Kinetic Physics of Electrons from the Inner Heliosphere to Mars

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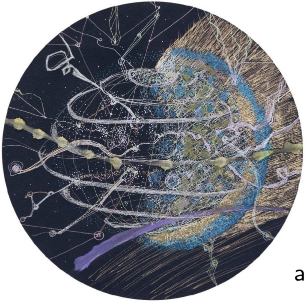
University of Helsinki, 17.06.2021



art: Beth Racette

Electrons from the Inner Heliosphere to Mars

Kinetics: Promises and Pitfalls

- Resolve finer physical processes (heat flow, kinetic waves, instabilities, etc.)
- Derive larger scale phenomena (fluid Eqs.)
- Rich in information

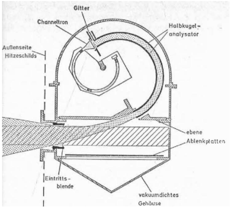
- Kinetic information may be unnecessary.
- Small-scale forces may be unknown (e.g. quasilinear diffusion)
- Solving the kinetic problem may be untractable or computationally expensive.

Kinetics: Research Program

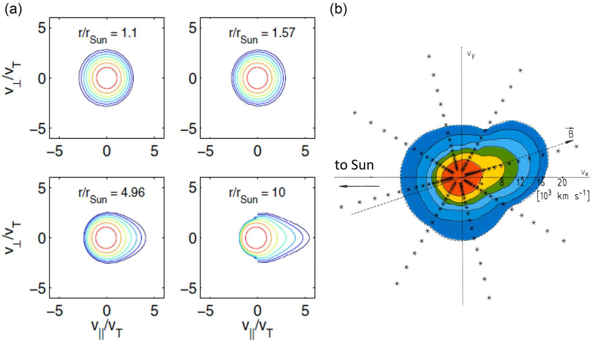
Theory: equation for $f(\mathbf{x}, \mathbf{v}, t)$

$$\frac{\partial f}{\partial t} = -\mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} - \frac{q}{m}\Big(\mathbf{E} + \mathbf{v} \times \mathbf{B}\Big) \cdot \frac{\partial f}{\partial \mathbf{v}}$$

... + collisions



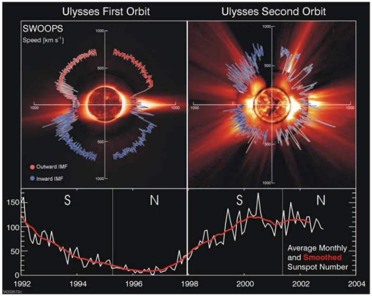
Observations: ESAs (Schwenn 1975)



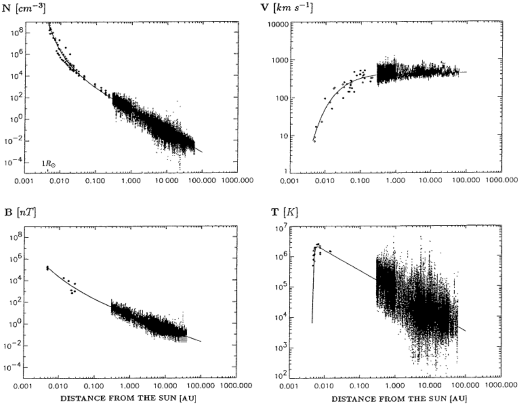
Solar wind e$^-$, E. Marsch review (Pilipp et al. 1987a, Smith et al. 2012)

Electrons from the Inner Heliosphere to Mars

The solar wind



McComas et al., 2003



Köhnlein, 1996

The solar wind is driven from a high pressure region in the corona. Density, temperature, and magnetic field all decrease with distance from the sun (as the solar wind expands).

Suprathermal electron populations

$$f(v_\perp, v_\parallel) = f_c + f_h + f_s$$

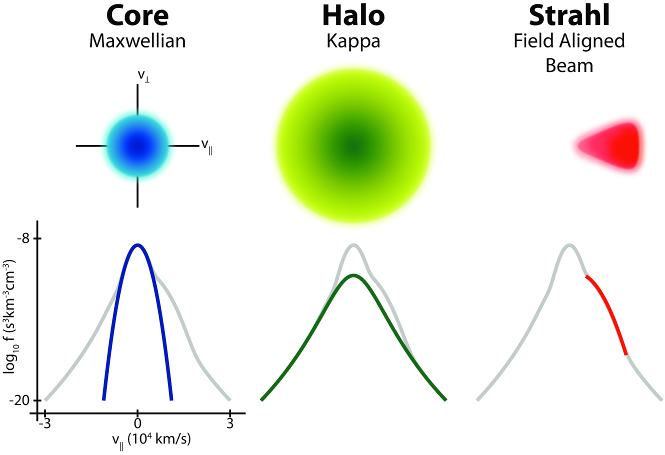


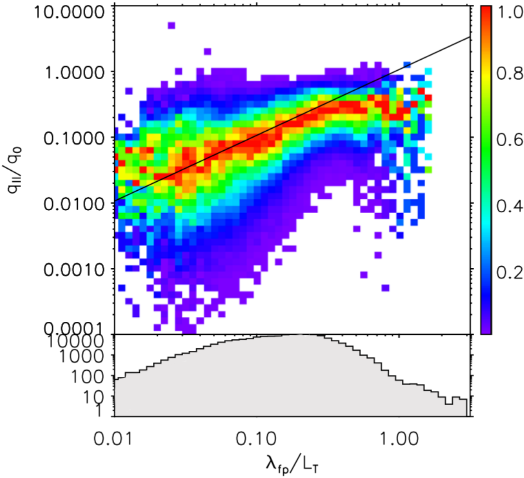
Illustration: M. Pulupa

Heat carried by electrons appears as a field-parallel *skewness* in the distribution function—relevant to SW expansion (Parker, 1958).

Thermal conductivity in the solar wind

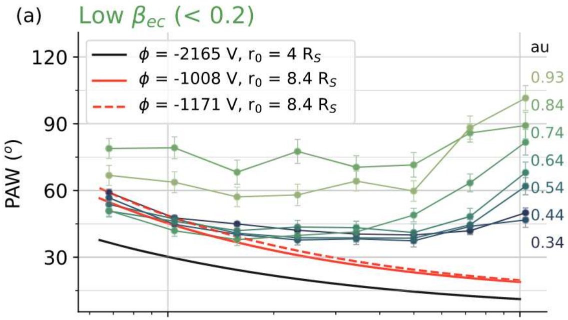
$$\gamma = \frac{\text{mean free path}}{\text{temp. variation scale}}$$

- $\gamma << 1$: $\mathbf{q} = -\kappa \nabla T$ (collisional)
- $\gamma >> 1 : q \sim nTv_{th}$ (collisionless)



Wind data, r=1 AU (Bale et al., 2013)

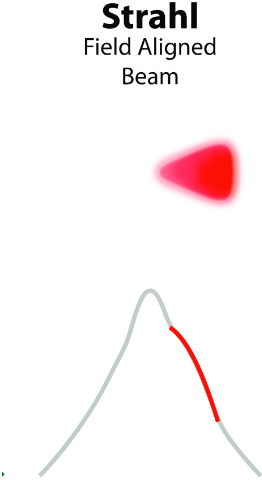
Collisionless Predictions too narrow! (Bercic 2019)



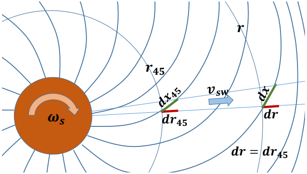
Energy →

Solid lines: collisionless model. Data: Helios ESA

Strahl: Intuitive Explanation



- Electrons focus into a beam along $\mathbf{B}$, as they try to conserve their magnetic moment ($\frac{v_\perp^2}{B}$)



- *But,* angular diffusion (provided, e.g., by Coulomb collisions with other particles) broadens the distribution somewhat.

Kinetic solution along a field line (Horaites et al., 2019)

Drift Kinetic Equation for $f(x, M, v_{\|})$, assuming $|\mathbf{v}| >> v_{sw}$:

$$v_{\|}\hat{b} \cdot \nabla f + \frac{MB(x)}{2} \nabla \cdot \hat{b} \frac{\partial f}{\partial v_{\|}} = \hat{C}(f)$$

advection   magnetic focusing   coulomb collisions

Variables: $\mathbf{b} \equiv \mathbf{B}/B$,   mag. moment $M \equiv v_{\perp}^2/B(x)$

The above equation can be solved with the appropriate change of variables!

Kinetic solution along a field line (Horaites et al., 2019)

Drift Kinetic Equation for $f(x, M, v_\parallel)$, assuming $|\mathbf{v}| >> v_{sw}$:

$$v_\parallel \hat{b} \cdot \nabla f + \frac{MB(x)}{2} \nabla \cdot \hat{b} \frac{\partial f}{\partial v_\parallel} = \hat{C}(f)$$

advection magnetic focusing coulomb collisions

Variables: $\mathbf{b} \equiv \mathbf{B}/B$, mag. moment $M \equiv v_\perp^2 / B(x)$

The above equation can be solved with the appropriate change of variables!

$$f(r, \mu, v) = \frac{C(v^2)}{r} \exp\left\{ -\Omega \frac{v^4(1-\mu^2)}{\sqrt{1 + r_{45}^2/r^2}} \right\}$$

$\mu = \cos\theta$, $r =$ heliocentric dist.

$\Omega = \left(\frac{m_e^2}{16\pi n_{45} r_{45} e^4 \Lambda} \right) =$ const., $r_{45} \approx$1 AU.

Angular FWHM of Strahl

Recalling $\mu = \cos\theta$, and approximating $\sin\theta \approx \theta$, we see strahl has Gaussian angular dependence:

$$f(\theta) \propto \exp\{-A(r, r_{45})n^{-1}K^2\theta^2\},$$

where $K \equiv \frac{m_e v^2}{2}$.

The full width at half maximum, (θ_{FWHM}), is given by the formula:

$$\theta_{FWHM} \approx 24^\circ \left(\frac{K}{100\ \mathrm{eV}}\right)^{-1} \left(\frac{n(r_{45})}{5\ \mathrm{cm}^{-3}}\right)^{1/2} \left(1 + \frac{r_{45}^2}{r^2}\right)^{1/4}, \quad (1)$$

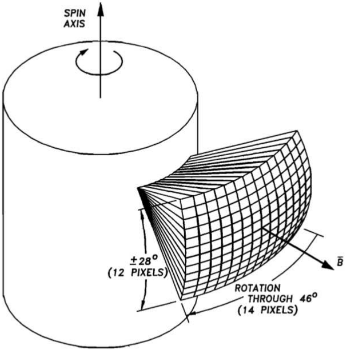
Note the scaling relations:

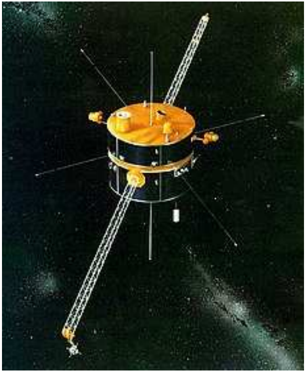
i For given n, $\theta_{FWHM} \propto K^{-1}$

ii For given K, $\theta_{FWHM} \propto \sqrt{n}$

Narrow strahl predicted! Need high angular resolution to detect it.

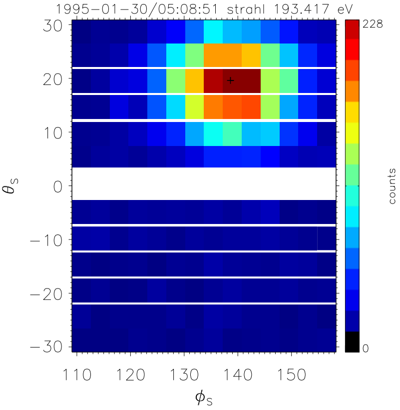
SWE Strahl Detector

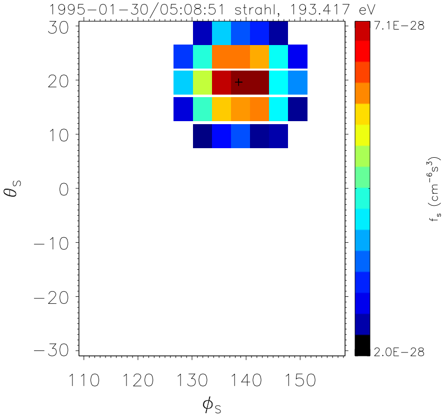




- Left: SWE strahl field of view (Ogilvie, 2000)
- Top right: SWE strahl detector (http://web.mit.edu)
- Bottom right: Wind spacecraft 1 AU (https://wind.nasa.gov)

SWE Strahl Detector



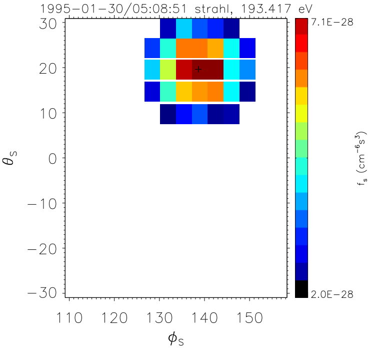


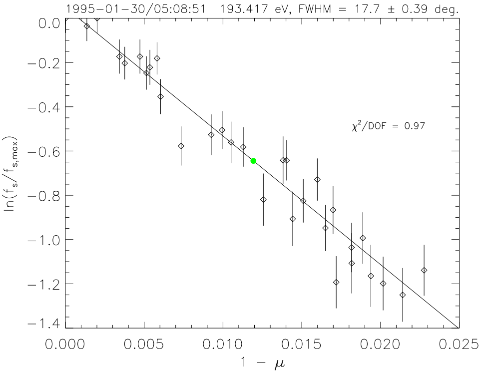
Raw counts

Cleaned distribution f (Horaites et al., 2018a)

Strahl electron counts measured at 3.5x4.5 degree resolution

Least squares: strahl width (Horaites et al., 2018a)

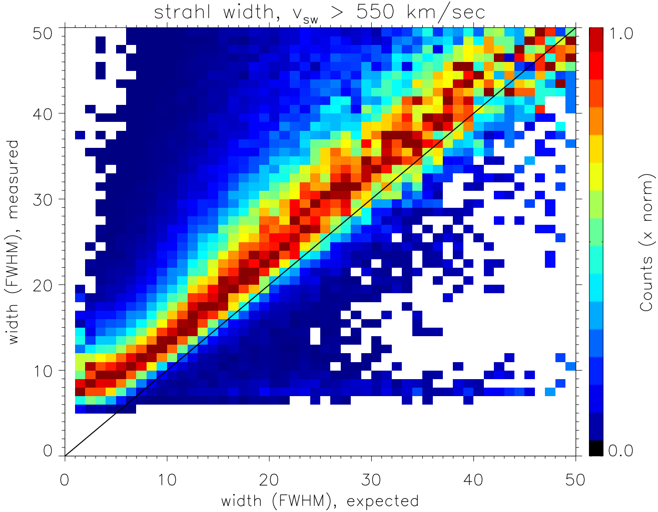




Model: $\ln\left\{\frac{f(\mu)}{f_{max}}\right\} \propto (1-\mu)$

Fit yields a "Measured θ_{FWHM}" (green dot).

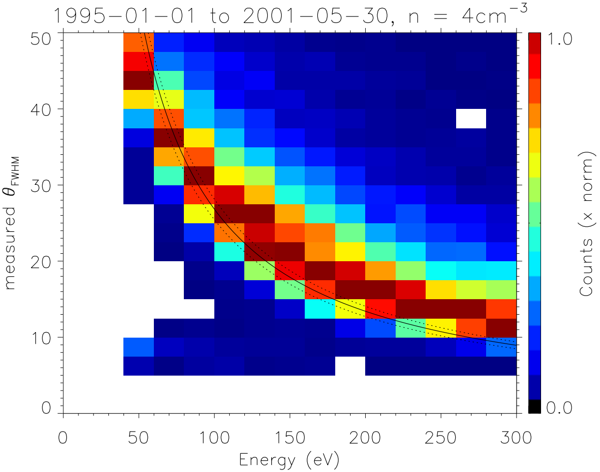
Model/Data Comparison: $v_{sw} > 550$ km/s



Horaites et al., 2019

Model/Data Comparison: $v_{sw} > 550$ km/s, $3.5 < n < 4.5$ cm^{-3}

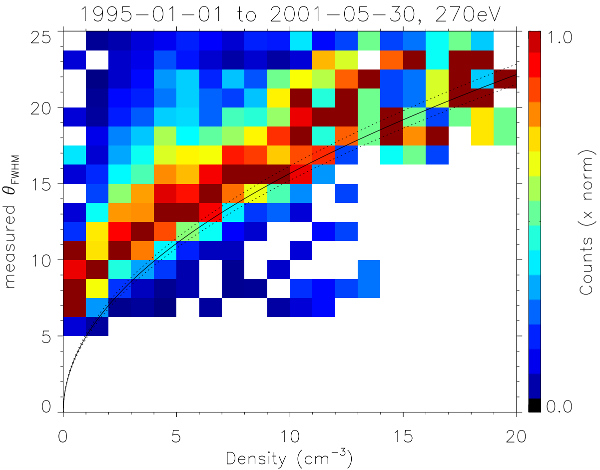
- For given n, $\theta_{FWHM} \propto K^{-1}$



Horaites et al., 2018a

Model/Data Comparison: $v_{sw} > 550$ km/s, $K = 271$ eV

- For given K, $\theta_{FWHM} \propto \sqrt{n}$

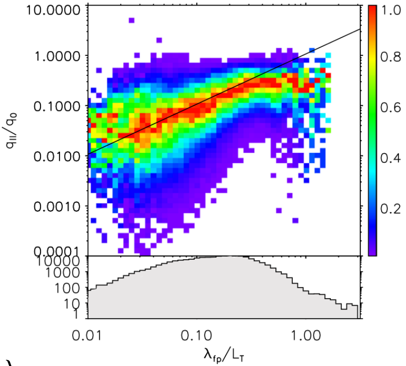


Horaites et al., 2018a

Measuring energy dependence: F_{ave}

$$f(r,\mu,v) = \frac{C(v^2)}{r} \exp\left\{ -\frac{v^4(1-\mu^2)}{\sqrt{1+r_{45}^2/r^2}} \left(\frac{m_e^2}{16\pi n_{45} r_{45} e^4 \Lambda} \right) \right\}$$

- Want to measure the function $C(v^2)$.
- But, $f(\mathbf{v})$ measured by SWE/strahl 1 energy at a time.
- Consider also that $\mathbf{q}$, and by extension the strahl, depends on collisionality ($\tilde{\gamma}$).

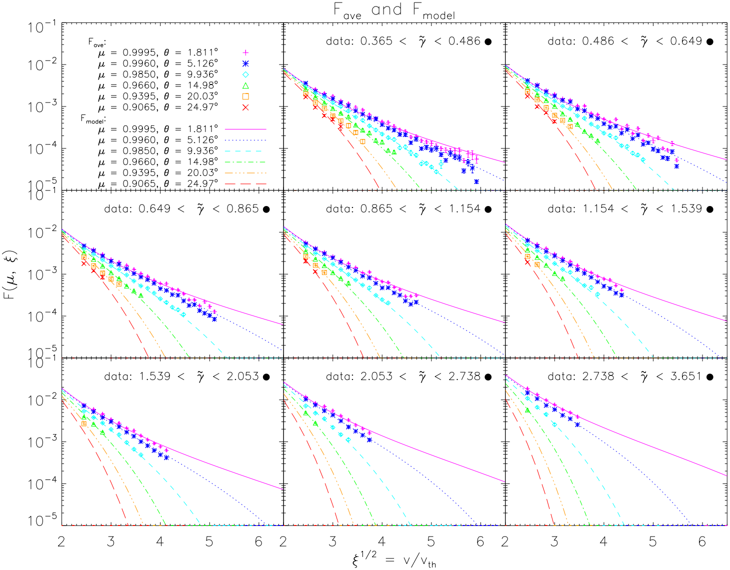


Approach: construct *averaged* distribution F_{ave} from all the strahl data, sorted by $\tilde{\gamma}$.

$$\tilde{\gamma} \equiv \frac{T^2}{2\pi e^4 \Lambda n r} \sim \frac{\lambda_{mfp}}{L_T}$$

Bale et al., 2013

F_{ave}, 2D fits $(\mu, (v/v_{th}))$



Horaites et al., 2018a

Related work

- Boldyrev et al. (2019, 2020) incorporates turbulent diffusion and large scale electric field.
- See Halekas (2020) for electrons/strahl in the Parker Solar Probe data
- Horaites (2019b) discusses collisionless formation of the halo. But halo is not well understood!

Electrons from the Inner Heliosphere to Mars

Overview

Field-aligned e^- ("strahl") in the solar wind

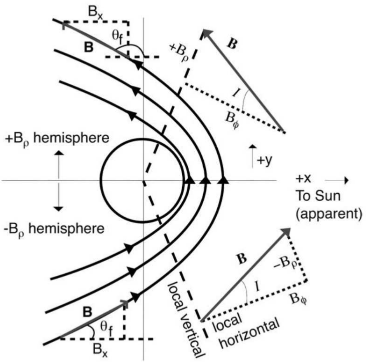
Electrons in the Mars's Magnetosheath: MAVEN Analysis

Conclusions

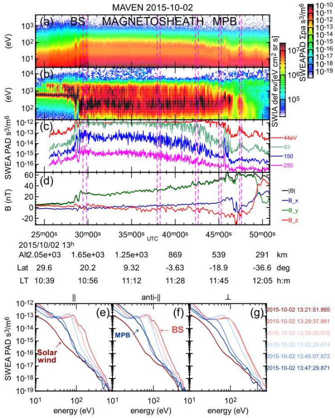
Motivations

- At Mars, only a handful of papers have considered the kinetics of electrons in the magnetosheath.
- The MAVEN Orbiter had a full suite of plasma instruments, including an e^- electrostatic analyzer.
- Electrons are very mobile. Magnetosheath electrons and can act as a snapshot of the global conditions.
- Some disagreement exists in the literature on the role of collisions in the Martian magnetosheath.

Electrons in the Martian Magnetosheath



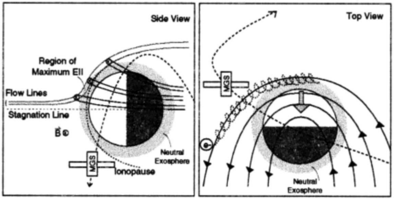
Crider et al., 2004



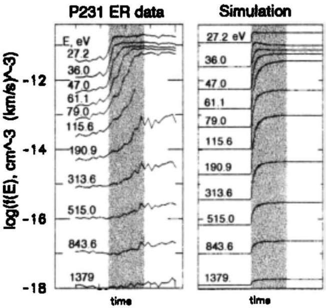
Schwartz et al., 2019

The electron distribution inflates at the shock (energization), and then "erodes" at the "MPB" (de-energization).

eVDF Erosion at the MPB: Collisionless vs. Collisional



Crider et al., 2000



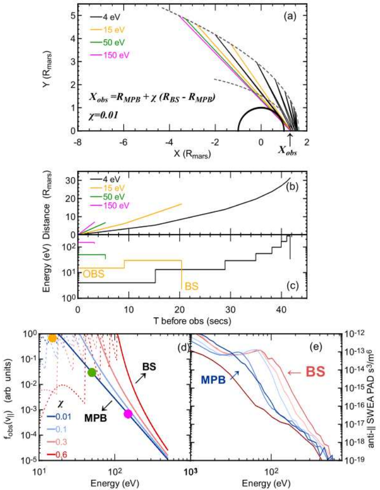
EII Simulation results

In the original explanation, the MPB erosion is the result of electron impact ionization (EII) with neutral Hydrogen and Oxygen.

Requires e^- to remain in the sheath for 400 sec!!

Collisionless Kinetics

EII too slow: can collisionless physics explain the eVDFs?



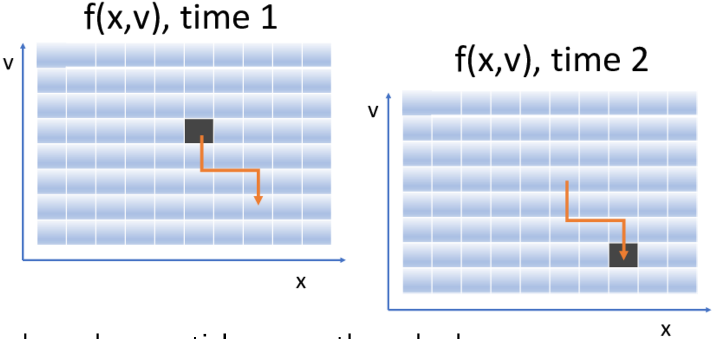
Results of kinetic simulations, Schwartz et al., 2019. (Anti-)Parallel electrons enter the sheath from a presumed solar wind distribution, and resulting distribution is calculated along a line intersecting the subsolar point.

Results are encouraging—let's apply collisionless kinetic theory to the MAVEN data.

Collisionless Kinetics: Liouville's Theorem

From Vlasov Equation: the solution $f(\mathbf{x}, \mathbf{v}, t)$ is *constant* along a particle's trajectory through phase space.

$$\frac{\partial f(\mathbf{x}, \mathbf{v}, t)}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} + \frac{q_e}{m_e}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f}{\partial \mathbf{v}} = 0$$



If you know how particles move through phase space, you can predict the final eVDF!

Applying Liouville's Theorem: Particle Trajectories

But how to predict the particle motion? Assume energy and magnetic moment (M) are conserved. For (anti-)parallel propagating electrons, M=0:

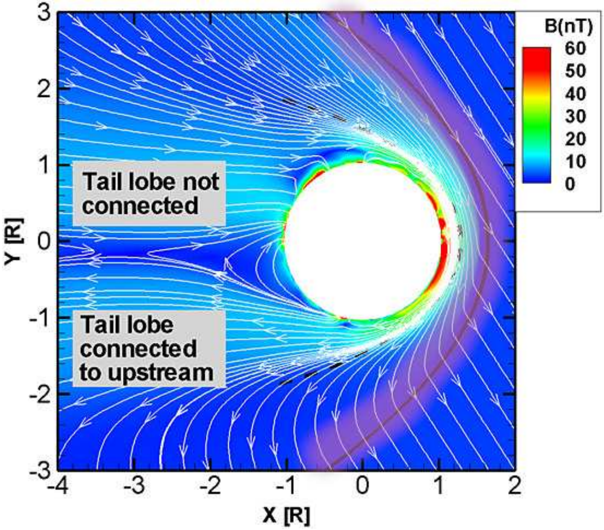
$$f_{2,\parallel}\left(v^2 + \frac{2\Phi_\parallel}{m_e}\right) = f_{1,\parallel}(v^2) \tag{2}$$

$$f_{2,\downarrow}\left(v^2 + \frac{2\Phi_\downarrow}{m_e}\right) = f_{1,\downarrow}(v^2) \tag{3}$$

$\parallel$ = parallel, $\downarrow$ = anti-parallel

Note: above, all field-aligned electrons (regardless of energy) are assumed to experience the same integrated electric field Φ. Particle drifts weaken this assumption somewhat.

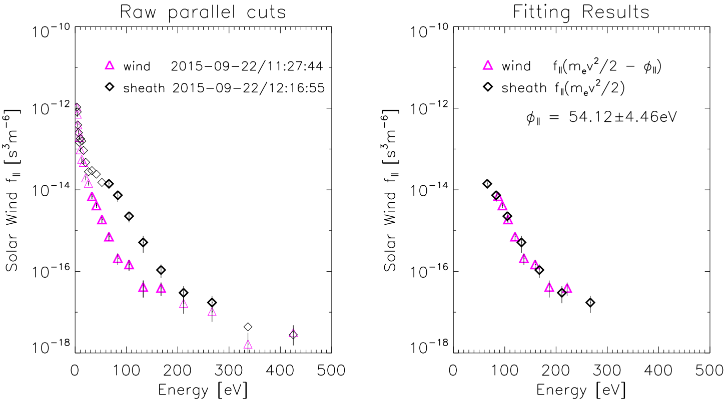
Visualization: Energization may depend on trajectory



Luhmann et al. 2015

Applying Liouville's Theorem: Parallel cuts

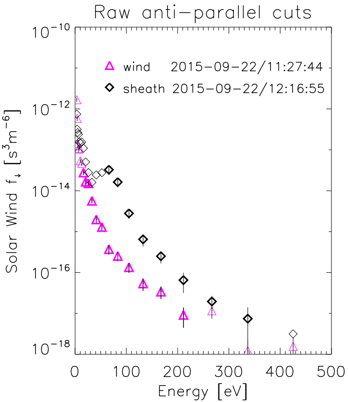
$$f_{2,\parallel}\left(v^2 + \frac{2\Phi_\parallel}{m_e}\right) = f_{1,\parallel}(v^2) \quad (4)$$



parallel cut (Horaites et al. 2021)

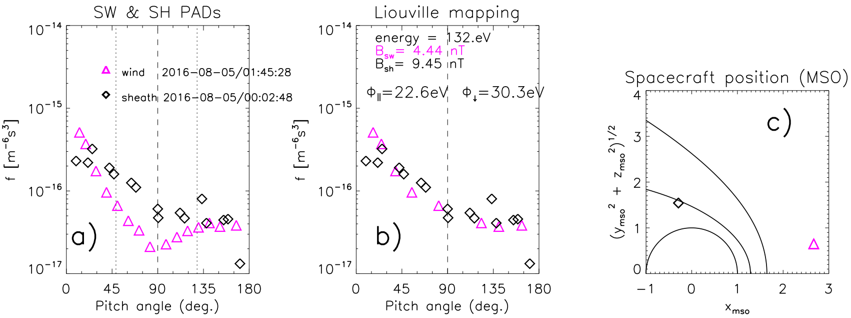
Applying Liouville's Theorem: Anti-parallel cuts

$$f_{2,\downarrow}\left(v^2 + \frac{2\Phi_\downarrow}{m_e}\right) = f_{1,\downarrow}(v^2) \quad (5)$$



anti-parallel cut (Horaites et al. 2021)

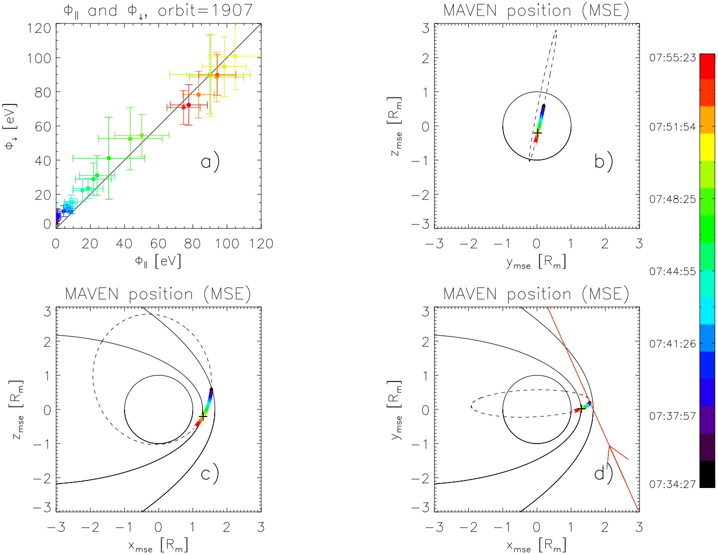
Applying Liouville's Theorem: Pitch Angle Mapping



At fixed energy, can map the pitch angle distribution (PAD) from solar wind to the sheath (mirror force, modified by electric field).

Confirms the assumption of collisionless behavior.

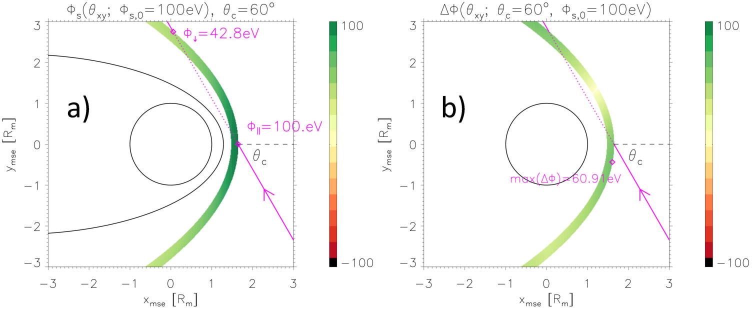
Isotropic Energization observed!



$$\Phi_{\parallel} \approx \Phi_{\downarrow}$$

Isotropic Energization observed!

Why is this interesting? Because in general $\Phi_{\|}$ and $\Phi_{\downarrow}$ may be expected to be different.

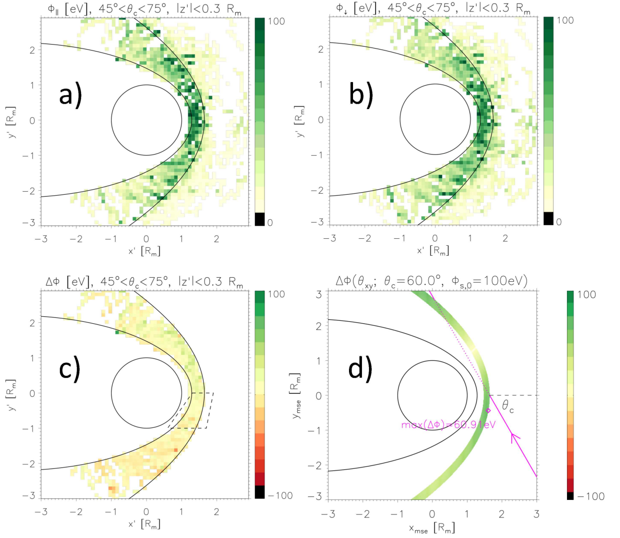


Left: Model of the cross-shock potential. Right: Predicted $\Delta\Phi$

Quantify the anisotropy:

$$\Delta\Phi = \Phi_{\|} - \Phi_{\downarrow}$$

Global statistics: $\Delta\Phi$, $z_{mse} = 0$ plane



a. $\Phi_\parallel$ b. $\Phi_\downarrow$ c. $\Delta\Phi = \Phi_\parallel - \Phi_\downarrow$ d. $\Delta\Phi$ (model)

Implications

$\Delta\Phi \neq 0$. So what?

- A model in which electrons are only energized at the shock (as has been previously assumed) does not work.
- What could cause isotropic energization? An electrostatic potential.

The $\sim$100eV acceleration provided by the electrons could be easily provided by the ambipolar electric field:

$$\mathbf{E_A} = -\frac{\nabla P_e}{e n_e}$$

If the ambipolar field is a nearly potential field, this would explain the observations!
This may be checked in future work..

Electrons from the Inner Heliosphere to Mars

Conclusions

- The strahl (runaway) electron population in the solar wind can be effectively described by the steady-state drift kinetic equation, which incorporates magnetic focusing and Coulomb collisions.
- In Mars's magnetosheath, the parallel ($\Phi_{\parallel}$) and anti-parallel ($\Phi_{\downarrow}$) energizations are very similar. This indicates that electrons are energized continuously throughout the sheath, not just at the shock front as is commonly assumed.
- The observation $\Delta\Phi \approx 0$ provides strong evidence that the electrons are energized by a (nearly) potential electric field in the sheath. This potential field is likely provided by the ambipolar (pressure gradient) field.