwellian. However, data returned from space missions from the late 1960s onwards had shown that *"The electron velocity distribution functions (eVDFs) observed in the solar wind typically exhibit three different components: a core, a halo and a strahl"* (Stverák *et al* 2009 p1 and references therein) in which the halo and strahl populations represent non-Maxwellian suprathermal tails to the Maxwellian core VDFs (ibid.). The entire VDF could alternatively be represented by a single kappa or power law distribution. Vasyliunas (1968) had pointed out that the advantage of using a kappa distribution (KD) was that is resulted in a more economical calculation than two Maxwellians but it was the pioneering work of Scudder (1992) which led to the concept of KDs being applied to the solar wind.

Scudder and Olbert (1979a,b), had previously shown that the strong velocity dependence of the Coulomb collision cross-section infers that the fastest electrons in a suprathermal tail may be essentially collisionless even though the bulk population is still collision-dominated. The suprathermal electrons could therefore transport more energy than the classical theory predicted and, in principle, lead to an increase of temperature with height. Scudder (1992) proposed that any small nonthermal tail in a kappa VDF which may exist in the lower chromosphere would be amplified in the upper chromosphere and transition region by what he termed the 'velocity filtration effect' whereby an attracting potential, either gravitational or electrostatic, selectively restrained the slower thermal electrons. Conservation of mass flux carried by the remaining suprathermal electrons required that they were accelerated to higher velocities (Scudder 1992). The velocity filtration mechanism thus led directly to maintenance of a suprathermal population in the lower corona which could help to explain the observed temperature increase with height. Scudder (1992) also showed graphically that the velocity filtration mechanism is an inherent property of any nonthermal distributions. Meyer-Vernet *et al* (1995) later demonstrated analytically that the heating effect is not solely an artefact of kappa distributions by showing that the same effect would be obtained with two Maxwellians representing the core and halo populations observed in the solar wind.

Maksimovic *et al* (1997) introduced the third generation (3G) of kinetic models of the solar wind by making the assumption that the VDF at the exobase in coronal holes was a KD. The authors pointed out that KDs represent a further set of solutions to the Vlasov equation, to which both the Boltzmann and the Fokker-Planck Equations reduce when collisions are ignored (ibid.). The suprathermal electrons in the KD require an even larger potential in the corona to equalise the electron and proton fluxes; this in turn leads to greater acceleration of the protons (Echim *et al* 2011). The 3G kinetic models could now achieve bulk speeds in excess of 450 km/s, thereby demonstrating *"the key role played by the suprathermal electrons in accelerating the solar wind protons to supersonic velocity"* (Lemaire 2010 p4).

However, the lower plasma temperature and density as observed in coronal holes implies a greater mean free path (mfp) at low levels which was inconsistent with the exobase at ~6 R_s used in previous models (Lemaire 2010). Reducing the exobase to ~1.1 R_s as required by the observed mfp meant that the gravitational force exceeded the electrostatic force at lower levels; the total potential function (gravitational plus electrostatic) therefore became non-monotonic with a peak at some height above the exobase. The potential peak traps those protons with insufficient energy to reach it. The consequent reduction in the proton flux must be balanced by a reduction in the electron flux which can only arise by a further increase in the potential drop, leading to a further increase in the terminal bulk speed of the protons. (Lemaire 2010)

Incorporating these findings allowed 3G kinetic model velocities to reach over 600 km/s (Lemaire 2010). However, the highest observed speeds of ~1,000 km/s still could not be generated by the models without assuming either an 'extreme' value of coronal temperature in excess of 2 MK at the exobase, or a kappa index of less than 3 (Echim et al 2011), neither of which are considered likely in present models. UV spectral data from the SOHO mission showed that the bulk electron temperatures in coronal holes seldom reach the generally accepted value of 1 MK (Wilhelm *et al* 2007 and references therein); on the other hand, a kappa index of less than 3 represents a very significant departure from a Maxwellian VDF which is difficult to explain.

The latest 4G kinetic models incorporate the Fokker-Plank Equation to allow for pitch angle scattering by Coulomb collisions beyond the exobase (Lemaire 2010). Zouganelis *et al* (2005) have shown that this results in similar bulk velocities at 1AU to those generated by the 3G collisionless models. Thus an extremely low kappa index (<3), or a closely similar second Maxwellian distribution representing the halo population, is still required.

Zouganelis *et al* (2004) summarized the advantage of the exospheric approach as follows: *"the main achievement of exospheric models is to furnish a possible driving mechanism for the fast solar wind, with a single assumption: the suprathermal electron VDF at the exobase."* (ibid. p543). Justification of that assumption remains a key goal of the kinetic modellers. Barnes (1992) had earlier stated: *"If it can be demonstrated convincingly that an appropriate electron distribution is a natural consequence of the heating of the lower corona, we must seriously reconsider the possibility that no additional acceleration mechanism is necessary to drive the solar wind."* (Barnes 1992, p52).

Shizgal (2007) reviewed the various attempts to identify a physical mechanism for the origin of the suprathermal VDFs before concluding: *"It appears that there is at present no rigorous single physical explanation for KDs in space physics."* (Shizgal 2007, p228). Echim *et al's* (2011) more recent review included *inter alia* Livadiotis and McComas' (2009) proposal involving Tsallis non-extensive statistical mechanics (see paragraph below) but the authors concluded that the question still remained *"fundamental yet unresolved"* (Echim *et al* 2011 p32).

Livadiotis and McComas (2009, 2011) demonstrated that kappa distributions are representations of quasi-equilibrium states arising from non-equilibrium generalizations of Maxwellian distributions. As Livadiotis and McComas (2011) stated: *"Space plasmas from the solar wind to planetary magnetospheres and the outer heliosphere are largely collisionless systems of particles, with long-range interactions, residing in non-equilibrium stationary states."* (ibid. p1). Livadiotis (2014) has shown that the presence of a potential energy function modifies the standard kappa distribution and allows anisotropic velocity distributions. Thus statistical mechanics can provide a physical explanation of the significance of KDs and support the observations that the solar wind contains an anisotropic element in the form of the strahl population but it may not be sufficient to explain the origin of the extreme KDs required by the kinetic models.

However, there are some anomalies which arise from the use of KDs. Scudder's (1992) velocity filtration mechanism also predicts a relatively high maximum electron temperature within a few solar radii (Echim *et al* (2011) by selectively restraining the slower electrons at lower levels but this maximum has not been observed, leading Zouganelis *et al* (2004) to suggest that *"kappa functions may not be adequate to model VDFs having suprathermal tails in the corona"* (ibid. p547), under the assumed radial dependence of the potential function.

KDs are symmetric VDFs in the velocity space; therefore focusing on the origin of the suprathermal electrons in the halo population overlooks the asymmetric strahl component commonly observed emerging from coronal holes. Maksimovitch *et al* (2005) analysed electron VDFs in the solar wind and showed that the halo population is present at all pitch angles but the strahl is usually anti-sunward moving (ibid.). Pierrard *et al* (1999) had previously explained: *"The strahl is mainly present in the fast wind. It represents the* *anisotropic component of halo electrons that stream away from the Sun with a drift velocity aligned with the local magnetic field direction"* (ibid. p17,021).

Maksimovitch *et al* (2005) demonstrated that the halo population increases with distance from the Sun at the expense of the strahl population; their analysis *"provide*[d]*, for the first time, strong evidences for a scenario that is commonly assumed: the heliospheric electron halo population consists partly of electrons that have been scattered out of the strahl."* (ibid. p1) As Maksimovitch *et al* (2005) recognized, the problem therefore shifts from the origin of the symmetrical suprathermal Maxwellian halo or kappa VDF to the generation of the anti-sunward strahl population. Pierrard *et al* (1999) had already shown theoretically that Coulomb collisions *en route* from the Sun could not generate the asymmetrical strahl electron population observed at 1AU; Maksimovitch *et al* (2005) concluded by wondering whether the anti-sunward fast strahl electrons may already exist in the lower corona. Thus it is necessary to find a satisfactory explanation of the origin of both the symmetric halo population and the anti-sunward strahl electrons in the lower corona.

Finally, the behaviour of the ions in the corona is also puzzling. The SOHO mission data unexpectedly revealed that hydrogen and the minority populations of heavier ions are much hotter than the bulk electrons in coronal holes (Kohl *et al* 1997). Similarly to the suprathermal electrons, the origin of the hot ions is uncertain; this point is discussed in more detail in s.III below.

Summary of section I

Hydrodynamic models require an additional source of energy to account for up to 50% of the acceleration of the fast solar wind. The mechanism by which this energy is delivered from the photosphere has yet to be identified conclusively as both the wave-turbulence driven and the reconnection-loop opening models have been shown to be quantitatively insufficient.

The latest 4G kinetic models have shown the need to take into account the enhanced Pannekoek-Rosseland electrostatic potential and the importance of suprathermal electrons in driving the acceleration. As Parker (2010) observed, the fast electrons are the horses that drag the cart loaded with protons. The symmetrical 'halo' suprathermal population can be modelled either by two Maxwellians or a single kappa distribution, or by a combination of both. The effect is the same in all cases. Scudder's (1992) velocity filtration mechanism shows how any small initial suprathermal population is amplified and transported to higher levels but the origin of the initial suprathermal population in the lower corona has yet to be fully explained. A further problem is that the predicted high electron temperature within a few solar radii has not been found.

Likewise, the origin of the asymmetric anti-sunward fast strahl electron beams observed emerging from the lower corona via coronal holes is also unexplained, as is the origin of the hot ions in the same location.

It is a striking fact that Scudder's (1992) velocity filtration mechanism and the above unexplained features of the various solar wind acceleration models are all characteristic of a plasma Double Layer, as will be explained in the following section. The presence of a Double Layer may also help to resolve the problem of the high electron temperatures at a few solar radii predicted by the kinetic models.

II. Plasma Double Layers

Introduction to section II

Plasma behaviour differs markedly from that of a gas due to the effect of electromagnetic forces in the partially-ionised medium. In particular, it has been known for many years that plasma has the ability to form filaments and to automatically generate Double Layer (DLs) when it is forced to carry an externally imposed electrical current. Other types of DLs which are current-free form when separate regions with different plasma characteristics are brought into contact. Recent work has shown that DLs can also form when a dense plasma expands into a less dense region.

The formation and behaviour of DLs have been reviewed by Block (1978), Hershkowitz (1985), Raadu (1989), Eliezer and Hora (1989), and Singh (2011). A brief outline is given below, including the relevance of DLs to astrophysical situations.

Description of Double Layers

DLs consist of two parallel but not necessarily planar sheets of plasma with equal but opposite net charge. DLs can be defined as *"discontinuities in the plasma potential* [which] *are related to regions of plasma without space charge neutrality"* (Eliezer and Hora 1989 p341). The charge separation between the layers is maintained by a balance between the electrostatic and inertial forces (ibid.); the balance is determined by the Poisson and momentum equations (Block 1978). The Poisson equation with $n_e \neq n_i$ must be used in order to obtain a double layer solution. Applying the further condition that the plasma is collisionless results in the Vlasov-Poisson system of equations, of which DLs represent solutions.

DLs are similar to Langmuir sheaths adjacent to a bounding surface (Langmuir 1929) but they do not require boundaries against which to form (Hershkowitz 1985). Classical DLs closely resemble standing laminar electrostatic shocks as described by Montgomery and Joyce (1969). (Raadu 1989 and references therein).

DLs are an important mechanism for accelerating charged particles due to the electric field which exists between the charge layers. DLs also offer a means whereby a collisionless plasma with nearly zero resistivity can support an electric field parallel to the magnetic field (see e.g. Block 1978; Ergun *et al* 1998).

Classical Current Carrying Double Layers

The physics of DLs in laboratory plasma was described by Langmuir (1929) who was the first to give a self-consistent theory of the space charge distributions in the regions he termed 'sheaths'. Bohm (1949) investigated the pre-sheath regions adjacent to the sheath itself and showed that these were important in creating the initial velocity distributions at the boundary of the DL by accelerating particles from the quasi-neutral bulk plasma into it. The boundary conditions adopted are critical to the resulting solution; various kinds of wave solutions, including shock waves or DLs, are possible depending on the plasma characteristics and the boundary conditions. (Eliezer and Hora 1989).

The discontinuity in the plasma potential across a classical Current Carrying Double Layer (CCDL) divides the plasma particles into four possible populations. On the high potential side free ions are accelerated through the DL whilst the electrons are reflected or 'trapped'; on the low potential side free electrons are accelerated up the potential drop whilst the ions are trapped (Eliezer and Hora 1989). The counterstreaming accelerated electrons and ions represent a current through the DL.

In principle, the presence of only three of the four possible populations is sufficient to maintain the DL (Block 1978). Montgomery and Joyce's (1969) laminar electrostatic shock solutions required free and trapped electrons and free ions. Bernstein, Greene and Kruskal

(1957) *"proved the existence of an unlimited class of solutions"* (Block 1978 p62) to the Vlasov-Poisson equations (the 'BGK solutions') which involved the same three populations. Knorr and Goertz (1974) extended the BGK solutions to include trapped ions, hence their solutions contained all four possible particle populations. The choice of the electron and ion velocities entering the DL is critical to the above solutions. However, Kan and Lee (1980) demonstrated that the velocity criteria can be relaxed if sufficient densities of trapped particles exist at the DL boundaries.

A CCDL acts as an electrical load dissipating energy which is transformed into the directed kinetic energy of the accelerated particles and so there has to be an external source maintaining the potential and driving the current (Raadu 1989). However, other forms of DL are also possible.

Current Free Double Layers (CFDL)

Whilst *"It was commonly thought that magnetic-field-aligned potential disruptions were driven by electron currents, .. the theoretical possibility of a CFDL has been known of for some time."* (Boswell 2006, L199). Indeed, Langmuir (1932) had identified current-free sheaths at lateral boundaries to a current-carrying discharge. Alfvén (1986) described the formation of this type of CFDL at a lateral boundary to a plasma discharge between an anode and a cathode, explaining that the CFDL develops because the faster electrons escape to the boundary in greater numbers; these attract a sheath of positive space charge which forms a DL with the negative surface charge. The DL grows until the potential equalises the radial electron and ion fluxes. Alfvén (1986) continued: *"If the discharge constricts itself the walls can be taken away (without removing the space charge they carry). In these double layers the net electric current is zero."* (ibid. p779; see also Peratt 2015 Ch. 5 p189)

Plasma also forms CFDLs to separate different regions of plasma from each other. "*It is well known from laboratory plasma that when two plasma of widely different characteristics are in contact with each other, a potential difference is produced between the main bodies of the two plasmas and an electric field is set up in a narrow layer between them. Such a layer is sometimes called a potential double layer."* (Hultqvist 1971 p751). The relevant plasma characteristics which can cause a CFDL were summarized by Alfvén (1986) as follows: "*If a plasma is inhomogeneous so that the chemical composition, density, and /or electron temperature differs in different parts of the plasma, the plasma may set up double layers which split the plasma into two or more regions, each of which becomes more homogeneous."* (Alfvén 1986 p779)

Hultqvist (1971) outlined the mechanism for a potential difference to be produced between two regions with different temperatures. Similarly to the case of a boundary CFDL, the higher electron flux from the hotter region causes a DL to form but in this case the initial effect is to equalise the bi-directional electron fluxes. However, if the cold plasma does not contain enough electrons to allow the fluxes to be equalised then the DL voltage drop will increase until sufficient ions are accelerated to help make the total current zero (ibid.).

Perkins and Sun (1981) proved that current-free DLs represent solutions to the Vlasov-Poisson equations. The authors also pointed out that *"any double-layer solution with current can be transformed into a currentless solution by symmetrizing the velocity distribution"* by choice of the appropriate frame of reference. (ibid. p118). Similarly, Stern (1981) stated that "*Double layer solutions not involving any net current flow are readily constructed;"* (ibid. p5839). A CFDL can satisfy the Vlasov-Poisson equations because Poisson's equation does not depend on the sign of the particles' velocity, thus " *net currents with either direction can correspond to the same potential profile .."* (Hershkowitz 1985 p366). As Ahedo and Sánchez (2009) stated, *"The current-free double layer (CFDL) constitutes a different subfamily* [of DLs]*"* (ibid. p1) in which the total net current is zero.

Double Layers in expanding plasmas

A DL will also form when a single-temperature region of plasma is initially confined and then allowed to expand into a vacuum, as discussed in e.g. Hairapetian and Stenzel (1991). In a plasma expanding into a vacuum, the electrons, being faster than the heavier ions, will tend to escape first and so establish an ambipolar electric field between the leading electrons and the ions; this electric field slows the electrons and accelerates the ions (ibid.). Bezzerides *et al* (1978) predicted that a two-electron temperature mixture of hot and cold electrons in a plasma expanding into a vacuum or low-density region will also form a CFDL. In their model, the hotter electrons lead the expansion away from the high-density region and set up an electric field, in a similar manner to the expansion of a single temperature plasma.

The predicted production of accelerated ions by the DL was confirmed by numerical analysis (Wickens *et al* 1978, True *et al* 1981) and particle simulations (Kishimoto *et al* 1983) amongst others. Hairapetian and Stenzel (1988) provided the first experimental evidence of a stationary CFDL in a collisionless, weakly-divergent, two-electron-population plasma expanding into a vacuum or low-pressure region. In this and a subsequent paper (Hairapetian and Stenzel 1991) the authors reported the now-familiar mechanism whereby a DL is formed at the position of the cold electron front by the energetic tail electrons leading the expansion. *"The ambipolar electric field accelerates a small number (~1%) of ions to streaming energies ... Upstream of the double layer both electron populations exist; but downstream, only the tail electrons do."* (ibid. p899, emphasis added). Hairapetian and Stenzel (1991) also investigated the effect of the background gas on the expansion and found that pressures in excess of 2 x 10^{-5} Torr led to sufficient ionisation of the background gas by the energetic electrons to prevent the formation of a DL (ibid. p900).

The position of a DL

Perkins and Sun (1981) had shown that the position of the DL is determined by the plasma density distribution function in combination with the potential. *"One component determines the potential change, while the second component determines the point where the double layer occurs"* (ibid., p117). Their solution had assumed Maxwellian VDFs on both sides of the DL in one-dimensional geometry. Ahedo and Sánchez (2009) showed that three different types of CFDL may develop in convergent / divergent nozzles, depending on the geometry of the nozzle and the velocities of the particles entering the nozzle; the geometry could arise from a physical nozzle or from magnetic confinement. Similarly to Perkins and Sun's (1981) result, the final position of the CFDL is controlled by the geometry and the velocities of the particles entering the nozzle.

Importantly, Hairapetian and Stenzel's (1991) experiment found that the initially propagating CFDL at the expansion front eventually comes to a halt at a position determined by the relative densities of the two electron populations. *"The double layer forms at a position where the transition in electron population occurs ($n_{tail} \geq n_M$), as predicted by earlier theoretical studies (by Bezzerides 1978, True 1981)"* (*Hairapetian and Stenzel* 1991, p911 and references therein).

Generation of turbulence

The conditions necessary for formation of a DL are similar to those for the onset of a Buneman instability (Foukal and Hinata 1991). Although turbulence is not necessary to maintain a DL once it has formed, turbulence is likely to result in the presheath region outside the DL. *"Since double layers accelerate electrons and ions alike, we expect plasma turbulence to be excited by the resultant energetic beams .."* (Foukal and Hinata 1991 p320).

Thus in a CFDL some of the energy of the accelerated ions will probably be lost by turbulent interaction with the plasma on the downstream low-potential side.

The role of DLs in astrophysics

The possible role of DLs in astrophysics has been discussed by a number of authors over many decades. A few examples are given below.

In relation to the Earth's environment, Alfvén (1958) postulated that a potential double layer could exist at the level of the upper ionosphere; this prediction was later supported by spacecraft observations (Ergun et al 2001). Block (1978) suggested DLs can accelerate auroral plasmas to kV energies. Stern (1981) showed theoretically that DLs could result from the interaction of the two different plasmas in the Earth's magnetosphere and ionosphere when modelled in a 1-D diverging flux tube geometry using the mirror ratio as the linear variable. Stern's conclusions included *"(1) Double layer solutions not involving any net current flow are readily constructed;"* and *"(3) Non-uniqueness of quasi-neutral solutions must be utilized to determine the position of such layers;"* (ibid. p5839). Stern (1981) also pointed out that the use of the mirror ratio variable allowed his analysis to be applied to open field lines extending to interplanetary space (ibid. p5840).

In the solar context, Jacobsen and Carlqvist (1964), Alfvén and Carlqvist (1967) and Carlqvist (1969, 1979, 1982) considered the role of DLs in solar flares and surges, a suggestion followed by Crow *et al* (1975), Raadu (1989), and Volwerk and Kuijpers (1994). Torven *et al* (1985) and Carpenter and Torven (1987) investigated the Alfvén-Carlqvist mechanism in the laboratory, noting its application to the solar atmosphere. Khan (1989) agreed in essence with Alfvén - Carlqvist's basic postulate about the role of DLs in solar flares but suggested that detailed observations implied that weak ion-acoustic Multiple DLs (MDLs) were a better explanation of the energy release associated with the particles accelerated in solar flares than the single strong DL proposed by the former authors. Issautier (2006) confirmed that *".. [stationary] double-layer structures have also been measured for the first time in the solar wind"* by the WIND mission (Issautier 2006 p41).

In the wider context, Alfvén (1981, 1986) suggested that DLs may play a fundamental role in astrophysical phenomena generally.

Recent studies of DLs in the solar atmosphere

Boswell *et al* (2006) commented pointedly on previous studies investigating whether DLs could play a role in solar physics: *"In the solar context, the potential significance of electrostatic DLs in the dissipation of solar flares has been previously realized ... All models of magnetic energy release and particle acceleration by a coronal DL make the assumption that a current is creating the DL."* (ibid. L199). In contrast, Charles and Boswell (2003) had demonstrated that CFDLs are formed spontaneously in a low-collisional laboratory plasma expanding from a high magnetic field region to a lower magnetic field region in a Helicon Plasma Device (HPD), a result later confirmed by other researchers (Boswell *et al* 2006 and references therein). Boswell *et al* (2006) suggested that this acceleration mechanism may operate at the base of coronal funnels where diverging field lines emerge from the photosphere (ibid. L200). However, the authors concluded that the CFDL may not be strong enough to accelerate the fastest terminal solar wind speeds (ibid. L201); also, the authors pointed out that *"in* [the] *case of the solar atmosphere an electron energization mechanism still has to be identified at the bottom of a funnel"* (ibid. L202).

Singh (2011) agreed with Boswell *et al* (2006) regarding the effect of the suprathermal electron population in forming a CFDL in a diverging magnetic field but countered that the scale length was inadequate for the HPD mechanism to operate in coronal funnels. Singh

(2011) suggested instead that magnetic reconnection between small magnetic loops adjacent to the base of coronal funnels and the open field lines inside the funnels could be the source of the suprathermal electrons. Singh and Araveti (2011) had calculated that either bulk heating of the electrons to a temperature $T_e > 64$ eV or heating of a small fraction of the electrons to high temperatures $T_{eh} > 158$ eV at the base of a coronal funnel would form a CFDL sufficient to accelerate the Ne^{7+} ions to the speeds measured by Tu *et al* (2005). However, the authors admitted that *"Heating of the chromospheric bulk electrons from less than 1 eV to 64 eV at the bottom of the funnels may not occur easily"* (Singh and Araveti 2011 p3).

Thus both models postulating a role for CFDLs at some intermediate height in coronal funnels require the prior existence of hot or suprathermal electrons but neither model can easily explain the origin of the necessary VDF at low levels.

Summary of plasma Double Layers

Research has demonstrated that stationary Current Free Double Layers can form in a variety of different situations, including when a spherical plasma expands into a lower density region. The expanding plasma may contain either a single temperature or a two-temperature electron population. Hairapetian and Stenzel (1991) confirmed experimentally previous theoretical studies which predicted that the CFDL becomes stationary at a position determined by the relative densities The same authors also demonstrated that a DL will not form if the pressure in the background plasma is high enough to allow a significant level of ionisation of the neutral gas by the outflowing particles.

The primary effect of a CFDL formed at the boundary of an expanding plasma by the fastest escaping electrons is to equalize the charge flow through the CFDL by retarding or reflecting the cooler thermal electrons whilst accelerating a fraction of the positive ions away from the surface. Because a CFDL acts as a localised velocity filtration mechanism similar to the type proposed by Scudder (1992), a CFDL is capable of generating a suprathermal electron population together with accelerated ions on the downstream side. The outflowing particle beams are expected to generate turbulence in the adjacent low-density plasma.

III. Modelling the solar photosphere in relation to a Current Free Double Layer

Formation of a solar CFDL

On the basis of the research discussed above, the expansion of the dense plasma in the Sun into the surrounding lower-density coronal plasma should be expected to form a CFDL. It is perhaps significant that the longitudinal (axial) profiles of ion density and streaming energy of the expanding plasma which forms a CFDL in Hairapetian and Stenzel's (1991) experiment (ibid. Fig 6 p904) are remarkably similar in form to the density and temperature profiles in the Sun's transition region and lower corona (Audouze *et al* 1994 p35) and may be evidence that the two phenomena are linked. A CFDL automatically ensures that the electron and ion fluxes are equal and in the same direction; there is therefore zero net outflowing current through the CFDL as is necessarily required in any model of the solar wind.

A stationary CFDL *below* the base assumed by the kinetic solar wind acceleration models would provide the suprathermal electron population needed to enable those models to explain the fastest solar wind speeds. Similarly, those models based on generation of CFDLs at some altitude above the base of coronal funnels could also be supplied with the necessary electron VDFs at low level. A CFDL below the base of the hydrodynamic models could also contribute to the necessary additional wave energy by turbulent interaction between the outflowing particle beams and the background plasma. Thus the existing models of solar wind acceleration may then take effect above the sub-photospheric CFDL and provide the additional acceleration up to the fastest observed solar wind speeds, albeit with some minor modifications discussed below.

The postulated CFDL would support a radial electrostatic field similar to the one included in the kinetic models but the main potential drop would be concentrated into a narrow region below the photosphere. This implies that the excessive electron temperatures at a few solar radii predicted by the kinetic models will probably not arise because the majority of the velocity filtration mechanism effect has taken place at lower levels. The hot electrons would then be expected to appear at low levels instead of at a few solar radii as predicted by present models based on a more extensive electrostatic potential distribution.

The nature of the photosphere

Under the hypothesised model, the photosphere would be interpreted as a region of counterstreaming flows consistent with the zone of ion reflection on the low potential side of the CFDL; it thus appears to be a presheath immediately outside the CFDL. The granulation in the photosphere seems to indicate that the trapped and accelerated particles self-organise into radial columnar structures, probably with the outflowing particles concentrated in the centres of the granules and the inflowing trapped ions (before reflection by the underlying CFDL) concentrated into the lanes between the granules. The separation of the flows implies that both the inflowing and outflowing streams form localised currents; of course, the total net current over the photosphere is zero in accordance with the characteristics of the underlying CFDL.

Apparently, the outflowing current in the presheath region or photosphere forms filaments which are surrounded by return current sheaths in a similar manner to those identified in emerging flux tubes (see e.g. Kuijpers *et al* 2014, and also below). This behaviour is consistent with the well-known behaviour of plasma to self-organise into filaments when forced to carry a current (e.g. Alfvén 1981; Peratt 2015). This tendency to filament may also explain the beam-like nature of the anti-sunward strahl electrons. A corollary of this identification of the photosphere with the presheath is that the thickness of the photosphere visible in sunspots may not represent the thickness of the CFDL itself.

Sunspots are often associated with the footpoints of magnetic flux tubes emerging from beneath the photosphere and forming coronal loops (e.g. Foukal 1976; Aschwanden *et al* 1999). These flux tubes are known to carry strong axial currents with return currents in sheaths bounding the flux tubes (Török *et al* 2014). Hairapetian and Stenzel (1991) found that electron currents preclude the formation of a CFDL: *"The double layer is annihilated when a field-aligned electron current is drawn through the plasma."* (ibid. p913). By analogy, the flux tubes may represent regions in which CFDL breaks down because an electron current flows along the flux tubes emerging from regions below it. Sunspots would therefore indicate 'holes' in the underlying CFDL. The apparently lower temperatures observed in sunspots may indicate that turbulent heating due to particle acceleration though the CFDL (Foukal and Hinata 1991) is occurring generally in the photosphere / presheath region but is not occurring in sunspots. Alternatively, the apparent lower temperature may be due to laminar particle flow along the magnetic field lines in the emerging loops and the consequent reduction in random thermal temperature compared to the adjacent turbulent regions. Hairapetian and Stenzel (1991) explained the distinction between thermal and laminar motions in the case of an expanding plasma: *"Because of rapid expansion in the strong pressure gradient, the neutral gas molecules are also accelerated to supersonic velocities while their random thermal energy decreases."* (ibid. p901).

The coronal heating problem

The ‘coronal heating problem’ arises from the observation that *“the Sun’s outer atmosphere undergoes a rapid inversion, from a relatively cool ($T < 10^4$ K) photosphere and chromosphere to a hot and ionized ($T > 10^6$ K) corona”* (Cranmer 2012). The problem has occupied researchers since the early part of the 20th century and it is closely connected to the question of the acceleration of the solar wind (ibid.) The rapid temperature rise occurs in the transition region between the chromosphere and the corona. The photosphere and chromosphere are therefore much cooler regions through which the thermal energy of the Sun must pass before heating the corona to multi-million degree temperatures. Despite considering Scudder’s (1992) mechanism, Issautier (2006) suggested that *“This unexpected behavior in contradiction with the second thermodynamic principle is still unexplained.”* (Issautier 2006, p27).

The high temperature of the corona is inferred from the ionisation states of the heavier elements such as iron, nickel and calcium, as indicated by the emission lines in their spectra given off when an ion moves to a lower energy state (Issautier 2006). This author continues: *“This requires the temperatures of the corona to be extremely high, around 1 or 2 million degrees.”* (ibid. p27). Thus the derivation of the high coronal temperatures rests on the unstated assumption that the ionized states of the minor ions are being created by thermal collisions in the same location as the ions are losing energy by emitting the observed spectra. The temperature gradient in the transition region (TR) is then derived from measurements of the altitude of the emissions. However, there are some discrepancies which have arisen between this traditional concept of a steep temperature gradient in the TR and recent observations.

Wilhelm *et al* (2007) plotted the inferred temperature jump with altitude in the transition region but were concerned that it has never been verified by other observations. On the contrary, proton temperatures derived from neutral hydrogen Lyman α emissions failed to find the predicted jump. (Marsch *et al.* 2000).

In contrast, Doppler broadening studies of the emission lines have apparently confirmed the high coronal temperatures (Echim *et al* 2011). However, interpretation of the Doppler broadening as an indication of temperature can be misleading as Wilhelm *et al* (2007) explain: *“The equivalent thermal velocity, corresponding to the Doppler width of the O VI 103.2 nm line, is truly remarkable because it reaches 600 km s^{-1}. If this is interpreted as a kinetic broadening it would give a minor-ion coronal temperature of more than 100 MK!”* (ibid. p163). In this case, interpreting the line width as kinetic broadening is obviously incorrect; this must call into question the reliability of similar interpretations which result in a temperature in the expected range of 1 - 2 MK.

The mechanism whereby the minor ions are heated to ionisation temperatures is also uncertain. Shizgal (2007) summarized the various different models suggested by other researchers but concluded that there was no consensus. Marsch (2006) had described the challenge presented to existing models, explaining that *“The energy requirements on heavy ions are tough”* (Marsch 2006, p14) because Coulomb friction is usually inadequate. Marsch continued: “*It appears rather difficult to drag out such heavy ions as He^+, or He^{2+}, or multiply-charged ions of any heavier element, against the Sun’s gravitational attraction.”* (ibid.).

The minor ion heating is unexpectedly dependent on the charge / mass ratio: *“measurements obtained for ions with Z_i/A_i larger than 0.25 show an upswing in wave power that is difficult to reconcile with traditional views of turbulent cascade.”* (Landi and Cranmer 2009 p804). Similarly, Tu *et al* (1998) found that the effective ion speeds decrease generally with increasing A_i/Z_i (sic) (ibid. Tables 2 & 3).

The electrons also show anomalous behaviour which is unsettling for the present theories because *"the electron density and temperature determine the ionization state of hydrogen, helium and heavier elements and govern the radiative losses in the VUV and soft X-rays through collisional line excitation"* (Wilhelm *et al* 2007 p163). The coronal electron temperature is also derived from the emission spectra which results in determinations of coronal temperatures of ~1.5 MK (Issautier 2006). However, as discussed above, the electron temperatures in coronal holes were found to be below 1 MK when they were determined from temperature-sensitive emission line ratios (Cranmer 2014). Esser and Edgar (2000, 2001) suggested that the discrepancy could be significantly reduced either if the electrons have a non-Maxwellian VDF or if the different charge states of ions of the same element have large differences in their flow speeds. However, the authors concluded that *"[t]he differential* [ion] *flow speeds assumed in the paper are .. probably two orders of magnitude larger than what can reasonably be expected to exist in the inner corona."* (Edgar and Esser 2001 p1062), which suggests that the problem has not yet been fully resolved.

The effect of a CFDL on the coronal heating problem

The above small selection of observations from the extensive literature demonstrate a number of inconsistencies in the interpreted observations of temperature in the transition region and corona. Collectively, these inconsistencies seem to suggest that the traditional concept of ionization by thermal heating in the locations at which emission lines are observed may not be the correct way to interpret the spectral observations; this may result in the apparent contradiction with the second law of thermodynamics embodied in the coronal heating problem.

By analogy with solar flares, in which *"The standard model .. separates the region where particles are accelerated from the region where the flare energy is dissipated as radiation"* (Kuijpers *et al* 2014 p33), it is here suggested that the same may be true of the minor ions in the corona generally. Under the present model, the minor ions may be created in the electric field of the postulated sub-photospheric CFDL and simultaneously accelerated to the heights at which their emission lines are observed.

For a given potential drop in a CFDL, the kinetic energy gained by an ion will be proportional to the charge on the ion, i.e. its degree of ionisation Z_i, and independent of its mass. This has two consequences. Firstly, an increase in speed with increase in Z_i/A_i (sic) as Tu *et al* (1998), Landi and Cranmer (2009) and Wilhelm *et al* (2007) reported should be expected if the ions had been accelerated through the potential difference in a CFDL.

Secondly, in the absence of collisions or other interactions, the height above the photosphere to which an ion would then rise against gravity would be proportional to its charge: mass ratio Z_i/A_i. For any given element, those ions with a higher degree of ionisation should be expected to rise to greater heights. This is exactly what the data indicate (Wilhelm *et al* 2007 Fig 1; Audouze *et al* 1994 p35), and is the principle reason for the derived apparent steep temperature gradient in the transition region. For different elements with the same degree of ionisation, ions of lighter elements would tend to rise to greater heights than heavier elements; again, this is broadly in line with observations (ibid.) but there appears to be some modification due to collisions. The number of collisions experienced by an ion will depend on the different collision areas of the ions, which also vary with velocity. It is beyond the scope of this paper to evaluate these effects quantitatively but they may, in principle, explain the data.

Whilst coronal temperatures are inferred from the emission spectra, the coronal heating rate is measured separately by the rate of EUV emission and X-ray intensities (Aschwanden 2001). The radiant energy of the emissions will provide a source of heating in the TR but, in the present CFDL model, this need not be sufficient to heat the plasma to the temperatures necessary to generate the ionisation of the minor elements by thermal collisions. If, as is here suggested, the minor ions are not thermally generated at the same altitudes as they are seen to be emitting then the apparent exceptionally steep temperature rise in the TR may be in part an illusion. Another puzzle may also be resolved with the help of the present interpretation. It is known that filaments in the corona are cool and yet can survive for periods of some months despite being embedded in the apparently multi-million degree temperatures of the surrounding corona (Raadu *et al* 1987). In the present model, the temperature of the corona may be substantially below that inferred by the traditional concept of ionisation by thermal collision.

IV. Summary and Conclusions

The acceleration of the fast solar wind has still not been fully explained. Kinetic models have to assume a source of suprathermal electrons at the model exobase but cannot explain their origin; likewise, hydrodynamic models require an additional energy input but the postulated sources of additional wave energy have been shown to be insufficient.

Separately, other researchers have identified and analysed the formation mechanism of Current Free Double Layers (CFDLs) in expanding plasmas and a number of space missions have identified Double Layers of various types in different regions of the solar system. Double Layers are therefore a well established phenomenon both in theory and in the laboratory and astrophysics. One effect of a CFDL is to act as a highly localised velocity filtration mechanism similar to the type proposed by Scudder (1992) which allows only the fastest electrons to escape through the adverse electric field in the CFDL and to appear in the downstream particle population. Another effect of a CFDL is to accelerate positive ions through the potential drop. The accelerated ions and escaping fast electrons form energetic beams of particles on the low-potential side which may cause turbulence in the downstream plasma, thereby dissipating energy.

The hypothesis presented in this paper is that expansion of the dense plasma in the body of the Sun will automatically result in the formation of a CFDL which, it is suggested, is located immediately below the photosphere. This qualitative model offers an explanation of the origin of the suprathermal electrons at the base of the kinetic models; it may also provide an additional source of wave energy which the hydrodynamic models require.

The acceleration of ions by the postulated CFDL may help to explain the high proton temperatures observed in coronal holes and also provide some insights into the coronal heating problem and the charge: mass ratio dependence of the altitudes and velocities of the heavy ions. One corollary is that the ions may not be generated by thermal collisions in the locations where they are observed to emit the spectral lines by which they are identified.

Further work will be necessary to quantify the compatibility of the present qualitative hypothesis with both existing observations and new data being received from current space missions and ground-based observations.

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