Magnetic islands in the Heliosheath: Properties and Implications

Kevin Schoeffler, Jim Drake, Marc Swisdak

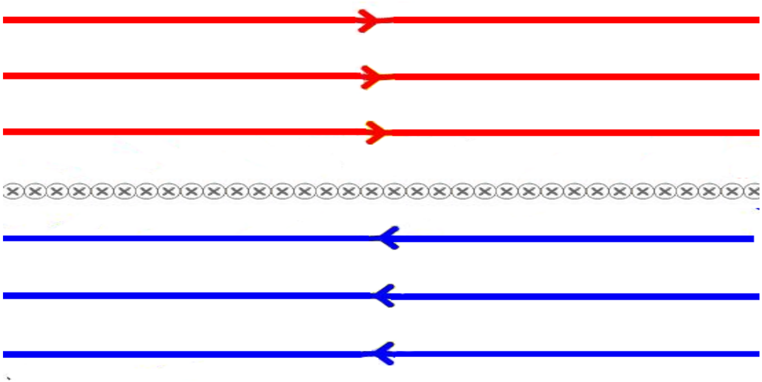
University of Maryland
College Park, Maryland

September 21, 2012

Outline

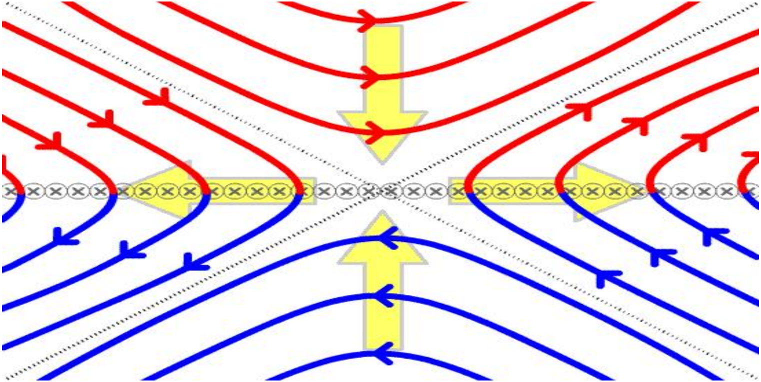
Outline

When does reconnection happen?



- Oppositely directed magnetic fields
- Current sheet in between
- When the current sheet is thin enough...

What is reconnection anyway?

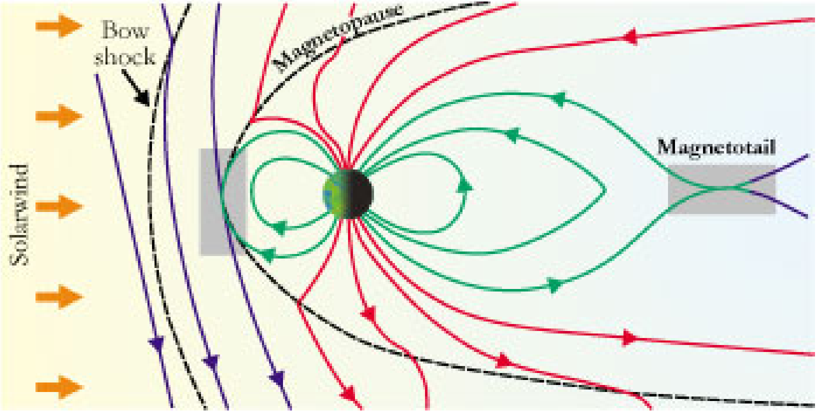


- An x-line develops
- Transfer of magnetic flux across the x-line
- Magnetic tension drives plasma out

How thin does it need to be?

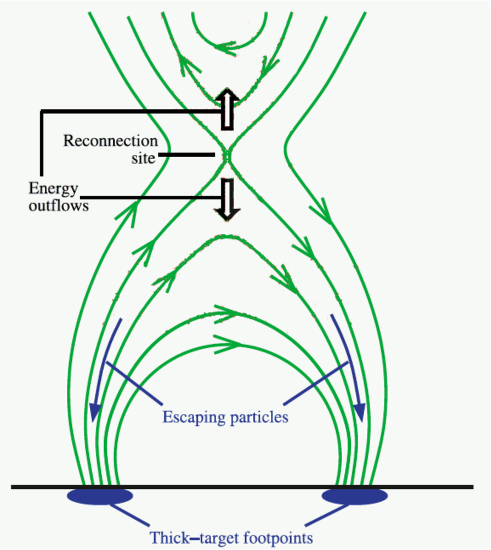
- Collisionless reconnection
  - Our simulations model collisionless plasma
  - The collisionless regime is valid in many space systems including the heliosheath
  - Collision time for electrons is $\sim$ 16 days at 1 AU
  - A solar wind electron could move $\sim$ 4 AU in this time
- Thin current sheets reconnect
  - Occurs at $w \approx d_i$ for collisionless plasma
  - $d_i = c/\omega_{pi} = c_A/\Omega_{ci}$ is the ion inertial length
- But where is it thin enough? ...

In the magnetosphere



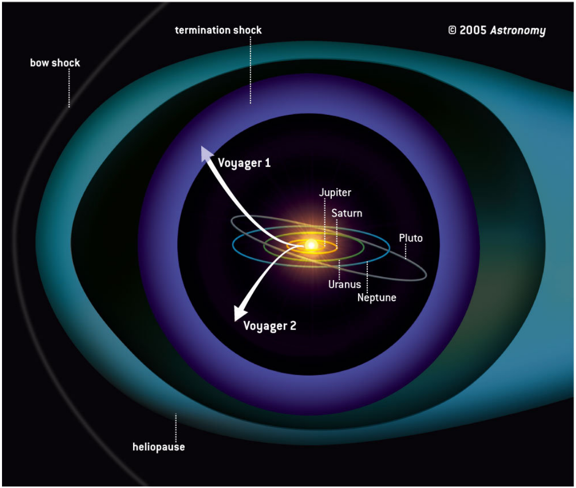
- Reconnection at the front (magnetopause)
- Reconnection at the tail (magnetotail)
- Energetic flows go towards poles, cause aurora

In the solar corona



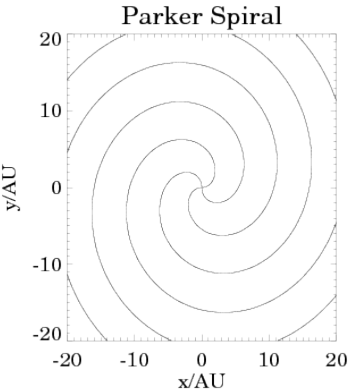
- Magnetic loops interact
- Reconnection occurs
- Energetic flows go towards footpoints

In the heliosheath



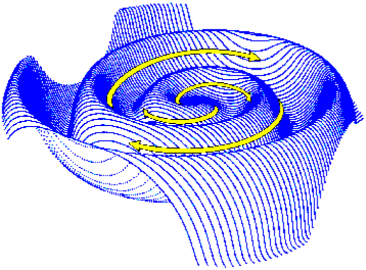
- Sun emits a solar wind
- Wind is supersonic
- Termination shock (TS) develops
- Heliosheath is on the other side
- But what about the magnetic fields? ...

Parker's Spiral



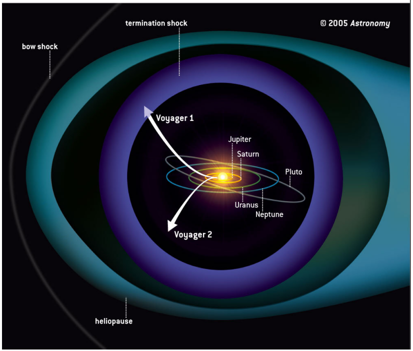
- Magnetic fields anchored to sun, frozen in to the plasma
- In the rotating frame
- Flow along field lines

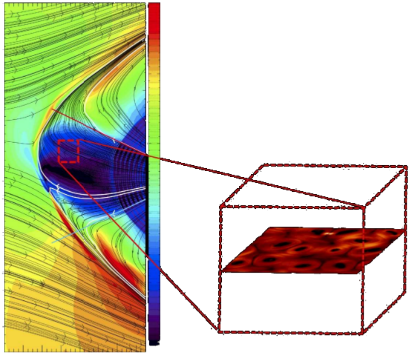
Heliospheric current sheet



- Current sheet exists
- Different axes cause flapping current sheet
- Current in ecliptic alternates between north and south
- Sectored fields

Sectored Fields in the Heliosheath

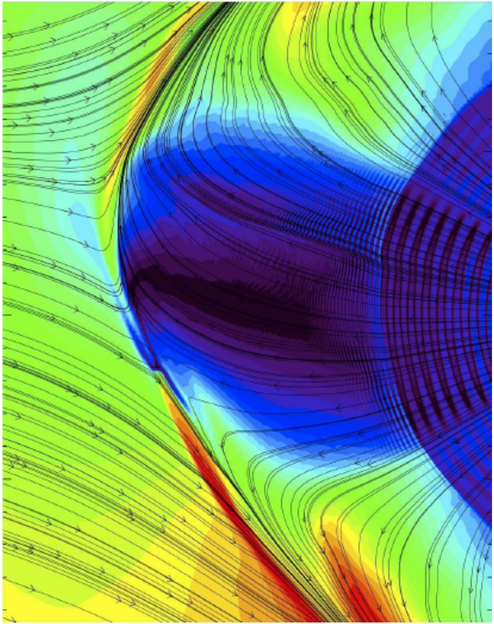




(Opher et al. 2011)

- Sectored fields found at solar system edge
- Compress in the heliosheath
- Ideal location for particle in cell (PIC) simulations
- Voyager can compare with simulations

Is it thin enough?

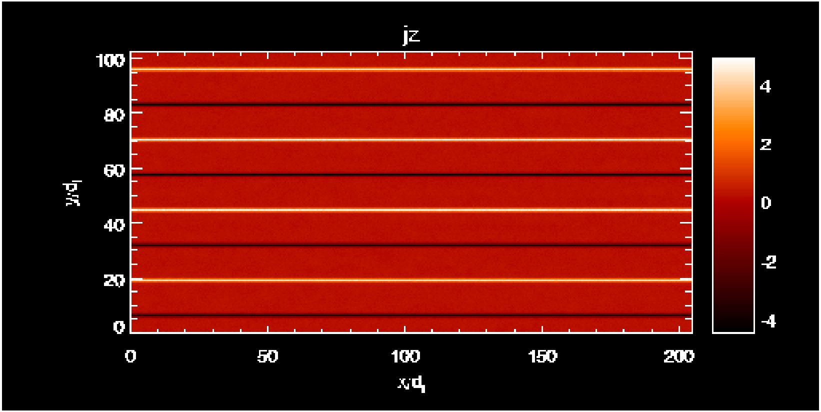


(Opher et al. 2011)

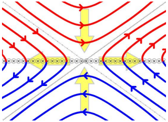
- Current sheet width 10,000 km upstream of shock
- Voyager measures $n = 0.001 cm^{-3}$ upstream
- $d_i \approx$ 7,200 km
- Predicted width 2,500 km downstream of shock
- Voyager measures $n = 0.003 cm^{-3}$ downstream
- $d_i \approx$ 4,200 km

Outline

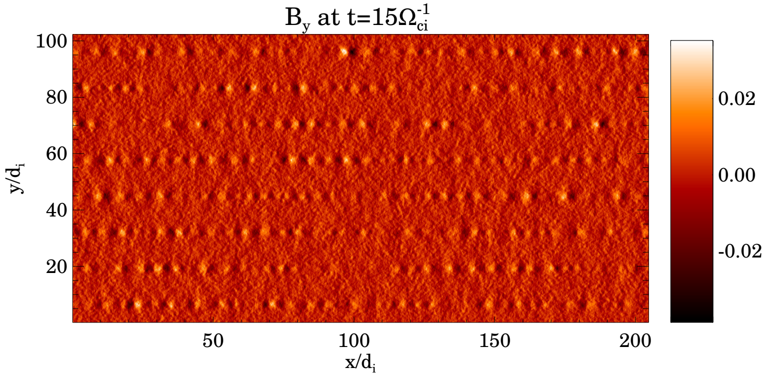
What do we simulate?



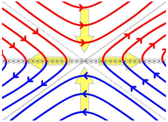
- Multiple current sheets are simulated
- Using a 2D particle-in-cell code
- Magnetic islands form
- Magnetic energy is released by reconnection



It begins to tear



- By $t = 15\Omega_{ci}^{-1}$ islands begin to form at $\lambda \approx 4\pi w$
- $1\Omega_{ci}^{-1}$ corresponds to ~ 1 minute in the heliosheath

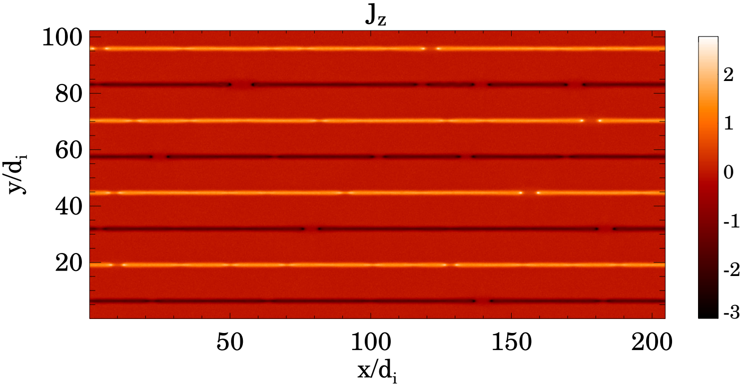


Plasma beta plays and important role

$$\beta = \frac{8\pi P}{B^2}$$

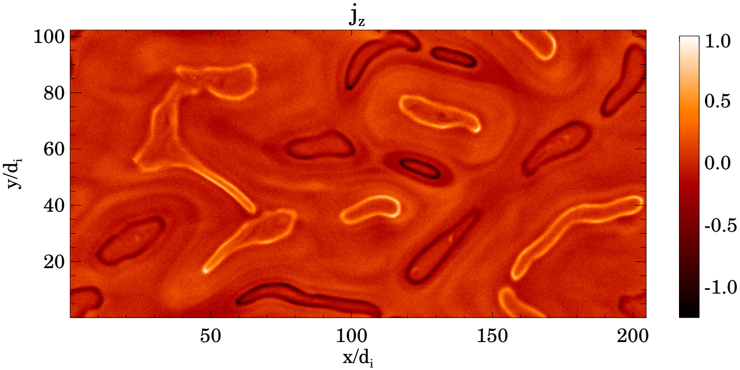
- For low β, magnetic fields dominate
- For higher β, pressure becomes important
- In many reconnection studies β is of order unity
- In the heliosheath, β can be as large as ~ 10

There's something different here



- For $\beta = 4.8$
- By $t = 40\Omega_{ci}^{-1}$ islands grow long
- The explanation of this phenomenon is described later

Long islands remain

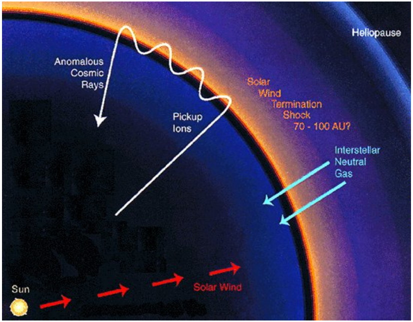


- We find long islands persist up until late time ($t = 120\Omega_{ci}^{-1}$)
- β has a large effect on the islands
- Not all of the magnetic energy is released

Outline

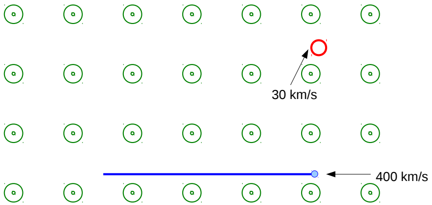
Outline

Anomalous Cosmic Rays



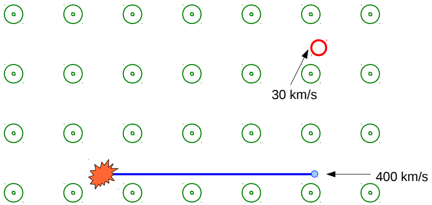
- Anomalous Cosmic Rays (ACRs)
  - Energetic ions heated in the outer heliosphere
  - 10 – 100 MeV
  - Originally high energy PUIs from interstellar medium
- Heating originally thought to be at the TS
  - Source beyond TS
  - Maybe heated in heliosheath islands

Pick-up Ions



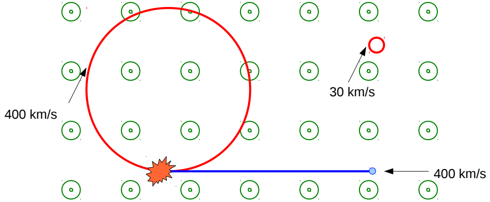
- Pick-up Ions (PUIs)
  - Interstellar neutral atoms picked up by the solar wind, when they are ionized
  - High energy PUIs (~ 1 keV) contribute greatly to β
  - Source of ACRs (Fermi process preferentially energizes energetic particles)

Pick-up Ions



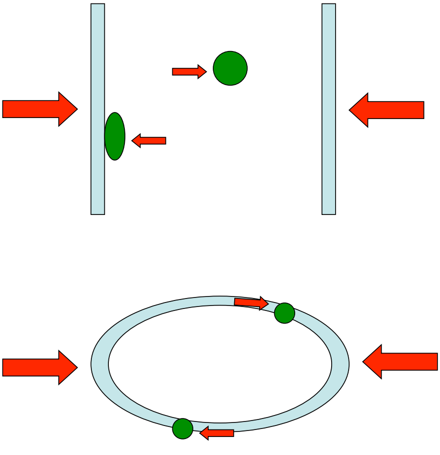
- Pick-up Ions (PUIs)
  - Interstellar neutral atoms picked up by the solar wind, when they are ionized
  - High energy PUIs ($\sim$ 1 keV) contribute greatly to β
  - Source of ACRs (Fermi process preferentially energizes energetic particles)

Pick-up Ions



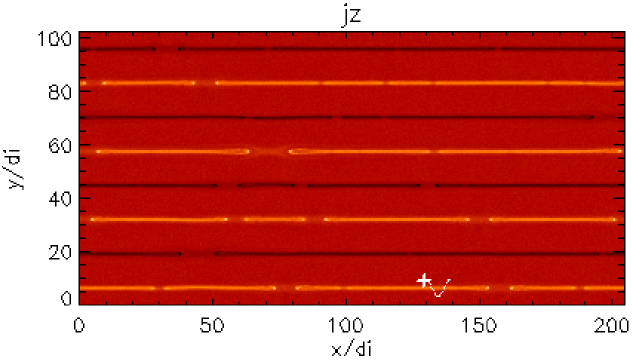
- Pick-up Ions (PUIs)
  - Interstellar neutral atoms picked up by the solar wind, when they are ionized
  - High energy PUIs (~ 1 keV) contribute greatly to β
  - Source of ACRs (Fermi process preferentially energizes energetic particles)

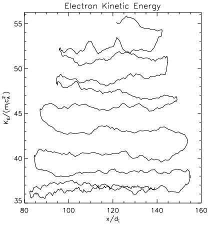
Fermi acceleration?



- Acts like two walls closing inward while balls bounce between them
- Energy is gained each time the ball hits the wall
- A magnetic island compressing to a circular shape acts as the closing walls
- A particle following the magnetic field acts as the bouncing ball

Fermi acceleration in action





- Electron tracked in code
- Picks up speed while bouncing between closing walls

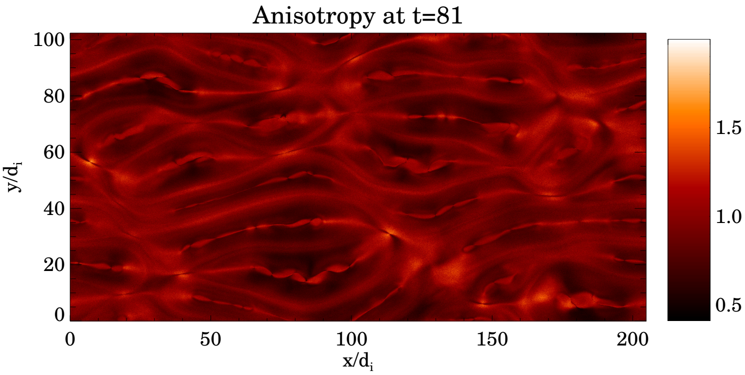
Outline

A pressure tensor?

$$\mathbb{P} = \begin{bmatrix} P_{\parallel} & 0 & 0 \\ 0 & P_{\perp} & 0 \\ 0 & 0 & P_{\perp} \end{bmatrix} = \frac{\mathbf{BB}}{B^2} P_{\parallel} + \left(\mathbb{I} - \frac{\mathbf{BB}}{B^2} \right) P_{\perp}$$

- For collisionless plasma, pressure is not isotropic
- The gyrotropic pressure tensor
- For higher β, pressure *tensor* becomes important

An anisotropy develops



- Energy gained in direction parallel to the magnetic field
- Anisotropy defined as $P_\perp / P_\parallel$
- Areas around islands become anisotropic

What is the deal with magnetic tension?

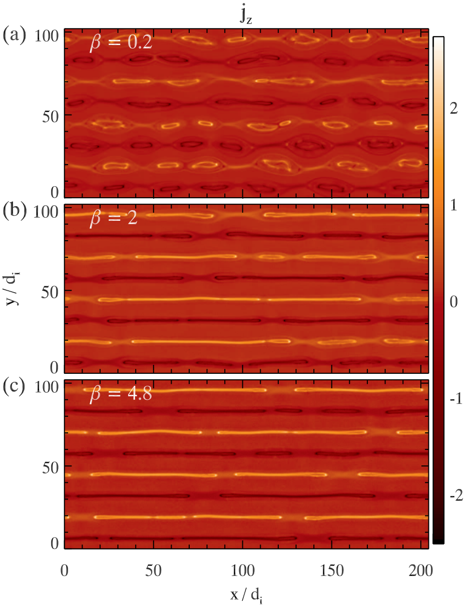
$$\rho \frac{d\mathbf{v}}{dt} = -\nabla \left(P_\perp + \frac{1}{8\pi} B^2 \right) + \nabla \cdot \left[\left(1 - \frac{\beta_\parallel - \beta_\perp}{2} \right) \frac{\mathbf{BB}}{4\pi} \right]$$

- MHD momentum equation with anisotropy
- For an Alfvén wave,
  - The plasma contains inertia
  - Magnetic tension provides restoring force
- For anisotropy with $P_\parallel > P_\perp$, tension is reduced
- For $\beta_\parallel - \beta_\perp > 2$, firehose instability occurs

Outline

Outline

β cannot be ignored



- By $t = 51\Omega_{ci}^{-1}$ clear islands have developed
- Island length is dependent on β
- What causes this dependence?

Will the the islands remain in tension?

The acceleration time t_a

time it takes for the ions to accelerate to Alfvénic outflow speeds

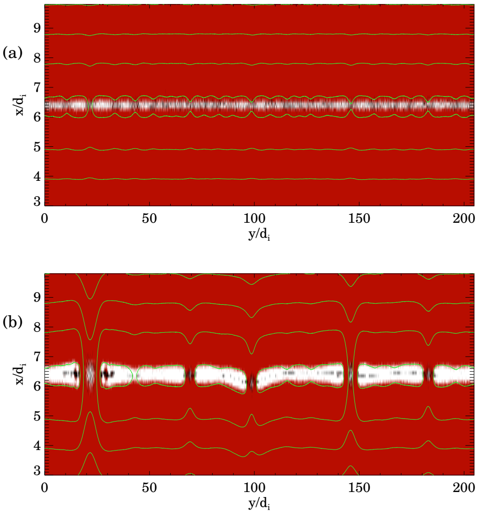
$$t_a = \frac{x_a}{c_A} \sim 10\frac{d_i}{c_A} = 10\Omega_{ci}^{-1}$$

The bounce time t_b

time it takes for a significant electron pressure anisotropy to develop

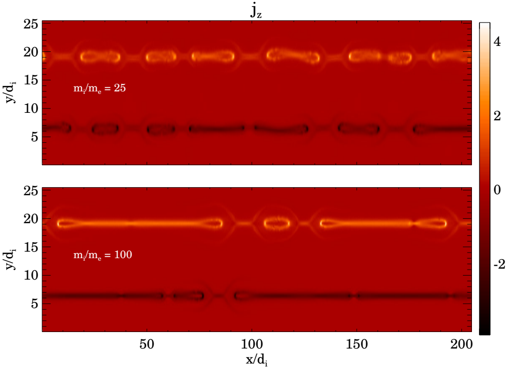
$$t_b = \frac{L}{v_{the}} = \frac{L}{v_A}\sqrt{\frac{1}{\beta_e}\frac{m_e}{m_i}}$$

Only the longest survive



- For small islands $t_a > t_b$
- When firehose condition met, reconnection suppressed
- For long islands $t_a < t_b$
- Reconnection develops before firehose condition

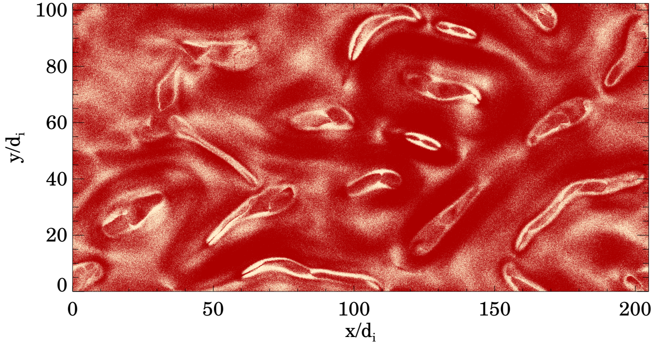
$$L_{crit} \approx 10 d_i \sqrt{\beta_e \frac{m_i}{m_e}}$$



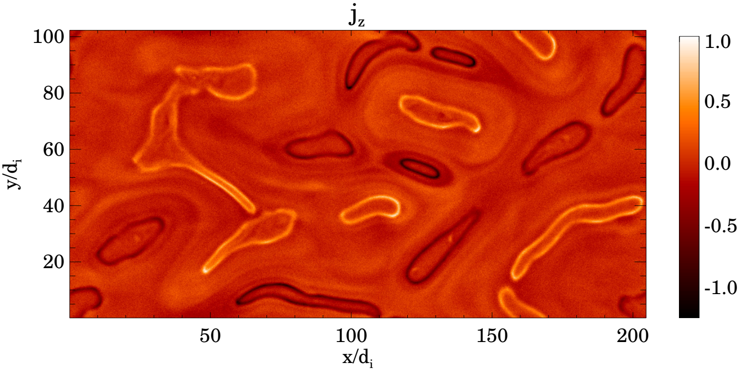
- We predict $L_{crit} \sim \sqrt{m_i/m_e}$
- We test at $\beta = 0.2$
- A dependence on m_i/m_e is observed in simulations
- We predict long island formation even at moderate β_e

Anisotropies found

- High β ($\beta = 4.8$), so many unstable points
- Anisotropy, low tension
- Ion pressure anisotriopy important



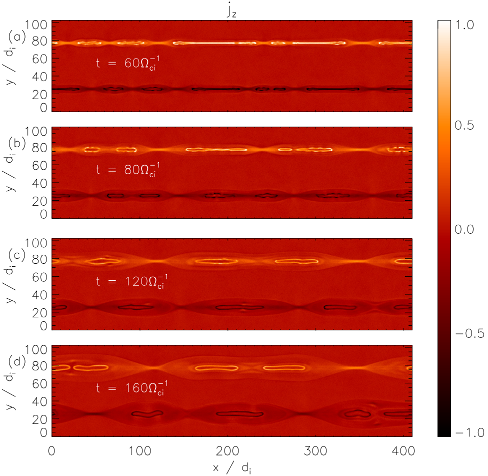
Long islands still remain



- Extended islands remain long
- In low β these islands would likely contract until round
- Marginal firehose stable islands have no tension
- Not all of the magnetic energy is lost

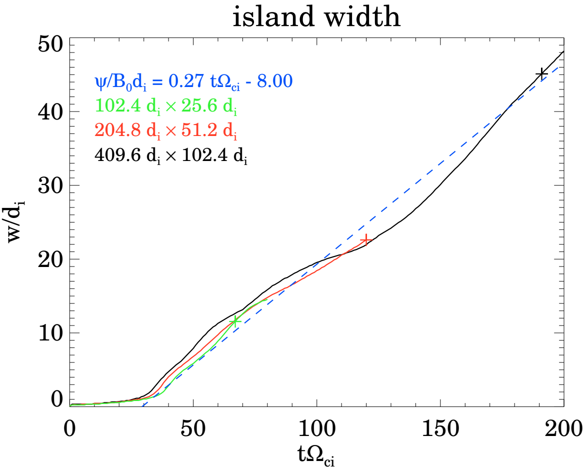
Outline

They don't stop growing



- Islands merge as they grow
- Long aspect ratio maintained
- Islands should reach sector spacing

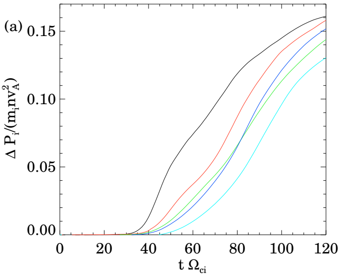
And they do it quickly

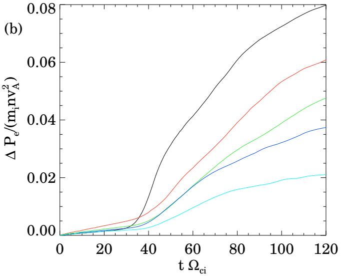


- Growth rate independent of system size
- Corresponds with about 60 days to reach the sector boundary
- This corresponds to 2.5 AU past TS

Outline

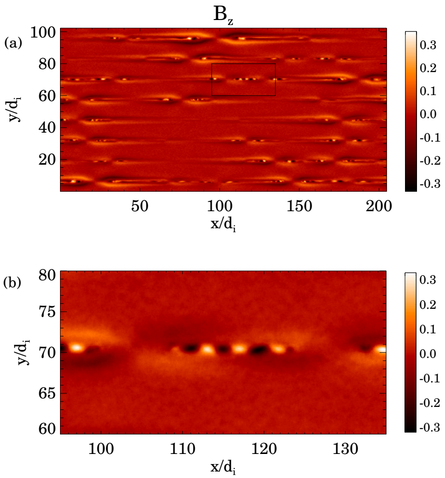
But where did the magnetic energy go?

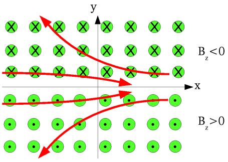




- Magnetic energy is transferred to ion and electron pressure energy
- Ion heating is insensitive to β
- Electron heating is suppressed at higher β

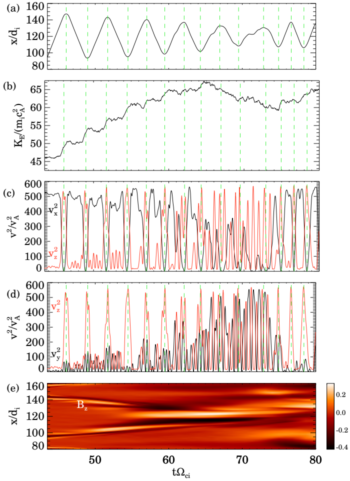
Weibel gets in the way





- Anisotropy induced instability emerges
- Develops in regions of small B
- Identified as Weibel instability
- It is electron scale

Acceleration limited



- Electron trapped in an island
- Energy gained at bounces
- Electron becomes scattered by B_z
- Parallel velocity transferred to perpendicular

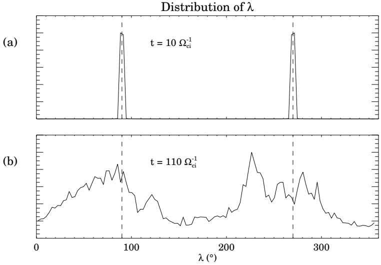
Outline

Outline

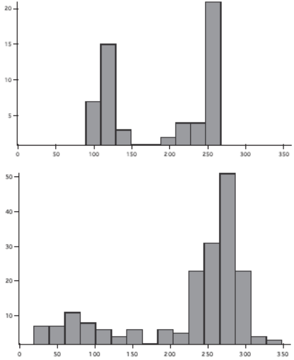
We can measure this

- Voyager can measure B_T,B_R, and B_N
- The angle $\lambda \equiv \tan^{-1}(B_T/B_R)$
- Peaked at $\lambda = 90^\circ$ and 270°
- When islands form, distribution broader

Simulation

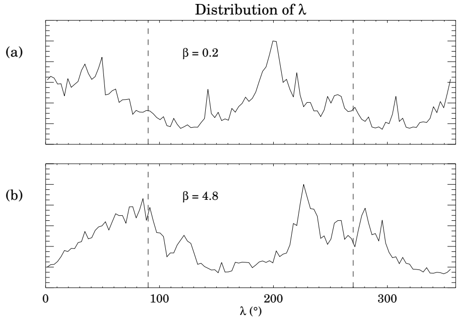


Voyager Data



(Opher et al. 2011)

Evidence of long islands



- Prediction of distribution based on shape
- Short islands lose peaks
- Long islands remain peaked, similar to observations
- Allows estimate of β in heliosheath

Outline

It is everywhere

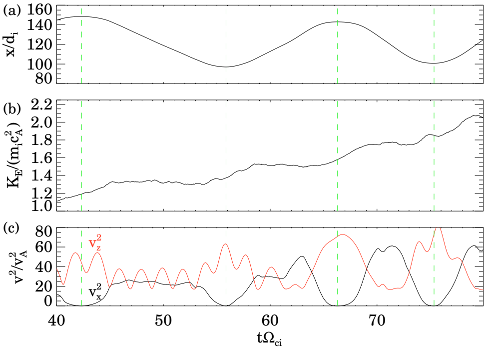
- High β systems occur in accretion discs, where $\beta \sim 100$ (Sano et al. 2004)
  - Most of the gravitational energy goes into magnetic fields
  - Magnetic energy is released as heat via reconnection
  - There is little evidence of electron heating, consistent with the suppression of heating in our simulations
- High β reconnection expected in the magnetosphere of Saturn (Masters et al. 2012)
  - Long islands should form at the magnetopause
  - Long islands may persist due to the high β
- The $\beta \sim 1$ in the magnetosphere of Earth is high enough for longer islands to form, even if they would later become round.

Outline

Summary

- Long islands are generated in thin current sheets
- Island length has a dependence on β_e, and m_i/m_e
- Islands can become longer due to merging
- Anisotropies play important role
  - Impedes reconnection involving small island formation
  - Keeps islands long, by weakening magnetic tension
  - Stops electron acceleration due to Weibel magnetic fields
- Voyager can find evidence that islands
  - Exist
  - Are long
- Could be important in other astrophysical systems

Ions accelerate too



- Ion trapped in an island
- Energy gained at bounces
- Ion is not scattered by B_z