Dynamics of Electron-Scale Current Sheet Equilibria based on MMS Observations

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November 22, 2022

Abstract

The vicinity of the electron diffusion region (EDR) at the core of magnetic reconnection is frequently characterized by agyrotropic electron velocity distributions such as perpendicular velocity-space crescents [J. L. Burch et al., Science, DOI:10.1126/science.aaf2939 (2016)]. Although the evolving EDR is not itself an equilibrium state, its evolution may be slow on electron-cyclotron time scales. When this is the case, homogeneous equilibrium models are limited in their ability to model dynamical processes, such as instabilities and wave generation, in the presence of agyrotropic populations. In order to better study these processes, we initiate implicit PIC simulations with inhomogeneous kinetic equilibria built upon agyrotropic electron velocity distributions measured by the FPI spectrometers on MMS. The methodology involves the following elements: 1. Modeling the observed agyrotropic (e.g., crescent) and background plasma distributions 2. Numerically evaluating self-consistent inhomogeneous equilibria – including anisotropy 3. Initializing 1D, 2D, and 3D PIC simulations with the equilibria 4. Evaluating the simulation output for instabilities and the persistence of the crescents Particle tracing and other visualization tools will be employed to illustrate the underlying dynamics of particles and fields – and their interactions.

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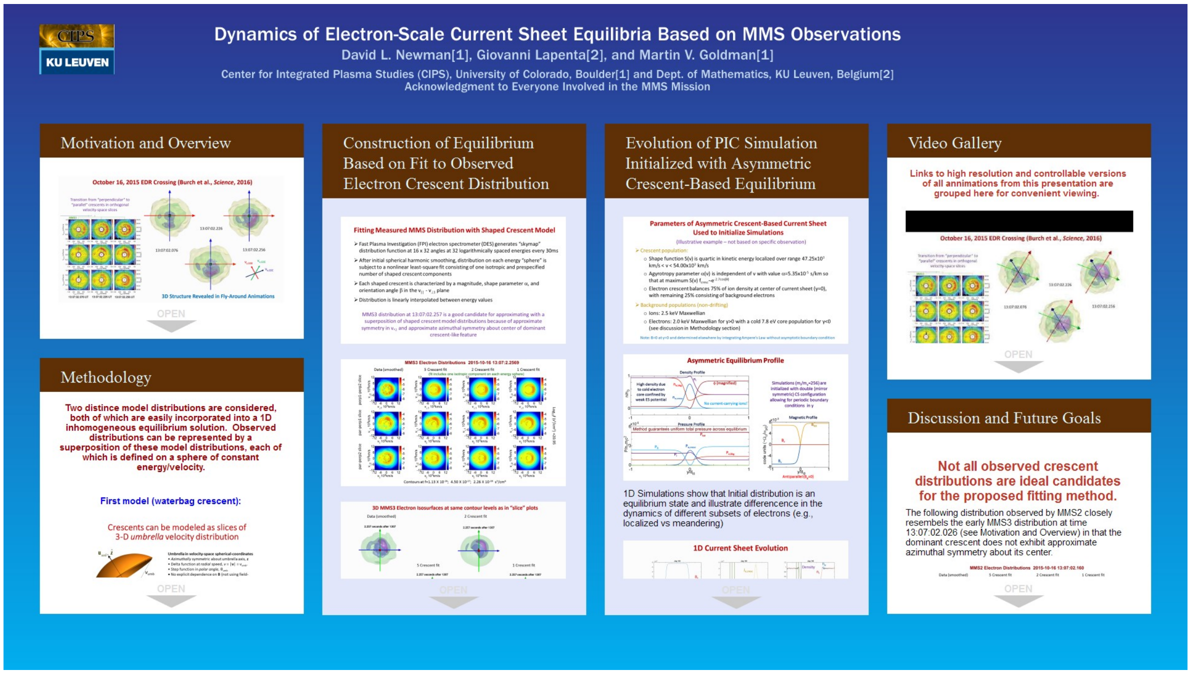

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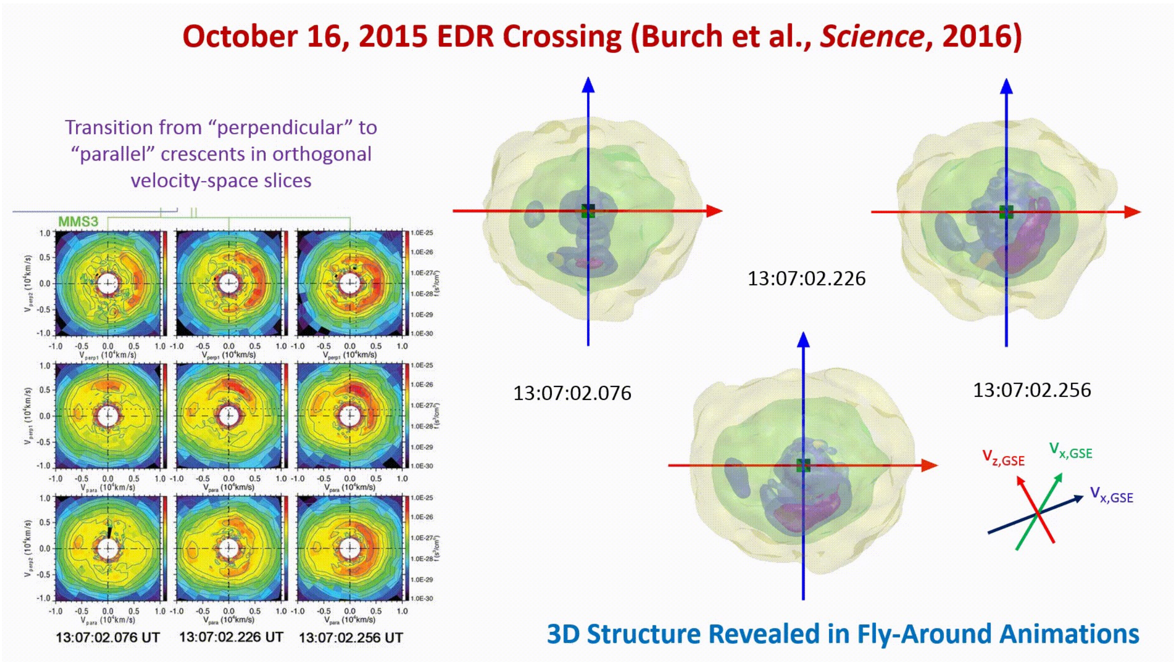
Acknowledgment to Everyone Involved in the MMS Mission

PRESENTED AT:

MOTIVATION AND OVERVIEW



The simultaneous observation by the four MMS satellites of agyrotropic electron distribtions know as "crescents" were a highlight of the first detailed analysis of an electron difussion region (EDR) crossing [Burch et al., 2016].

Challenge:

To incorporate observed crescent distributions into kinetic equilibria -- which are necessarily inhomogeneous due to the presence of agyrotropy. These equilibria can then be used to initialize kinetic simulations in order to study dynamical processes such as instability and wave generation.

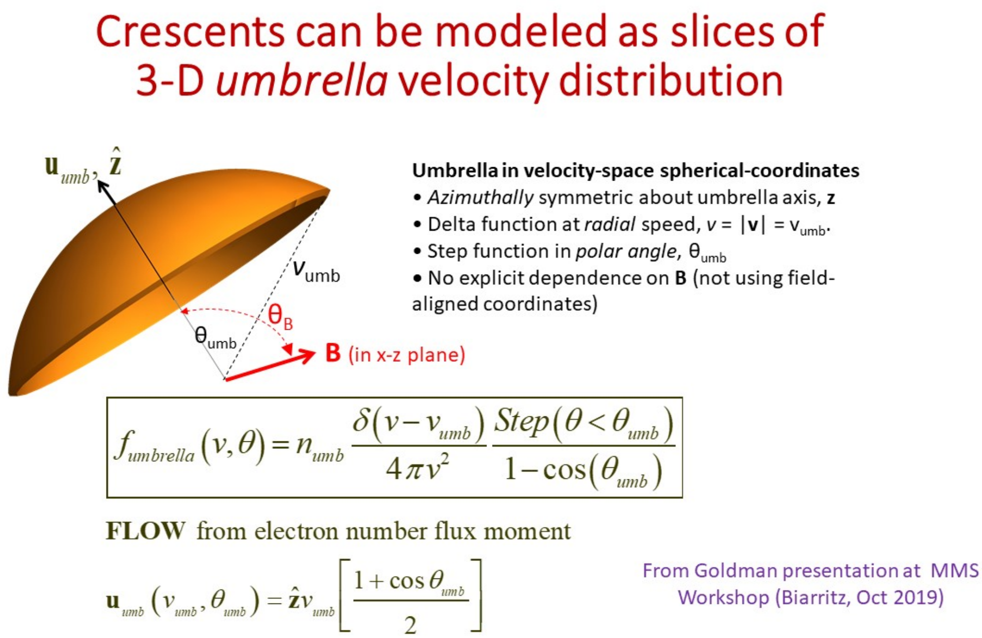
Overview of Presentation Layout:

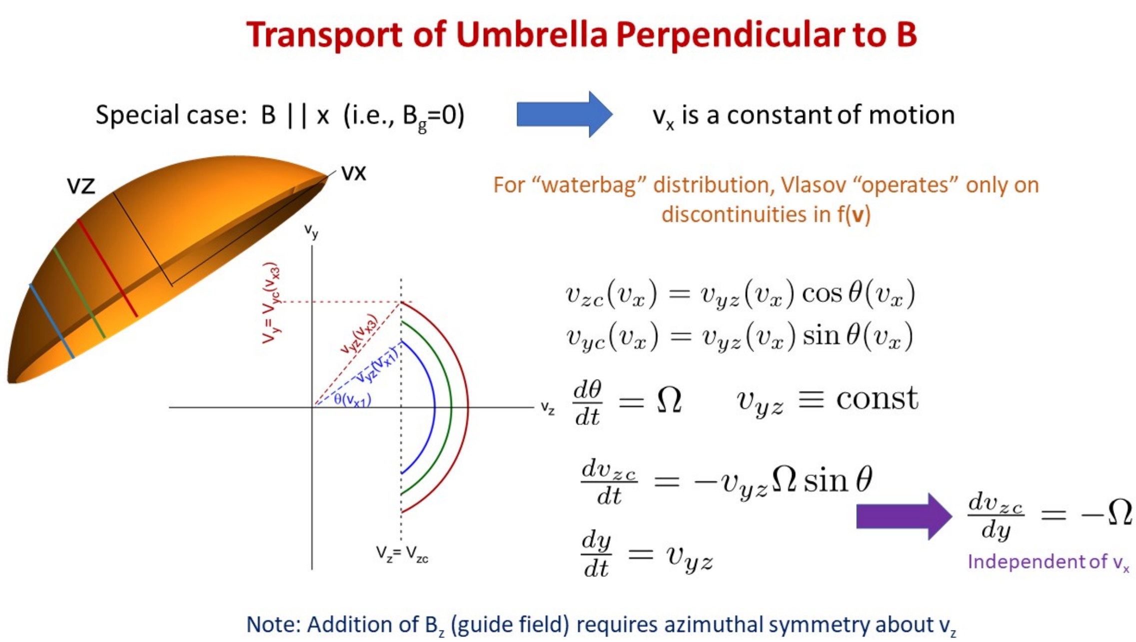
- Below: Methodology for approximating observed crescent distributions with model distribution functions that are readily incorporated into an inhomogeneous model
- Near-Right: Equilibrium solution based on the rightmost MMS3 distribution (above)
- Middle-Right: Kinetic simulations initialized with a simpler, but asymmetric, crescent-based equilibrium showning particle dynamics in 1D and subsequent evolution in different 2D planes
- Far-Right (upper): Gallery of high-resolution videos with frame control
- Far-Righ (lower): Discussion and Future Goals

METHODOLOGY

Two distince model distributions are considered, both of which are easily incorporated into a 1D inhomogeneous equilibrium solution. Observed distributions can be represented by a superposition of these model distributions, each of which is defined on a sphere of constant energy/velocity.

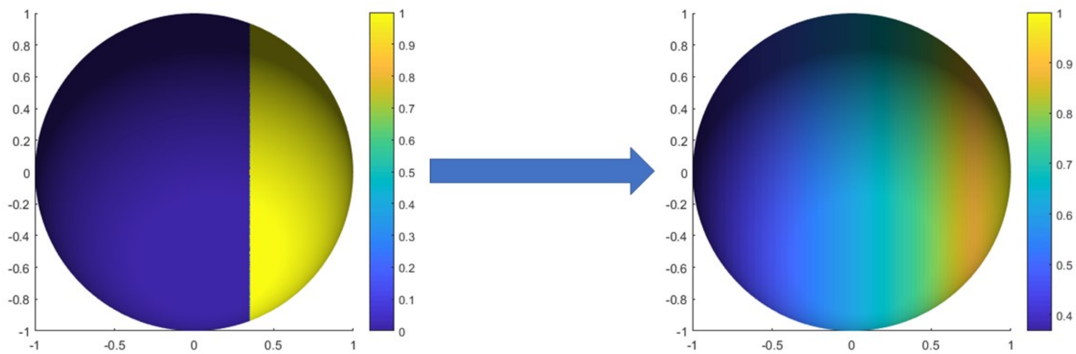
First model (waterbag crescent):





Second model (shaped crescent);

From Waterbag (Umbrella) to Shaped Crescent Model Distribution



Step function in θ Exp($v\alpha$ cosθ)

Superpositions built on both model distributions can be readily incorporated when constructing an inhomogeneous equilibrium

The shaped crescent model is motivated by an analysis of drifting Maxwellians, which are fundamental to the well-known *Harris current-sheet* equilibrium

Harris Equilibrium:
Prototype for Shaped Crescent Model
(drifting Maxwellians)

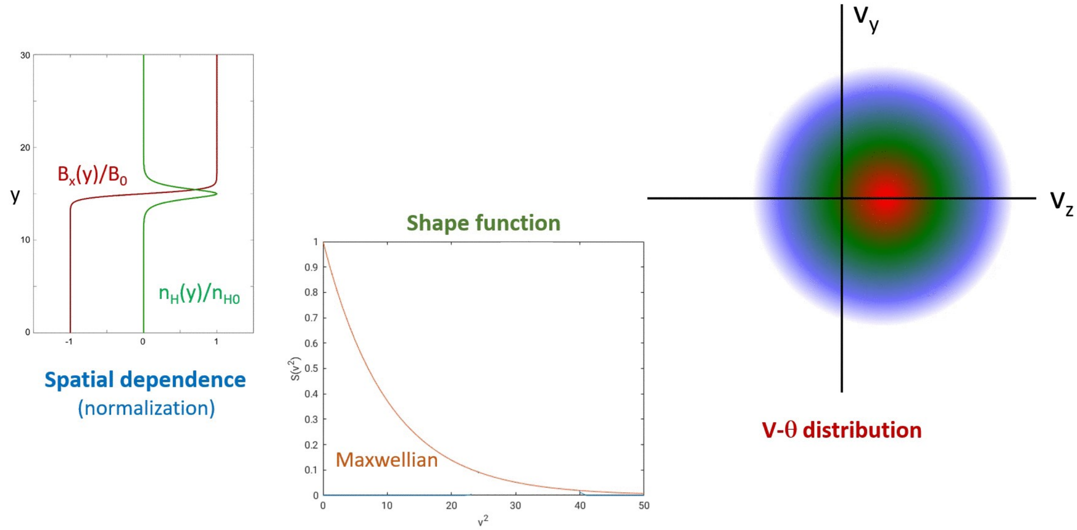
$$f(\mathbf{v}) = Ne^{-(v_x^2+v_y^2+[v_z-v_d]^2)/2v_{th}^2}$$

$$= Ne^{-v_d^2/2v_{th}^2} \quad e^{-v^2/2v_{th}^2} \quad e^{v\cos(\theta)v_d/v_{th}^2}$$

Normalization Shape Essential Agyrotropy

(includes spatial dependence) $S(v^2)$ $\frac{v_d}{v_{th}^2} \equiv \alpha$

From Drifting Maxwellian to Crescent



A simplified Vlasov analysis shows that a shaped-crescent distribution preserved its shape as it traverses a magnetic field perpendicular to the spatial gradient

Vlasov Equilibrium (1D-2V)

Time-independent Vlasov equation (m**a**=Lorentz force)

$$\mathbf{v} \cdot \nabla f \quad = \quad -\mathbf{a} \cdot \nabla_v f$$

Reduced dimensionality

$$f(\mathbf{x}, \mathbf{v}, t) \equiv f(y, v_y, v_z)$$

Polar coordinates (perpendicular to **B**)

$$v_y \equiv v \sin\theta; \qquad v_z \equiv v\cos\theta; \qquad \mathbf{B} \equiv B(y)\hat{x} \equiv \partial_y A_z(y)\hat{x}$$

Vlasov redux

$$v\sin\theta \cdot \partial_y f(y, v, \theta) \quad = \quad -\Omega_c(y) \cdot \partial_\theta f(y, v, \theta)$$

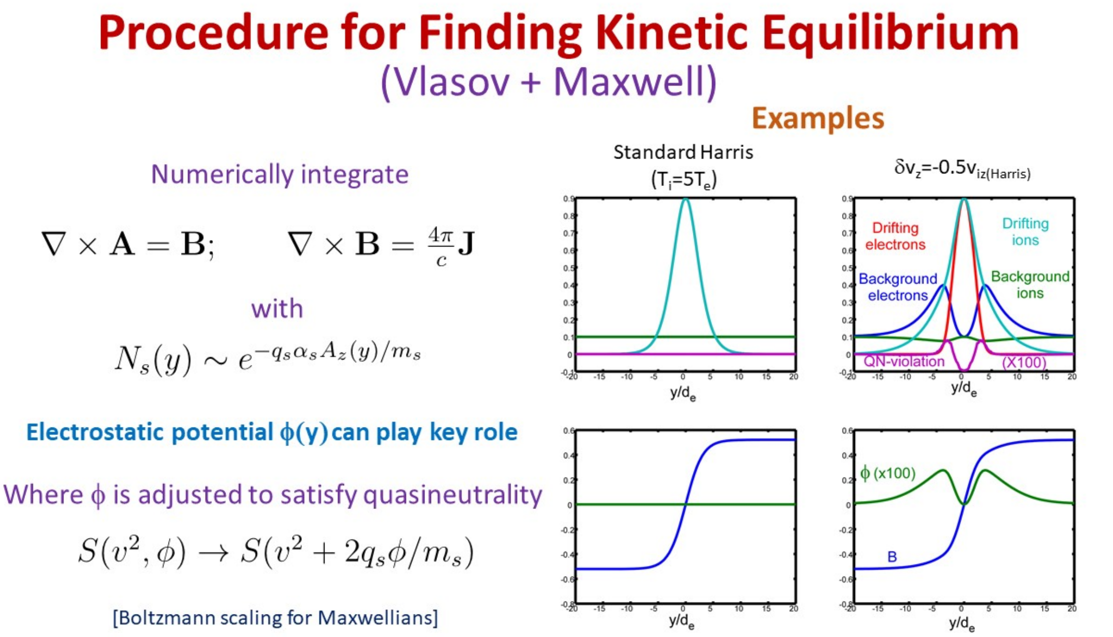
Solution:

$$Ansatz: \qquad f(y, v, \theta) = n(y)s(v)e^{v\alpha(v)\cos\theta}$$

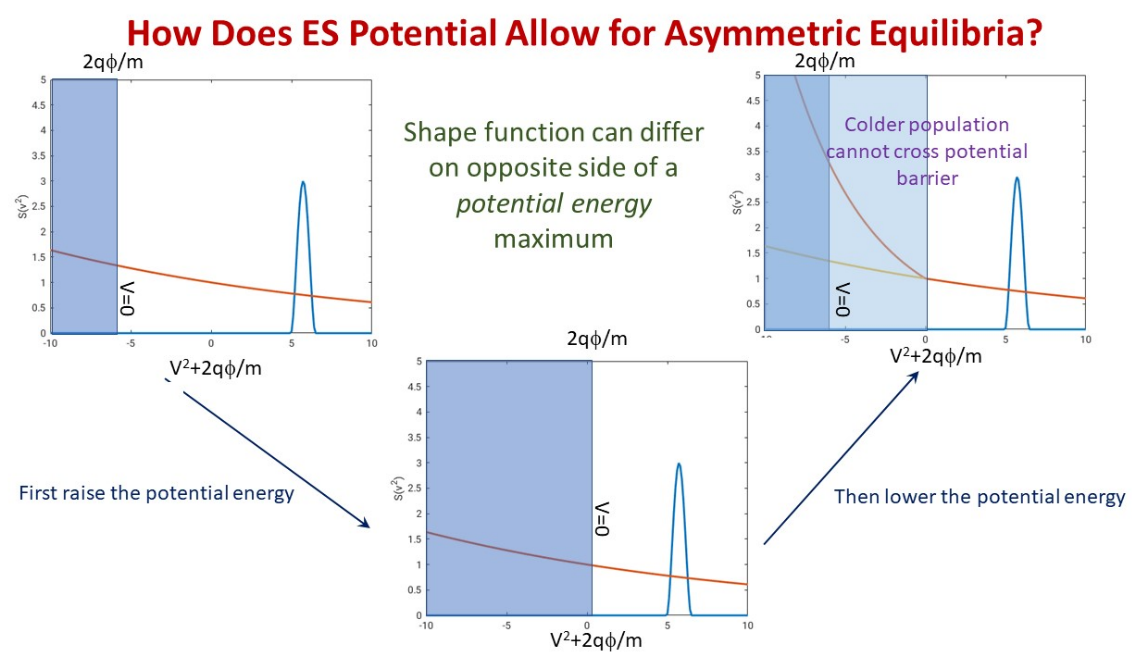
$$n(y) = n(0)e^{q\alpha(v)A_z(y)/mc}; \qquad A_z(0) = 0$$

$$s(v) \quad \text{and} \quad \alpha(v) \quad \text{arbitrary}$$

Integration perpendicular to B leads to a 1D spatially inhomogeneous equilibrium. A variant of this analysis can be employed for umbrella (waterbag) model distributions.



This method is not restriced to symmetric equilibria provided there is an electrostatic potential that can provide a barrier between different populations of a given species.

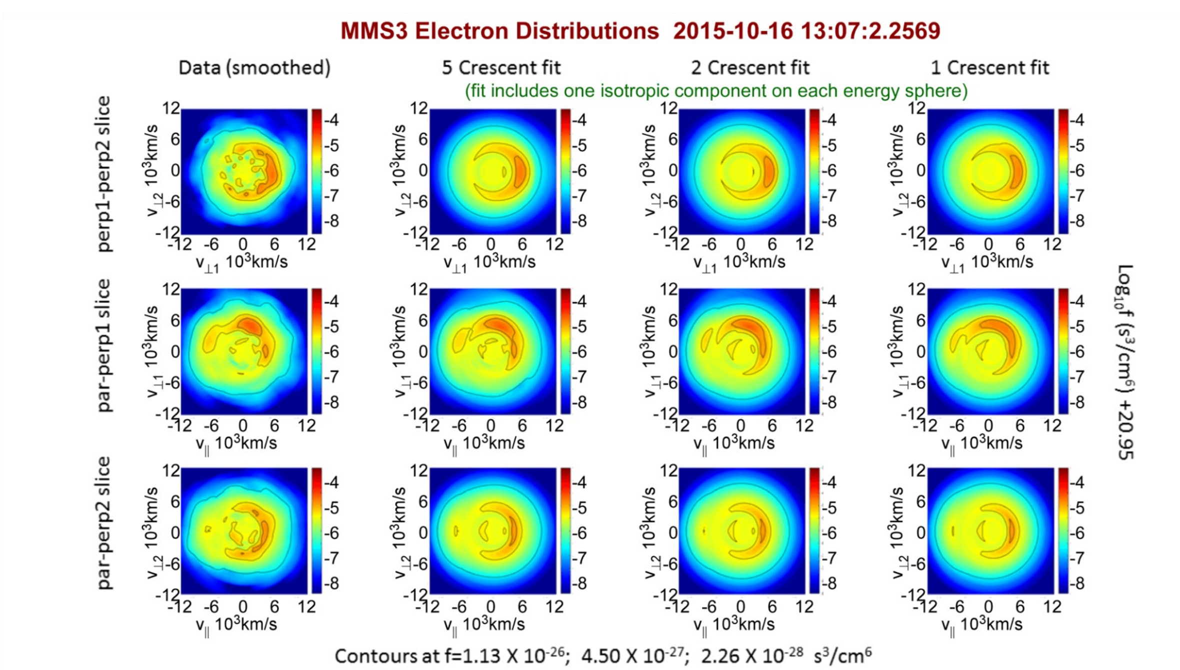


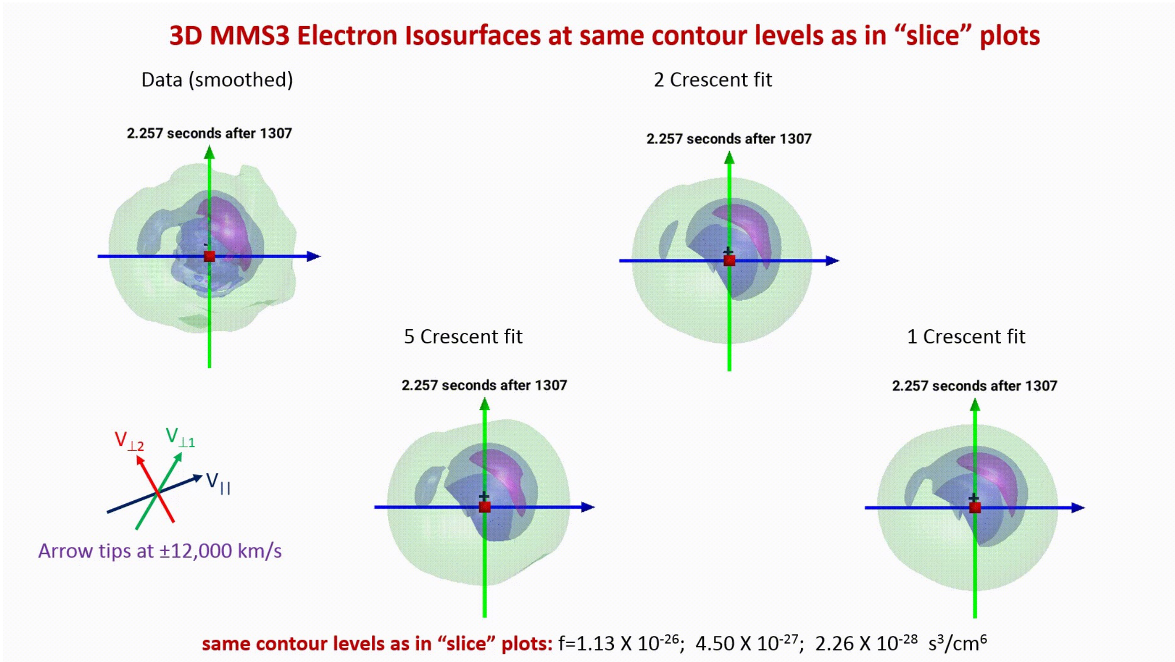
CONSTRUCTION OF EQUILIBRIUM BASED ON FIT TO OBSERVED ELECTRON CRESCENT DISTRIBUTION

Fitting Measured MMS Distribution with Shaped Crescent Model

- Fast Plasma Investigation (FPI) electron spectrometer (DES) generates "skymap" distribution function at 16 x 32 angles at 32 logarithmically spaced energies every 30ms
- After initial spherical harmonic smoothing, distribution on each energy "sphere" is subject to a nonlinear least-square fit consisting of one isotropic and prespecified number of shaped crescent components
- Each shaped crescent is characterized by a magnitude, shape parameter α, and orientation angle β in the $v_{||}$ - $v_{\perp 1}$ plane
- Distribution is linearly interpolated between energy values

MMS3 distribution at 13:07:02.257 is a good candidate for approximating with a superposition of shaped crescent model distributions because of approximate symmetry in $v_{\wedge 2}$ and approximate azimuthal symmetry about center of dominant crescent-like feature



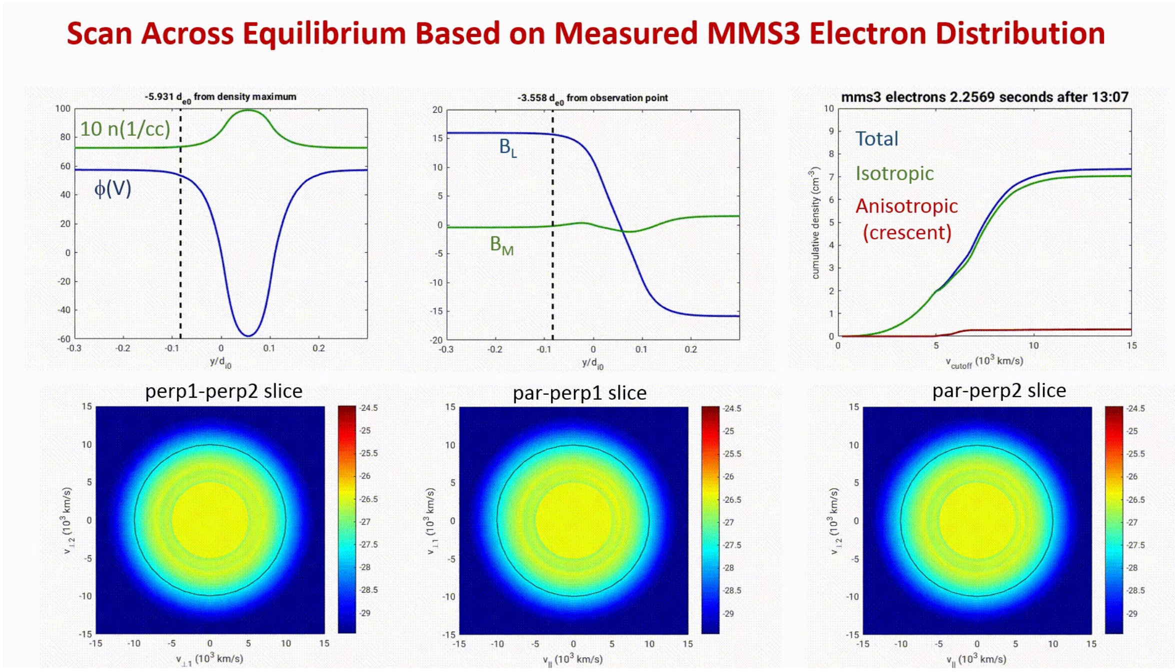


Improvement to the quality of the fit for >1 model crescent component at each energy is marginal.

Equilibrium Based on Observed MMS3 Distribution

Additional assumptions of model

- Fit to electron distribution consists of isotropic component plus *two* shaped crescent components
- Direction of crescents restricted to within ±60 degrees of $v_{\perp 1}$
- Ions are modeled as a non-drifting Maxwellian distributions with temperature T_i=375 eV and Boltzmann dependence on ϕ
- For ϕ<0, low-energy electron distribution is modeled as a flat-top (no cold population)



Note: Apparent discontinuity in orientation of $v_{\|}$-$v_{\perp 1}$ distribution results from fact that $v_{\perp 1}$ component of flow vector is always positive

EVOLUTION OF PIC SIMULATION INITIALIZED WITH ASYMMETRIC CRESCENT-BASED EQUILIBRIUM

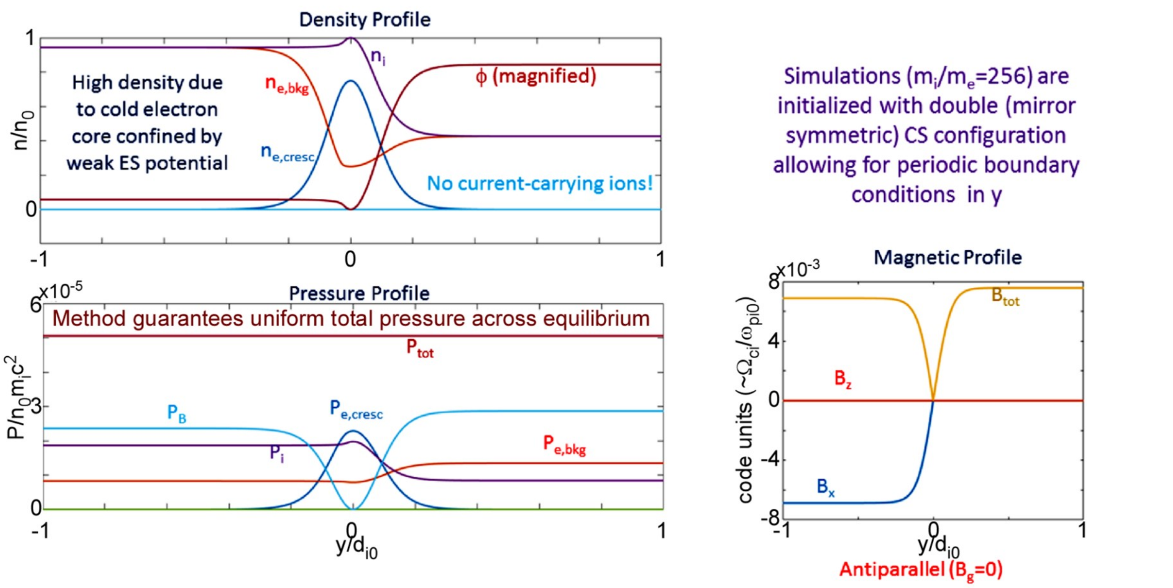
Parameters of Asymmetric Crescent-Based Current Sheet Used to Initialize Simulations

(Illustrative example – not based on specific observation)

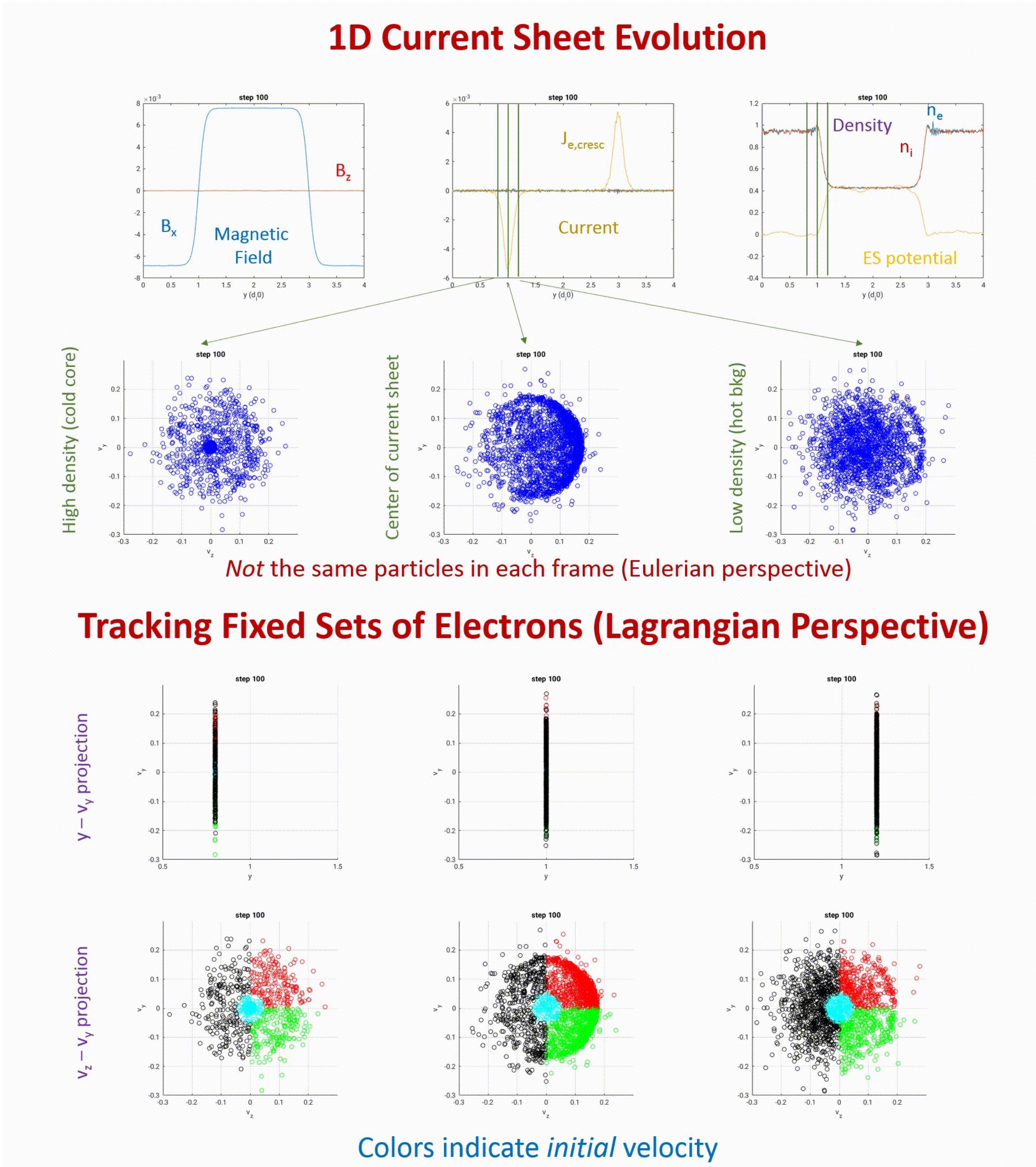
- Crescent population:
  - Shape function S(v) is quartic in kinetic energy localized over range 47.25×10^3 km/s < v < 54.00×10^3 km/s
  - Agyrotropy parameter $\alpha(v)$ is independent of v with value $\alpha = 5.35 \times 10^{-5}$ s/km so that at maximum S(v) $f_{cresc} \sim e^{-2.7\cos(\theta)}$
  - Electron crescent balances 75% of ion density at center of current sheet (y=0), with remaining 25% consisting of background electrons
- Background populations (non-drifting)
  - Ions: 2.5 keV Maxwellian
  - Electrons: 2.0 keV Maxwellian for y>0 with a cold 7.8 eV core population for y<0 (see discussion in Methodology section)

Note: B=0 at y=0 and determined elsewhere by integrating Ampere's Law without asymptotic boundary condition

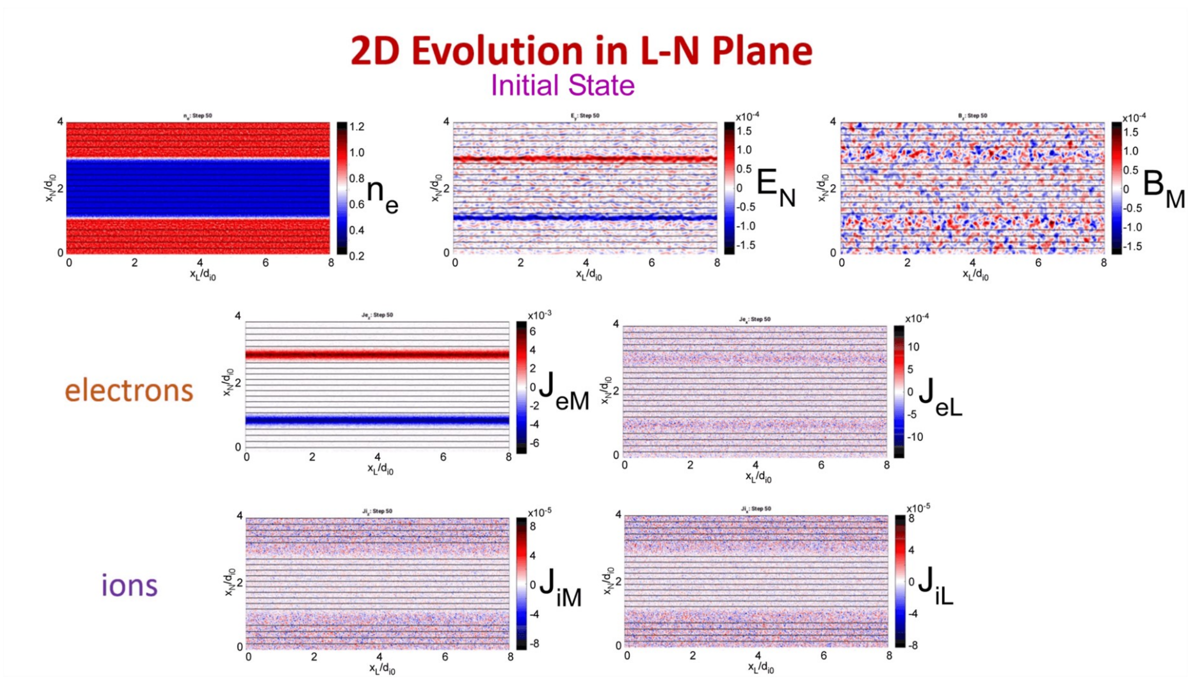
Asymmetric Equilibrium Profile



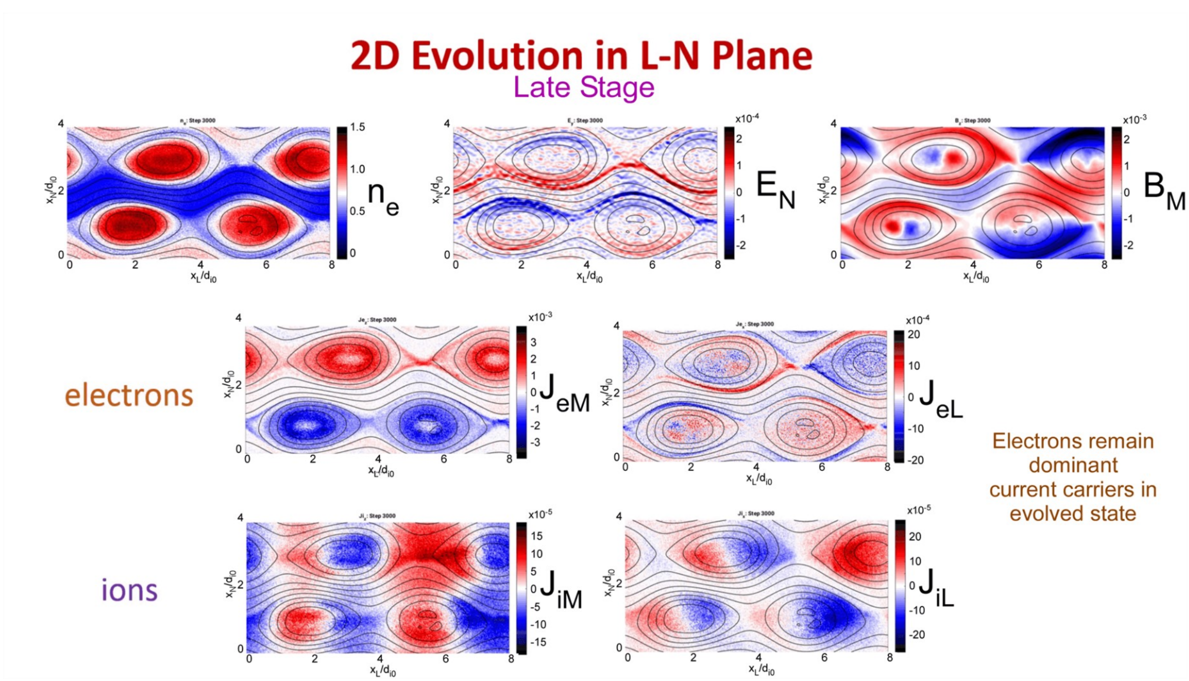
1D Simulations show that Initial distribution is an equilibrium state and illustrate differencence in the dynamics of different subsets of electrons (e.g., localized vs meandering)



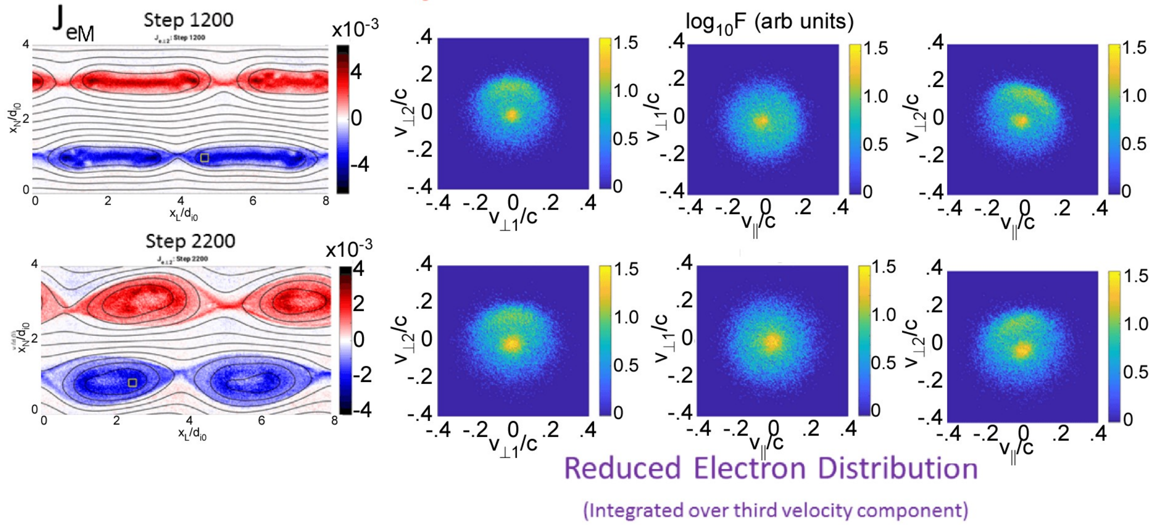
2D simulations show that while the initial state is an equilibrium, it is nevertheless an unstable equilibrium subject to instabilities that depend on the plane in which the simulation is carried out.



Intermediate stages of evolution can be followed in the *Video Gallery.*



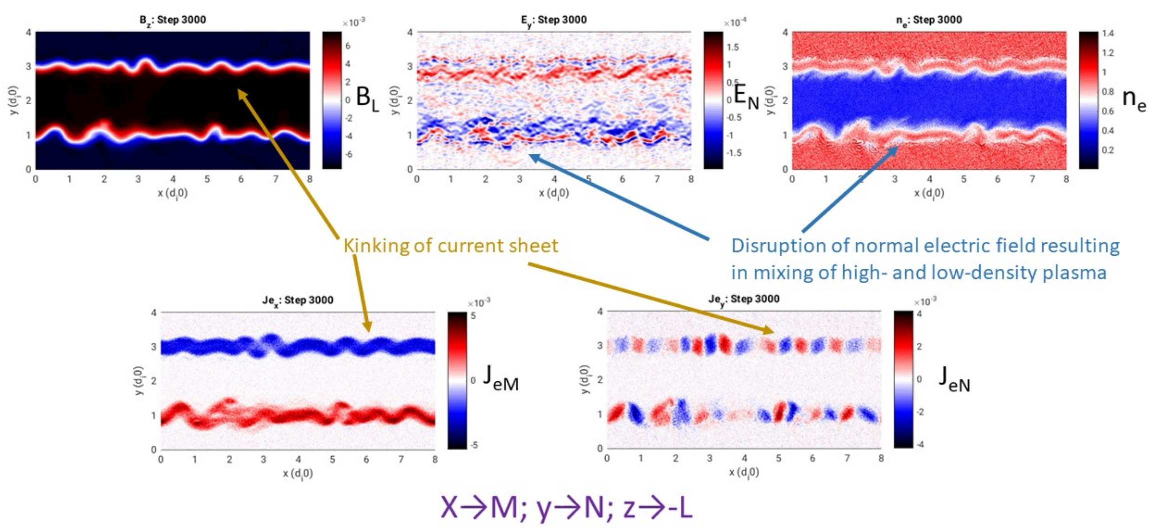
Crescent Distributions Persist in Regions of Strong Perpendicular Current



Rotating the initial distribution about the v_N axis is equivalent to rotating the simulation plane. Rotations through 90 and 45 degrees result in instabilities that differ from one another and from the simulations without rotation

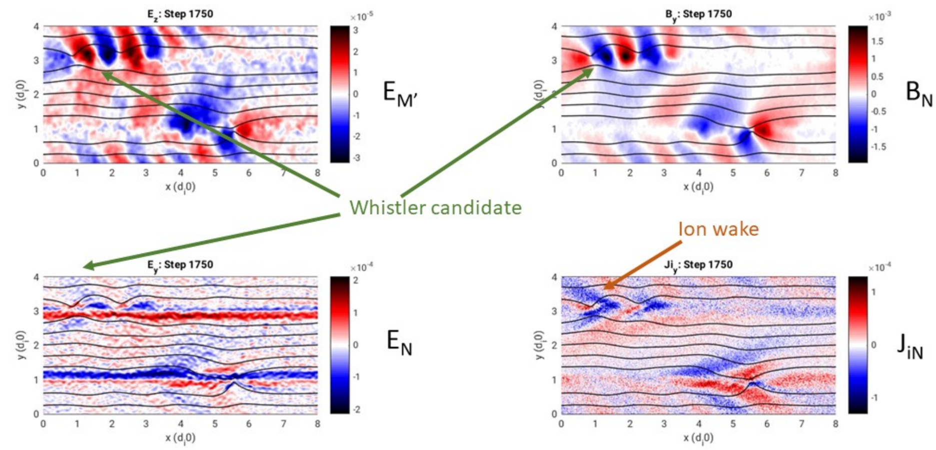
2D Evolution – Distribution Rotated by 90 Deg

(Follow dynamical evolution in *Video Gallery*)



2D Evolution – Distribution Rotated by 45 Deg

(Follow dynamical evolution in *Video Gallery*)



$X \rightarrow L'=(L+M)/2^{1/2}$; $y \rightarrow N$; $z \rightarrow M'=(M-L)/2^{1/2}$

VIDEO GALLERY

Links to high resolution and controllable versions of all annimations from this presentation are grouped here for convenient viewing.

[VIDEO] https://www.youtube.com/embed/LTIiL9paXbc?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0

[VIDEO] https://www.youtube.com/embed/D41xMNyICG8?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0

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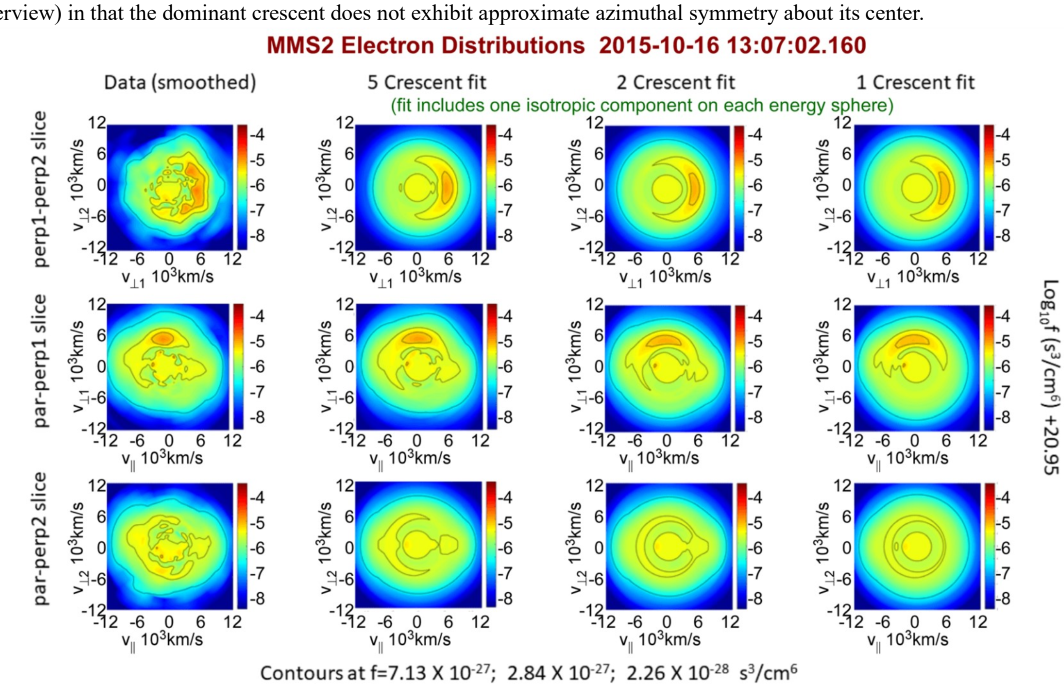
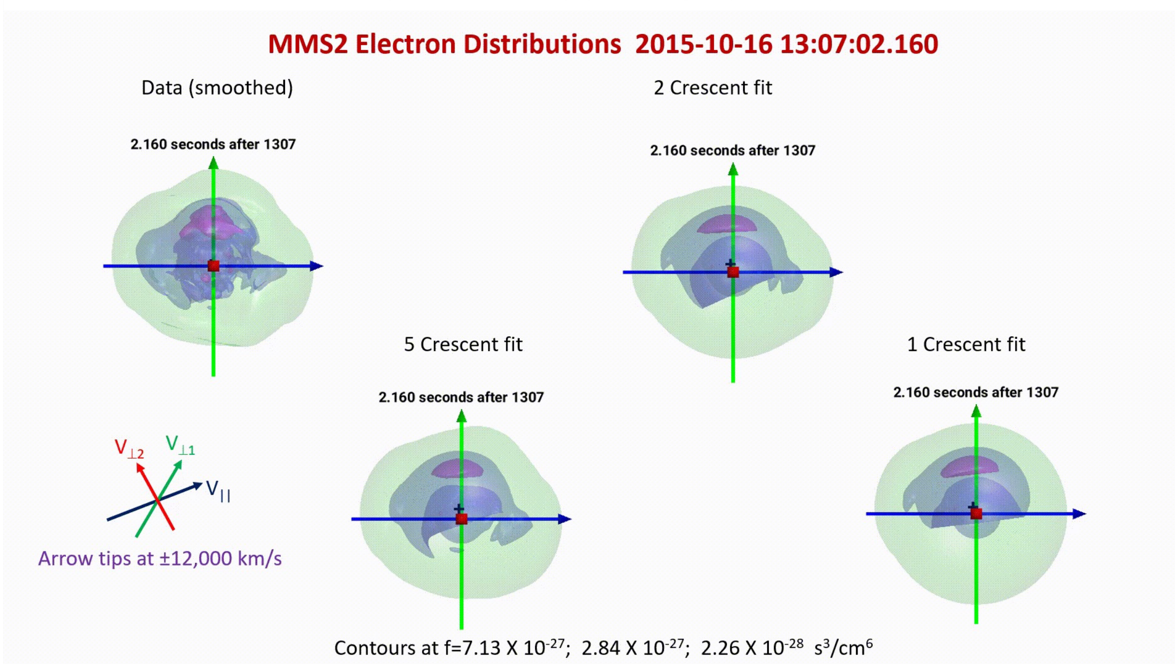
DISCUSSION AND FUTURE GOALS

Not all observed crescent distributions are ideal candidates for the proposed fitting method.

The following distribution observed by MMS2 closely resembels the early MMS3 distribution at time 13:07:02.026 (see Motivation and Overview) in that the dominant crescent does not exhibit approximate azimuthal symmetry about its center.





A simpler model in which the magnetic field cannot rotate (with zero guide field) can accommodate such crescents, but has not been implemented yet.

Association between crescent-based equilibria and current sheets is ***not*** coincidental

If the crescent is the primary carrier of perpendicular current, the interaction of that current with the magnetic field (via Vlasov and Ampere) will lead to a reversal of the magnetic field in a region where the current is maximal.

The present study therefore shares aspects with previous investigations of generalized kinetic current-sheet equilibria, which often exhibit crescent-like features [see selected references].

Goals for Ongoing and Future Study

- Incorporate observation-based equilibria into PIC simulations
- Include more complex potential profiles with both maxima and minima to allow for multiple populations of both ions and electrons
- Run larger simulations in 2D as well as 3D
- Employ virtual satellite diagnostics in the simulations to compare with MMS observations

ABSTRACT

The vicinity of the electron diffusion region (EDR) at the core of magnetic reconnection is frequently characterized by agyrotropic electron velocity distributions such as perpendicular velocity-space crescents [J. L. Burch et al., Science, DOI:10.1126/science.aaf2939 (2016)]. Although the evolving EDR is not itself an equilibrium state, its evolution may be slow on electron-cyclotron time scales. When this is the case, homogeneous equilibrium models are limited in their ability to model dynamical processes, such as instabilities and wave generation, in the presence of agyrotropic populations. In order to better study these processes, we initiate implicit PIC simulations with inhomogeneous kinetic equilibria built upon agyrotropic electron velocity distributions measured by the FPI spectrometers on MMS.

The methodology involves the following elements: • Modeling the observed agyrotropic (e.g., crescent) and background plasma distributions

• Numerically evaluating self-consistent inhomogeneous equilibria -- including anisotropy (as illustrated in the accompanying figure)

• Initializing 1D, 2D, and 3D PIC simulations with the equilibria

• Evaluating the simulation output for instabilities and the persistence of the crescents

Particle tracing and other visualization tools will be employed to illustrate the underlying dynamics of particles and fields -- and their interactions.

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