Atypical electron holes

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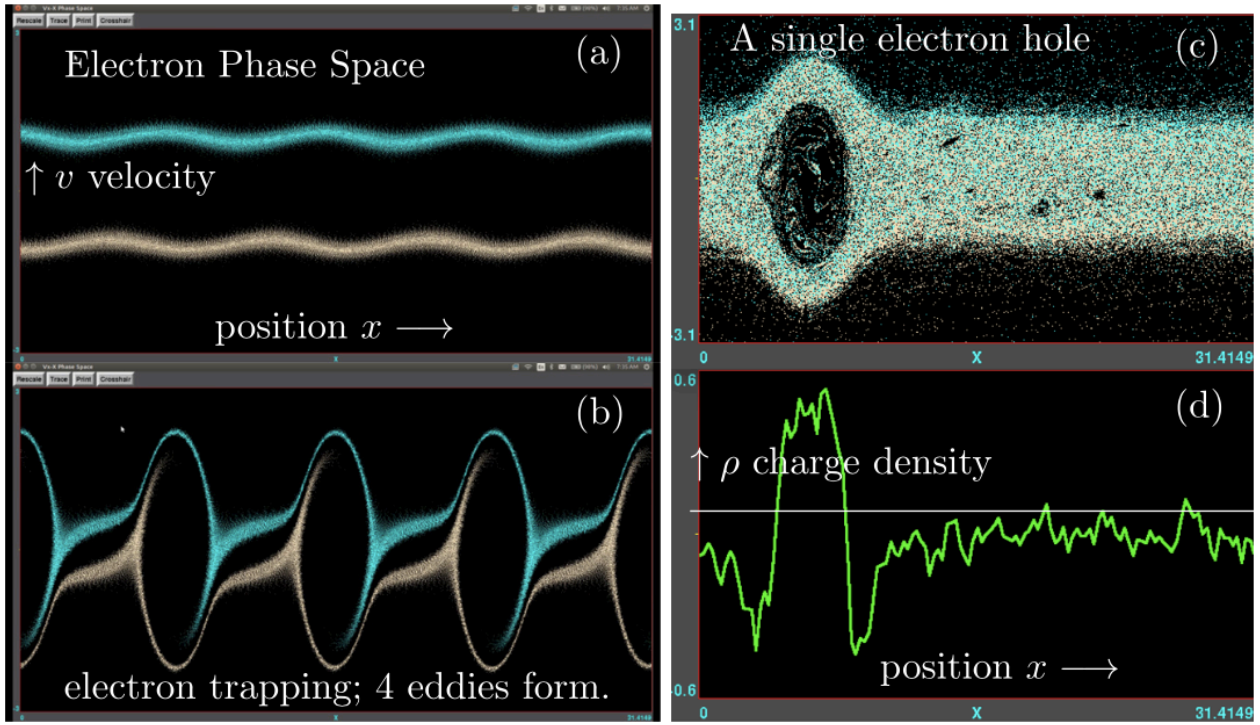
Electron phase space holes – solitary structures we are interested in

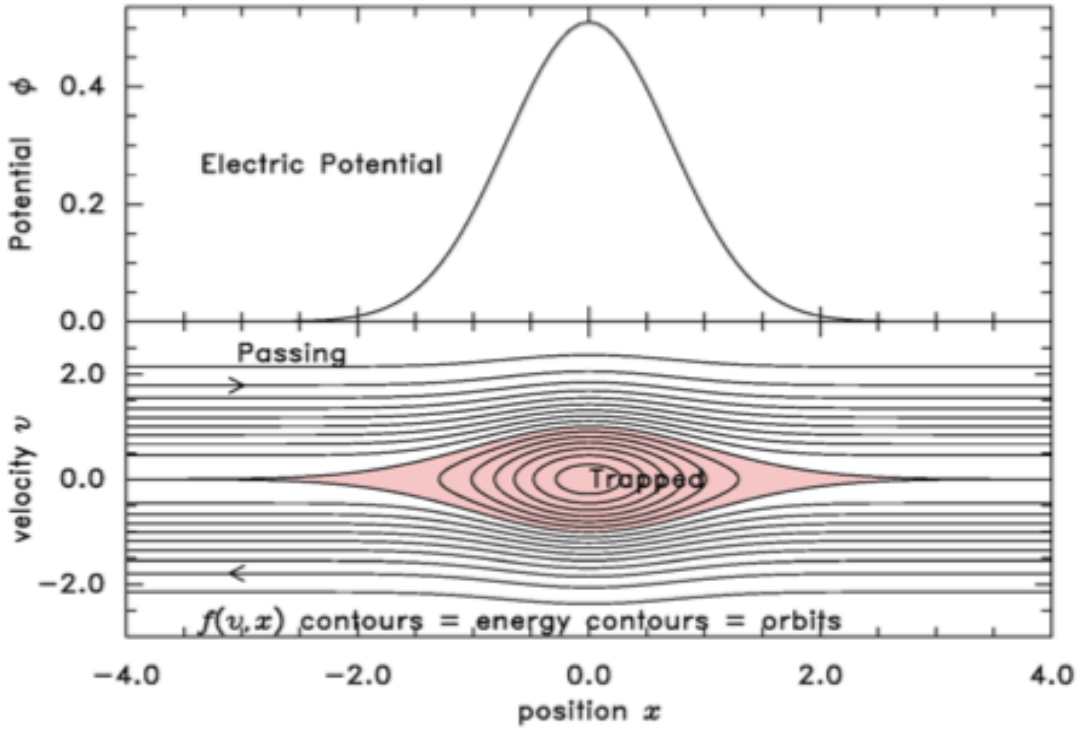


Electron-phase-space holes are formed in a nonlinear stage of various electron streaming instabilities (bump-on-tail, two-stream, Buneman)

see, e.g., Omura+, jgr, 1996; Drake+, Nat., 2003

In spacecraft measurements they are observed as solitary waves with positive potentials

these solitary waves are kinetic modes existing due to a depletion of the phase space density of trapped electrons



see, e.g., Hutchinson, Phys.Plasmas, 2017

Theoretical description

An electron-hole is purely kinetic phenomenon, since it arises as a solitary solution of the Vlasov-Poisson system(written in the structure rest frame)

$$v\frac{\partial f}{\partial x}+\frac{\partial \phi}{\partial x}\frac{\partial f}{\partial v}=0$$

$$\frac{d^2\phi}{dx^2}=-4\pi e(n_i-n_e)$$

$$n_e(\varphi)=\int f_e(v,x)dv \qquad n_i=n_0$$

Using the Liouville's theorem a solution of the Vlasov equation
can be written in terms of the Full Energy:

$$w=(v-u)^2-\varphi$$

$$f_e(v,x)=\pi^{-1/2}\exp\left[-(M+\sqrt{w})^2\right],\ v-u>\sqrt{\varphi(x)}$$

$$f_e(v,x)=\pi^{-1/2}\exp\left[-(M-\sqrt{w})^2\right],\ v-u<-\sqrt{\varphi(x)}$$

$$f_{tr}(v,x)=\pi^{-1/2}\exp\left[-M^2+\beta w\right],\ -\varphi_0<w<0$$

Where we have introduced normalized variables

$$v\to v/v_T,\ x\to x/\lambda_D,\ e\varphi/T_e\to\varphi$$

By integrating the distribution over the velocity we obtain the density as a function of the potential:

$$\frac{d^2\phi}{dx^2}=n_e(\phi)-n_0=-\frac{dV}{dx}$$

$$n_e(\phi)=\int f_e(x,v,\phi)dv$$

This system can maintain a soliton-like Solution, which in the low-amplitude limit has a form of:

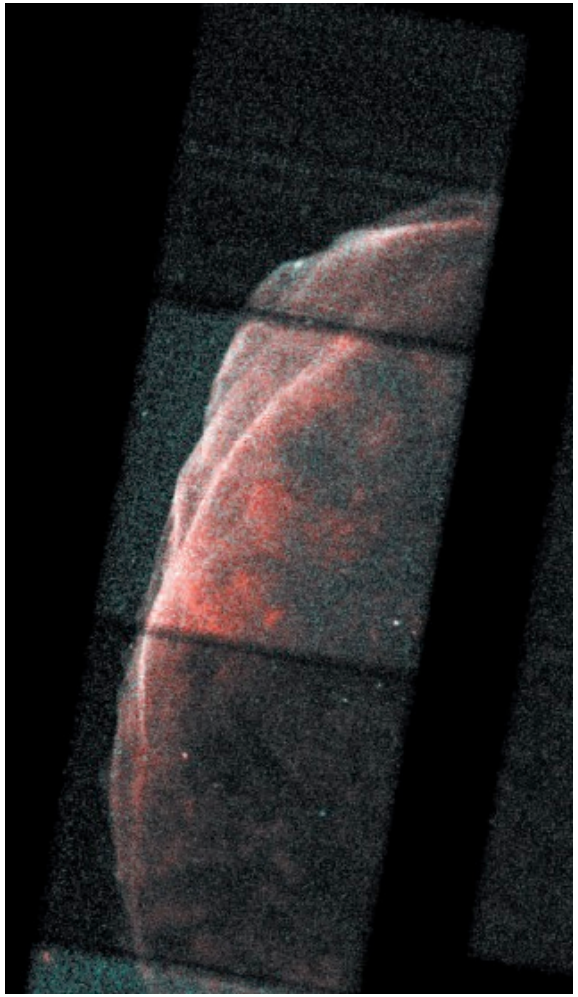
$$\phi(x)=\psi\,\mathrm{sech}^4(x/4).$$

Where Ψ is the amplitude of the soliton.

(see review by Schamel, Phys. Scr., 1986)

astrophysical applications

Chandra measurements
of synchrotron emission in a SNR



Bamba+, ApJ, 2003

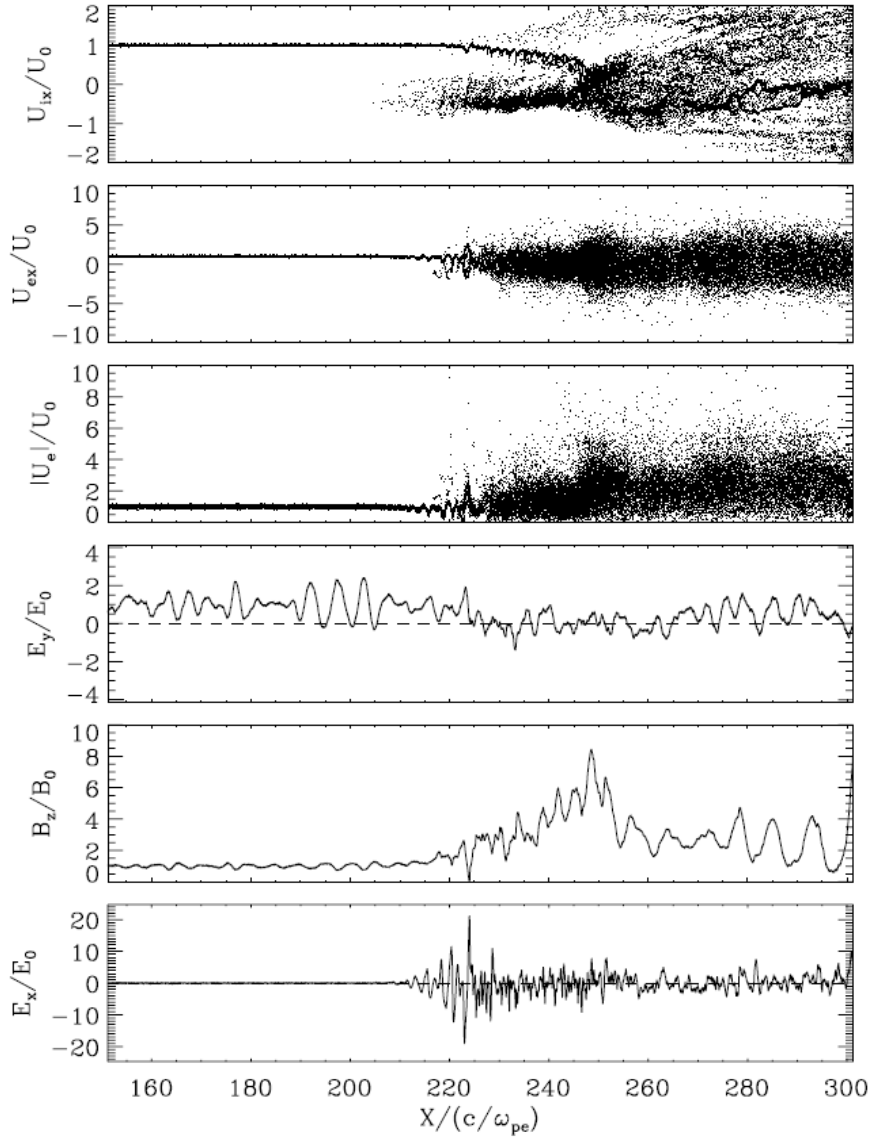
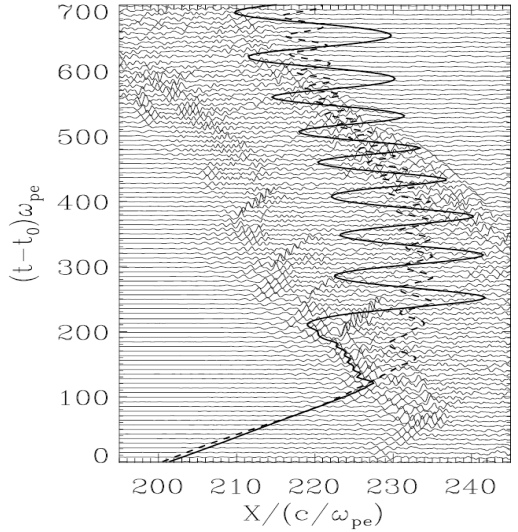
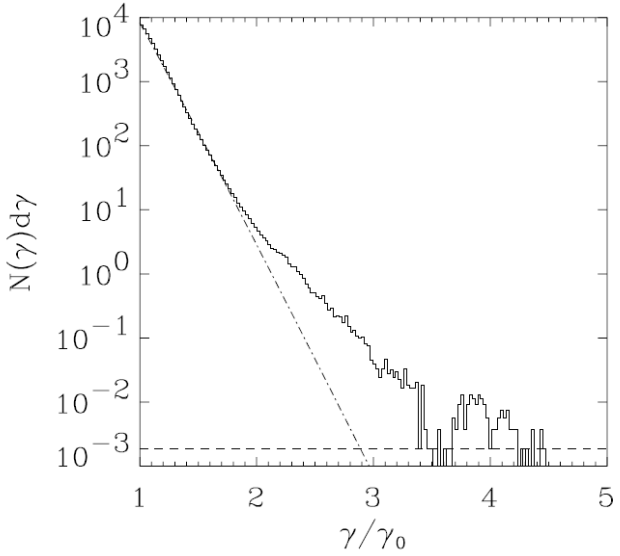


FIG. 1*a*

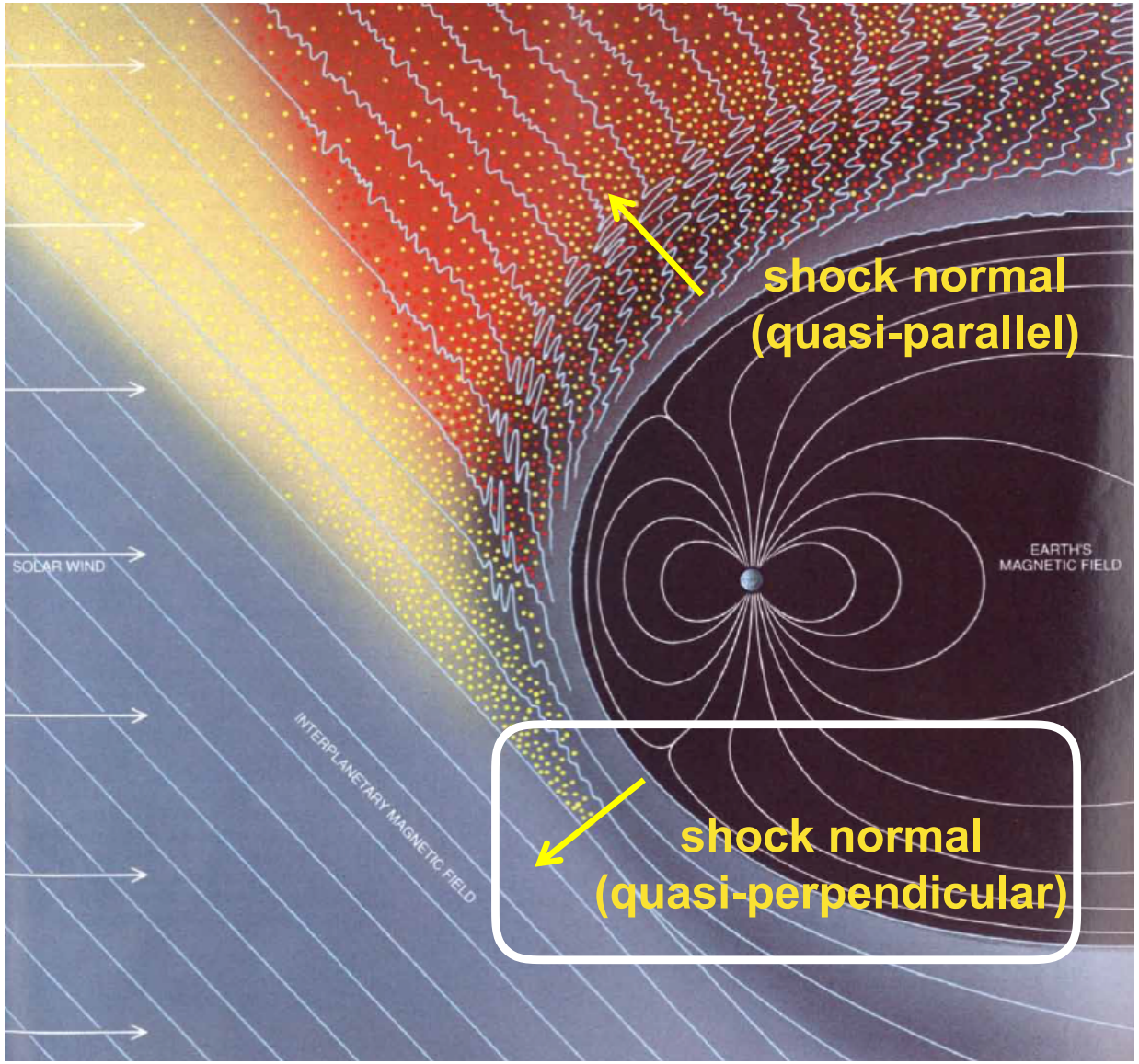
Hoshino+, ApJ, 2002

electron surfing acceleration &
injection problem



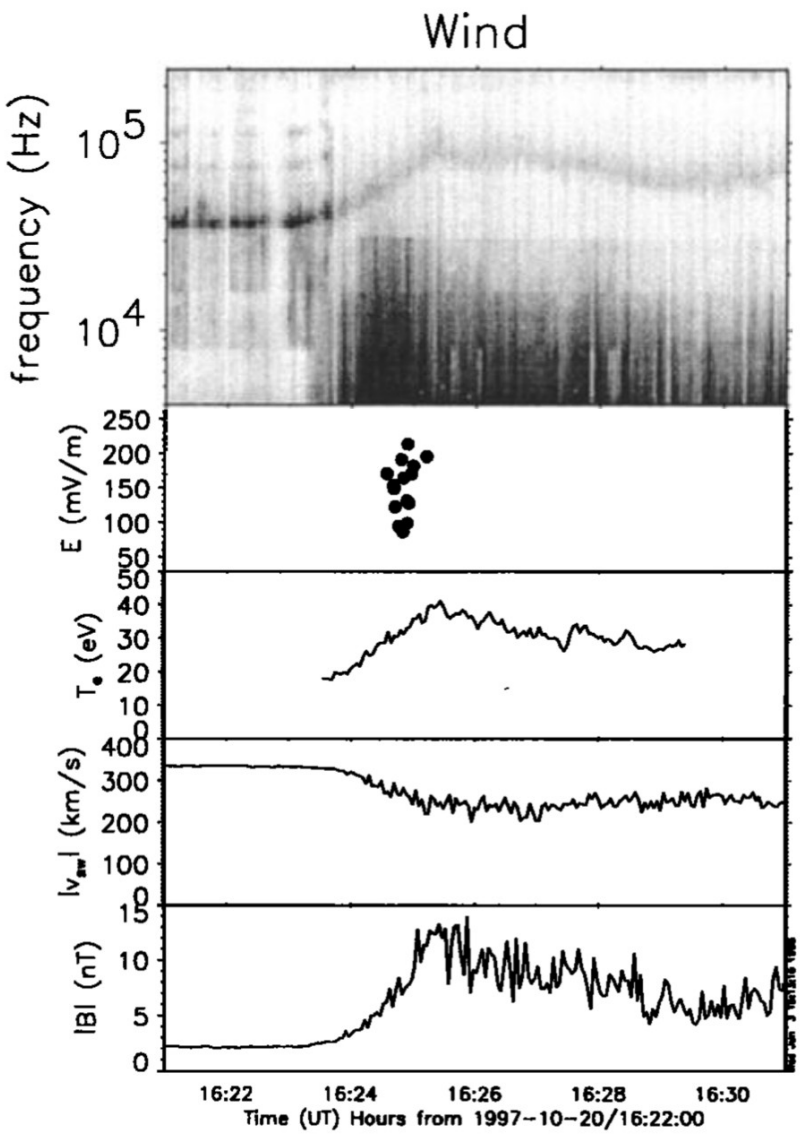


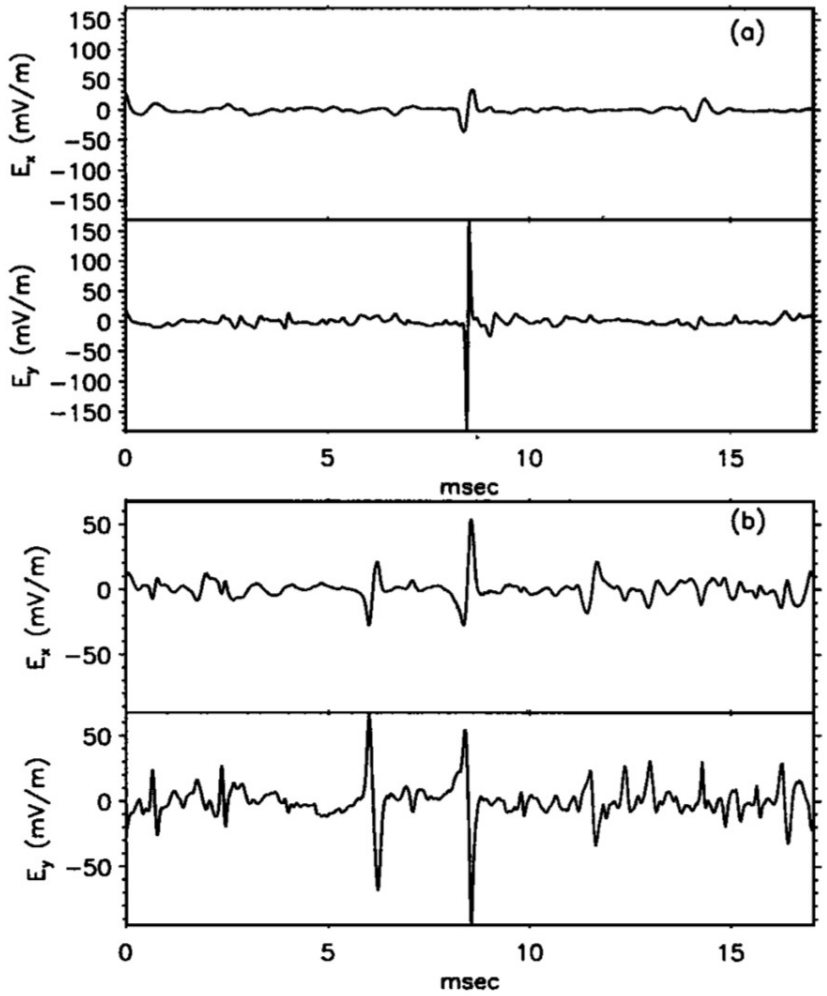
the Earth's bow shock



- **Solar wind is supersonic and super-Alfvenic**
- **Shock wave formation from Earth's magnetic field slowing down solar wind**
- **Earth's bow shock is supercritical and collision less**
- **Quasi-perpendicular (perpendicular to magnetic field) or quasi-parallel (parallel to magnetic field)**
- **We will focus on quasi-perpendicular shocks**

bipolar electrostatic structures measured by Wind spacecraft

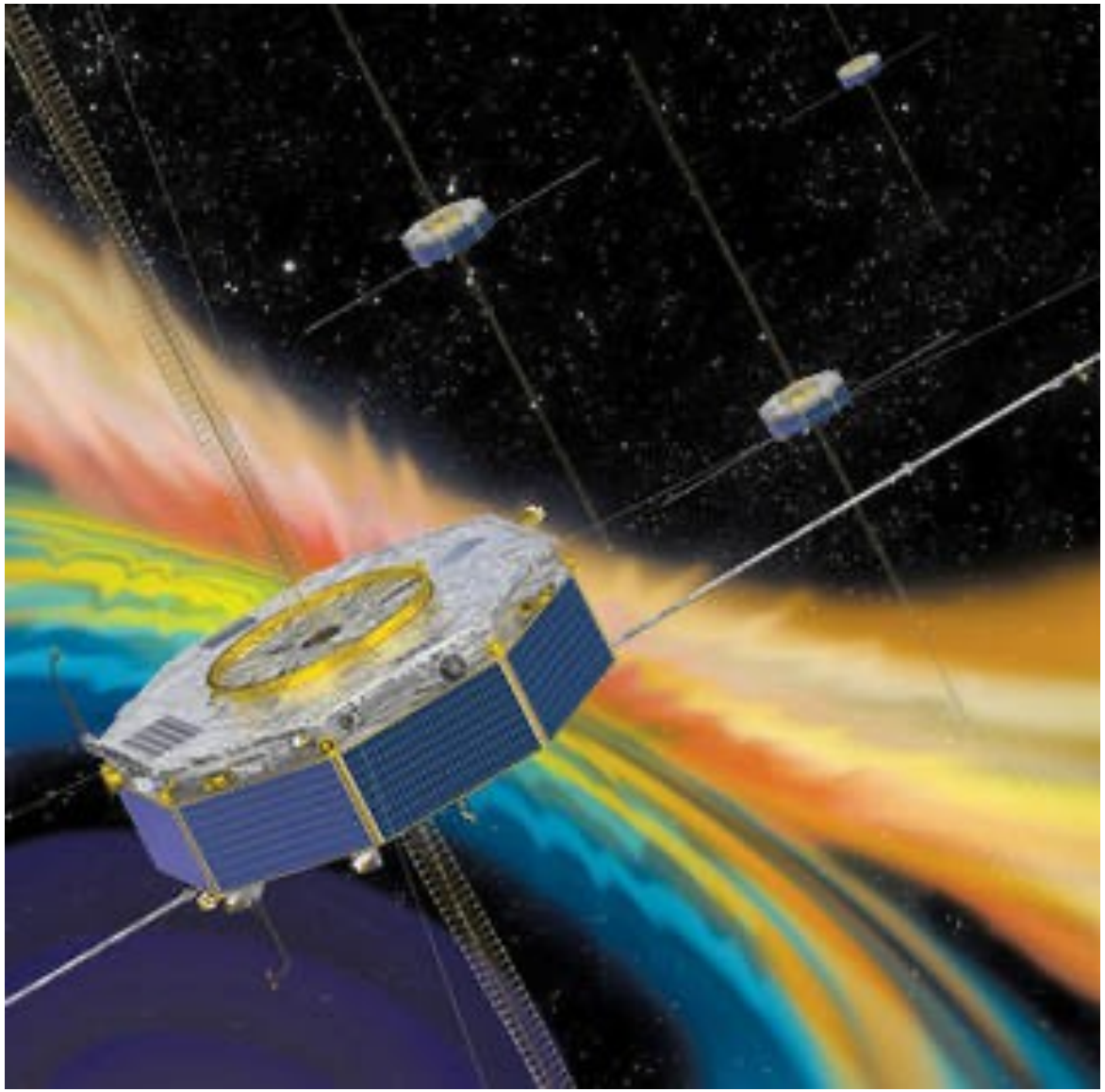




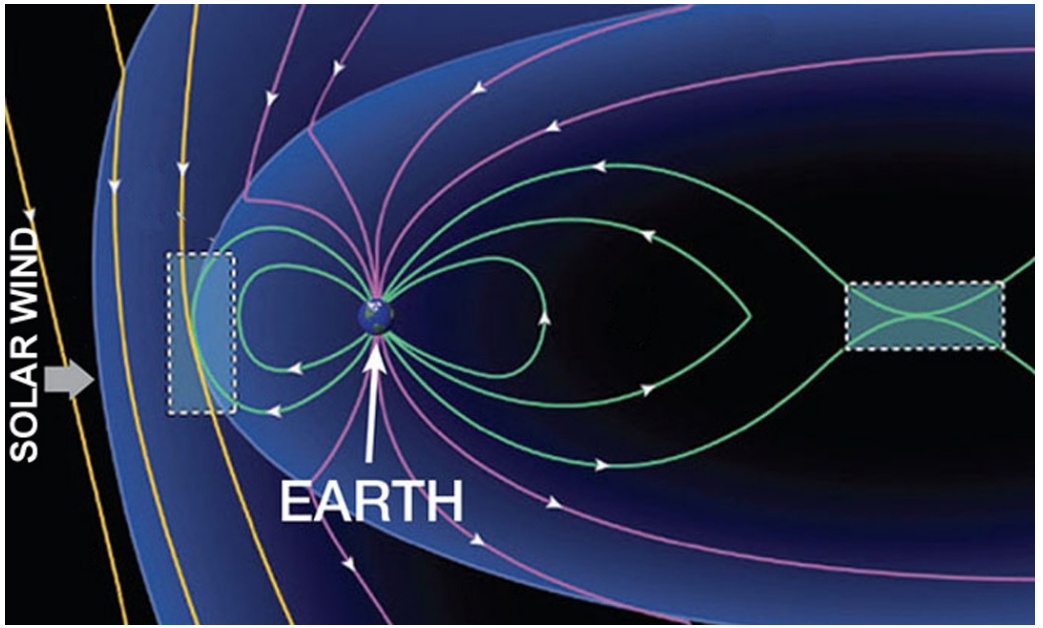
- High amplitude bipolar electric field spike found in transition region of the bow shock
- A few milliseconds in duration
- Debye-scale structures
- Theorized to be electron phase space holes (positive potential) which may thermalize electrons

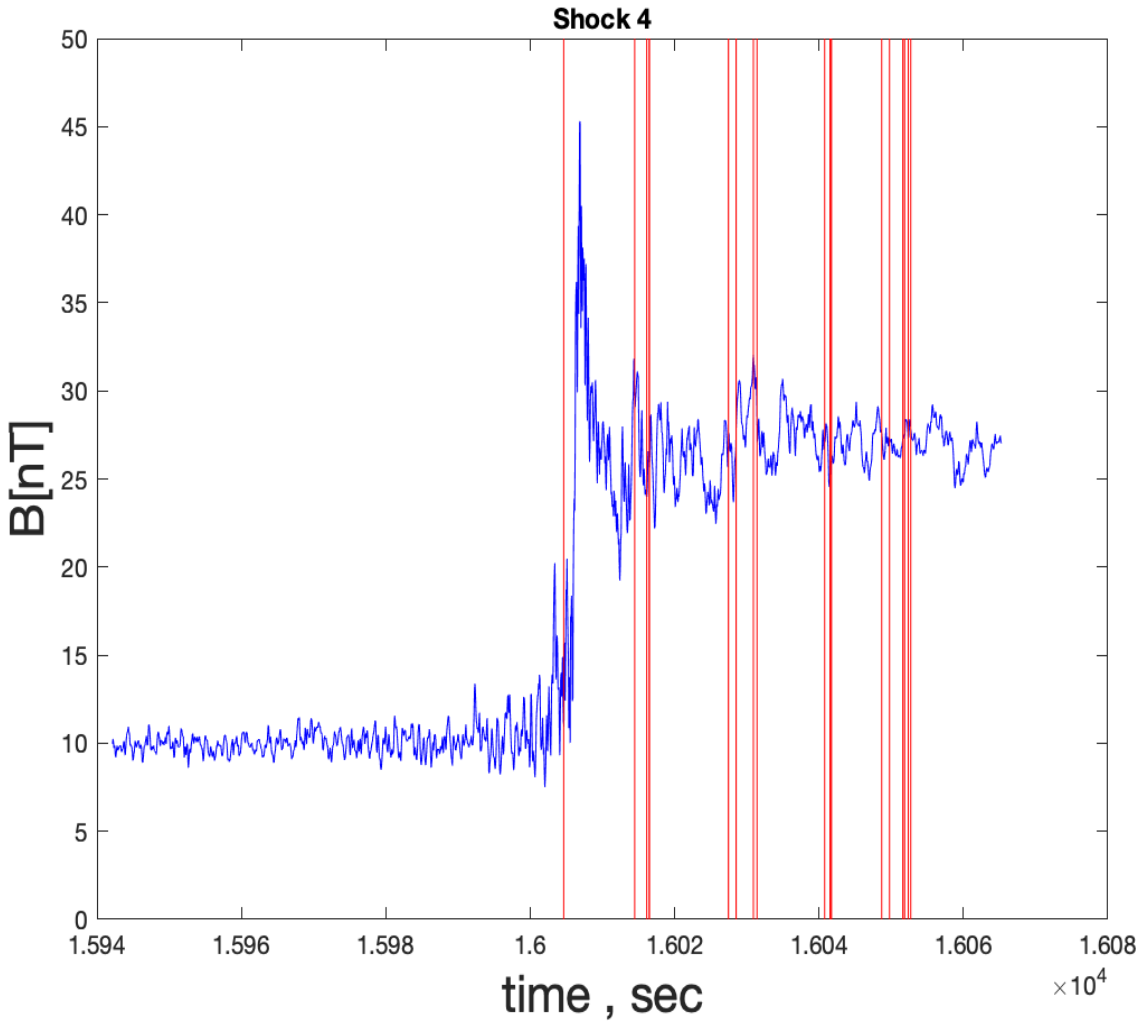
Bale+, grl, 1998

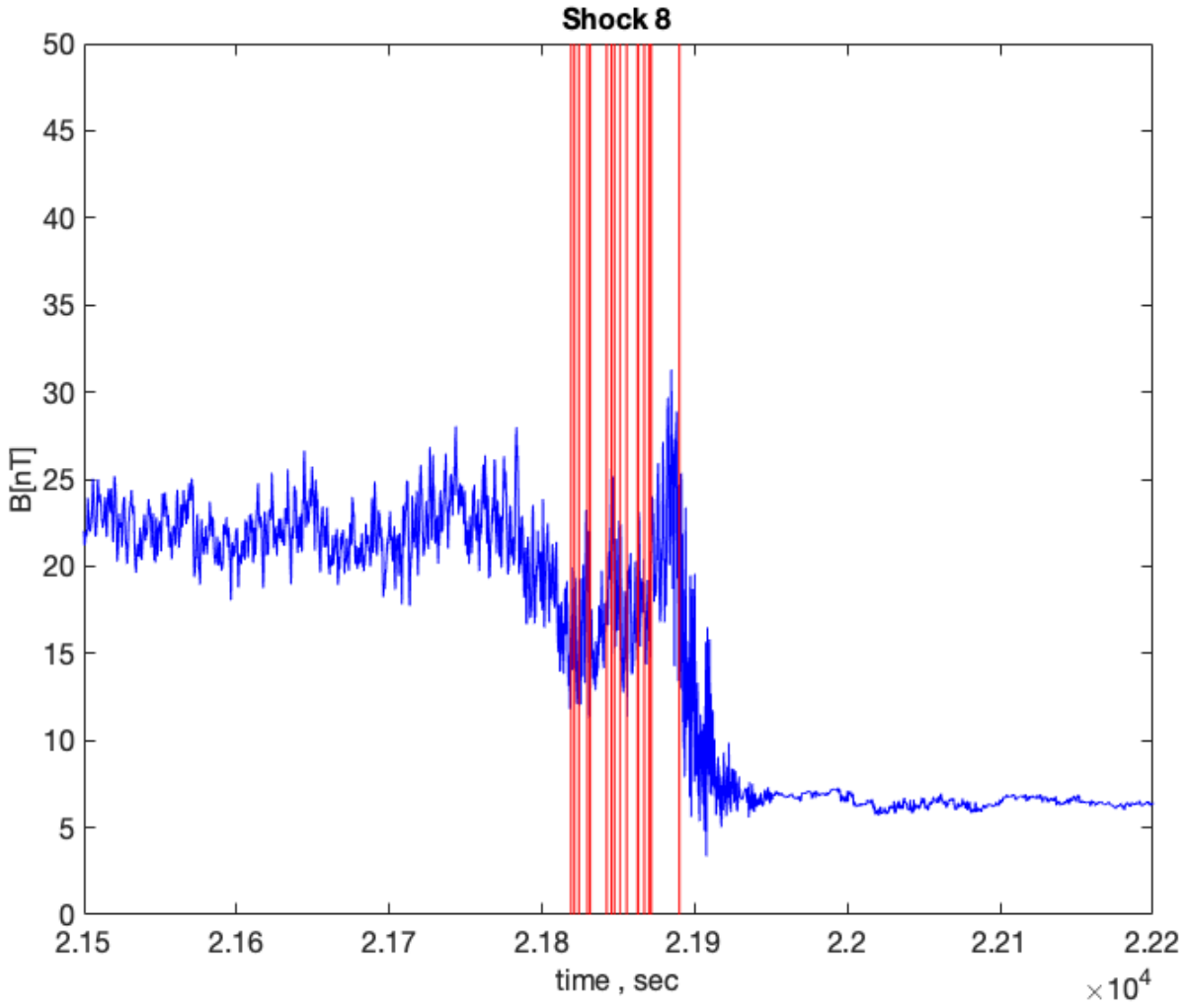
MMS



- Magnetospheric Multiscale mission
- Launched in 2015
- Studies Earth's magnetosphere
- Four identical spacecrafts flying in a tetrahedron
- 3D electric field measurements; fast particle measurements

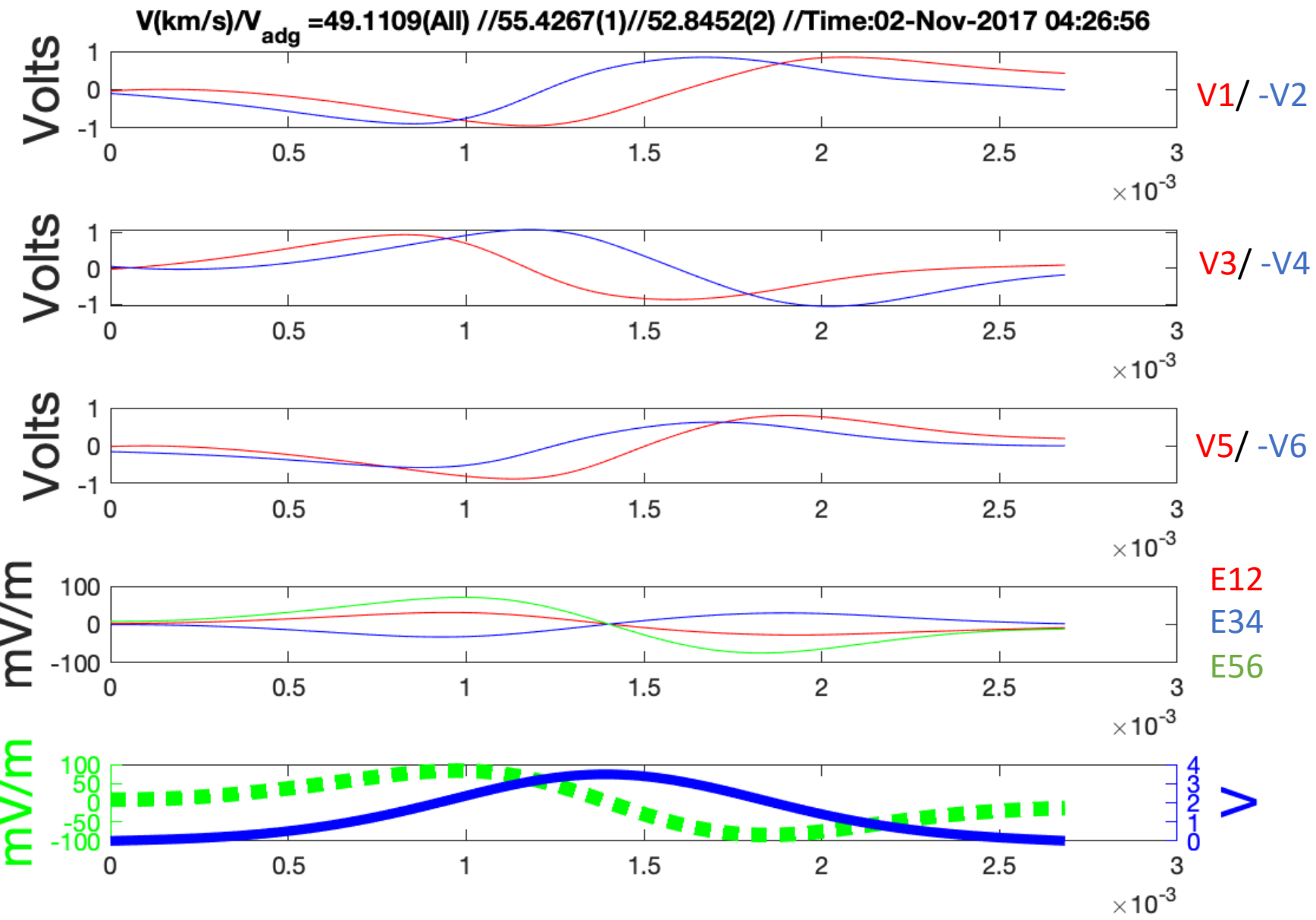






The plots represent the times of the events and the magnetic field magnitude.
The graphs indicate that the positive-soliton-like structures are mainly observed in the downstream region.

An instance of the one particular structure



$Angle_{kE}$ = 3.1680 deg

$V_{ionic\ acoustic}$ = 56.57 km/s

$V_{in\ the\ ionic\ frame}$ = 19.51 km/s

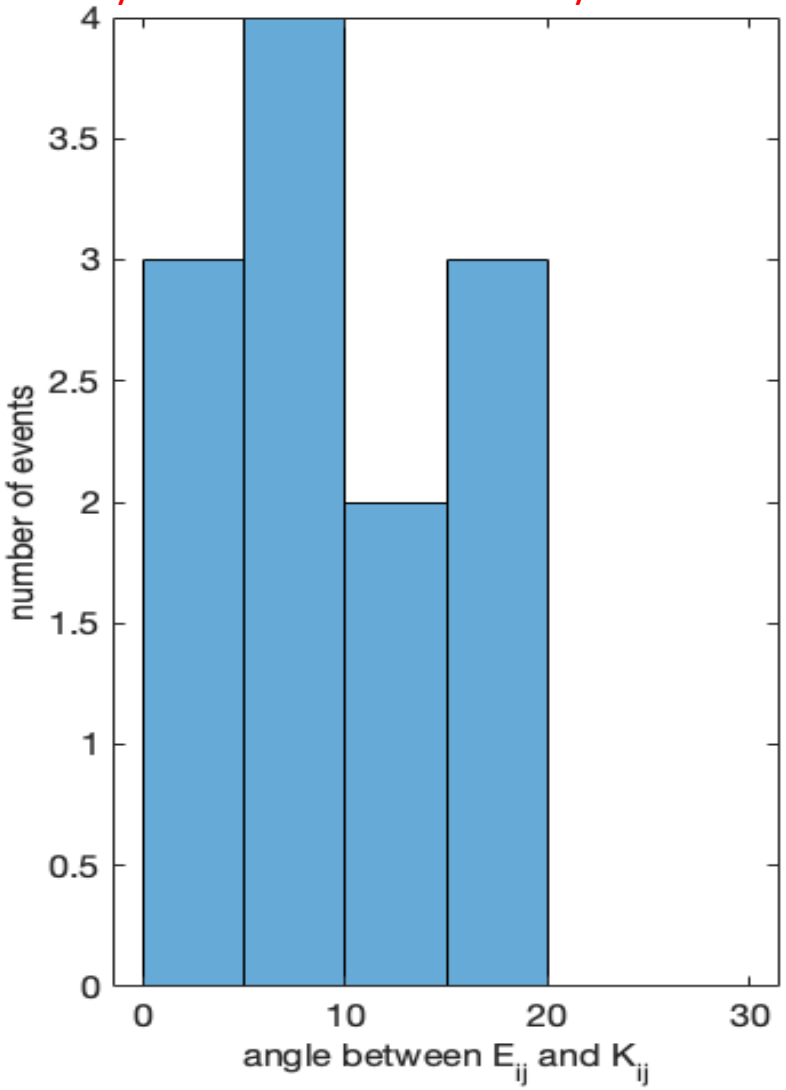
$Angle_{kB}$ = 23.7 deg

$L_{peak\_to\_peak}$ = 24.34 m

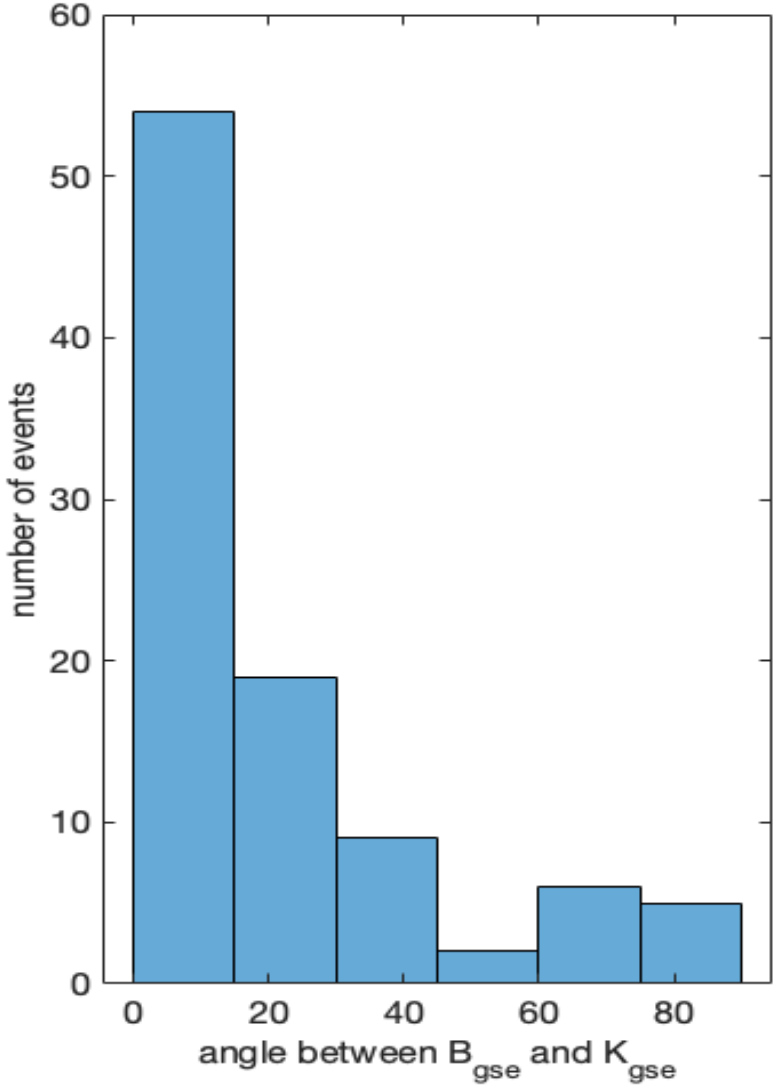
L/L_{debye} = 3.94

$e\phi_{max}$ = 0.1025 T_e

Only 12 structures with 3 delays are included



All 95 structures are included



The polarisation direction and the direction of propagation differ from each other less

Second histogramm indicates that about half of the strutures propagates along the magnetic field

The histograms represent the distributions:

(1) angles between the electric field polarization direction and the direction of propagation(calculated through delays)

(2) angles between the direction of propagation and the magnetic field(in GSE)

What is the nature of these positive structures ?

An Ion-acoustic soliton

- Positive potential
- Debye-scale structure
- Arises from the hydrodynamic description
- Has a speed greater than the ion acoustic speed
- Its Amplitude and scale are correletad:

  Mach $\propto \phi$ and $\phi \propto L^{-1/2}$ (Sagdeev, 1966)

or

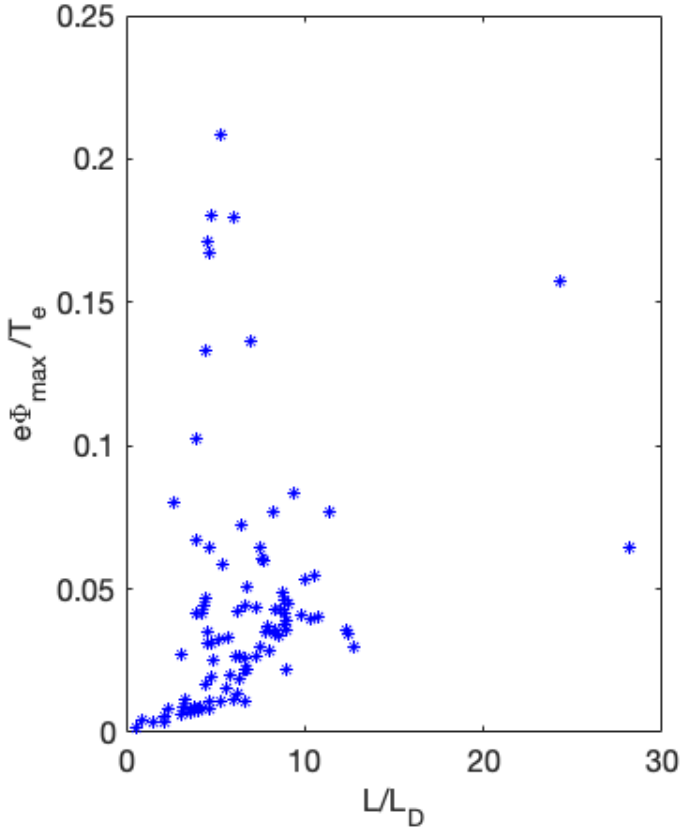
An Electron-phase-hole

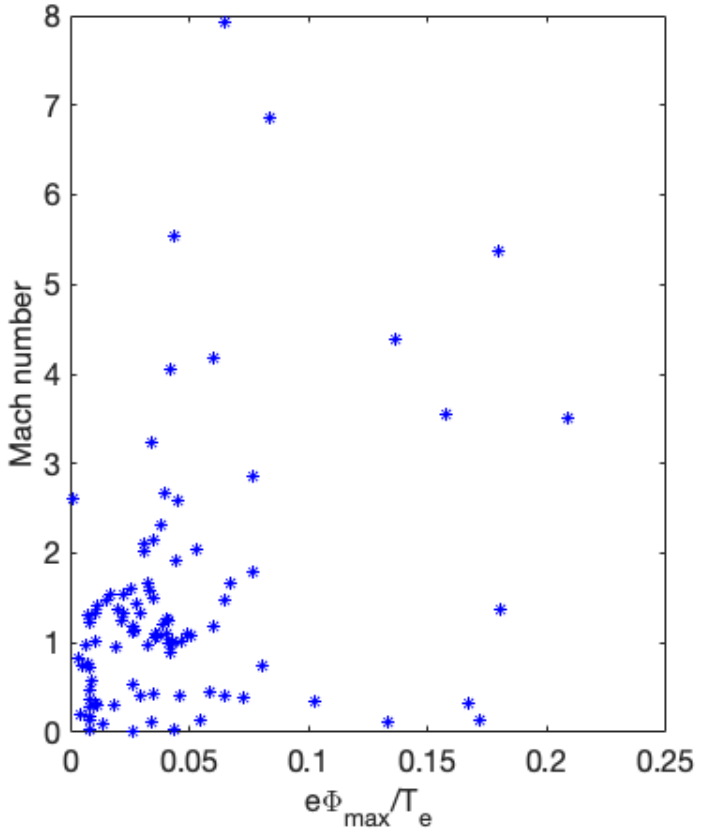
- Positive potential
- Debye-scale structure
- Purely kinetic phenomenon
- Can have a speed either greater or lesser than the ion acoustic speed
- No strict correlation between an Amplitude and a scale :

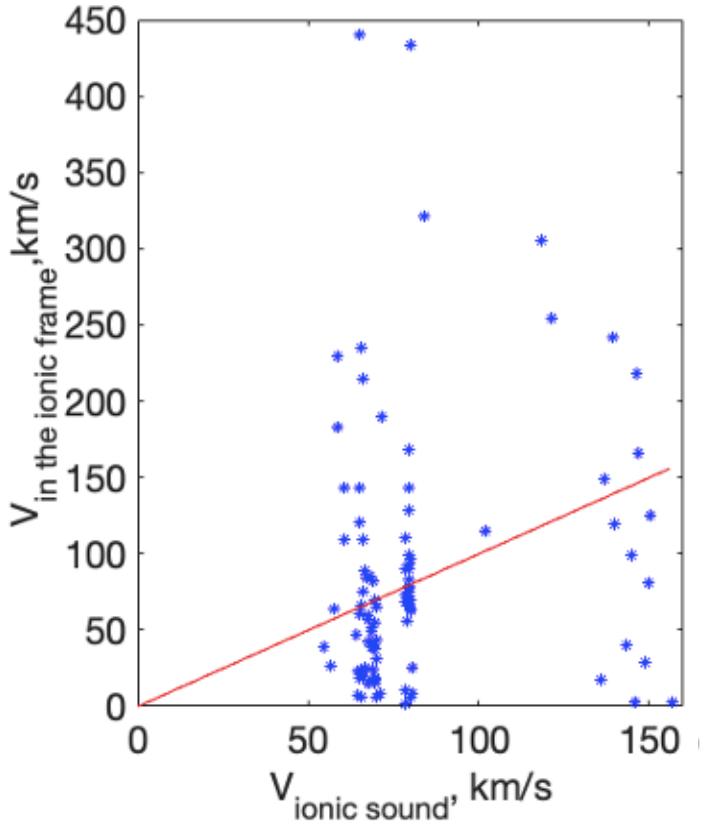
  $L >$ const $\phi^{1/4}$ (e.g., Hutchinson, 2017)

A soliton or a hole ?
That is the question!

Arguments against the Ion-acoustic soliton



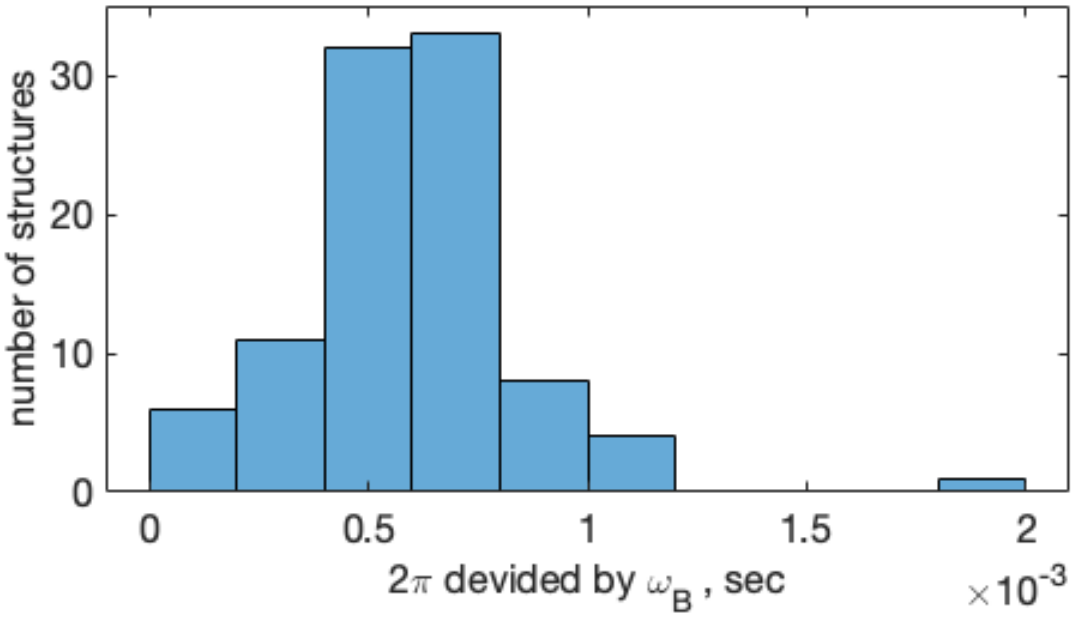


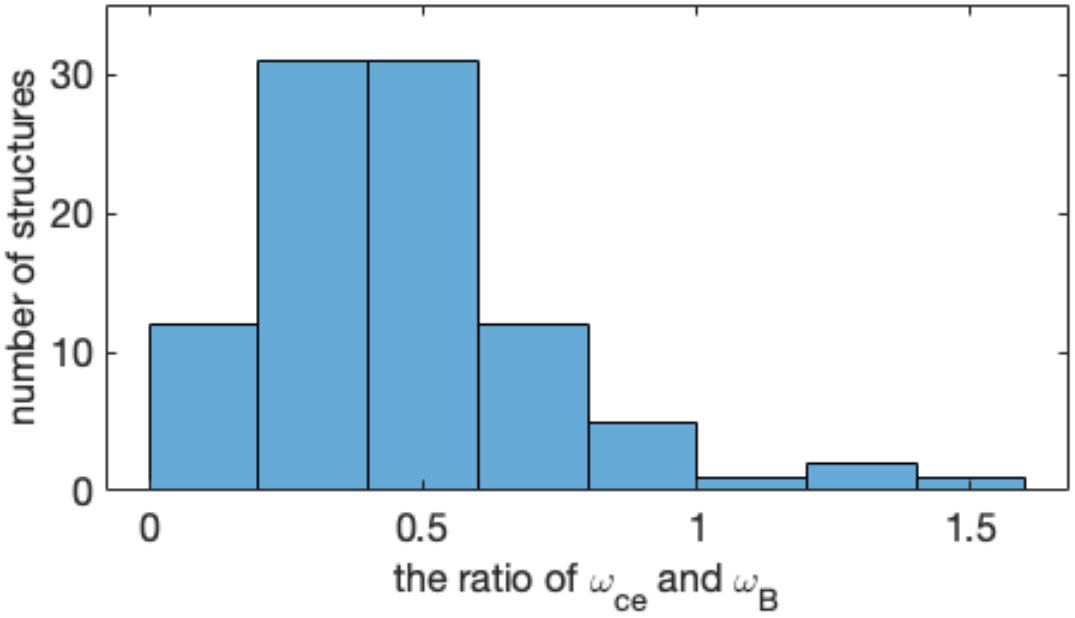


These plots yield that there is no correlation between the Mach number/Amplitude and Width which implies that these structures hardly can be ion-acoustic-solitons, since for them theory predicts such correlations

Mach ∝ Amplitude
Amplitude ∝ 1/sqrt(Width)

transverse instability of electron holes





Electron holes in the Earth's bow shock violate the transverse instability criterion(Muschietti+, prl, 2000)

$$\omega_B < \omega_{ce}$$

Therefore the lifetime of these electron holes should be a few bounce periods (Muschietti+, prl, 2000; Hutchinson, prl, 2019)

$$\tau_{EH} \sim afew \times 2\pi/\omega_B = afew \times \frac{2\pi}{\omega_{pe}} \frac{l}{\lambda_D} \sqrt{\frac{T_e}{e\varphi_0}}$$

The plot above gives an estimation for the life-time and happens to be of a few milliseconds

Conclusion

- We have proved that Bipolar structures with $\phi>0$ are electron holes rather than ion acoustic solitons

- We have found the Electron holes being shortly living structures and argued that it is caused by the violation of the transverse instability criterion