Solar Surface Transistor Action

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***Abstract*—Both observational evidence and theoretical study suggests the presence of a plasma double layer (DL) above the surface of the Sun. Such a DL, together with a single charge layer (SL) directly below it, provides a possible explanation for the existence of the temperature minimum in the lower corona, the x-ray emissions observed above sunspots, and the enigmatic variations observed in the intensity of the solar wind current. This plasma sheath is arguably a generic feature, in varying degree, around all stars.**

***Index Terms*— Plasma sheaths, plasma properties, solar atmosphere, solar corona, solar wind velocity, temperature inversions, photosphere, velocity distribution.**

I. INTRODUCTION

One of the most persistently enigmatic observations of the near-solar environment is the temperature inversion that includes the rise in temperature from approximately 5000K on the photosphere to over 2 million K in the lower corona. Immediately above the photosphere, the chromosphere supports a temperature rise from ~5,000K to 20,000K with increasing altitude above the solar surface. Above that, the transition region is a thin, irregular layer in the Sun's atmosphere that separates the chromosphere from the hot lower corona. In this transition region temperatures rise from ~20,000K to over 2 million K. This abrupt *rise* in temperature with increasing altitude above the surface has been one of the most unrelenting enigmas in our knowledge of the workings of the Sun [1]. Because the solar atmosphere is constituted of plasma, it has recently been suggested that a well-known plasma phenomenon, the double layer (DL) may be involved in a causal way in this mechanism.

"Hydrogen is fully ionized at the temperatures observed in the transition region and is therefore difficult to see. Instead of hydrogen, the light emitted by the transition region is dominated by such ions as C_{IV}, O_{IV}, and Si_{IV} (carbon, oxygen, and silicon each with three valence electrons stripped off). These ions emit light in the ultraviolet region of the solar spectrum that is only accessible from space."[2] The photosphere is a partially ionized region and the lower corona is almost fully ionized. Such plasma cells are often separated by double layers.

It is presently well-known that the solar neighborhood is permeated by matter in the plasma state. The Sun's surface area partially defines its electrical capacitance within that plasma. Although the immediate surroundings of any such body within a plasma are determined by its voltage relative to the plasma neighborhood, this quantity cannot be measured in the case of our Sun not only because of its size and temperature but also because of Langmuir sheathing effects. Because of observations made of several solar phenomena, it is reasonable to assume a positive voltage (anode) level for the Sun relative to the inter-planetary plasma.

Hannes Alfvén first postulated the existence of DLs in the solar atmosphere.[3] Although he suggested the location as being axial, the exact position of the DL can only be inferred over time from observations of measurable solar phenomena. At this point it seems likely that such a (DL) charge sheath surrounds the solar surface.

II. STRUCTURE OF THE DOUBLE LAYER

A. Qualitative Properties of the DL

As a result of observations of the temperature minimum in the lower corona and variations in the solar wind, it is proposed that a double layer (DL) which determines the essence of the electrical properties of the photosphere and chromosphere exists widely just above the visible surface of the Sun.

The normal photospheric surface consists of a crowded collection of "granules" which are identical in behavior to the tuft plasma observed on anodes in electrical discharges.

A simplified two-dimensional radial cross-section taken through a photospheric granule is shown in the three plots in figure 1. The horizontal axis of each of these plots is distance, measured radially outward, starting at a point near the bottom of the photosphere. Several enigmatic observed properties of the Sun are explained through reference to these three plots. These are purely plasma phenomena and have no equivalent in the standard solar model. These plots are observed and measured in laboratory plasmas.

In the case of the Sun (or any star) a spherical geometry obtains. An exact description of the voltage distribution with respect to solar radial distance is not known from either observation or experiment. Therefore we assume a voltage distribution similar to that measured in laboratory discharges in a cylindrical geometry. It is argued that although the overall geometry is indeed spherical, the transition region is so thin (a few thousand km in radial distance in contrast to the 1.4 million km solar diameter) that the cylindrical column can reasonably approximate what occurs across this thin layer.

The bottom plot in figure 1 (Charge Density) shows the presence of a single charge sheath or single layer (SL) in the range a to b. It also shows a DL in the region c to e. This structure is often observed near the anode of laboratory static plasma discharges. Thus the proposed DL structure is simply an extrapolation in size of well-known plasma phenomena.

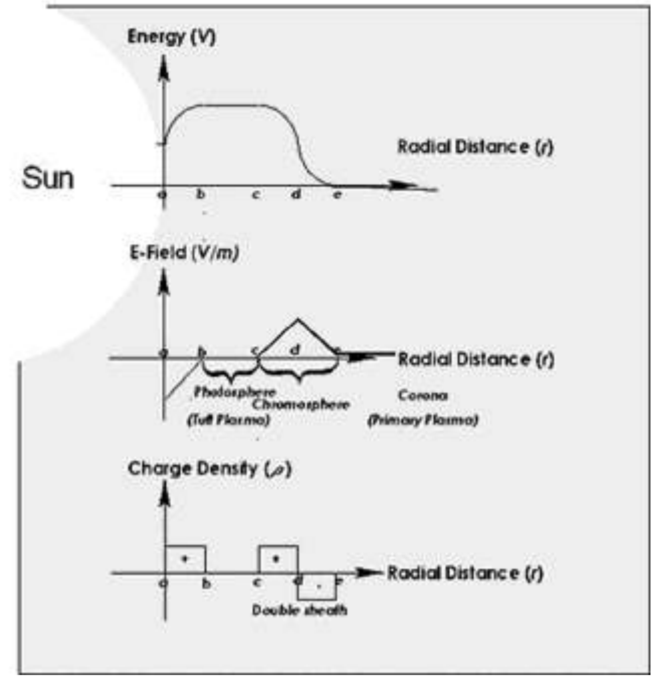

Figure 1. Plasma voltage, electric field, and charge density in a photospheric tuft.

The first plot in figure 1 shows the energy per unit charge of a positive ion as a function of its radial distance out (up) from the solar surface. The second plot (*E*-field), shows the outward radial force experienced by such a positive ion. Hannes Alfvén [4] warned that one of the most misunderstood properties of electric plasma is its excellent (although not perfect) conductivity. Even such an excellent conductor will support a weak electric field. Therefore, in this *E*-field plot, the highly conductive plasmas of the photosphere (region b to c) and the corona (from point e outward toward the right) are regions of almost (but not) zero electric field strength. Stronger fields are contained within the single layer and DL.

The third plot shows the locations of the charge densities that produce the first two plots. This, of course is a direct application of Maxwell's (Gauss' Law) expression:

$$\nabla \bullet D = \rho \tag{3}$$

which in integral form for the assumed approximately cylindrical volume is

$$\int_0^r \rho(r) A dr = \oint_{\text{Surface area}} \varepsilon E \bullet dA = \varepsilon E A \tag{4}$$

Thus we have

$$E(r) = \frac{1}{\varepsilon_r \varepsilon_0} \int_0^r \rho(r) dr \tag{5}$$

The chromosphere is the location of the plasma DL.

The three the plots shown in figure 1 are related by the relationships:

$$E = -\frac{dV}{dr} \tag{6}$$

and from (5) charge density

$$\rho = \varepsilon \frac{dE}{dr} . \tag{7}$$

The value of the *E*-field, at every point *r*, is the negative of the gradient of the energy plot at that point. The value of the charge density at each point, *r*, is the gradient of the *E*-field plot at that point. This is shown in the idealized curves in figure 1.

The two layers of opposite charge density (the DL) are necessary to produce the compound shaped voltage curve between points c and e. The current that the plasma carries sustains the charge separation in the DL. Irving Langmuir[5] discovered the requirement that in order to sustain this separation of charge, the current densities of the positive-ion and electron flows across it are such that: (electron current / ion current)^2 = ion mass/electron mass which in the case of simple hydrogen means that i_e must be approximately 43 times i_{+ion}. This requirement is easily met in laboratory plasmas wherein DLs are often observed.

Because the DL is located between points c and e, a +ion to the right of point e senses no electrostatic force from +ions to the left of point c. Electrostatic effects in the primary plasma (corona) and the secondary plasma (photosphere) are effectively insulated from each other by the presence of the DL.

B. *Derived Properties*

The voltage plot in figure 1 is valid for positively charged particles. Because a positive ***E***-field represents an outward radial force per unit charge on any such particle, the region wherein the ***E***-field is negative (a to b) constitutes an inward force. This region of the lower photosphere is, thus, an energy barrier that positive ions must surmount in order to escape the body of the Sun. Any +ions attempting to escape outward from within the Sun must have enough energy to get over this energy barrier. Thus, the presence of the single positive charge layer at the bottom of the tuft plasma serves as a constraint on the unlimited escape of +ions from the surface of the Sun.

In the case of a sunspot, however, the granule (photospheric tuft) disappears. Therefore at sunspot umbrae the restraining mechanism provided by the voltage rise (a to b in figure 1) is unavailable to hold back a flood of +ions from escaping from the body of the Sun. Instead of rising to the level shown from points b to c, the voltage simply decays from its intersection with the vertical axis exponentially downward. Evidence of such a flooding is made obvious in images taken of the photosphere, the chromosphere and the lower corona – all in the same area of the solar surface. Such images were obtained by the SOHO - MDI / EIT consortiums and the Yohkoh / SXT Project. The x-ray image of the lower corona shows brilliant radiation directly above the location of the sunspot seen in the photosphere image. The flood of accelerating positive ions escaping from sunspots is colliding with atoms in the corona and is emitting x-rays. In some x-ray images of the Sun, we can see "coronal holes" – large dark regions. At times of lower solar activity (sunspot minima), the holes spread over most of the corona and (in x-ray) it "switches off."

C. The Temperature Minimum Enigma

Any black-body source of radiant energy should obey an inverse square law. That is to say, the farther away a measurement is made, the less radiant energy will be received per unit area. A wood stove is hottest at its core, a bit less on its outside surface, and the radiant energy per unit area generally lessens inversely with distance. This analogy was used by Dwivedi and Phillips[6] to describe the problem of the 2 million Kelvin temperature of the Sun's lower corona: "It is as though you got warmer the farther away you walked from a fireplace."

Near the Sun's visible surface - the photosphere - its atmosphere is coolest, approximately 6000K. It is cooler at the deepest part of its sunspots. But then, with increasing distance from the photospheric surface, the temperature of the atmosphere first begins to fall off, but then reverses itself and rises smoothly – then abruptly jumps to 2 million K in the tenuous lower corona. Standard models view this temperature discontinuity as an inconvenience for which several ad hoc explanations have been offered.

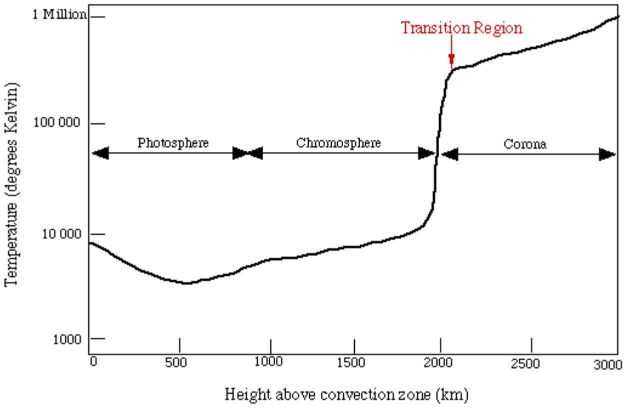

Figure 2. The temperature profile of the Sun.
(Note: The vertical axis in figure 2 is logarithmic.)
Image Credit: Big Bear Solar Observatory

It has been suggested that magnetic loops and magneto-hydrodynamic (MHD) waves throw heat out into the lower corona. The question of what mechanism converts thermal energy directly into magnetic fields inside the Sun and then performs the inverse operation in the lower corona remains unanswered. Dwivedi and Phillips state as much: "Astronomers have implicated magnetic fields in the coronal heating; where those fields are strongest, the corona is hottest. Such fields can transport energy in a form other than heat, thereby sidestepping the usual thermodynamic restrictions. The energy must still be converted to heat, and researchers are testing two possible theories: small scale magnetic field reconnections the same process involved in solar flares – and magnetic waves." The notion that magnetic field lines reconnect is impossible to reconcile with Maxwell's equation ($\nabla \bullet B = 0$). Magnetic field "lines" do not actually exist in three-dimensional space and therefore cannot move. They are simply graphic artifices to aid visualization of the field's strength and direction. A magnetic field is a continuum, not a set of discrete lines.

D. The DL Mechanism

Charged particles do not experience external electrostatic forces when they are in the range b to c in figure 1 - within the photosphere plasma. Only diffusion motion and random thermal movement occurs. Temperature is simply the measurement of the violence of such random movements. This is where the Sun's 6,000 K surface temperature is measured. The top plot in figure 1 shows that positive ions have their maximum electrical potential energy when they are in this photospheric plasma. But their kinetic (thermal) energy is relatively low. At a point just to the left of point c, any random movement toward the right, radially outward, that carries a + ion even slightly to the right of point c will result in it's being swept away, down the energy hill, toward the right. This movement of charged particles due to an ***E***-field constitutes a drift current. This current of accelerating positive ions becomes a constituent of the solar wind.

As positive ions begin to accelerate down the steep potential energy gradient from point c through e, they convert their high electrical potential into kinetic energy – they gain extremely high outward radial velocity and lose side-to-side random motion. Thus, they become de-thermalized. In this region, in the upper photosphere and lower chromosphere, the movement of these ions becomes highly organized (parallel). This is the location of the temperature minimum.

E. The Transition Zone

When these rapidly traveling + ions pass point e and leave the chromosphere they move beyond the intense radially directed ***E***-field force that has been accelerating them. Because of their high kinetic energy (velocity), any collisions they have at this point with other ions or with neutral atoms are violent and create high amplitude random motions, thereby re-thermalizing the plasma to a higher level than it was in the photospheric tufts (in the range b to c). Thus, when +ions fall through the voltage drop contained in the chromosphere, they convert the high electrical potential energy they had in the photosphere into kinetic thermal energy. This kinetic energy of the +ions is released into the lower corona by collisions with the ions and atoms there. This is what is responsible for the high temperature observed in the lower corona. This is the site at which x-ray emissions are observed to occur.

F. Evidence of the DL's Existence

Ions just to the right of point e are reported to be at temperatures of 1 to 2 million K. Nothing else but exactly this kind of mechanism could be expected from the anode tuft - double layer model. The re-thermalization takes place in a region analogous to the turbulent white water that boils up at the bottom of a smooth laminar water slide. In the standard models no such phenomenon exists - and thus neither does a simple explanation of the temperature discontinuity.

III. FLUCTUATIONS IN THE SOLAR WIND

Fluctuations in the velocity of solar wind ions have long been observed over the range of from several seconds to several days [7]. The power spectral density of these fluctuations generally decreases exponentially with their duration. However, in May of 1999 the solar wind completely stopped for about two days. The standard solar model has no ready explanation for what causes these variations. Outside the plane of the ecliptic the solar wind is steady and rapid, at speeds between 600-800 km/s; this is called the fast solar wind and it is known to emanate from solar coronal holes. In the plane of the ecliptic, near the heliospheric current sheet, the wind is slower, denser, and more variable, with typical speeds between 200 and 600 km/s and fluctuations of two or more per day. This is called the slow solar wind and its location of origin on the Sun is less well known.

IV. TRANSISTOR ACTION AS A POSSIBLE CAUSE

Perhaps the single most interesting property of the three plots presented in figure 1 is that they are almost identically the plots of energy per unit charge (voltage), electric-field strength, and charge distribution found in a solid-state *pnp* transistor. Of course in that solid-state device there are different things going on at different energy levels (in the valence band and in the conduction band) within a solid crystal. In the solar plasma there are no fixed atomic centers, and so there is only one energy continuum in which things happen.

In a transistor, the amplitude of the collector current (analogous to the drift of +ions in the solar wind toward the right) is easily controlled by raising and lowering number of charge carriers injected into the base region. This is controlled on the macroscopic level by externally adjusting the difference between the energy levels at points a and b (the base-emitter voltage). Is the same mechanism (a voltage fluctuation between the anode-Sun and its photosphere) at work in the Sun?

For example, if the Sun's voltage with respect to the heliopause were to decrease slightly, say because of an excessive flow of outgoing +ions, the voltage rise (the energy barrier) from point a to b in the energy diagram of figure 1 would increase in height and so reduce the solar wind flux thus providing a negative feedback effect.

The analogy is that the body of the Sun serves as the emitter of a *pnp* juction transistor. The photosphere serves as the base, and the lower corona serves as the collector. As with any analogy, these broad similarities can be overworked (and should not be). But similar causes and effects in different applications do often offer insights into solutions that are otherwise elusive. The ability of digital transistor circuits to “cut-off” the collector current and the ability of the described mechanism in the Sun's atmosphere to cut off the solar wind are examples of such an analogy.

V. FUSION IN THE DOUBLE LAYER

The z-pinch effect of high intensity, parallel current filaments in arc mode plasma is very strong. Nuclear fusion may well be taking place within the DL above the photosphere. The result of this fusion process may be the metals that give rise to absorption lines in the Sun's spectrum. Traces of sixty-eight of the ninety-two natural elements are found in the Sun's atmosphere. Most of the radio frequency noise emitted by the Sun emanates from this region. Radio noise is a well-known property of DLs.

The electrical power delivered to the plasma at any point is the product of the ***E***-field (Volts per meter) times current density (Amps per square meter). This product yields power density (Watts per cubic meter). The current density is relatively constant over the height of the photospheric / chromospheric layers. However, the ***E***-field is by far the strongest at the center of the DL. Nuclear fusion requires high levels of power – and that power is available in the DL.

It has also been reported [8] that the neutrino flux from the Sun may vary inversely with sunspot number. This is to be expected in the solar DL hypothesis if the source of those neutrinos is z-pinch produced fusion that is occurring in the double layer – and sunspots are locations where there is no DL in which this process can occur.

VI. SUMMARY

The failure of the hypothetical magnetic reconnection mechanism to explain several observed solar phenomena is clear. A three-layer charge density structure, similar to the SL, DL anode tufting combination that is familiar to plasma engineers is a hypothesis that offers a reasonable explanation of the temperature minimum at the base of the corona and also the as-of-yet otherwise unexplained fluctuations in the amplitude of the solar wind.

REFERENCES

[1] J.D. Scudder., “The cause of the coronal temperature inversion of the solar atmosphere and the implications for the solar wind.” Solar Wind Seven; Proceedings of the 3rd COSPAR Colloquium, Goslar, Germany, Sept. 16-20, 1991 (A93-33554 13-92), p. 103-112.

[2] D.H. Hathaway, “The Transition Region” Available: http://solarscience.msfc.nasa.gov/t_region.shtml

[3] H. Alfvén, “Double Layers and Circuits in Astrophysics.” *IEEE Trans. On Plasma Sci.* Vol PS-14, No. 6. Dec. 1986 pp. 779-793.

[4] H. Alfvén, *Cosmic Plasma*, 1981 D. Reidel Pub. p.12-13.

[5] I. Langmuir, Physical Review (1929).

[6] B. Dwivedi and K. Phillips, "The Paradox of the Sun's Hot Corona", *Scientific American*; June 01, 2001.

[7] Available: http://spacephysics.ucr.edu/index.php?content=solar_wind/proc/p1.html

[8] K. Sakurai (Kanagawa Univ.), *Nature* 278, 146, 8 March 1979.

[9] D.E. Scott, “Real Properties of Electromagnetic Fields and Plasma in the Cosmos”, *IEEE Trans. On Plasma Sci.* July 2007.

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