The Electric Fields and "Lightning Jets" of the Sun and Solar Wind

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Electric fields are endemic to plasmas, and are often concentrated in Sheaths, resulting in particle acceleration.

Here, electric effects are calculated for the Solar interior, photosphere, and corona, based on standard 1-D radial models by Bahcall (2005) and Fontenla (1993) and Avrett (2015).

Energetically, these electric fields can accelerate protons out of the 2keV gravity well and up to the 1.3 keV energies observed in the Solar Wind. As with Earth lightning, this acceleration occurs within an "avalanch breakdown" of resistivity, here modelled as ~10<sup>7</sup> filamentary "Lightning Jets", each of ~5.minutes duration, each charge-neutral overall.

The spatial average of these Lightning Jets provides light scattering measured for the K-Corona, and the satellite-measured characteristics of the Solar Wind.

The inevitable small charge imbalances and plasma polarization will generate strong local magnetic fields, as observed on the solar surface and in the heliosphere.

ESA / NASA Solar Orbiter and Parker Solar Probe mission statements: Big Question #1: What heats the Corona and energizes the Solar Wind ? This Answer: gravito-electric and photo-electric fields of the Solar Plasma, with Q<sub>sun</sub>~ 235. Coulombs .

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Perspective: Electro-Magnetic Plasma p+/enot Hydro-Magnetic Fluid

#### (1-D Energetics) Electric Fields of the Sun and Solar Wind



A gravitating plasma of electrons and positive ions *necessarily* develops charge separation and strong electric fields. The heavy ions are contained by gravity, but the light electrons are mainly contained by the positive radial electric field.

In the collisional fluid regime of the Core, simple e-/p+ momentum balance then requires  $eE(r) \sim \frac{1}{2} m_p g(r)$ . When several ion species are present, radial stratification by q/m alters this equation somewhat. For the Sun, the Bahcall 2005 model (24% He) develops an electric potential drop (0->Rs) of 5.kV and a charge displacement of Q~75.Coulombs. The gravitational potential drop is 8.keV/m<sub>p</sub>, with g(Rs) = 2.8eV/Mm.

Over the 2.Mm of the Photosphere, there is a rapid transition from plasma to neutral Hydrogen, and from photo-opaque to transparent.

Here, the solar energy flux  $\Gamma_{\epsilon}$  provides the dominant outward force on electrons, balanced by  $e \sim \Gamma_{\epsilon} \sigma_{\gamma e} / c$ . We model  $\sigma_{\gamma e} = 3 \times 10^4 \sigma_{T}$ .

This generates ~10.eV/Mm, levitating "runaway" protons in episodic pinched "lightning jets", spatially averaging to the Flux ~ $10^{17}$  /s.m<sup>2</sup> \*(r/Rs)<sup>-2</sup> observed by spacecraft.

The 235.C of net charge then gradually accelerates the protons to velocity  $v_w$ ~500.km/s and kinetic energy KE~1300.eV, accompanied by neutralizing electrons.

The solar light scattered from the p+/e- Wind is observed as the K-Corona, replacing the model of a hydrostatic atmosphere at ~200.eV (van de Hulst, 1950).

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### (3-D) Electric "Lightning" Jets form as "pinched p+ current" in breakdown channels



The strong outward Solar energy flux  $\Gamma_{\mathcal{E}}$  induces weak electric fields E, by displacing a small fraction (~10<sup>-36</sup>) of the plasma electrons outward. This amounts to Q ~ 75.Coul at R<sub>s</sub>. For r > R<sub>s</sub>+2.Mm, Q ~ 235.C and E(r) ~ 1.5 m<sub>p</sub>g(r), providing the electrical energy to accelerate Solar Wind protons.

As with Earth lightning, the electrical energy is released in episodic filamentary Jets, by an avalance breakdown of resistivity in the weakly ionized plasma sheath of the Photosphere.

This breakdown occurs most readily along the cool edges of surface Convection Cells [ $\# \sim 10^7$ ,  $A_{cell} \sim (0.5 \text{Mm})^2$ ], which continuously re-form every  $\sim 5.\text{minutes}$ .

"Current pinch" effects will favor small Jets (~5.km)<sup>2</sup> with energies >10.eV, glowing in the neutral background gas as "spicules" and "campfires".

Each Jet has (p+/e-) currents  $I \sim (+/-) 5 \times 10^9$  Amps, giving B < (+/-) 0.2 T, depending on species overlap.

"Failure to Launch" would result from too much neutral mass entrained in an accelerating Jet, causing an extended atmosphere of hot plasma.

Satellite-observed magnetic field fluctuations represent temporal fluctuations, dynamical intertwining, and electrical polarization of currents in the p+/e- Jets.

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v1

Electrostatic energies are included. The electron/photon cross section in Jets is  $\sigma_{\gamma\epsilon} \sim 3 \times 10^4 \sigma_T$ , where  $\sigma_T \sim 10^{-28} m^2$  (=1 barn).

Differences from prior models:

**1** The traditional "hydrostatic gas at 200.eV" model of the K-corona is *replaced* by light scattering from the (correlated) p+/e- Wind with  $\sigma_{\gamma\epsilon} \sim 10^4 \sigma_T$ , as inferred from standard Core/Photosphere models.

The Avrett semi-empirical model fits wide-ranging spectral data, extending  $n_B$  past the Photosphere to merge with "static gas" models, apparently invoking "turbulent pressure" to support the protons.

2 The pesky "temperature" jump" at ~2.Mm zHeight is replaced by the *coherent flow* energy, which follows directly from electric minus gravitational energy.

3 The "non-thermal velocity" and "reduced gravity" in the Photospheric models may represent "Failure to Launch" (returning mass), due to too much neutral gas entrained in a Jet or bundle of Jets.

	Equlibrium Stellar Fluid Eqns:	mass m <sub>p</sub> m <sub>e</sub>	charge e p <sup>+</sup>	photon $\gamma$	s			
1a	$\nabla^2 \Psi(r) = G m_p n_p(r)$	Gravity			$m_p \Psi'$	$\approx 2.8  eV/$	' Mm	$@R_s$
1 <i>b</i>	$\nabla^2 \Phi(r) = -k_1 e \left( n_p - n_e \right)$	Electric Po	otential		Gm	${n_p}^2 \sim 10^{-36}$	$k_1 e^2$	!!
2	$\nabla \bullet \Gamma_{\varepsilon}(r) = \frac{d}{dt} \varepsilon(r)$	Fusion En	ergy Flux	]	$\epsilon_{\gamma} \sim 6$	5. <i>MW   m</i>	$2^{\circ} @ R$	5
3	$-(4aT^3)T'(r) l_{\gamma} = \frac{4}{c}\Gamma_{\varepsilon}$	Thermal E	energy Dif	fusion				
40	$n [n_pT]' + n_p m_p \Psi' + (+e)n_p \Phi' = 0$	Proton	n Fluid Mo	mentum				
4 <i>b</i>	Thermo- $[n_eT]' - \frac{\Gamma_{e\gamma}}{c  l_{\gamma e}} + n_e m_e \Psi' + (-e) n_e \Phi' = 0$ Electric							
4a + 4b	$\overline{4b} \left[ (2n)T \right]' - \frac{\Gamma_{\epsilon\gamma}}{c  l_{\gamma e}} + n  m_p \Psi' = 0 $ Total (Fluid) Momentum							
4a - 4b	$\frac{\Gamma_{\varepsilon\gamma}}{cl_{\gamma e}n_e} + m_p \Psi' + (2e)\Phi' = 0$	Electric F	ield (Parti	cle)				
	$-\frac{1}{2}m_p g(r)$	$\approx eE(r)$	Gravi in hig collis	<mark>to-Electr</mark> h-densit <i>ional</i> Cor	ic A y S. e A	. Pannekoek . Rosseland ( .E. Eddingtor	1924) 1	
(particle $\sigma_{\gamma e}$ =	$\frac{1}{l_{\gamma e} n_e} \frac{1}{l_{\gamma e} n_e} \qquad \qquad$	eE(r)	Photo-E	lectric : N i.e. whe due to	Vhen "pł en γ/e- ci correlate	noton drag" o ross-section i ed e-/p+ (1 <	dominate s <i>large</i> < $\sigma_{\gamma e} < 1$	es gravity, $10^{-28}  \mathrm{m}^2$

v2

### Ohm's Balance in Wires, Collisional Plasma, Photo-Sheath and Lightning Jets of the K-Corona and Solar Wind



In wires, Ohm's "law" expresses the balance between an "external" electric force on the electrons and the average collisional drag on the flow.

In the Core of a gravitating hydrostatic plasma like the Sun, force-balance on light electrons and massive ions *requires* a static Electric field. For the Core of the Sun, this arises from a net charge Q ~ 75.Coulomb. [ Eddington 1924; Spitzer 1966; Krall & Trivelpiece 1967 ]

In contrast, the solar Photosphere is a low-temperature plasma sheath (aka "double layer"), with a mega-meter transition from plasma to neutral gas, and from photo-opaque to transparent. Here, the solar energy flux  $\Gamma_{\epsilon\gamma} \sim 64.$  MW/m<sup>2</sup> causes an additional outward displacement of electrons, generating a static outward electric field strong enough to "levitate" surface protons, limited by neutral gas "drag".

A simple 1-D force model suggests that high velocity (thermal-tail) protons could accelerate as "runaways", when the electric force exceeds the initial drag force, as commonly happens in laboratory plasmas.

In a 3-D model, filamentary "lightning jets" will occur due to localized "breakdown" of the partially ionized photosphere, as occurs with Earth lightning. Current "pinch" forces may concentrate the protons into filamentary "jets", on scales of (5.km)2.

The NASA/ESA Solar Orbiter EUV images showing episodic "campfires" suggest that this breakdown ionization occurs on the down-welling (cold) edges of surface convective cells with sizes ~  $(0.5Mm)^2$  and lifetimes ~5.min.

The spatially-averaged proton jets (accompanied by low energy electrons) then constitute the K-Corona and Solar Wind. The satellite-observed magnetic field fluctuations reflect temporal fluctuations, dynamical intertwining, and electrical polarization of these Jets.

related "atomic"	$10^{-28} \mathrm{m}^2 \equiv \mathrm{barn}$
$\sigma_{\rm a}(\gamma, H^*) \sim \pi a_0$	$^2 = 0.6  \mathrm{x10^8  b}$
$\sigma_{\mathrm{a}}(\gamma, H^-; bf)$	$\sim 0.5 \text{ x} 10^8 \text{ b}$
$\sigma_{\rm a}(\gamma, H + e^-; ff)$	$\sim 0.5 \text{ x} 10^8 \text{ b}$
•	related "atomic" $\sigma_{a}(\gamma, H^{*}) \sim \pi a_{0}$ $\sigma_{a}(\gamma, H^{-}; bf)$ $\sigma_{a}(\gamma, H + e^{-}; ff)$

 $\sigma_{\rm M} \equiv 3.4 \, \mathrm{x} 10^4 \, \mathrm{b}$ 

e-/p+/ $\Gamma\gamma$  Bremsstrahlung collisions

$$\sigma_{\text{Brems}} \sim \frac{n_{\text{p}}}{3 \times 10^{23}} \, \boldsymbol{E}_{\text{e}}^{-1/2} \, \boldsymbol{\sigma}_{\text{M}}$$

isolated e-

Thomson cross-section

$$\sigma_{\text{Thomp}} = 0.7 \, \text{b}$$

The photon-electron absorption/scattering cross-section  $\sigma_{\gamma e}$  varies by about 8 decades, depending on the elecron correlation with more massive charges.

Atomic cross-sections, including Hy Rydberg and Hy Negative Ion, dominate throughout the lower photosphere.

Bremsstrahlung photon scattering occurs during particle collisions, increasing with the density of ions, and increasing as the electron energy  $E_e$  decreases (towards recombination).

The modelled  $\sigma_M$  represents an *average* over density clumping, current filamentation, and recombination/heating processes, which are outside the simple 1-D radial model.

