A Note on the Acceleration of the Solar Wind

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Abstract: The solar wind (SW) has several enigmatic properties among which is the unexplained high maximum velocity of the fast SW (~ 800 km/s). Additionally, after leaving the Sun, this stream of charged particles accelerates – increases its velocity. Previously proposed mechanisms have not fully explained how this increasing velocity can occur nor how it can attain its high final value. A numerical analysis is performed on an assumed fast solar wind velocity profile that quantitatively identifies the acceleration experienced by a proton within that wind as a function of its radial distance. An electric-field strength required to produce the assumed acceleration of such singly charged particles is also quantitatively determined, presented and discussed. The application of Maxwell's equations to a non-quasi-neutral plasma identifies the shape of a solely positive (+ion) charge density that will produce this electric field in a spherical geometry such as the one in which the Sun finds itself.

1. Introduction

Charged particles (both electrons and positive ions) stream from the Sun in what has become known as the solar 'wind'. There are at least two different categories of this flow[1], the slow solar wind and the fast solar wind. These variations are described, in the accepted view, as follows:

1. The slow solar wind generally comes from lower solar latitudes. The *slow solar wind of the minimum type* originates from above the more active regions on the Sun. The low helium content in this type of solar wind indicates a greater release height. It is not clear yet how the slow solar wind can be released at all. The *slow wind of the maximum type* emerges from substantially larger areas distributed all over the Sun. It contains twice as much helium as the minimum type. Typical values: Velocity = 250-400 km/s and Proton density = 10.7 cm^{-3}. The plasma of the slow solar wind resembles the composition of the photosphere.
2. The fast solar wind apparently emanates from magnetically open coronal holes which are representative of the inactive Sun, i.e. the 'quiet' Sun. Consistently, the 'quiet' type solar wind is found in high-speed streams. Although the major coronal holes usually cover the polar caps at latitudes beyond 40–60°, the solar wind emerging there over-expands significantly and fills up all the heliosphere except for the 40° wide streamer belt close to the heliomagnetic equator. Typical values: Velocity = 400-800 km/s and Proton density = 3.0 cm^{-3}. Its composition resembles that of the corona.

Note that the fast solar wind has a maximum velocity roughly twice that of the slow wind, but its density is less than a third of the slow wind. The problem referred to in 1., above, of "how the slow wind can be released at all" is because, given the Sun's gravity, its constituents theoretically cannot achieve 'escape velocity[2]' which is approximately[3] 619 km/s.

2. Measurements of the Solar Wind

Quantitative data on the velocity profiles of both of these variants of the solar wind have been obtained from a few *in situ* observations but predominantly from inferred measurements. It is well known that the velocities of both types of wind increase (accelerate) with distance from the Sun. Finding a consistent explanation of why, and how this acceleration occurs has been an elusive goal.

Probes that have approached (or will approach) the Sun closely are:

- Luna 1 (1959), Earth to Moon mission. Confirmed the existence of the solar wind.

- Mariner 2 (1962). Mission to Venus. No quantitative solar wind measurements taken.
- Mariner 10 (1973). Flew near to Mercury which is 85 solar radii (SR) . No quantitative solar wind measurements taken.
- Helios (1976), approached to within 0.29AU= 63.8 SR. Measured solar wind. Found 15 times as many micrometeorites at 0.29 AU than near Earth's orbit.
- MESSENGER (2012). Mission to Mercury. No quantitative solar wind measurements taken.
- Bepi-Columbo (2015?). Mission to Mercury. No quantitative solar wind measurements are planned.
- Solar Probe Plus (2018?), 8.5 SR. Quantitative solar wind measurements planned, but not closer than 8.5 SR.

All of these were (will be) in essentially equatorial orbits that do not reach higher solar latitudes (the location of the fast solar wind).

In 1990, the Ulysses probe was launched to study the solar wind from high solar latitudes. Ulysses did get into high solar latitudes (see figure 1), but only at great distances from the Sun – locations where maximum solar wind velocity had already been attained (where the acceleration had essentially stopped).
Indirect (inferred) 'measurements' include:

- Monitoring the activity of the auroras.
- Measuring the velocity of solar flares and CMEs.
- Radio scintillation studies.

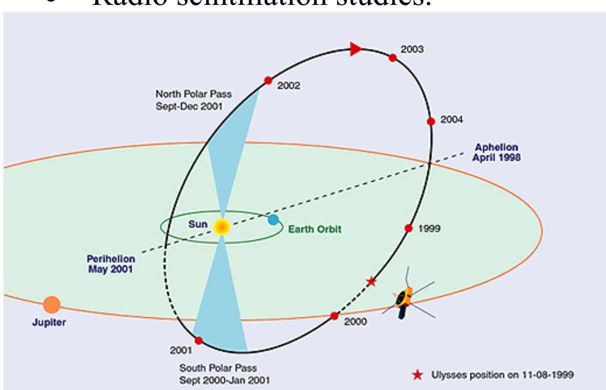

Figure 1. Ulysses' orbit.

3. Earlier Models of Solar Wind Velocities

Helio-astronomer Eugene Parker developed a model[4] that attempted to explain the acceleration of the fast solar wind. It was based on the ideas of Sidney Chapman and involved hydrodynamics, but not electro-dynamics. "Parker modeled the solar wind as a steady-state outflow. His model assumes that the solar wind flux behaves like an ideal gas expanding ***isothermally*** into a vacuum. The pressure contribution of the magnetic field is neglected. The solar wind flux velocity as a function of radial distance is obtained from Euler's equation of motion and the equation of continuity, assuming spherical symmetry and steady state (with all time derivatives equal to zero)." Parker's model did not achieve universal acceptance. One paper stated[5], "However, the acceleration of the fast wind is still not understood and cannot be fully explained by Parker's theory." Pressure implies collisions between particles, but the corona is essentially collisionless[6] plasma. Additionally, the Sun's lower corona is not a good location to assume isothermal reactions. Temperatures there vary from ~ 6,000 Kelvin to over 2 million K in a relatively short distance.

A letter to the journal *Nature*[7] offered this comment:

> "The solar wind is a supersonic outflow of coronal plasma into interplanetary space, and is the agent that carries solar disturbances to the Earth. Direct measurements of the wind speed over a range of distances—from the orbit of Mercury to beyond the outermost planets and now over the solar poles – show that the acceleration is largely complete by 70 solar radii (SR). But, there are no direct measurements nearer the Sun with which to constrain theoretical models of the acceleration. In principle, the speed of the solar wind in the acceleration region can be inferred by indirect methods such as radio scattering, but this is not straightforward as these data provide a measure of the wind properties integrated along the lines of sight. Here we report radio-scattering measurements of the speed of the south polar stream which have been corrected for this path integration, and also for the potential bias due to the presence of plasma waves. Our results indicate that the acceleration of the polar wind is almost complete by 10 SR much closer to the Sun than had been expected. This suggests that ***the acceleration of the solar wind and the heating of the solar corona occur in essentially the same region, and thus that the underlying mechanisms may be strongly linked.***" [Emphasis added.]

Then, in the late 1990s[8], the Ultraviolet Coronal Spectrometer (UVCS) instrument on board the SOHO spacecraft observed the acceleration region of the fast solar wind emanating from the poles of the sun, and found that the wind accelerates much faster than can be accounted for by thermodynamic expansion alone. Parker's model predicted that the wind should make the transition to supersonic flow at an altitude of about 4 solar radii from the photosphere; but the transition (or 'sonic point') now appears to be much lower, perhaps ***only 1 solar radius*** **above the photosphere,** ***suggesting that some additional mechanism accelerates the solar wind away from the sun.*** [Emphasis added.]

4. Present Modeling of the Solar Wind

More recently, in 2005, investigators at L'Observatoire de Paris have stated[9]:

> "It has been more than four decades since the existence of the solar wind has been confirmed by the measurements of the Mariner 2 spacecraft. However, the solar wind's acceleration at supersonic speeds of about 700-800 km/s still remains unexplained. Parker's theory, based on thermal conduction, results in a very low speed; this led most of the scientists to look for an additional form of energy in order to explain this acceleration. A team of astronomers working at LESIA[10] at the Paris Observatory has proposed an alternative theory based on the role of electrons that are not in thermodynamic equilibrium; these electrons would be the main driving force of the acceleration. This approach explains, for the first time, the fast solar wind without any assumption of additional energy."

The LESIA group was the first to offer a model of SW acceleration that includes electrical effects. This can be considered a breakthrough. The LESIA data, shown below in figure 2, is clearly presented and that is the reason it is used as the basis for the numerical computations that are presented here. However, the calculations being presented here do not support the LESIA conclusion that negative charges (electrons) are involved in the acceleration process.

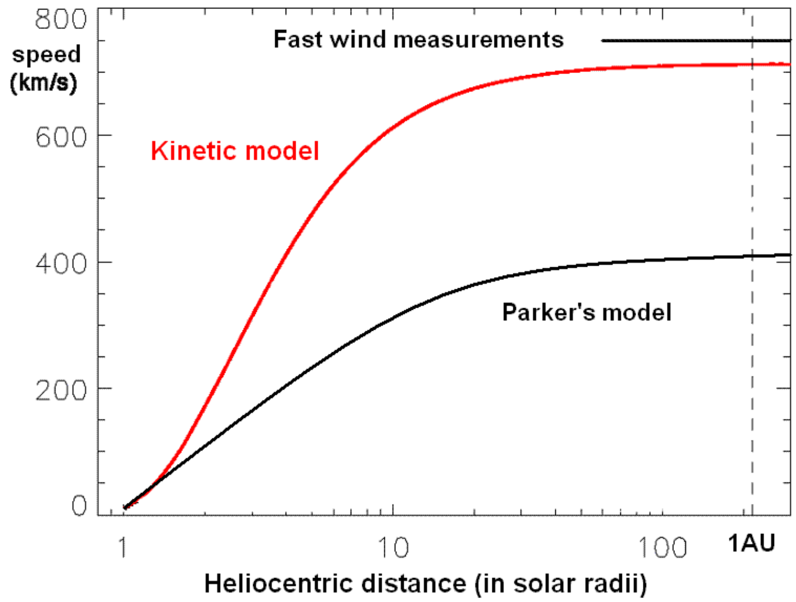

Figure 2. Solar wind speed profile derived by the LESIA group as a function of the heliocentric distance. The upper (Kinetic model) curve shows the result of their model. The lower curve shows an example of Parker's model.

For reference, the orbital distances of Mercury, Venus, and Earth are as follows:

	SR	AU
Mercury	84.97	0.387
Venus	158.74	0.723
Earth	220	1

The LESIA data (Kinetic model curve above) exhibits a non-monotonic[11] inflection point which gives rise to an acceleration maximum at very low (but greater than $r = 1$ SR) radial heliocentric distance.

On March 8, 2013 NASA announced[12] they had discovered the source of the acceleration of the solar wind. They used data from a older probe named Wind that has been at the Earth-Sun Langrange point, L1, since 2004 (originally launched in 1994). Although this probe has never approached the regions where solar wind acceleration occurs, the release confidently stated:

> "The source of the heating in the solar wind is ion cyclotron waves. Ion cyclotron waves are made of protons that circle in wavelike-rhythms around the sun's magnetic field. According to a theory developed by Phil Isenberg (University of New Hampshire) and expanded by Vitaly Galinsky and Valentin Shevchenko (UC San Diego), ion cyclotron waves emanate from the sun; coursing through the solar wind, they heat the gas to millions of degrees and accelerate its flow to millions of miles per hour."

Charged particles moving within a magnetic field will revolve (as they do in a cyclotron) at what is called the gyroradius or Larmor radius. At higher energies such oscillations give rise to what is termed *magnetobremsstrahlung* or *synchrotron radiation*[13]. This circular component of the motion of electrically charged particles moving in a magnetic field is what gives rise to the helical shape of Birkeland currents. The NASA release went on to say, "Chemical elements of the solar wind such as hydrogen, helium, and heavier ions, blow at different speeds; they have different temperatures; and, strangest of all, the temperatures change with direction. We have long wondered why heavier elements in the solar wind move faster and have higher temperatures than the lighter elements … This is completely counterintuitive." It certainly is.

What should be expected from any collisional source of acceleration is that the affected particles ought to be accelerated inversely as their masses. Something with three times the mass of a test particle ought to be accelerated only one third as much as the test particle.

However, a possible cause of heavier ions moving faster than expected (almost as rapidly as, say, monatomic hydrogen) is that they can become multiply ionized – the heavier the ion, the more the opportunity to do so. But NASA does not mention any *electric-field* forces which might help to resolve the 'counterintuitivity' of their observations. They suggest that plasma waves have the ability to selectively accelerate massive particles more strongly than less massive particles. Their description of the exact process remains somewhat superficial, however.

Nevertheless, NASA has now put forth the idea that 'ion cyclotron waves' produce the acceleration of the solar wind despite the fact that three years ago, in a 2010 paper,[14] D.A. Roberts stated explicitly that "hydromagnetic waves, whether turbulent or not, cannot produce the acceleration of the fast solar wind and the related heating of the open solar corona. … In particular, turbulence does not play a strong role in the corona as shown both by observations of coronal striations and other features, … We consider possible 'ways out' of the arguments presented, and suggest that in the absence of wave or turbulent heating and acceleration, ***the chromosphere and transition region become the natural source****, if yet unproven, of open coronal energization through the production* **of nonthermal particle distributions**." [Emphasis added.]

5. A Numerical Analysis of the LESIA Solar Wind Profile

Although figure 2, above, does not represent actual observed data, it is the velocity profile generated by the LESIA group's model. We accept it as being a reasonable approximation of real data and use it to determine a quantitative account of the acceleration experienced by the ions in the fast solar wind. In the work presented here, the heliocentric distance is denoted as either r or x. The LESIA figure shows velocity as a function of distance, not time. Therefore, the slope of that curve cannot be used directly in determining the acceleration which is $a(t) = {dv}/{dt}$, not ${dv}/{dx}$. If the upper curve in the figure is sampled at each of the distances plotted logarithmically along the x-axis, we obtain the first two columns (A and B) in Table 1. The remaining columns are defined below the table.

Table 1 Numerical Analysis of the Velocity of the Solar Wind Presented in LESIA's Kinetic Model (Figure 2)

A	B	C	D	E	F	G	H	I	J	K	L	M
X (SR)	Vel (km/s)	Delt x (SR)	Delt x (km)	x (km)	x (m)	t (This segment)(s)	t (Total) (s)	t (To)(days)	Del Vel (km/s)	Acc (km/s^2)	Acc (m/s^2)	E (v/m)
1	10	1	681342	681342	6.81E+08	68134	68134	0.789	10	1.47E-04	0.147	1.47E-09
2	170	1	681342	1.36E+06	1.36E+09	4008	72142	0.835	160	3.99E-02	39.92	3.99E-07
3	315	1	681342	2.04E+06	2.04E+09	2163	74305	0.860	145	6.70E-02	67.04	6.70E-07
4	410	1	681342	2.73E+06	2.73E+09	1662	75967	0.879	95	5.72E-02	57.17	5.71E-07
5	470	1	681342	3.41E+06	3.41E+09	1450	77417	0.896	60	4.14E-02	41.39	4.13E-07
6	520	1	681342	4.09E+06	4.09E+09	1310	78727	0.911	50	3.82E-02	38.16	3.81E-07
7	550	1	681342	4.77E+06	4.77E+09	1239	79966	0.926	30	2.42E-02	24.22	2.42E-07

8	580	1	681342	5.45E+06	5.45E+09	1175	81140	0.939	30	2.55E-02	25.54	2.55E-07
9	595	1	681342	6.13E+06	6.13E+09	1145	82285	0.952	15	1.31E-02	13.10	1.31E-07
10	610	1	681342	6.81E+06	6.81E+09	1117	83402	0.965	15	1.34E-02	13.43	1.34E-07
20	675	10	6813420	1.36E+07	1.36E+10	10094	93496	1.082	65	6.44E-03	6.44	6.43E-08
30	690	10	6813420	2.04E+07	2.04E+10	9875	103371	1.196	15	1.52E-03	1.52	1.52E-08
40	698	10	6813420	2.73E+07	2.73E+10	9761	113132	1.309	8	8.20E-04	0.82	8.19E-09
50	705	10	6813420	3.41E+07	3.41E+10	9664	122797	1.421	7	7.24E-04	0.72	7.23E-09
60	710	10	6813420	4.09E+07	4.09E+10	9596	132393	1.532	5	5.21E-04	0.52	5.20E-09
70	712	10	6813420	4.77E+07	4.77E+10	9569	141962	1.643	2	2.09E-04	0.21	2.09E-09
80	715	10	6813420	5.45E+07	5.45E+10	9529	151492	1.753	3	3.15E-04	0.31	3.14E-09
90	718	10	6813420	6.13E+07	6.13E+10	9489	160981	1.863	3	3.16E-04	0.32	3.16E-09
100	720	10	6813420	6.81E+07	6.81E+10	9463	170444	1.973	2	2.11E-04	0.21	2.11E-09
200	725	100	68134200	1.36E+08	1.36E+11	93978	264422	3.060	5	5.32E-05	0.05	5.31E-10

Definition of the columns in Table 1:
C = Distance increment between points in solar radii (SR).
D = Distance increment between points (km).
E = Total radial distance measured from the Sun's center (km).
F = Total radial distance measured from the Sun's center (m).
G = Time taken by a particle to go from the previous point to this point, $\Delta t = \Delta x/v$ = km/(km/sec) = sec $= D_n/B_n$.
H = Total time (sec) taken for the particle to get to this point.
I = Total time (days) taken for the particle to get to this point.
J = Gain in velocity from last point to this point $= B_n - B_{n-1} = \Delta v$ (in km/s).
K = Acceleration $= \Delta v/\Delta t = J_n/G_n$ (in km/s^2).
L = Acceleration $= \Delta v/\Delta t = J_n/G_n$ (in m/s^2).
M = Electric field strength under the assumption that $f = eE = m_p a$. $M_n = E = m_p a/e = (1.6\times10^{-27}/1.60\times10^{-19})L_n$.

Plotting the first three points in column L, acceleration in m/sec^2, we see an essentially linear relationship of acceleration to distance at low altitudes above the solar surface:

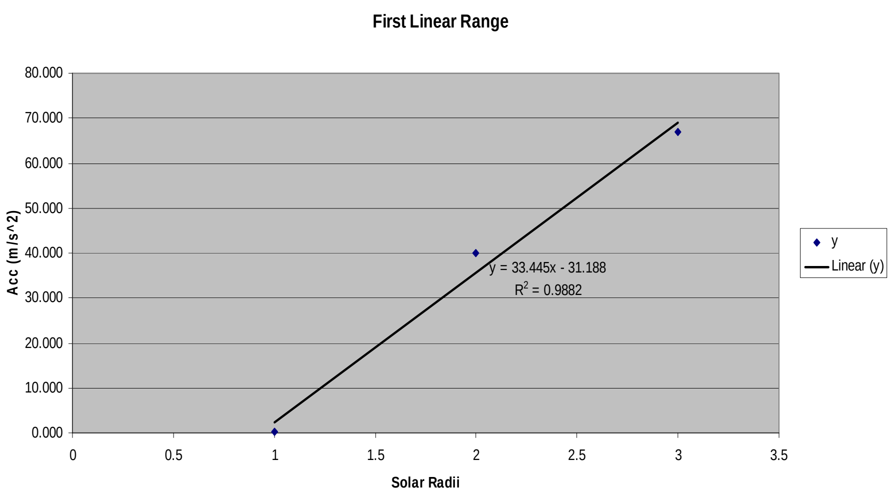

Figure 3. Acceleration as a function of radial distance from the photospheric surface of the Sun up to 3 SR.

The plot in figure 3 is monotonic and (almost) linear with a high value of R^2, the coefficient of determination. For greater radial distances, r > 3 SR, the acceleration plot is monotonically decreasing as is shown in figure 4.

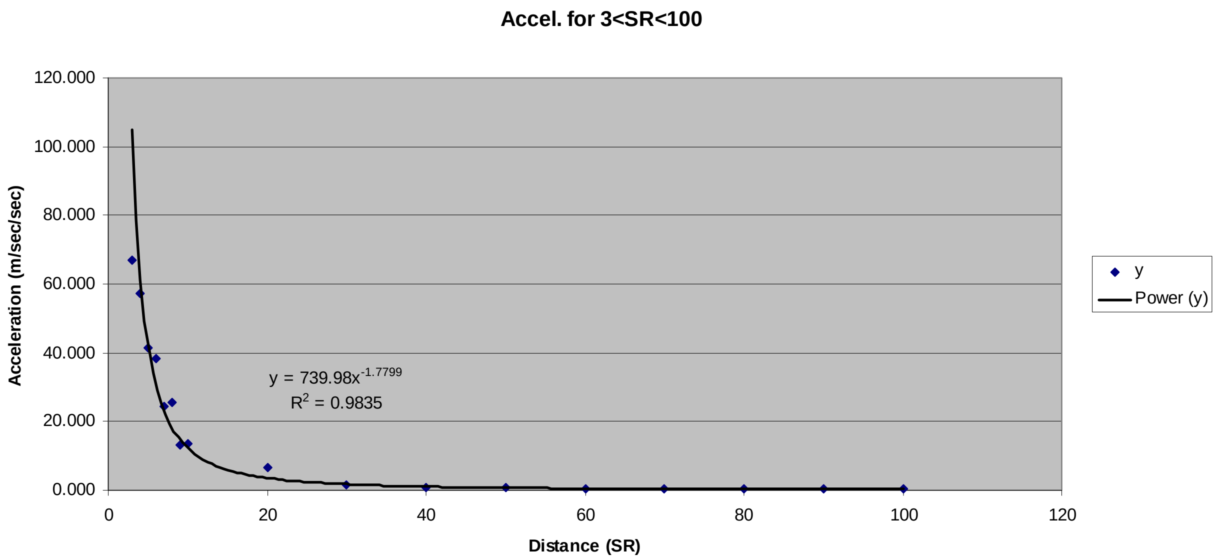

Figure 4. Acceleration of the fast solar wind for distance, 3SR < *r* < 100 SR.

From this data, the acceleration experienced by a solar wind particle may be described[15] as:

$$a(r) = 33.445r - 31.188 \;\text{ for } 0 < r < 3 \text{ SR} \tag{1}$$

and

$$a(r) = 739.98r^{-1.7799} \;\text{ for } r > 3 \text{ SR} \tag{2}$$

We assume the LESIA data is an accurate description of fast SW velocity but our use of it is, of course, subject to any errors in our sampling process or subsequent computations. Subject to these caveats, we will assume expressions (1) and (2) represent typical approximate data about the acceleration of the fast solar wind. We can thus assume (using $f = ma$) that we now know the applied accelerating force as a function of radial distance, $f(r)$. However, these expressions do not suggest a mechanism for achieving this force or acceleration.

6. An Electrical Mechanism

When seeking an effective mechanism for accelerating a charged particle such as a proton or other positively charged ion, an obvious idea would be to investigate the effects of the presence of an electric field. Although it is now becoming accepted that low valued ***E***-fields can exist within plasma, such a possibility has been a historical anathema in astrophysics. This author has written about this as follows[16]:

> Some early plasma researchers and many modern astrophysicists believe that plasmas are perfectly conductive and so will 'freeze' magnetic fields within them. The typical plot of plasma voltage vs. current demonstrates that this cannot happen. Every point on the plot (except the origin) has a non-zero voltage coordinate. In other words, it requires a small electric field within a plasma (no matter what mode it is in) to maintain it. No matter in which mode it is operating, plasma is not an ideal conductor.
>
> Another way of realizing this is to examine the resistivity of plasma. Consider the typical *VI* plot shown in figure 5. The ***static resistivity*** of a plasma at any *V-I* operating point is equal to the slope of a straight line drawn from the origin of the volt/ampere plot out to that point. This means that, in every possible mode in which a plasma can operate, it has, in all of them, a non-zero static resistivity. A non-zero-strength ***E***-field is necessary to produce the current density. For example, the static resistivity of a plasma in the high current end of the dark mode can be fairly large. In the arc mode, static resistivity is typically extremely low – but not zero. The highest conductivity (lowest static resistivity) plasmas are those operating in the arc mode. But even in that mode, any current density, no matter how small, requires a non-zero-valued electric field. No plasma is an 'ideal conductor.'

Many astrophysicists assume that Debye shielding is 100.000% effective in plasma at all scales. However there are some exceptions to that generalization. Goedbloed[17] and Poedts in their text on MHD (2004) stated: "By definition, plasmas are an interactive mix of charged particles, neutrals, and fields that exhibits collective effects. In plasmas, charged particles are subject to long-range, collective Coulomb interactions with many distant encounters. Although the electrostatic force drops with distance ($\sim 1/r^2$), the combined effect of all charged particles might not decay because the interacting volume increases as r^3."

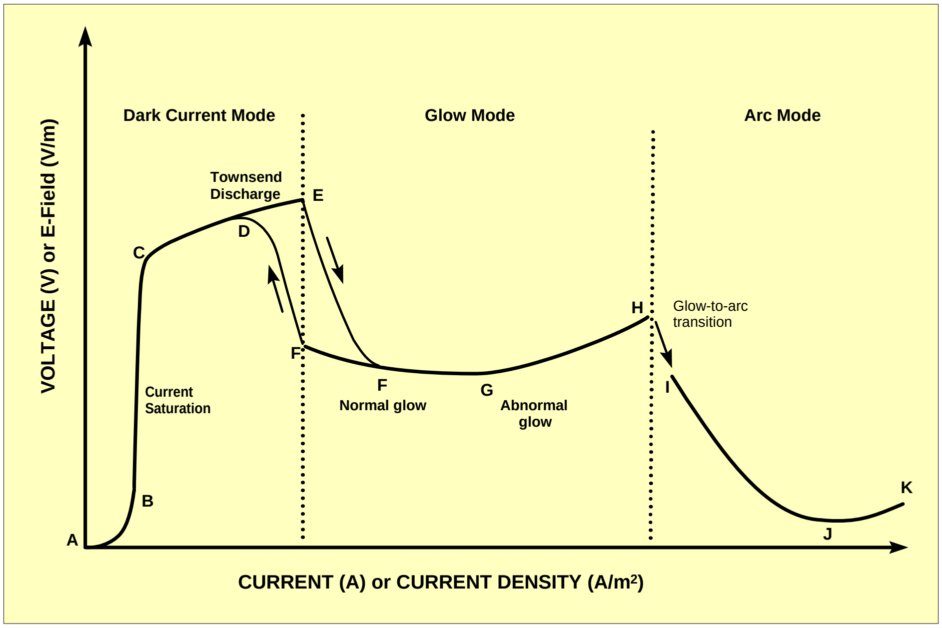

Figure 5. A typical static, plasma discharge, volt-ampere plot. This is representational of both the overall terminal *VI* plot of a laboratory discharge and the point description of *E*-field vs. current density within the plasma.

Under the influence of an electric field, the force of acceleration, f_a, on an electronic charge, e, is $f_a = eE = ma$, so the electric field required to produce an acceleration, a, of a proton is:

$$E(r) = \frac{m_p}{e} a(r) . \tag{3}$$

The ***E***-field values required by equation 3 are tabulated in column M in Table 1. We propose that mechanism as being the accelerating force for positive ions in the solar wind.

Note the extremely low numerical values in that column. The maximum value of required electric field strength occurs at approximately 3SR and is ~0.7 μV/m. This is because of the extreme effectiveness of the electric force in accelerating charged particles. These values are so low that heavier (more massive) ions would still be accelerated by what would be considered surprisingly low ***E***-field strengths. And as noted earlier, when heavier elements are completely ionized (as most are in the corona) they carry multiple positive charges and thus experience higher accelerating forces than do single protons. This does not explain NASA's observation that, "We have long wondered why heavier elements in the solar wind move faster and have higher temperatures than the lighter elements … This is completely counterintuitive." But, the acceleration of an ionized atom varies as the charge to mass ratio, q/m. Heavier ions will not be as strongly accelerated as a lone proton, but they will be much more rapidly accelerated by an electric field than they would be by any non-electrical force which would produce an acceleration proportional only to $1/m$.

An electric field that exists because of the presence of an electric charge distribution, $\rho(r)$, obeys Maxwell's equation, Div $E = \rho/\varepsilon$. In the spherical geometry of the Sun's surroundings[18,19], this is given by:

$$div\overline{E} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 E_r\right) + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}\left(E_\theta \sin\theta\right) + \frac{1}{r\sin\theta}\frac{\partial E_\varphi}{\partial\varphi} = \frac{\rho(r,\theta,\varphi)}{\varepsilon} \tag{4}$$

where ε is the permittivity of the plasma medium.
In the case where there is no azimuthal nor altitudinal variation, (4) becomes

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 E(r)\right) = \frac{\rho(r)}{\varepsilon} \tag{5}$$

Because of inherent imprecision in present evaluations of the permittivity of the plasma near the Sun, we must leave ε as an unevaluated multiplicative constant. The permittivity value may be a variable as well. Therefore, we can determine only the functional shape of $\rho(r)$[20] from (2), (3) and (5) above, not the numerical value of its density. This results in:

$$\rho(r) = 100 - \frac{62}{x} \text{ for } 1 < r < 3 \text{ SR} \tag{6}$$

and

$$\rho(r) = 1675x^{-2.7799} \text{ for } 3 < r \text{ SR} \tag{7}$$

These expressions describe a positive charge density that approaches zero asymptotically. See figure 6.
R.R. Grail[21] stated that "Our results indicate that the acceleration of the polar wind is almost complete by 10 SR much closer to the Sun than had been expected." The present work agrees well with that comment.

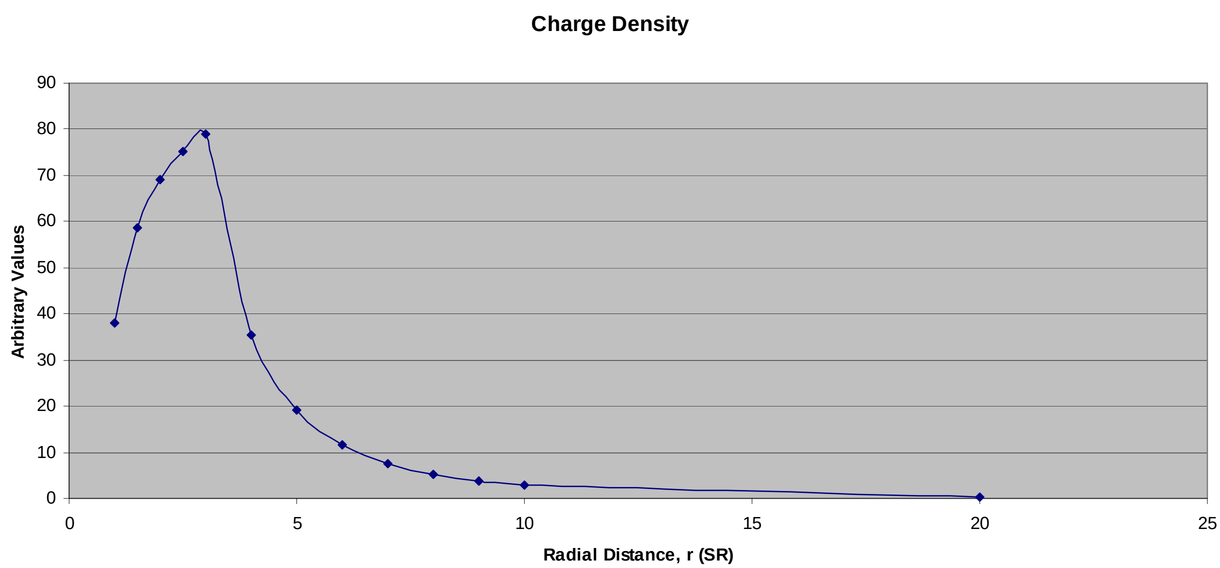

Figure 6. Charge Density as a function of radial distance from the Sun's center. Vertical axis values are arbitrary.

We conclude from the above discussion that the charge density shown in figure 6 and enumerated in expressions (6) and (7) creates an electric field (which is the force per unit charge on the particles in the solar wind). This force produces the acceleration on a proton shown in figures 3 and 4 and as described by expressions (1) and (2). This, in turn, produces the velocity profile predicted by LESIA shown in figure 2.

It is important to note that the required charge density as shown in figure 6 is everywhere greater than zero. Thus, only positive charges (+ions) are involved in the acceleration mechanism. No participation of electrons in the required charge distribution is indicated.

7. An Extension of the Electronic Sun Hypothesis

It is not the purpose of this work to present a description of the Electronic Sun (ES) hypothesis[16,18] . However, it should be pointed out that the solar wind acceleration mechanism described here is an obvious consequence of that model. The ES hypothesis states that outward bound positive ions and protons (that will become constituents of the solar wind) rise up from the photosphere, accelerate through a plasma double layer (DL) and collide with neutrals, other atoms, and ions in the lower corona. Their radially directed (kinetic energy) velocity is thereby brought almost to a standstill. Electrons that were associated with these ions drift downward, back out of the lower corona, and serve to maintain the DL as per the Langmuir requirement[22]. These electrons tend to fill the 'electron trap' that is formed by the relatively high-voltage photospheric plasma granule cells. This is a probable cause of the relatively short life-times of those cells (usually measured in hours or days).

The ionic kinetic energy transformed into thermal activity at the base of the corona produces the greater than 2 million Kelvin temperatures measured there by spectroscopic observation. It also results in the almost complete ionization of the coronal plasma. But then, what happens to those positively charged ions? They are still there. These now relatively quiescent positive charges constitute the 'excess' positive charge density region (over and above the quasi-neutral charge densities of the background plasma) referred to in the above discussion and shown in figure 6.

8. Stability of the 'Excess' Positive Charge Density

A question that might be asked by critics of this proposed mechanism for producing the required electric field strength is, "What maintains the positive charge density in the shape that it must maintain (shown in figure 6)?" To maintain a distribution of matter that is more concentrated than it would normally be in quiescent conditions, there must be a power input to it. A case-in-point is the steady state large standing-wave that can form at the bottom of certain water slides. In figure 7, the wave would collapse if the strong flow coming in from the left were to stop. The height of the water wave is higher than what would be expected in a more slowly moving river. A continuous flow of ions maintains the 'excess' charge density in figure 6.

Figure 7 Continuously stable standing-wave maintained by the flow coming in from the left.

9. Summary of Results

The purpose of this paper is to present a numerical analysis technique and the application of Maxwell's equations to a sample solar wind velocity profile that was generated by a model[9] developed by the LESIA group at the Observatoire de Paris. It is not real solar wind speed data but, it is typical of solar wind velocities described in other publications[23]. As more accurate, real velocity data become available in the future, the numerical technique described here can easily be re-applied to it. The results of this present sample analysis suggest the following conclusions:

- Including electric-field forces on the charged particles of the solar wind results in a model wherein a distribution of excess positive ions in the lower corona accelerates solar wind +ions to speeds of 700–800 km/s in the ***collisionless*** coronal plasma. Earlier models, such as Parker's that utilize only phenomena such as plasma waves, thermal turbulence, and pressure gradients, have been unable to produce these levels of acceleration and velocity. Why these mechanisms are still proposed in an acknowledged collisionless plasma is unclear.
- A proton (a positive single electronic charge) in a collisionless environment can be accelerated from rest to a velocity of 730 km/s by giving it 4.46×10^{-16} Joules of kinetic energy. This is equivalent to ~2780 eV (allowing it to fall through a voltage drop of 2780 V). A piece-wise linear integration of the ***E***-field values in column M (Table 1) yields a value of over 3000 V. This total voltage is achieved, over large distances, by ***E***-field magnitudes that do not exceed one microvolt per meter (< 1 mV/km).
- Heavier (multiply ionized) particles can achieve accelerations almost as great as single protons under the influence of such an ***E***-field. Selective acceleration of heavy ions however remains unexplained.
- Applying Maxwell's equations in their proper spherical coordinate form is shown to be essential in this geometry. Using rectangular (Cartesian) coordinates leads to a false requirement that includes negative charges – electrons – in order to explain the decrease in the wind's acceleration beyond ~3 SR. But, electrons are not involved in the accelerating mechanism derived here. Only a distribution of positive charges (protons and +ions) is required as shown in figure 6 and enumerated in expressions 6 and 7.
- Raising the question of 'escape velocity' is inappropriate in a system of electric plasma which is subject, over a great distance, to electrical forces that are much stronger than collisional forces. (See 1. in the Introduction section of this paper.) In any event a ballistic (explosive) acceleration process that would require attainment of an 'escape velocity' does not take place. An electric–field provides a continuous, smooth acceleration.
- An important value that remains unknown is the value of the permittivity of the coronal plasma which, in turn, would yield a numerical evaluation of the peak magnitude of the required charge distribution. Without it, only the general shape of this distribution can be obtained as has been done here.
- NASA's Solar Probe Plus, now scheduled for a 2018 launch, will approach the Sun to within a distance of 8.5 SR (0.034 AU = 5.9 million km). Even if the model presented here is substantially correct, the predicted radial electric field (~0.2μV/m at that location) will probably not be measurable even this close-in. It seems all or at least most of the electrical 'action' occurs closer to the body of the Sun itself.

10. Closing Remark

It is surprising that it has taken so long for the electric-field to be considered as a possible causal force in astrophysics. It was some sixty years ago that Hannes Alfvén wrote[24], "Certainly we have seen plenty of evidence of electrical phenonena out in space. Within the last few decades we have discovered several important electrical effects in the heavens: strong stellar magnetic fields such as could only be caused by large electric currents, radio waves emanating from the Sun and from many star systems, and the energetic cosmic rays, which are ***electrically charged particles accelerated to tremendous speeds***." [Emphasis added.]

The electrical mechanism presented here offers a uniquely simple and consistent explanation of what, for decades, has been an enigma in helio-astronomy – discovering and quantifying the process that causes the observed acceleration of the fast solar wind.

References and Endnotes

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