International Space Sciences School
Heliospheric physical processes for understanding Solar Terrestrial Relations
21-26 September 2015

George K. Parks,
Space Sciences Laboratory, UC Berkeley, Berkeley, CA

Lecture 2: Solar Wind Issues and Suggestion of a “new” interpretation

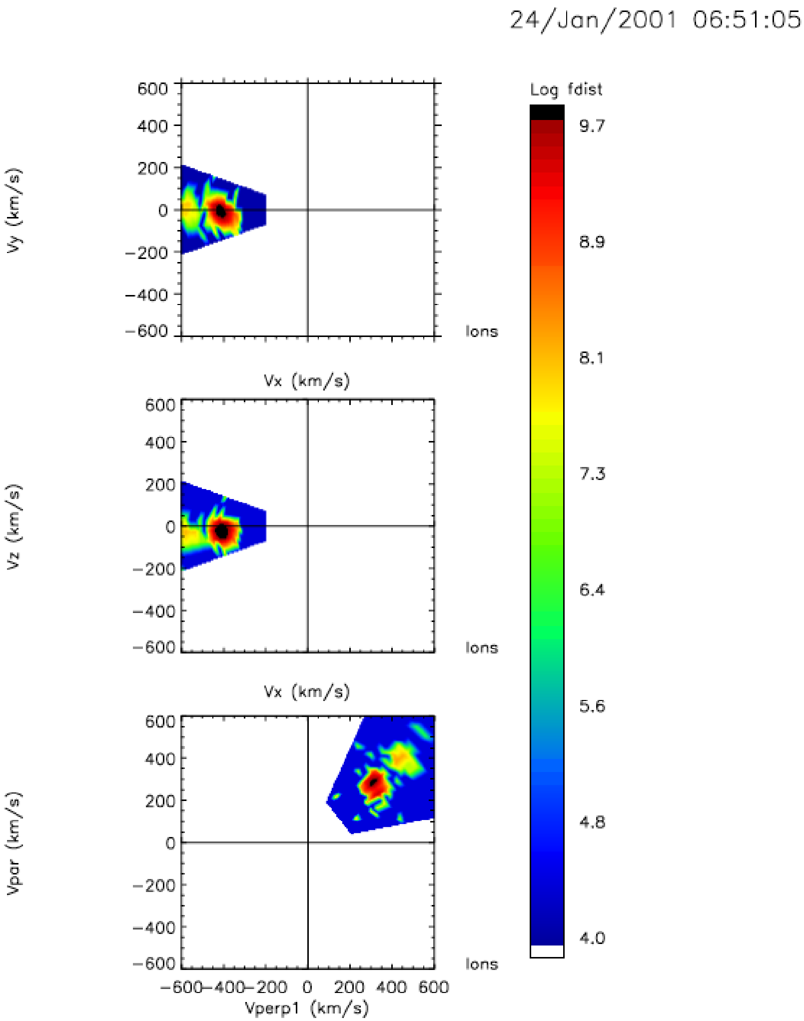
- Solar wind has been studied for nearly 50 years. While most of the SW observations come from 1 AU, observations have been made as close as *0.3 AU* from the Sun *by Helios* and to the *end of the heliosphere* by *Voyager*.

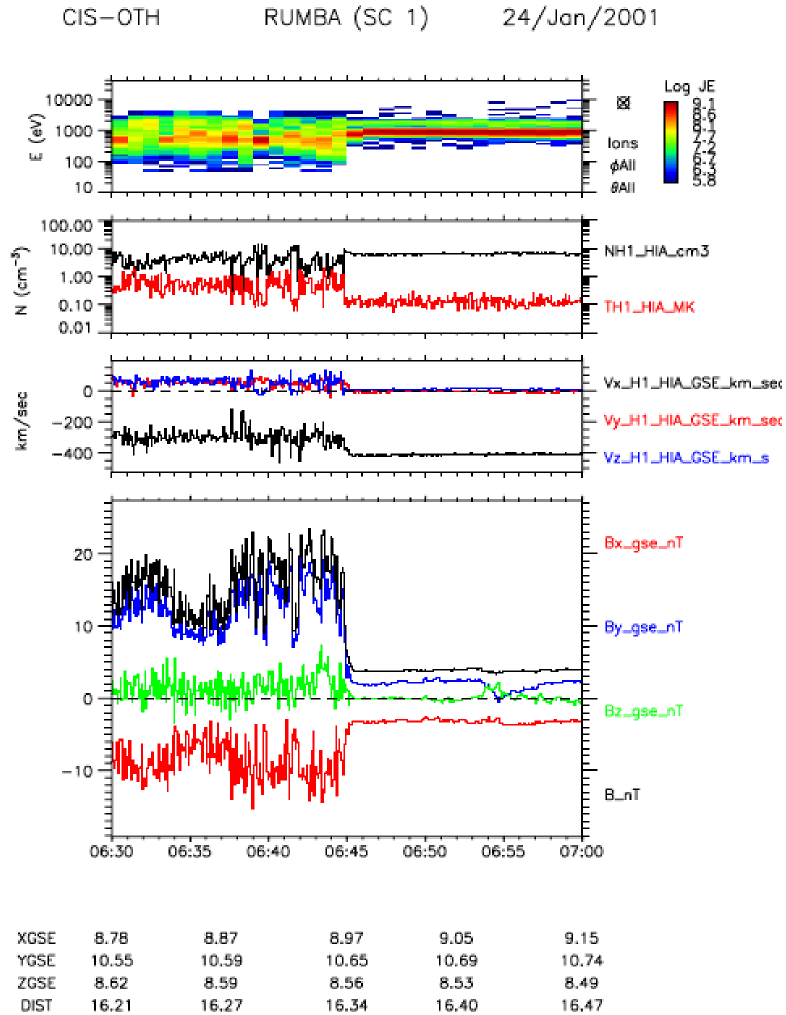
- The solar wind problem is related to *how particles escape* planetary and stellar atmospheres.

- Existing models treat SW as either *fluid or particles*. Fluid models drive SW by thermal energy. Expansion becomes *supersonic*. Original fluid model did not have magnetic field.

- Kinetic models drive the SW by electric field. If the accelerated *particles can overcome the gravitational binding energy*, particles will escape into space.

- This lecture will briefly review fluid and kinetic *SW models, discuss what the issues are and identify features* that have not been considered by either models. We then sugest a *"new"* interpretation of these SW features.





- A key feature about the SW is that it is a *beam* in velocity space.
- The beam is *displaced* relative to the frame at rest (SC, Sun).
- Bulk parameters are derived from the SW *beam distributions*.

Issues with fluid Models of the SW.

$$\frac{d}{dr}(r^2\rho_m U) = 0$$

$$\rho_m \frac{d}{dr} U = -\frac{dp}{dr} + -\rho_m \frac{GM}{r^2}$$

$$\mathrm{p} = \mathrm{nk}_B(T_e + T_i)$$

$$\mathrm{p} = \mathrm{p}_o \left(\frac{\rho_m}{\rho_{mo}}\right)^{5/3}$$

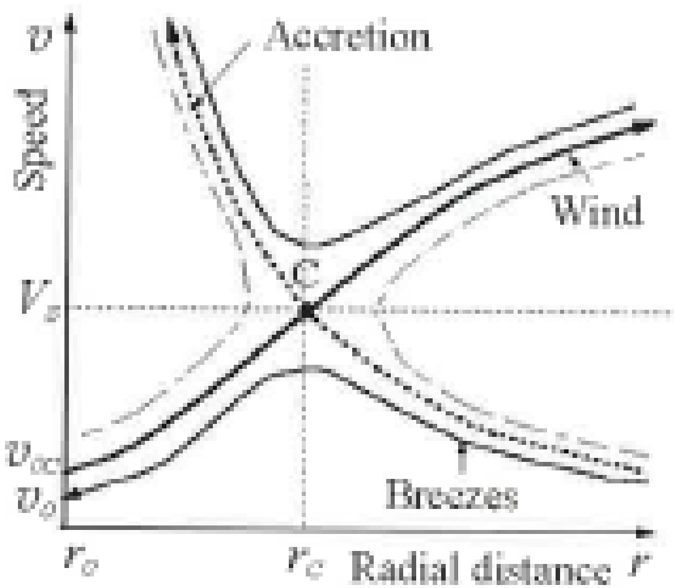
Assumes SW is ideal and obeys adiabatic equation of state.

$$(U^2/C_s^2 - 1)dU/dr = (2 - GM/C_s^2 r)U/r$$

C_s is the sound speed

$$\frac{U^2}{U_C^2} - 2\ln\left(\frac{U}{U_c}\right) = 4\ln\left(\frac{r_c}{r}\right) + 4\left(\frac{r_c}{r}\right) - 3$$

U_c is the flow speed at critical distance $r_c = GMm_i/4kT$.



- There are four branches of the solutions that are mathematically acceptable. However, physical arguments eliminate the three and only *one* is satisfactory for the SW.

- Solution of the SW starts with U< Vs near the base of the solar corona, reaches V_s at the critical distance r_c and continues to increase beyond r_c.

• The fluid SW driven by the *available heat energy* at the Sun and the important issue is to understand how heat is transported outward against the gravitational binding energy (Meyer-Vernet, 2007).

$$\frac{V_{sw}^2}{2} \approx \frac{5k_B T_o}{m_p} - \frac{M_\odot G}{r_o} + \frac{Q_o}{n_o m_p V_o}$$

Three terms on the right hand side: (1) *enthalpy per unit mass* (heat content) due to protons and electrons, (2) *gravitation binding energy*, and (3) *heat flux per unit mass*. The bulk flow speed is small at the Sun, hence its flow kinetic energy is ignored.

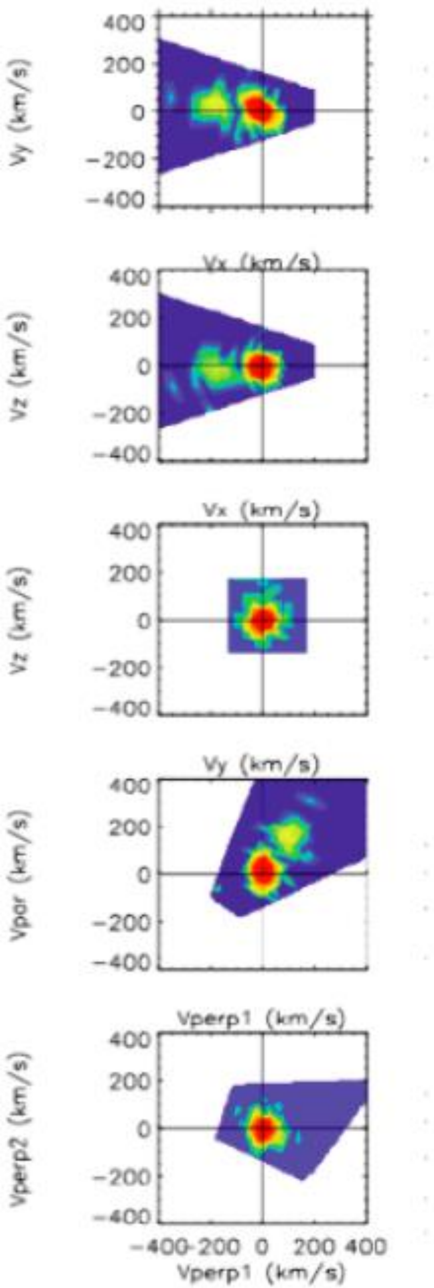
• $V_{sw}^2/2$ = 1.6 x10^{11}J/kg (V_{SW} = 4x10^5m/s).

• *Enthalpy* ~0.8 x 10^{11} J/kg and *gravitational* binding energy MG/r_o ~2x10^{11} J/kg (Use T_o= 2x10^6 ^{o}K, r_o = 7x10^8 m, and M=2 x 10^{30} kg)

• The available enthalpy is *not sufficient* to overcome the Sun's gravitation energy indicating *heat flux* (last term) is important.

$$\frac{V_{sw}^2}{2} \approx \frac{5k_B T_o}{m_p} - \frac{M_\odot G}{r_o} + \frac{Q_o}{n_o m_p V_o}$$

- Heat conductivity models indicate $Q_o \sim 3.7 \times 10^7 k^{3/2} (m_e)^{-1/2} T_o^{7/2}$.
- Estimate $n_o m_p V_o$ by projecting Earth's observations back to Sun using continuity equation: the last term is then $\sim 2\times10^{11}$ J/kg. Can just *balance* the gravitational term.
- The left side $V_{sw}^2/2$ cannot be accounted for by enthalpy, 0.8×10^{11} J/ kg, *not* adequate to produce a terminal velocity of 400 km/s.
- Enthalpy is extremely sensitive to T because heat flux varies as $T^{7/2}$. If T is changed by 15%, the right hand side becomes *negative!*
- Original model Parker assumed *uniform T* requiring *infinite* heat conductivity.
- Fluid models *difficult to explain* observations especially fast solar wind that comes from *colder regions* of solar corona where temperature can be$\sim 10^5$ ^oK.



- Fluid models assume that the Sun is hot and *solar atmosphere is expanding* outward.

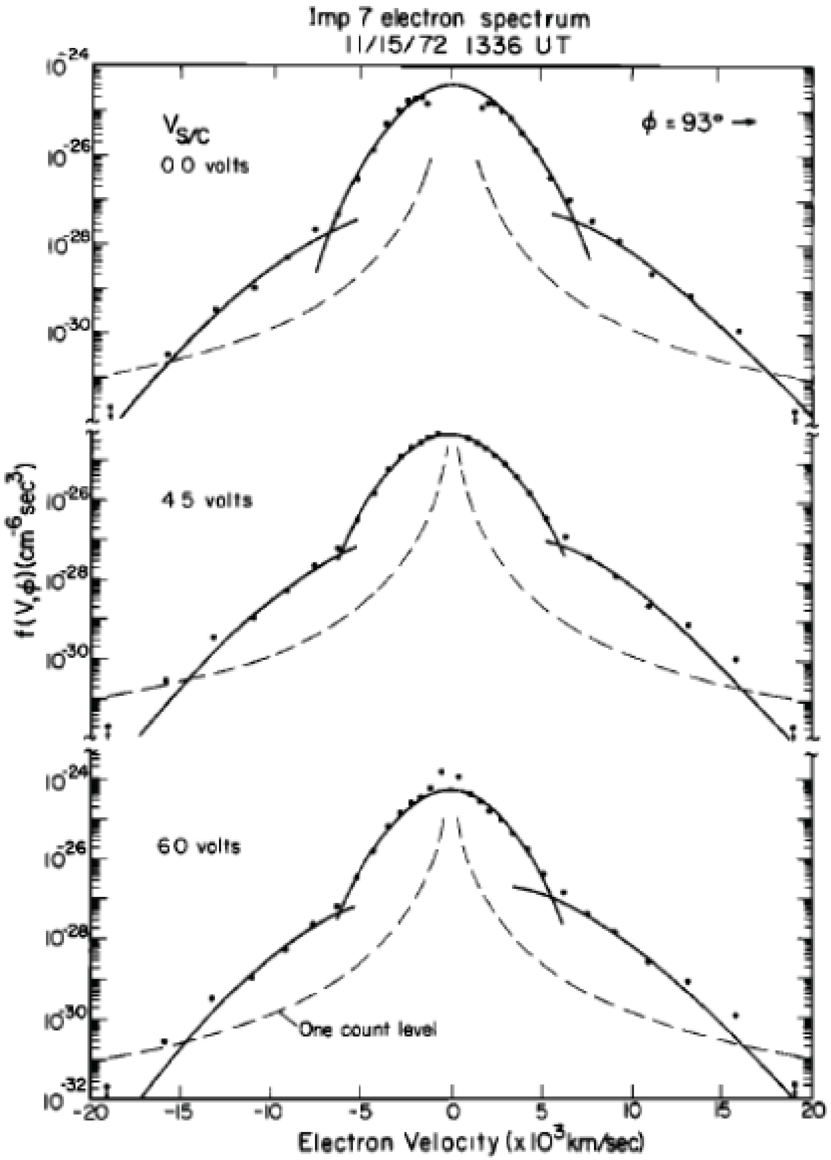
- SW can be represented by a drifting Maxwellian distribution

$$f(v) = C exp-(\mathbf{v}-\mathbf{U})^2/v_{th}^2$$

where $C = n_o/(\pi^{3/2} v_{th}^3)$, $\mathbf{v}$ is thermal velocity, $\mathbf{U}$ is the expansion velocity of the solar atmosphere.

- SW often plotted in moving plasma frame.

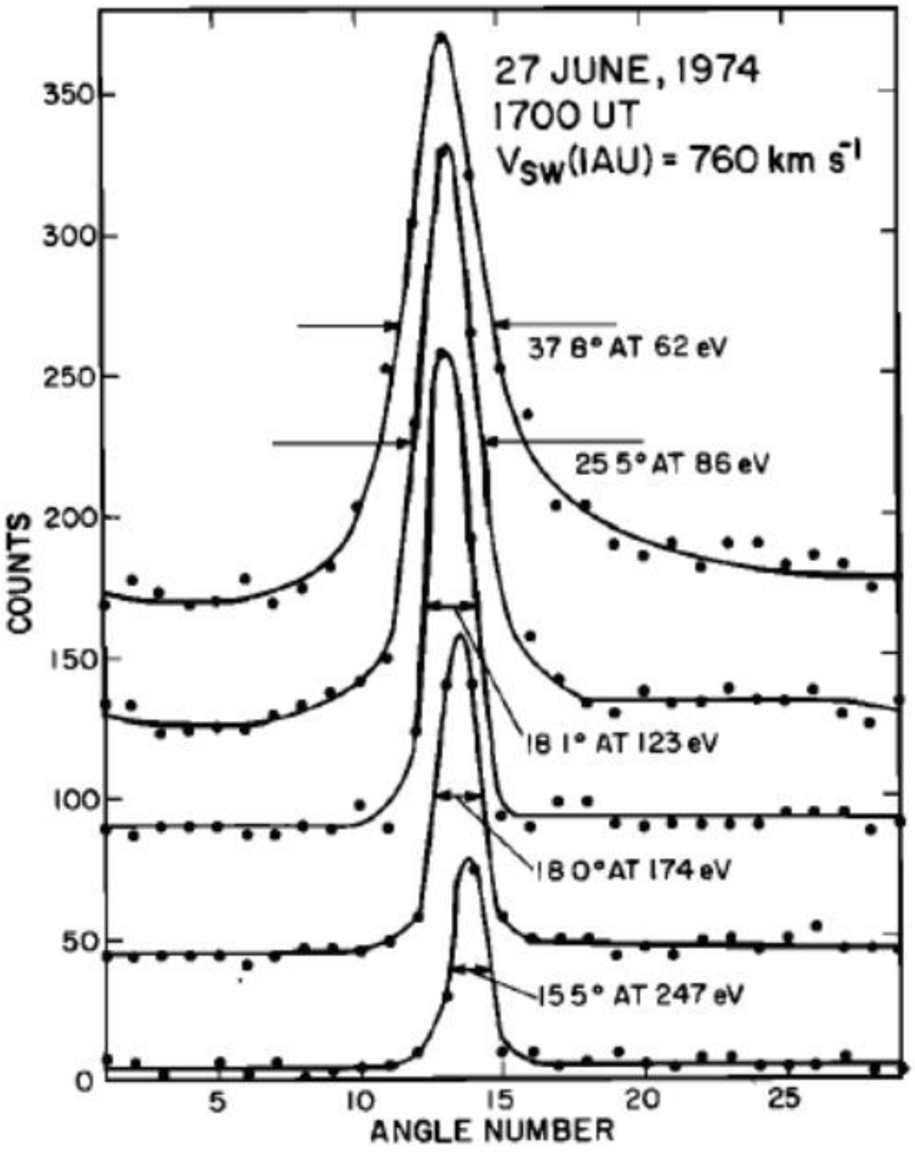
What do we know about the SW electrons?



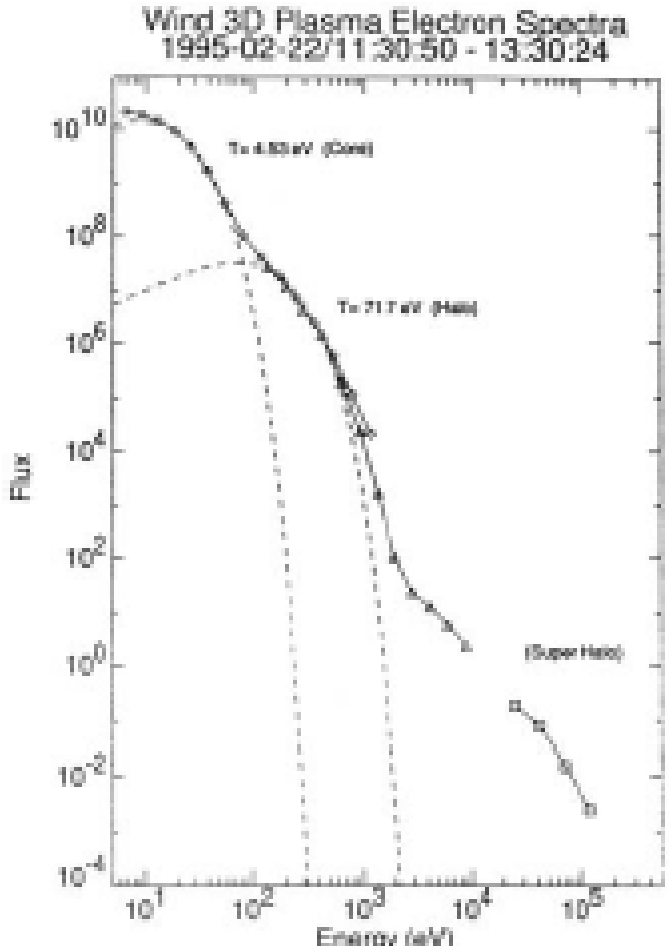
• Electron distributions in the solar wind showing the *core and halo* components (IMP 7 measurements, Feldmann et al., 1975).

.

• The solid line is a bi-Maxwellian fit to the data (solid points).



- Electron beams observed at various energies in the *fast* solar wind.
- The high energy halo component (*strahl*) is field-aligned.
- The beam is more field-aligned at higher energies (Feldmann et al., 1978)

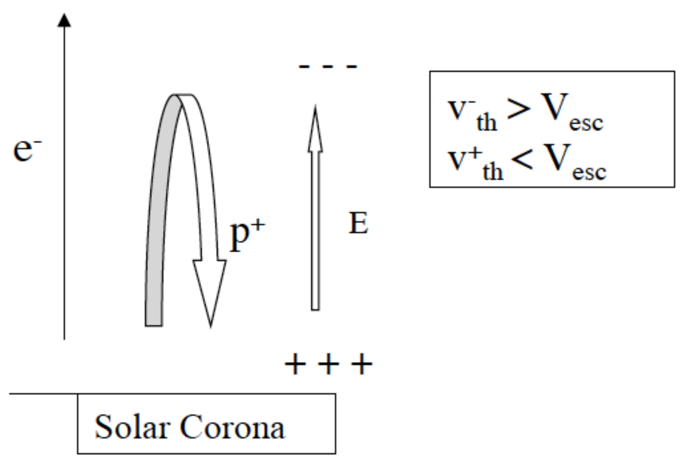


Lin, 1996

- Differential Energy Spectrum of SW electrons from ~5 eV to >100 keV. (Lin, 1985; Wang et al., 2015).
- *Core* ~5 eV – 50 eV (isotropic).
- *Halo* ~50 eV - 1 keV (isotropic); high energy *Strahl* is field-aligned.
- Suggestion is that strahl comes from the solar corona.
- *Super-halo* ~1 keV - >100 keV isotropic.

Kinetic model of SW

Escape of plasma from stellar surfaces



- Original kinetic model due to Chamberlain (1960). He adopted Jean's model (1925), which calculates the number of neutral particles escaping planetary atmospheres.

- The original model has since been improved by Lemaire and Scherer (1971) and more recently by the French and Belgium groups (Maksimovic, Pierrard, Meyer-Vernet, Issautier, Zougnelis).

Flux of particles (cm^2/sec) leaving outward with a velocity v $> v_{esc}$

$$J_{esc} = n_o \left(\frac{m}{2\pi k_B T}\right)^{3/2} \int_{v_{esc}}^{\infty} e^{m(v_x^2+v_y^2+v_z^2)/2kT} v_x dv_x dv_y dv_z$$

where n_o is the density of particles at $r = r_o$ and v_x is the positive normal component. Integration taken for all values of v_x, v_y and v_z and $v_x^2+v_y^2+v_z^2 > v_{esc}^2$.

- Once a particle escapes the Sun, it is in a hyperbolic trajectory and is permanently lost from the solar (stellar) atmosphere.

• If collisions ignored for $r > r_o$, total energy of the particles conserved.

$$mv^2/2 + mg\Phi_g + Ze\Phi_E = mv_o^2/2 + mg\Phi_g(r_o) + Ze\Phi_E(r_o)$$

and one can show

$$v_{esc}(r_o) = \left[\frac{2e\phi_E(r_o)}{m_e}\right]^{1/2}$$

• Original model used the hydrostatic equilibrium model proposed by Pannekoek (1922) and Rosseland (1924). This model yields

$$\Phi_E \sim (m_i/2e)\ \Phi_g$$

• The ratio of fluxes of electrons and ions escaping the atmosphere then becomes

$$J_{esc}(e) = (m_i/m_e)^{1/2} J_{esc}(i)$$

• *More electrons will leave* the atmosphere than ions. The sun will become *positively charged*!

• Improved Model adds *two important constraints:*

(1) Require *charge neutrality* $n_i(r_o) = n_e\ (r_o)$

(1) *Zero net flux* leaving the Sun. Same flux of electrons and ions leave the Sun.

• Electron Flux

$$J^e_{esc}(r_o) = \frac{n_o(r_o)}{2\sqrt{\pi}} v^e_{th} \left(1 + \frac{v^2_{esc}}{v^2_{th}}\right) e^{-v^2_{esc}/v^2_{th}}$$

• Ion Flux

$$J^i_{esc}(r_o = \frac{n_p(r_o)}{\sqrt{\pi}} v^i_{th}$$

Require $J_{esc}^{e}(r_o) = J_{esc}^{i}(r_o)$.

Obtain

$$\left(1 + \frac{v_{esc}^2}{v_{th}^2}\right) e^{-v_{esc}^2/v_{th}^2} = 2\left(\frac{m_e}{m_i}\right)^{1/2}$$

where

$$v_{esc}^2/v_{th}^2 = e\phi_{Eo}/k_B T_{eo}$$

$$v_{esc}^2/v_{th}^2 \sim 5$$

$m_e/m_i \sim 5.4 \times 10^{-4}$, and

If $T_{eo} = 10^6$ °K, $\phi_{Eo} = 490\ eV$.

Maksimovic, 2001; Ch. 6 of Parks, 2004 (Ch 6)

Solar wind models continually improving.

• Some kinetic models predict that the presence of the non-Maxwellian high energy tail can increase the solar wind speed and may account for the fast solar wind.

• Other models predict that cyclotron resonance heating occurring at the source may account for the bulk acceleration of the solar wind.

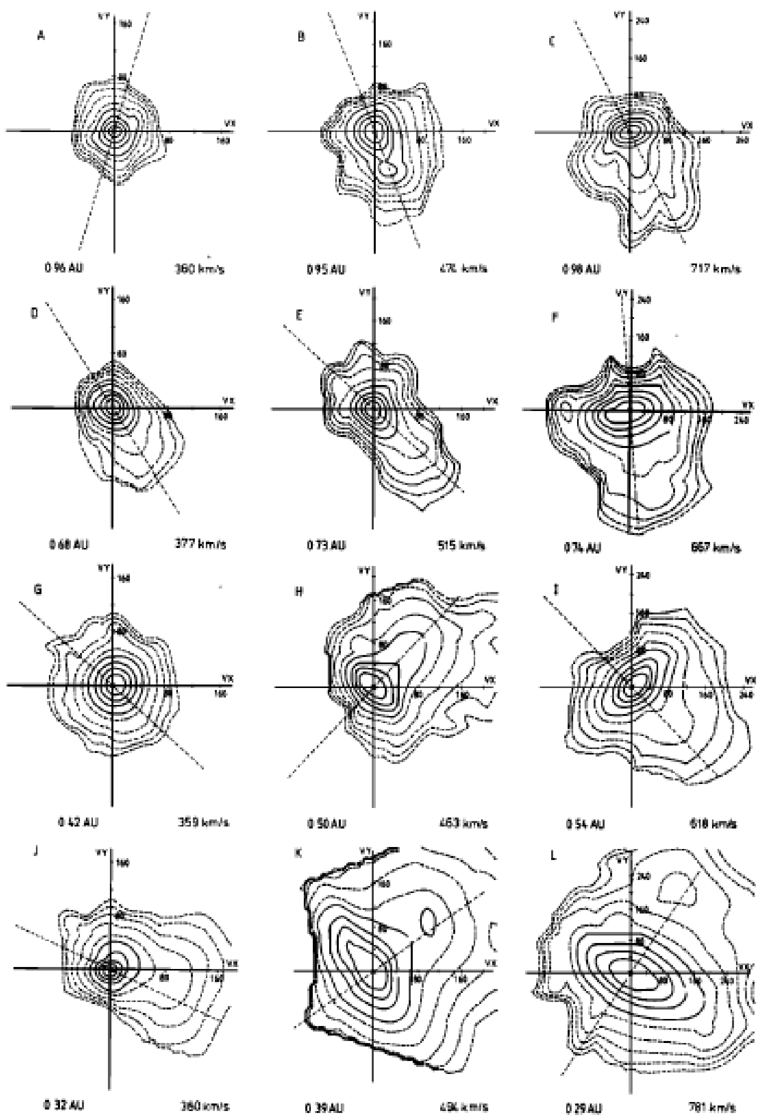
• Models have also included spiral interplanetary magnetic field.

• A few papers has modeled high speed solar wind from collision-dominated lower-coronal heights into the collisionless interplanetary space using the Fokker-Planck collision operator to describe the Coulomb collisions of electrons.

CAVEAT: SW models are based on observations made in the vicinity of 1 AU. We still do not know

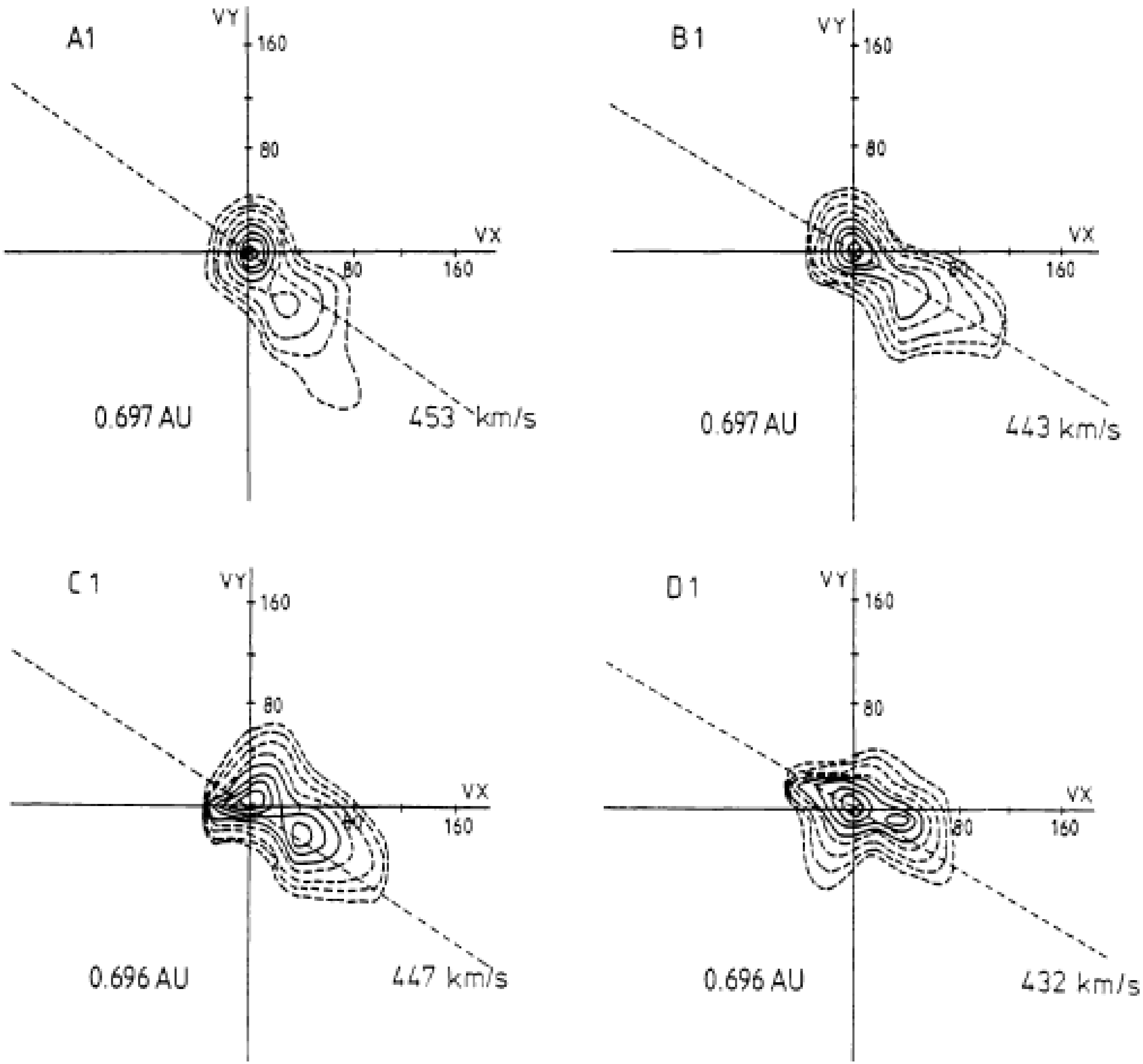
- How much of the features measured near 1 AU represent the *original properties* of the SW.
- Has the SW been modified in transit from Sun to Earth?
- For example, where is the temperature anisotropy observed at 1 AU produced?
- Some models invoke wave-particle interaction along the way. Probably true but not firmly established.

Helios Observations



Marsch, 1982

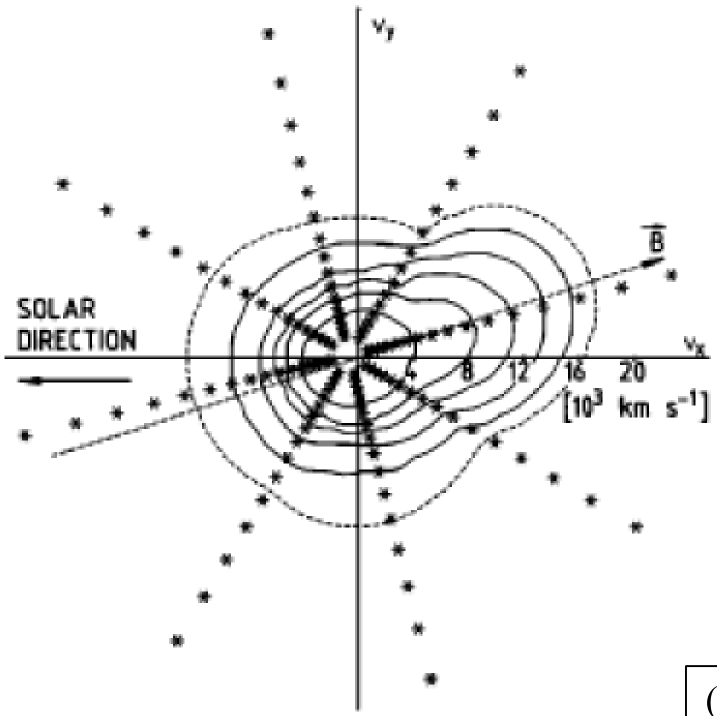
- He^{++} ions *removed* from the measured distributions.
- Different SW speeds:
  Left ~350 km/s,
  Middle ~500 km/s
  Right ~750 km/s.
- Heliocentric distances:
  top row ~0.95 AU,
  second row ~0.7 AU,
  third row ~0.5 AU
  fourth row, ~ 0.3 AU.
- Nonthermal tails and secondary peaks *aligned along B*. There are *Multiple field-aligned beams*
- Anisotropy with $T_{\parallel} > T_{\perp}$, $T_{\parallel} < T_{\perp}$,
- SW distributions are *Field-aligned*!



- SW He^{++} ions show similar features as H^{+} ions.

- He^{++} also *field-aligned* and includes *multiple beams*

Helios Electrons

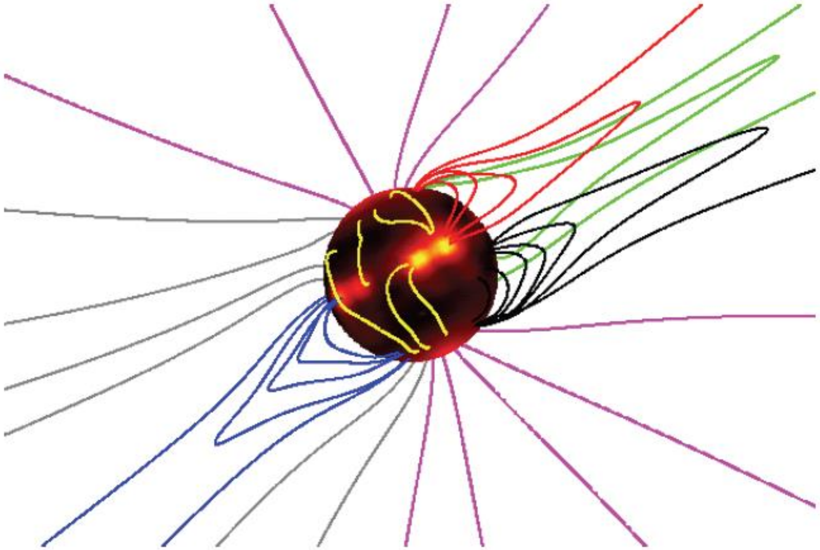


(Pilipp et al., 1987)

• 2D electron distribution (Helios) plotted in the SW frame. The core and *field-aligned* halo components.

- Suppose the Sun has a general dipole *magnetic field*.

- Magnetic field on the Sun is *very complex* and depending on the solar cycle, there are also small scale transient structures in addition to the general "dipole field." *Ignore transient* fields.



$$f(\mathbf{v}) = Ce^{-(\mathbf{v}-\mathbf{U})^2/v_{th}^2}$$

- Particles are trapped and moving in a "*dipole-like field*" executing gyrating, longitudinal and drift motions as trapped particles do in Earth's radiation belts.

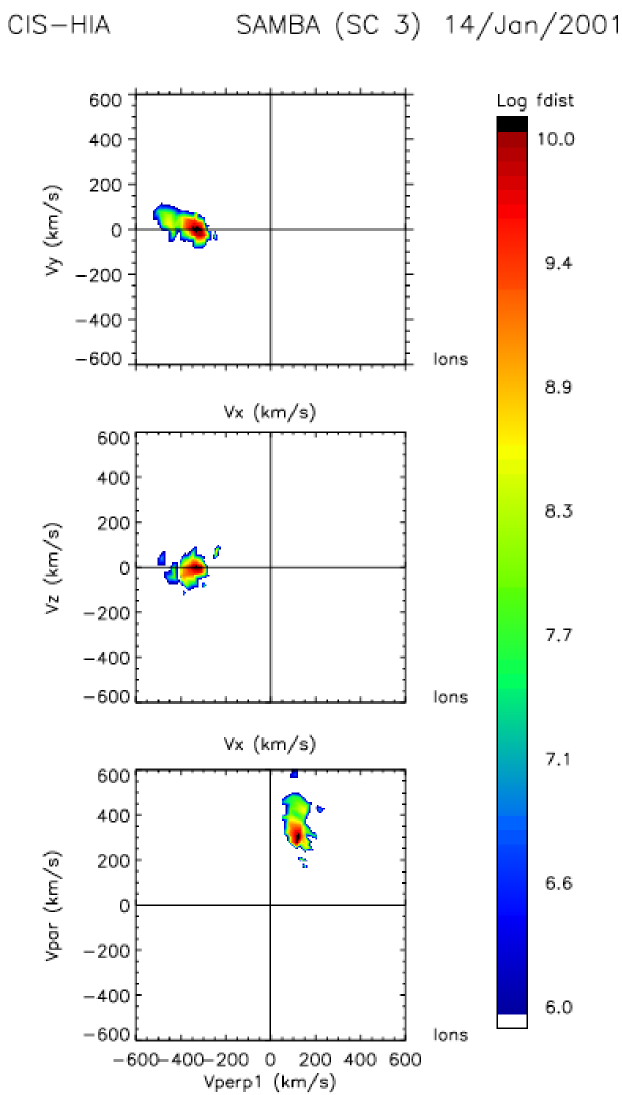
- To produce a SW, the GCs of these particle must *move away* from the Sun by crossing the dipole field. How can this be done?

- Lorentz equation has already shown us the equatorial particles will cross the magnetic field only when they experience an *electric field perpendicular* to the magnetic field direction.

- Examine particles on the Sun's equatorial plane at coronal altitudes.

- If **B** = (0, 0, B) and **E** = (0, E, 0), particles will move away from the Sun.

- $\boldsymbol{U} = \boldsymbol{E}x\boldsymbol{B}/B^2$, so we can get information on $\boldsymbol{E}_\perp$ *by measuring* $\boldsymbol{U}$ if we know B



- SW Data interpreted with "frozen-in-field" assumption, that *all particles are traveling together* applies only to direction *perpendicular to B*.

- However, SW particles have a significant component *parallel* the magnetic field direction.

- H^+ and He^{++} SW flowing *parallel* to B *can have different velocities*. The different ions need not travel at the same speed.

- Suppose Field-aligned beams are accelerated by $E_{||}$.

- FAB distribution function can be represented by (for a simple potential drop)

$$f(v_{||}) = C\ exp–[(W – q\Delta\varphi)/kT]$$

- What would ESAs measure? Assume H^{+} and He^{++} originate at same height. Energy per charge after going through a potential drop Δφ is

$$(W/q)_{+} = (W/q)_{o+} + \Delta\varphi$$

$$(W/q)_{++} = (W/q)_{o++} + \Delta\varphi$$

These equations show

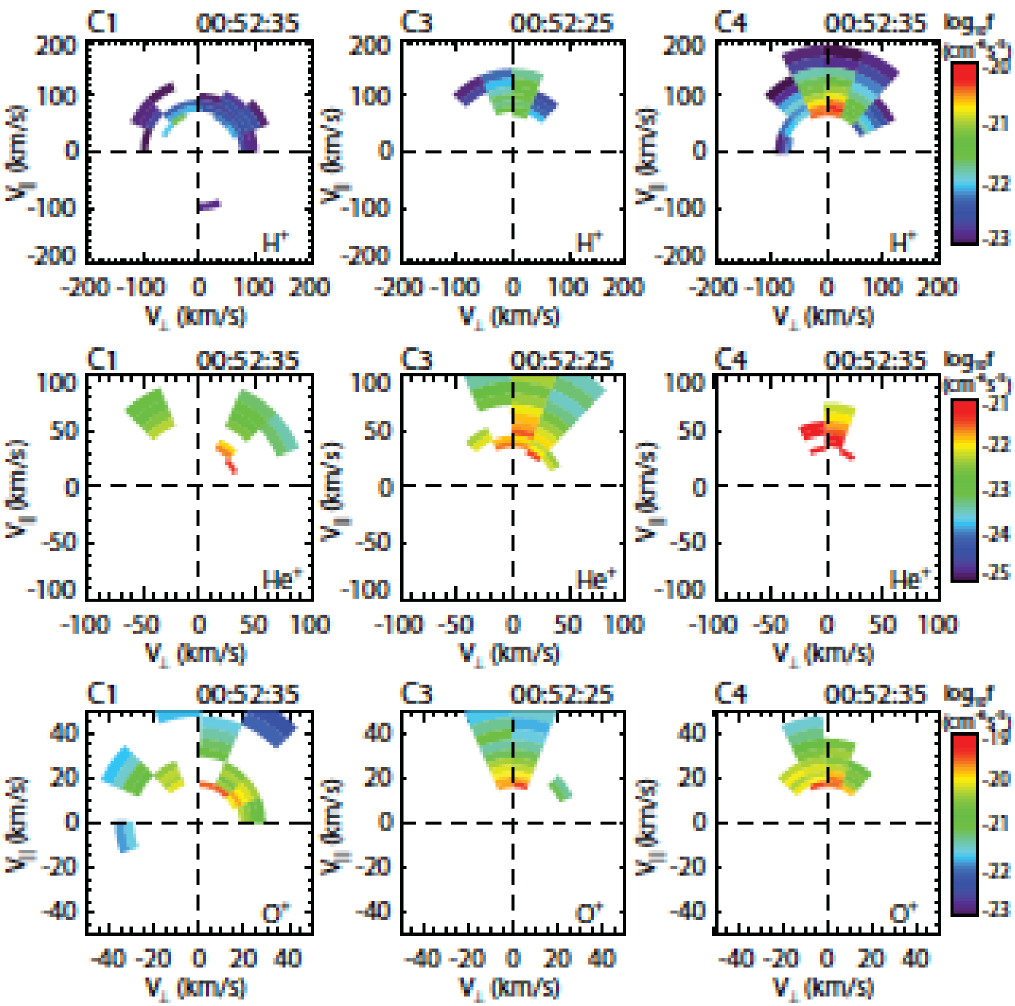
$$v_{+} = (2e\Delta\varphi/m_{+} + 2W_{o+}/m_{+})^{1/2} \sim (2e\Delta\varphi/m_{+})^{1/2} \qquad if\ e\Delta\varphi >> W_{o+}$$

$$v_{++} = (e\Delta\varphi/m_{+} + 2W_{o++}/2m_{+})^{1/2} \sim (e\Delta\varphi/m_{+})^{1/2} \qquad if\ e\Delta\varphi >> W_{o++}$$

Then

$$v_{+} = (2)^{1/2}\ v_{++}$$

Multiple Field-aligned ion beams above Earth’s aurora



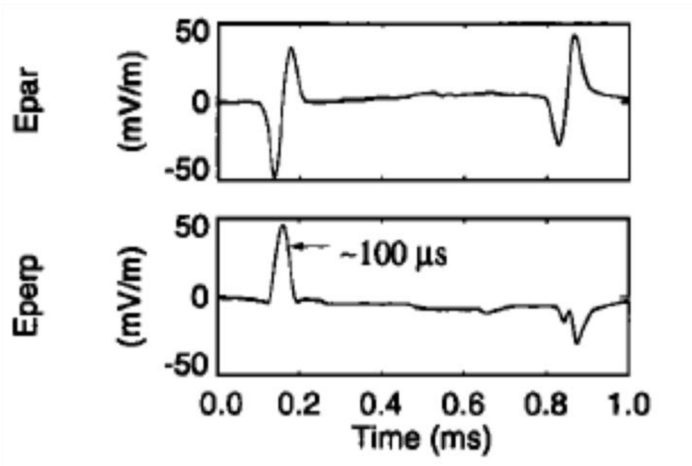
• Field-aligned beams with as many as five discrete beams have been observed with each having a different velocity.

• Can determine if the different ion species have gone through the same or different amount of potential drops.

• Examine the beam velocity ratios of the different ions. Theory predicts if $V(O_+/H_+) = 4$, and $V(He_+/H_+) = 2$, ions have gone through same amount of potential.

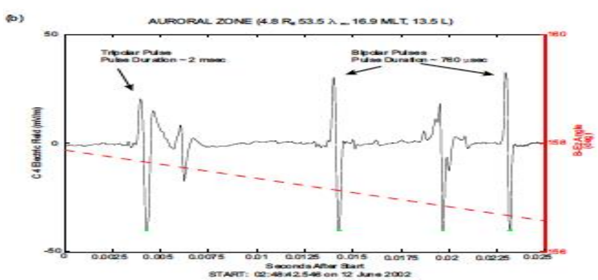
Examples of Double Layers from Earth

- "Spiky" E-field and $E_{||}$ first observed in auroral ionosphere (Mozer, 1977).
- $E_{||}$ interpreted as *Double Layers* (Temerin, 1982; Bostrom, 1988).

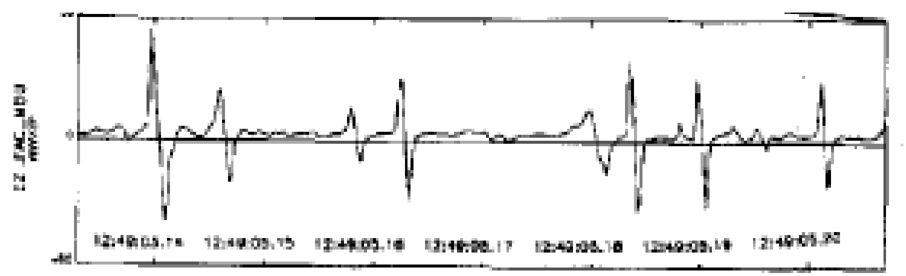


- Bipolar, parallel direction.
- Unipolar, perpendicular direction
- More complex structures.

Ionosphere: Ergun, 1998

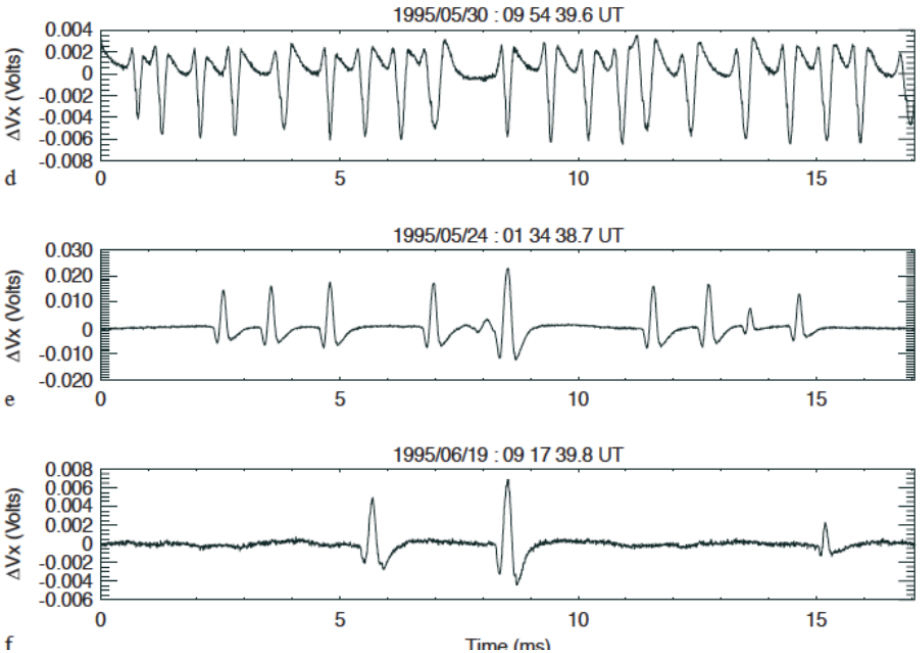


4 RE: Pickett, 2004



Plasma Sheet: Cattell et al., 2001

Does the Sun have $E_{\parallel}$?



from Mangeney et al., (1999)

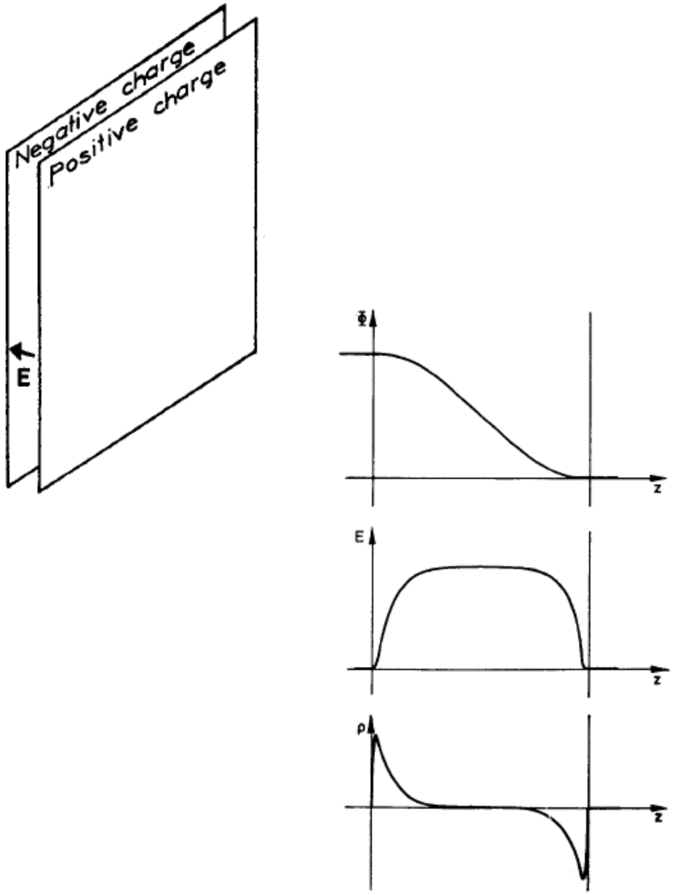
- ESWs have been detected by Wind at L1.

- These milli-second structures have dimensions of a few tens of Debye lengths and are aligned along the magnetic field direction, closely resembling the ESWs observed in the auroral ionosphere, although the amplitudes are much smaller.

- SW ESW amplitudes become smaller toward Earth.

- We don’t know if the ESWs measured by WIND are produced on the Sun and propagated out or produced locally in the SW.

Double Layer



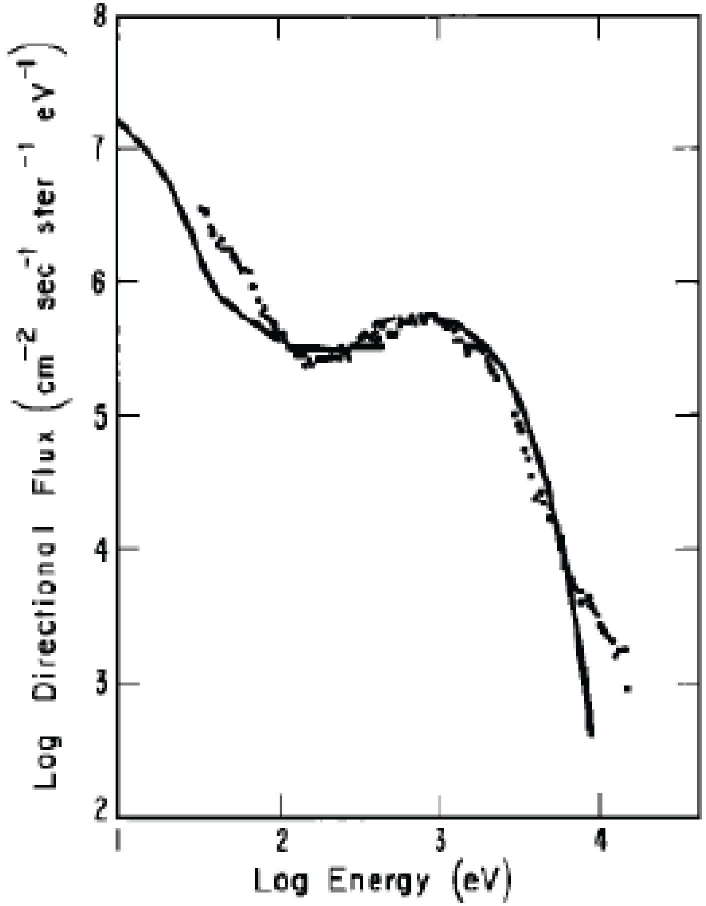
• Auroral field-aligned currents are sufficiently intense to produce *space-charge regions* where charge neutrality is not maintained. *High potential difference* could be developed along the magnetic field direction.

• DLs do not maintain local charge neutrality.

• DLs have opposite charges on each end.

• A strong electric field exists inside DLs.

• Auroral DLs aligned along B, produce $\boldsymbol{E}_{\|}$.

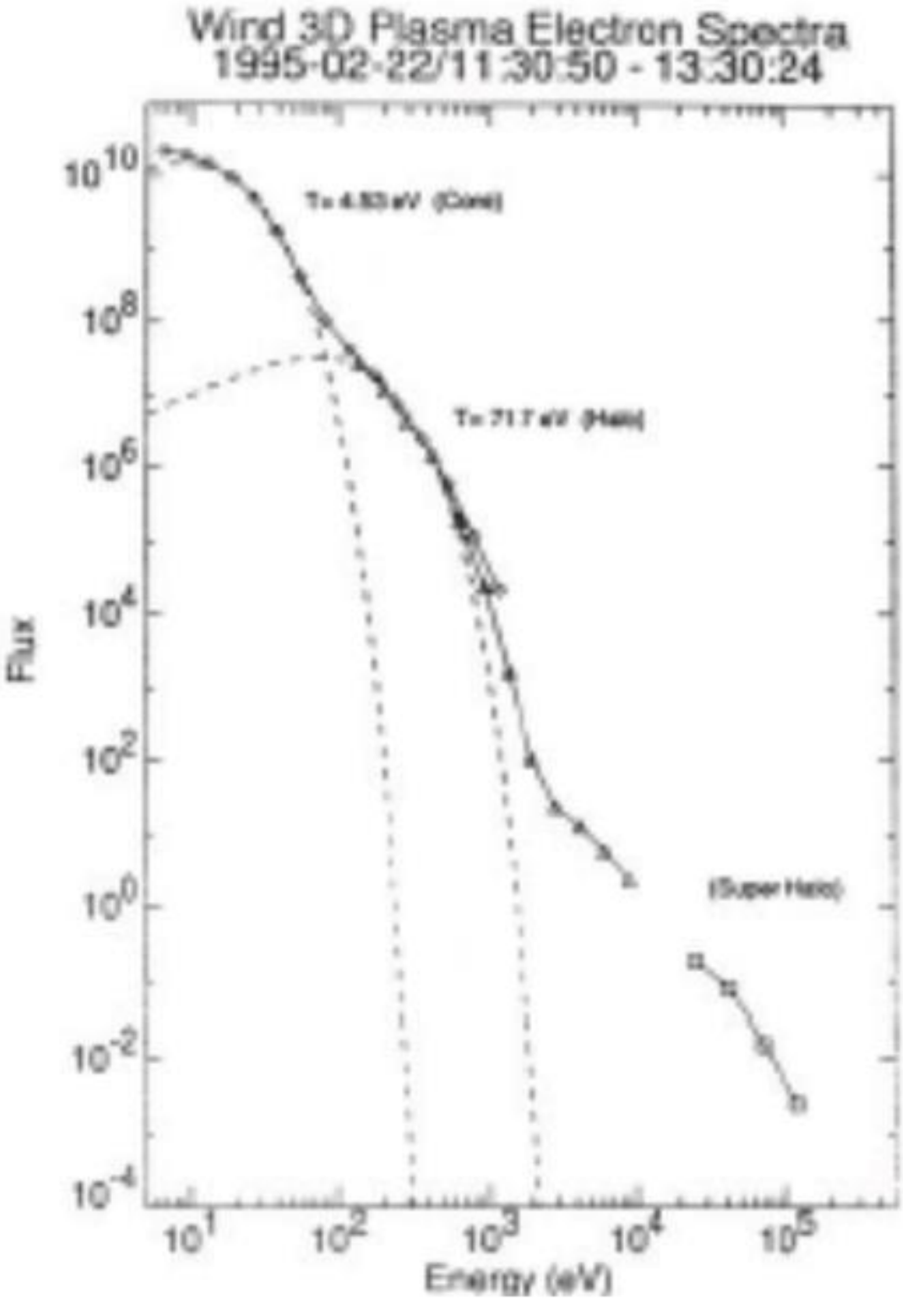


From Evans, 1974)

• On Earth, well formed beams are observed at energies of a few keV accelerated by the potential drop.

• The auroral beams show $\Delta\phi$ is typically a few hundred eV to ~keV.

• However, the beam is always accompanied by *lower* and *higher* energy electrons that are nearly isotropic.



- SW electron distribution "*resembles*" electron distributions above Earth's aurora.

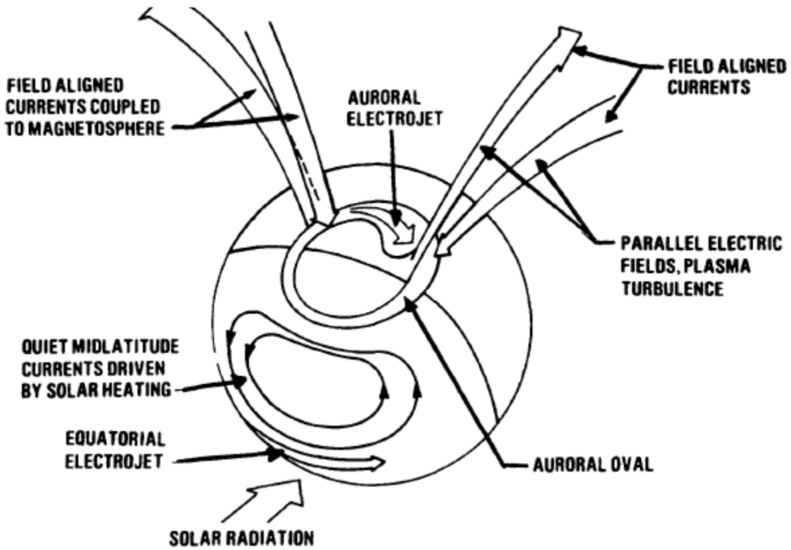
- Suppose the SW beam is the *strahl* component.

- Can interpret core and isotropic halo electrons as *secondaries* produced by the strahl beam that have been redistributed to lower energies by instabilities.

- *Non-thermal super-halo* electrons are not explained by this simple potential drop model.

- *Speculate* that the super-halo electrons are field-aligned halo electrons that have been accelerated by instabilities to "run away" energies by $\mathbf{E}_{\|}$, followed by pitch-angle scattering, producing isotropic distribution.

What is known about the Auroral Current System



- Field-aligned auroral currents are driven by $E_{||}$.
- Auroral current system has *Upward* and *Downward* current regions and two potential structures: One accelerates ions (electrons) upward (downward) and the other accelerated ions (electrons) downward (upward).
- How $E_{||}$ and $J_{||}$ are related is not understood.
- A possible source of $\mathbf{E}_{||}$ is *many DLs* distributed along B.

Summary:

- Interpretation of SW measured by ESA data has assumed that

"all particles are traveling at the same mean velocity in steady-state plasmas with a frozen in magnetic field"

Hundhausen, 1968

- This assumption is valid for particles traveling only *perpendicular to B*. Various ions traveling *parallel to B* can have any velocity.

- Stereo data show ions and electrons becomes *field-aligned* close to the Sun.

- The picture of SW based on frozen in field model *needs to be re-examined!*

- We have applied the Earth's auroral model to solar coronal atmosphere. We are suggesting that SW field-aligned beams are produced by $E_{||}$.

- Future observations of the SW from Solar Orbiter and Solar Probe Plus will be very interesting.

The End