SLAMS at parallel shocks and Hot Flow Anomalies

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Pulsations/SLAMS

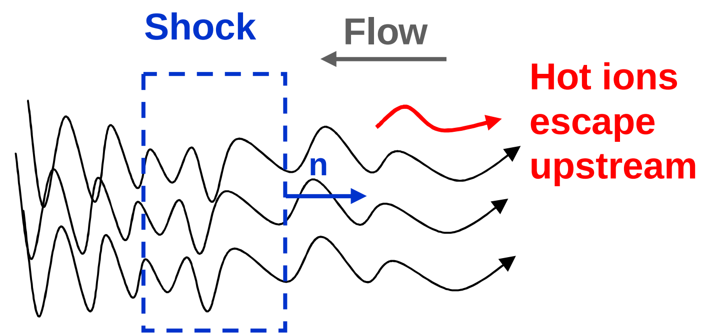
- Rapid growth ~ seconds
- Structured on scales ~100-150 km (~ ion inertial length)
- Overall size > 1000 km (~10 ion inertial length)

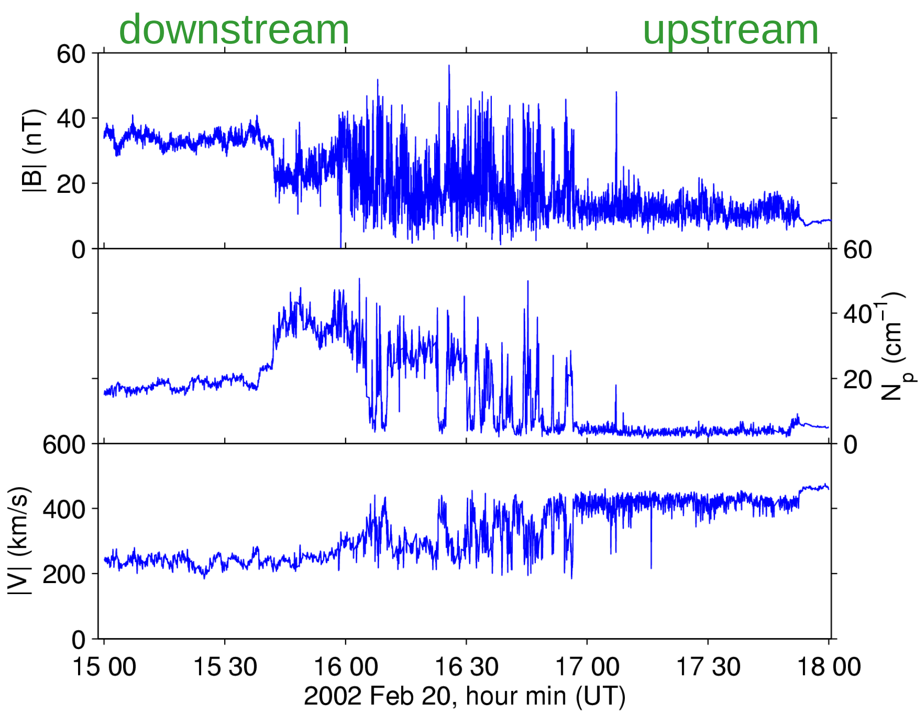
Hot Flow Anomalies

- Expanding sheet of hot plasma around discontinuity
- Evolution of dual ion distribution to single hot distribution
- Rapid expansion drives shocks
- Time evolution ~minutes

Parallel bow shock

- Magnetic field ~ parallel to shock normal
- i.e. significant flux threads shock surface
  - Extended spatial transition
- Disturbed transition in **B**
  - Not motion of a single surface
  - Embedded within transition are pulsations/SLAMS (short, large-amplitude magnetic structures)
- Intrinsically spatially extended and time varying
- Energetic ions escape upstream
  - Essential to shock process



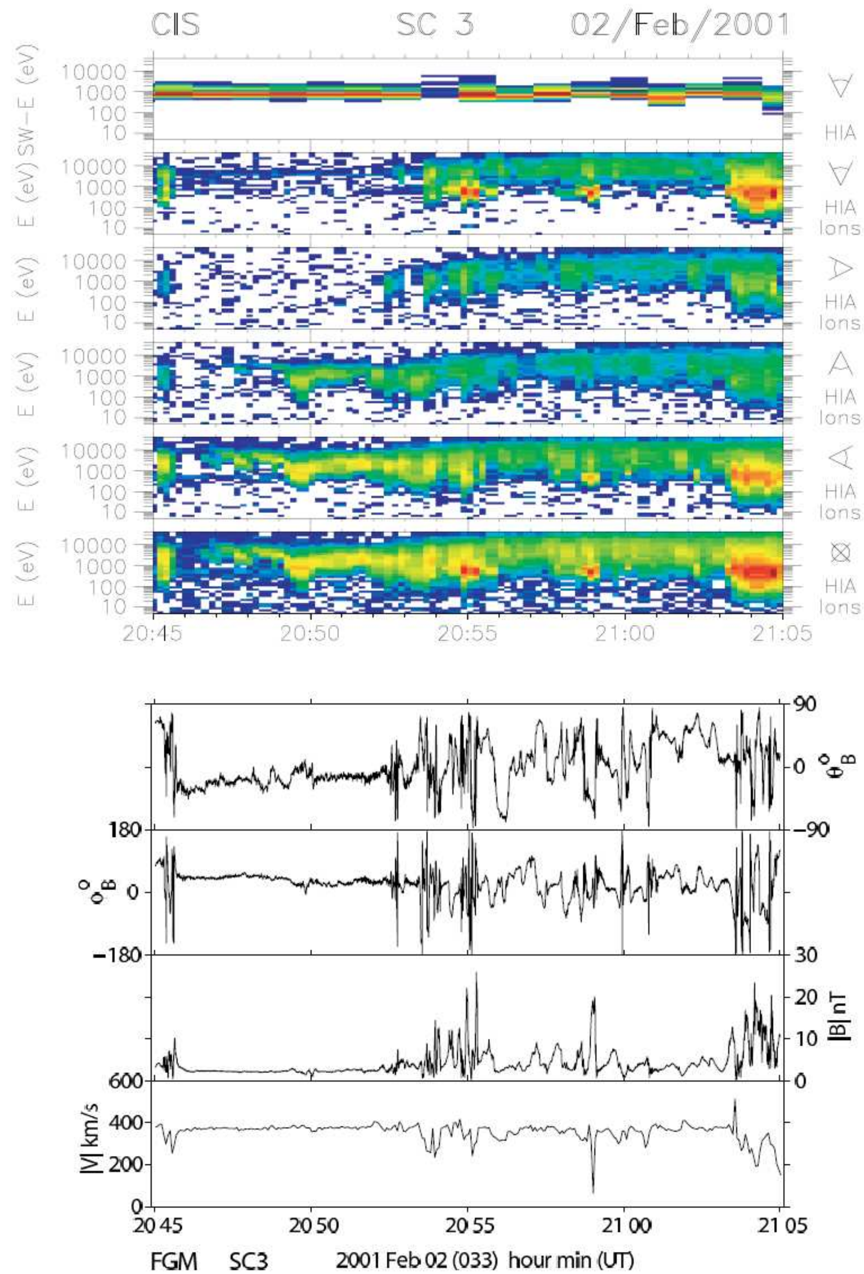


SLAMS growth and hot ions

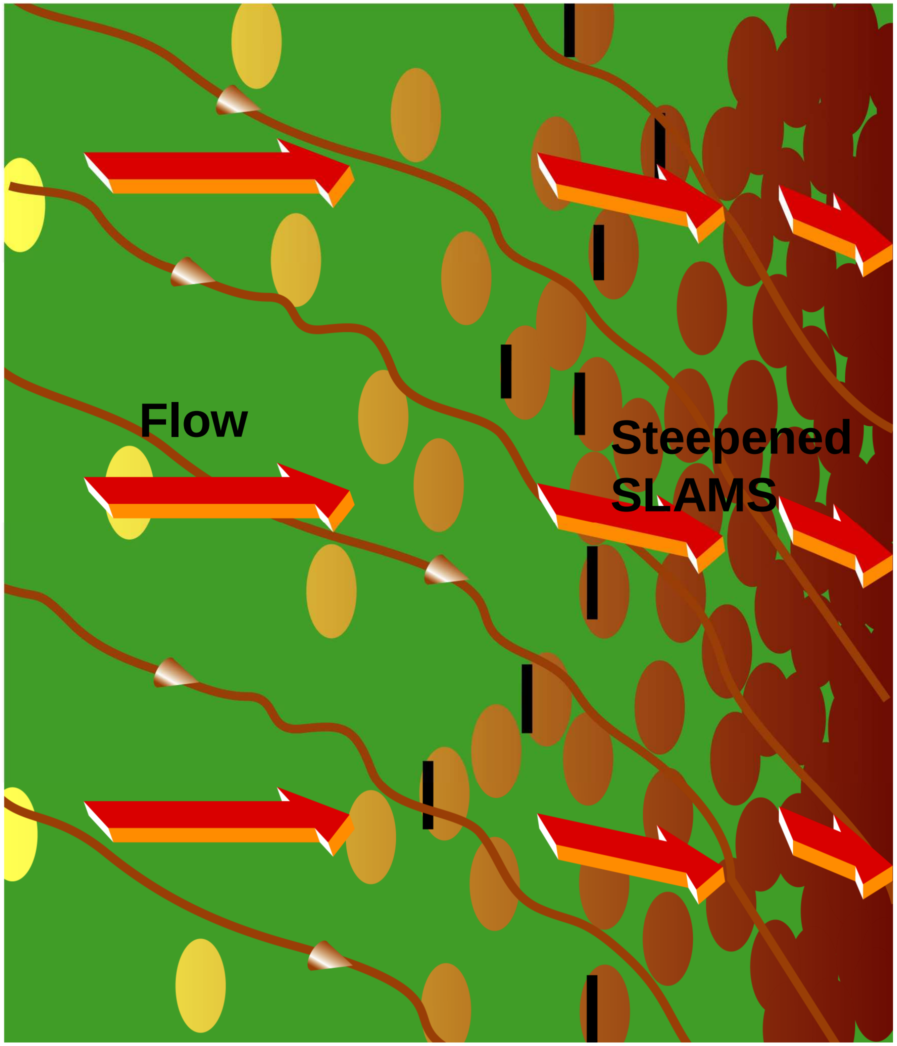
- Foreshock populated with low frequency waves
- Waves propagate sunward in plasma frame
- Waves convected Earthward by solar wind
- Interaction with energetic particle pressure gradient
  - Waves grow into pulsations/SLAMS

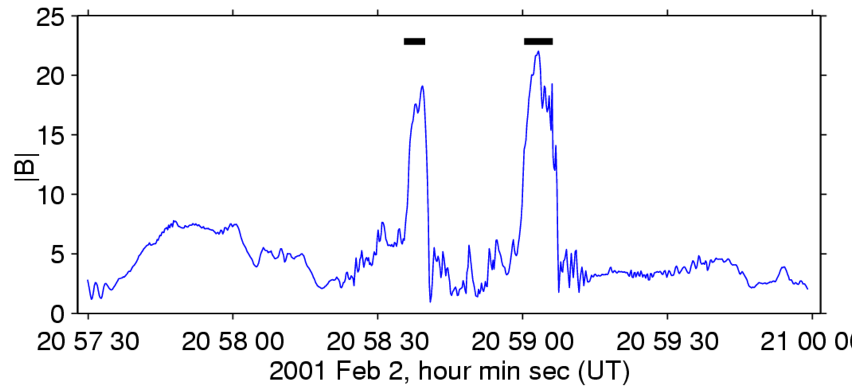
[Giacalone et al, 1993; Dubouloz & Scholer,1995]

- Ensemble of pulsations/SLAMS form shock transition



Parallel shock schematic





- Shock is spatially extended + reforming in time
- Patchwork of pulsations/SLAMS (0.5×1 R_E) [Schwartz and Burgess, 1991]
- Larger SLAMS start to stand in flow
- Pulsations found both in upstream and downstream plasma

Knowledge before Cluster

- From…
  - Dual-spacecraft missions: ISEE 1&2, AMPTE
  - Numerical simulations
- SLAMS properties
  - Rapid growth from interaction of waves with energetic particle pressure gradient
  - Propagating sunward, carried Earthward by solar wind; refract as approach bow shock
  - Simulations → size ~1000x3000 km
  - Larger amplitude SLAMS have higher velocities, nearly standing in solar wind flow
  - Associated with partially thermalised plasma
  - Observed correlation length ~ 1000 km (shorter than low frequency foreshock waves)
- Open questions
  - Overall size?
  - Shape perpendicular to plasma flow?
  - Presence of internal structure?
  - Growth rate?
  - Evolution with time: Refraction? Changing shape?
  - Effect on the plasma (spatial extent/cyclic reformation)

SLAMS at different spacecraft scales

600 km

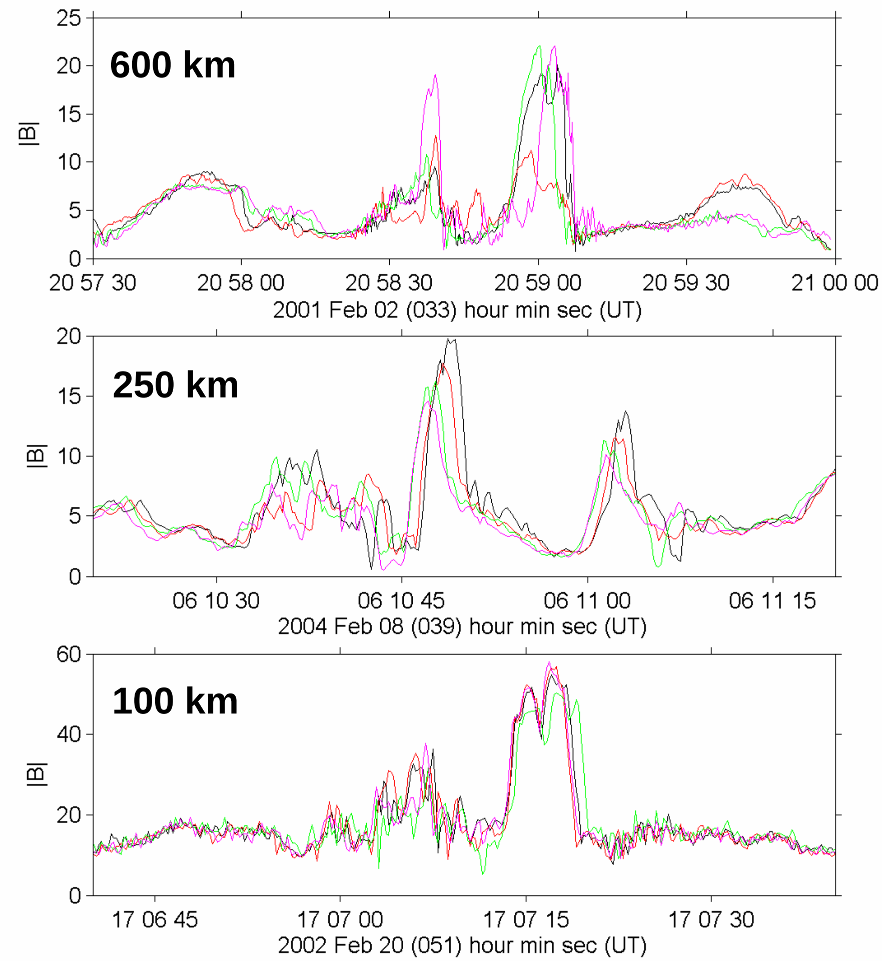
- Structure typically seen at all 4 spacecraft
  - Pulsation size > 600 km
- Dissimilar profiles
  - Internal structure
  - Hard to calculate orientation/motion

250 km

- Rapid growth over a few seconds
  - Growth rate

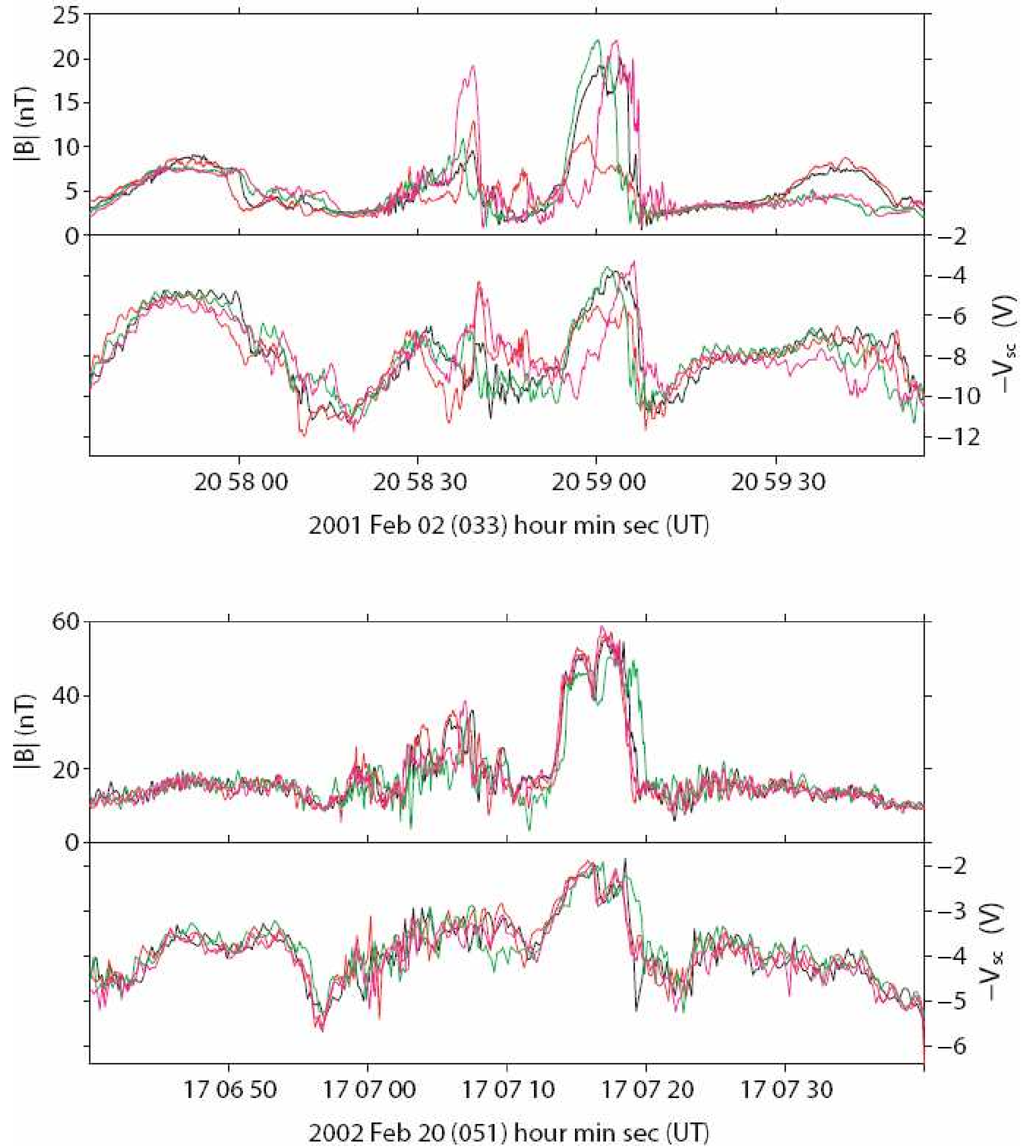
100 km

- Small difference in signatures
  - Gradient scale
- Similar profiles but time differences very small
  - Orientation/speed
  - Sensitive to local ‘ripples’?

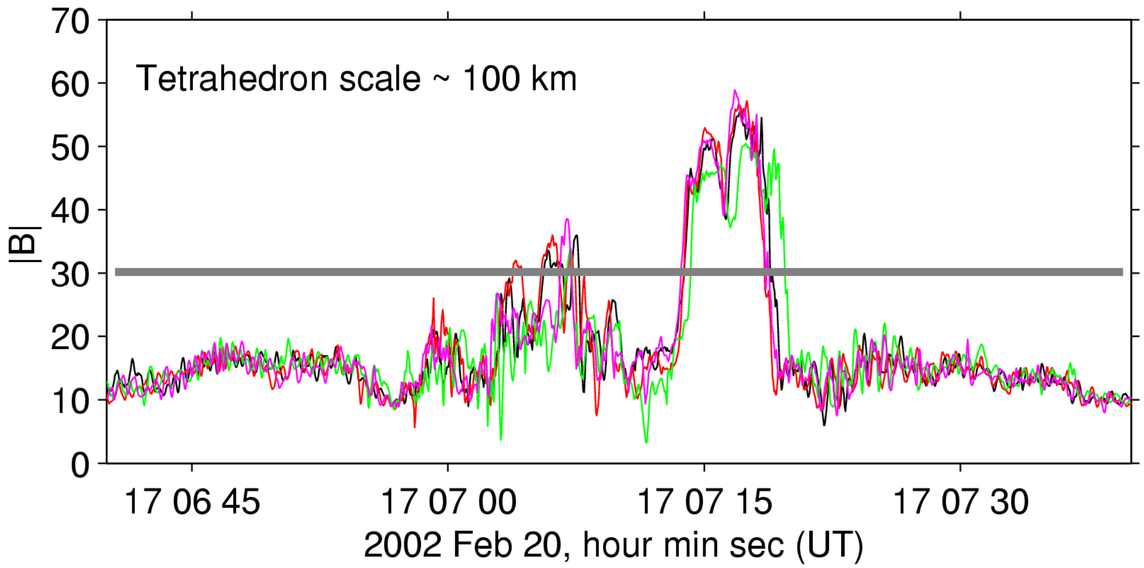


SLAMS electric fields and plasma density [Behlke et al, 2003, 2004]

- Magnetic field and density signatures
  - Correlated – fast mode structures
  - Not identical – different sub-structure
- Electric field signatures
  - Measured E agrees with motional E calculated from SLAMS velocity
  - Locally plasma moves at SLAMS velocity
  - Presence of small scale Electric field spikes
  - SLAMS associated with solitary waves (SWs) moving parallel to B at speed exceeding typical ion thermal speed
    - Do not fit current SW models

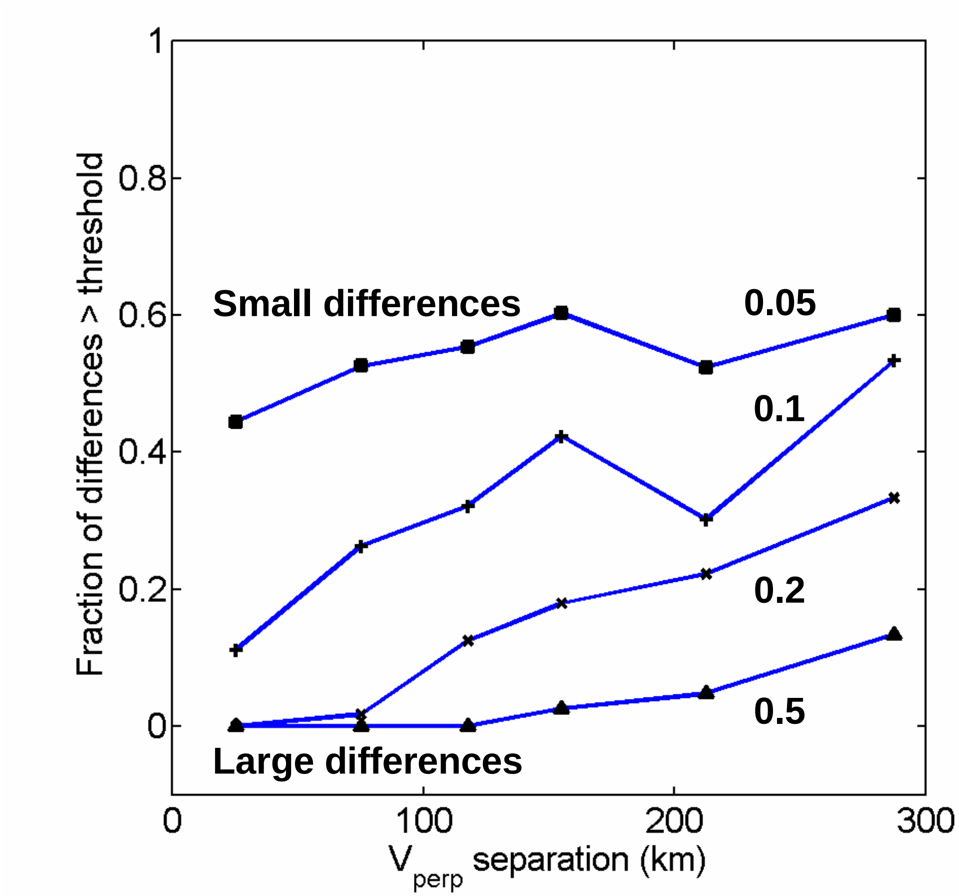


Estimation of B gradient scale in SLAMS



- Quantify the size of differences between SLAMS at different spacecraft
  - How often do substantial differences occur?
  - Do large differences occur more often when a spacecraft pair has a large separation perpendicular to the plasma flow direction?

Distribution of differences between spacecraft



- Combine data from 100 and 250 km separations
- Very small differences common – small scale waves/noise?
- Large differences not observed unless spacecraft > 100-150 km apart
  - Does not depend strongly on flow parallel spacecraft separation
  - No significant time evolution on such short time scales

- Gradient scale ~ 100-150 km
  ~ ion inertial length

SLAMS growth rate

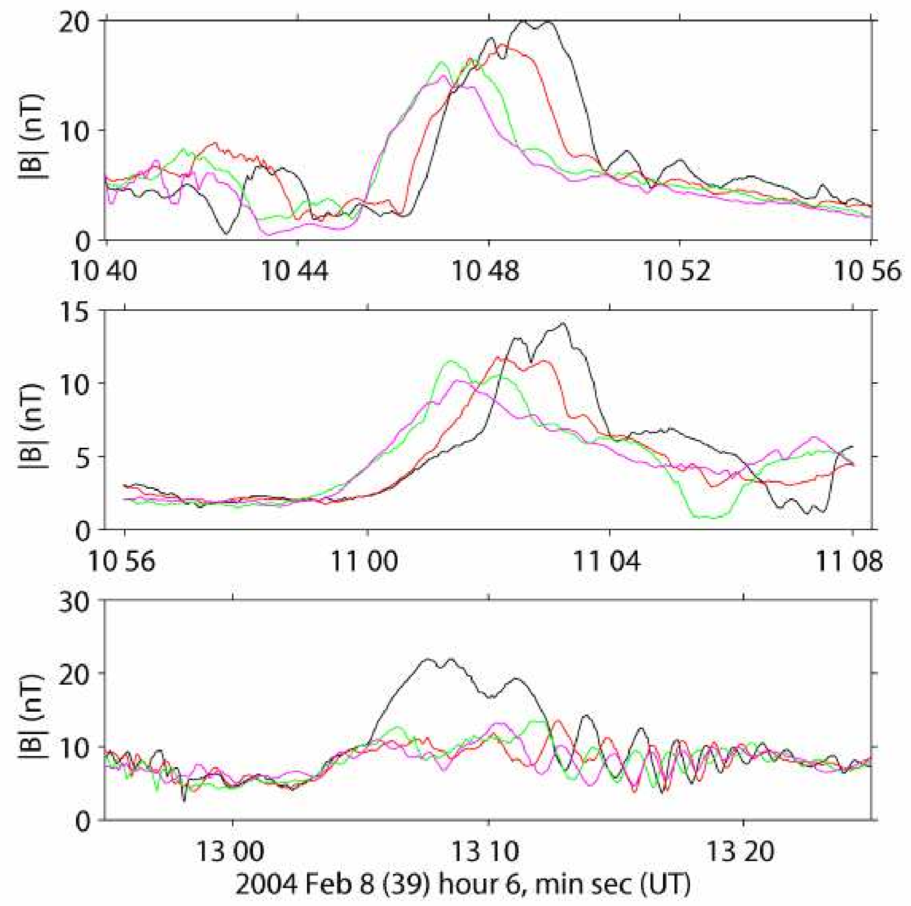
- Simulations suggest that growth should occur on timescale of seconds

- Observe a variety of signatures
- Peak size increases, change in shape

- Signatures of growth common over few seconds but not seen in all cases

- Data from 2004:
- Spacecraft separation ~250 km
- Five quasi-parallel shock crossings
- Statistical analysis of pulsation size

- Look for statistically significant signatures of growth



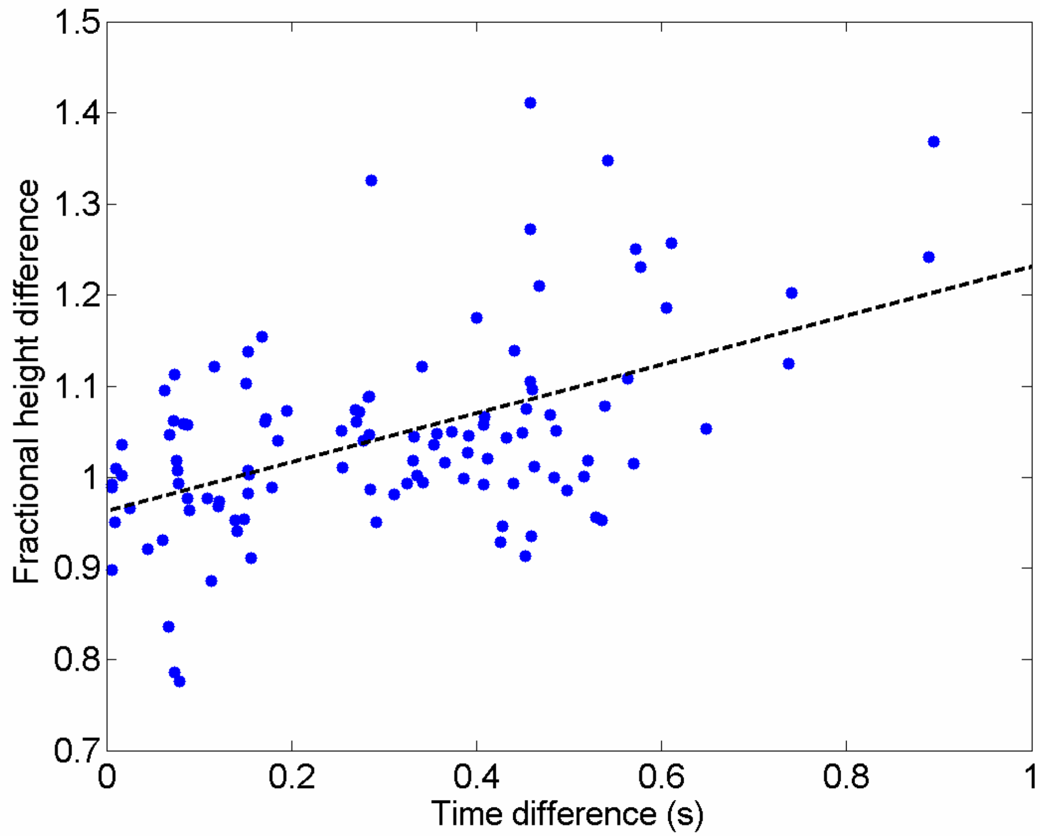
SLAMS growth rate

Data from 2004 (250 km)

- Gradient = 0.27 ± 0.04
  → growth rate >25%/second

- Locally pulsations grow rapidly: timescale ~ few seconds

- Not sensitive to separation of spacecraft across the flow
  - Flow parallel and flow perpendicular separations are correlated
  - Patchy sampling



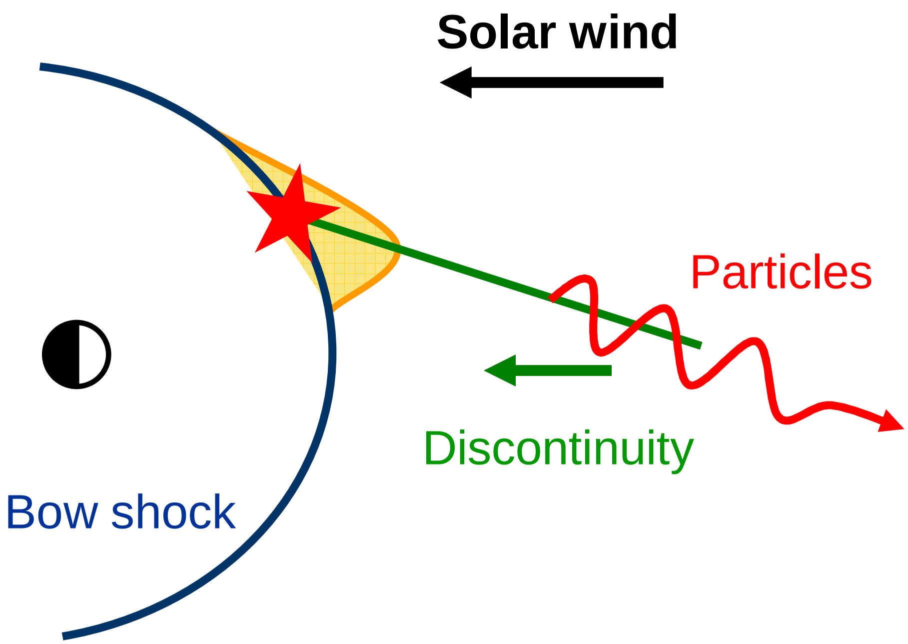
Summary

Mode	Fast mode structures Correlated magnetic field and density enhancements
Size	Overall size > 600 km; smaller correlation scale than ULF waves
Gradient scale	~100-150 km ~ion inertial length
Growth rate	~20% per second

What next

Evolution	SLAMS size ordered by suprathermal density Proxy for distance from shock Explain where and when SLAMS grow?
Orientation	Not ordered by suprathermal density No evidence for refraction Normals measure local boundary shape? How measure underlying ordering if present?

Hot Flow Anomalies



Mechanism

- **Magnetic field discontinuity** tracks slowly across shock surface
- **Energised ions** reflected from shock, focussed along discontinuity
- **Bubble** blown by overpressure into upstream plasma
- **Shocks** driven by rapid expansion

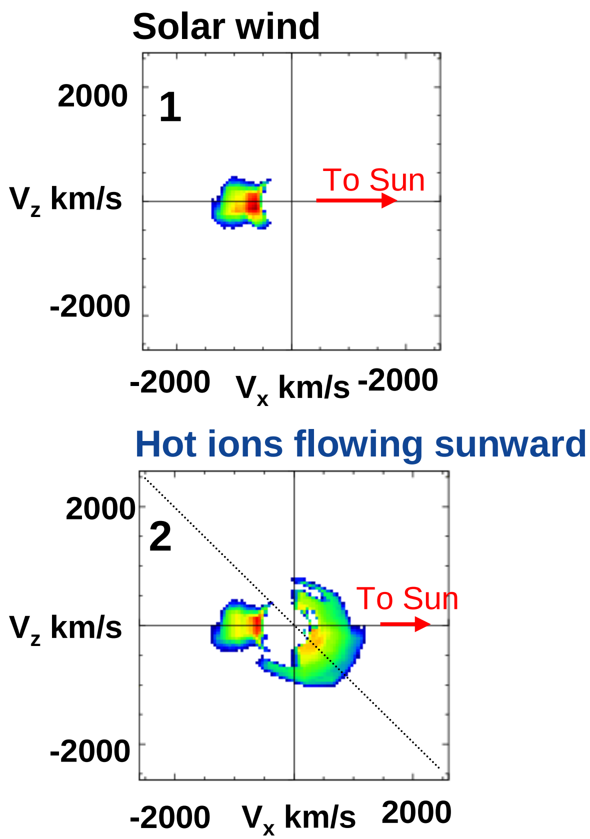
Importance

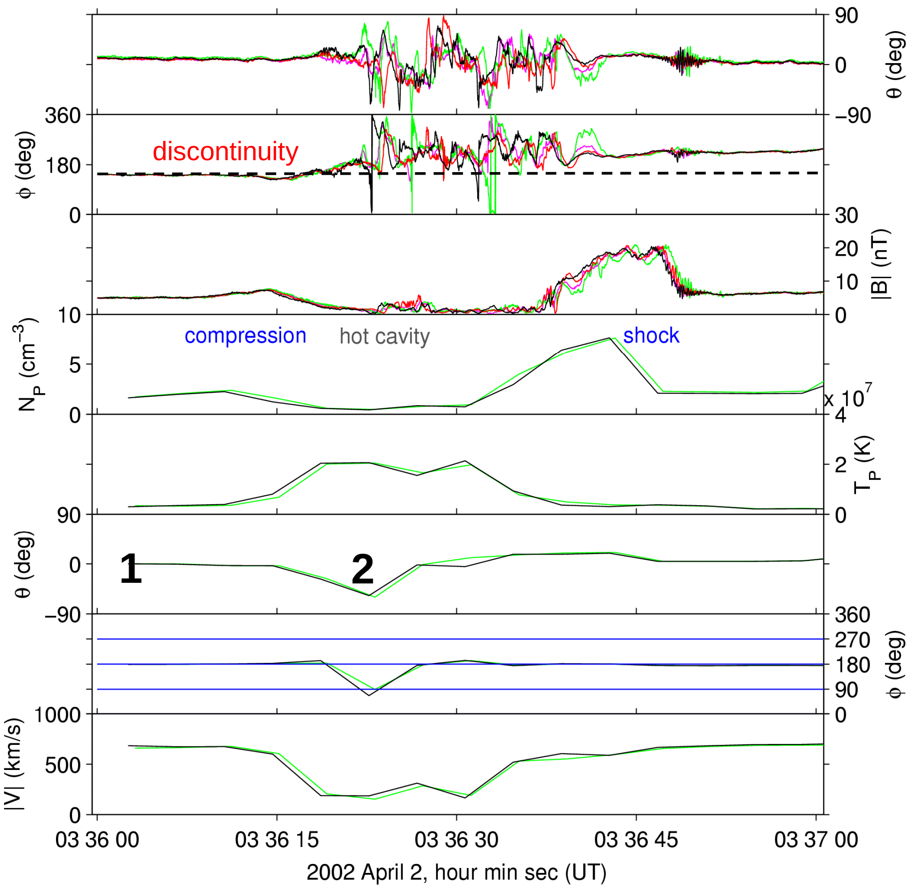
- **Small ΔB** can cause big response
- **Energetic particles** injected upstream
- **Seed population** for subsequent Fermi acceleration?
- **Generic process** at solar & astrophysical shocks?

Questions

- **Size, shape, growth?**
- **Particle signatures** dependence on HFA properties?

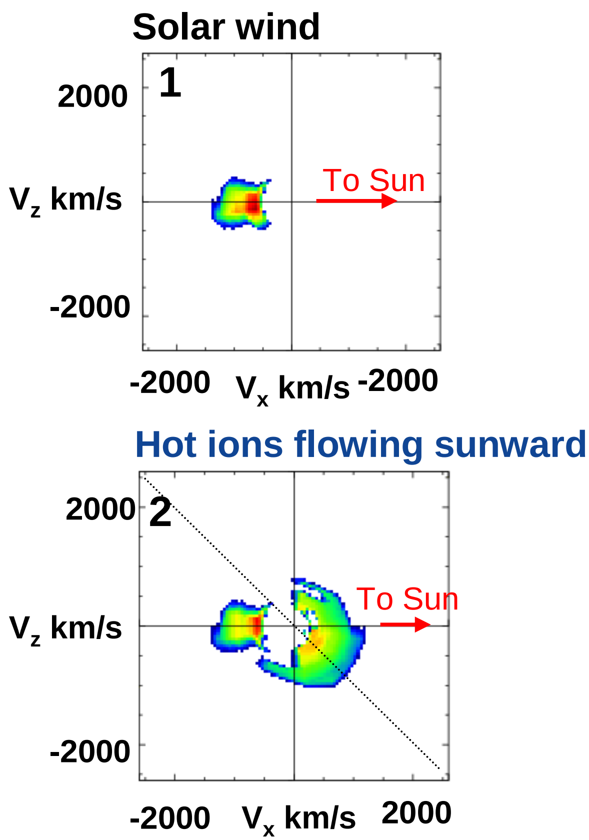
April 2 2002: HFA 1

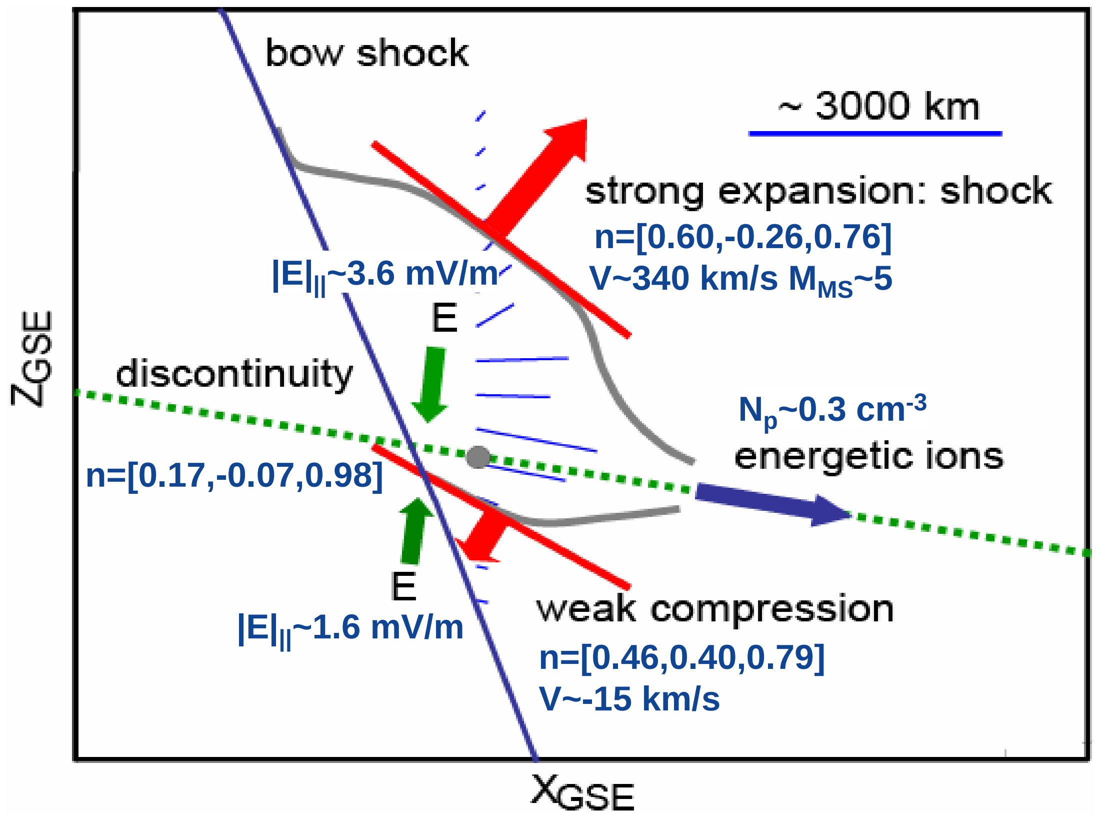




- Cavity containing hot ions flowing sunward and weakened solar wind beam
- Compression (entry) and shock (exit) bounding the cavity
- Interplanetary discontinuity within cavity n=[0.17, -0.07, 0.98]
- Small scale fluctuations inside cavity: |B| decorrelated on ~100 km scales

April 2 2002: HFA 1 sketch based on observations





- Motional E consistent with focussing of ions along discontinuity
- Beam has same density as weakened solar wind beam ~ 0.3 cm^{-3}
- Vertical scale of ~3000 km; Differences in Y components: curvature?
- Edges (in X-Z) are nearly parallel → expanding sheet, extended in plane of discontinuity

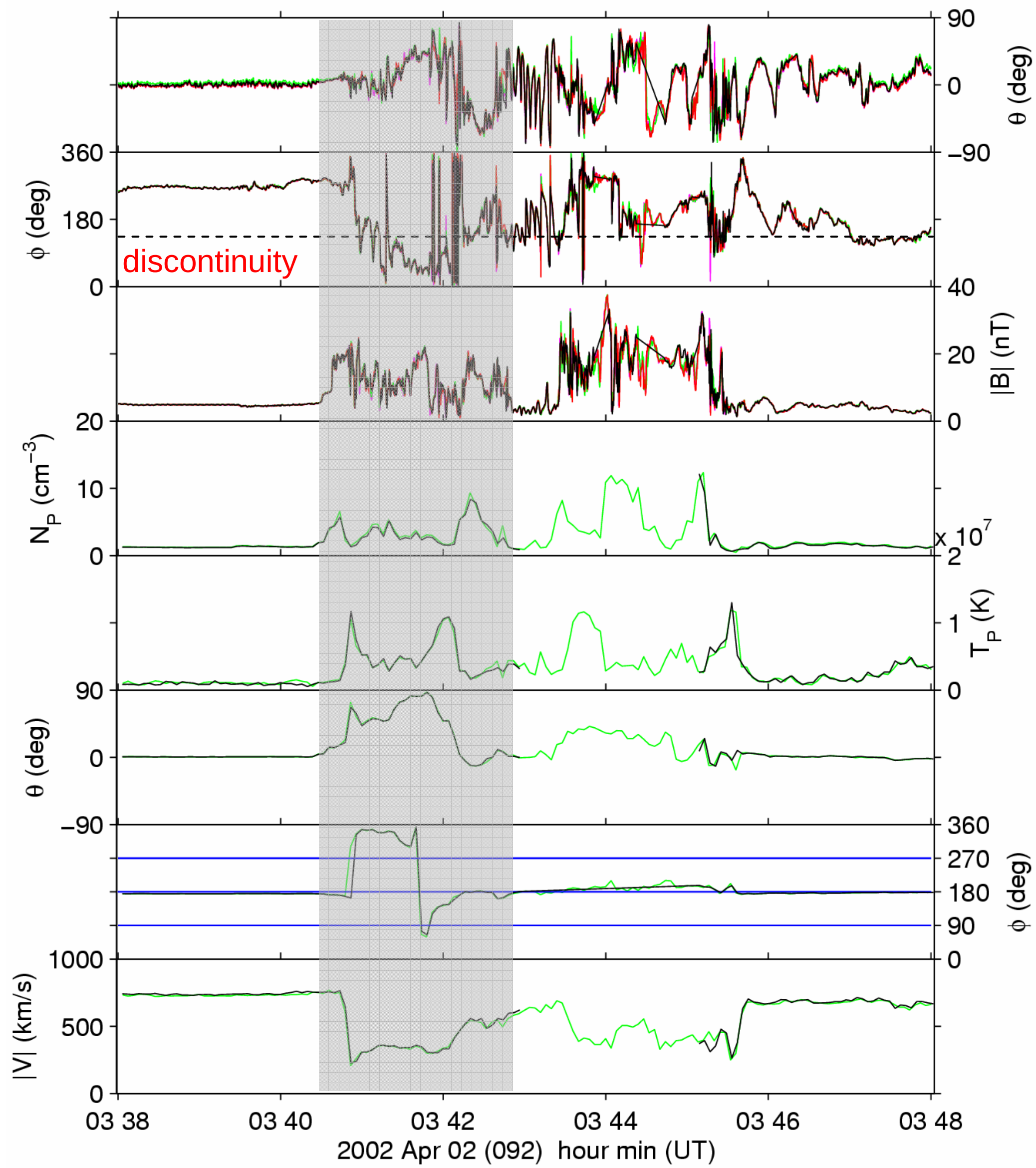
April 2 2002: HFA 2

- TD normal entirely in z direction
  - n ~ [-0.02, -0.02, 1.00]
  - Long interaction time

- Leading compression in two parts
  1. n_1=[0.01, 0.01, 1.00]; $V.n_1$ ~ 145 km/s
  2. n_2=[0.04, 0.11,0.99]; $V.n_2$ ~ 305 km/s
     Shock, M_{MS} ~5

- Northward motion + Northward plasma deflection

- Brief re-entry into solar wind
- More complex re-encounter



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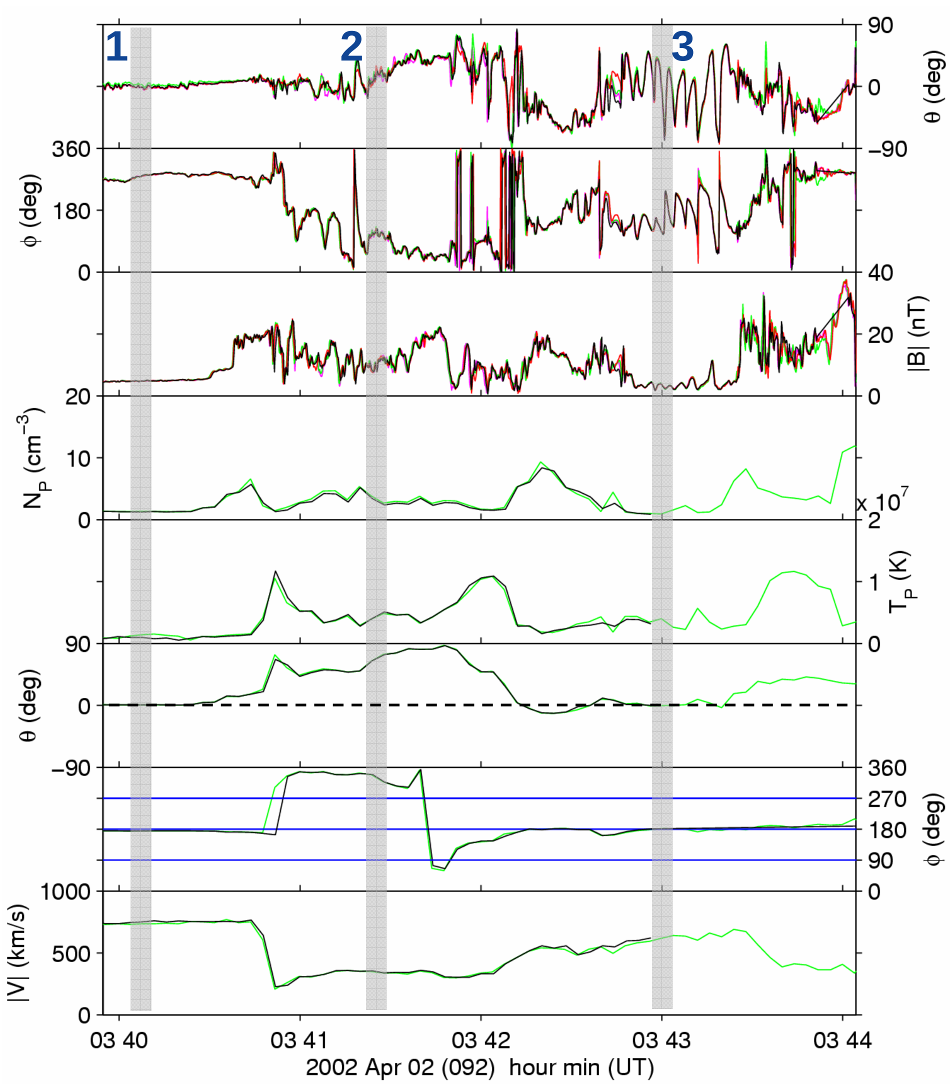
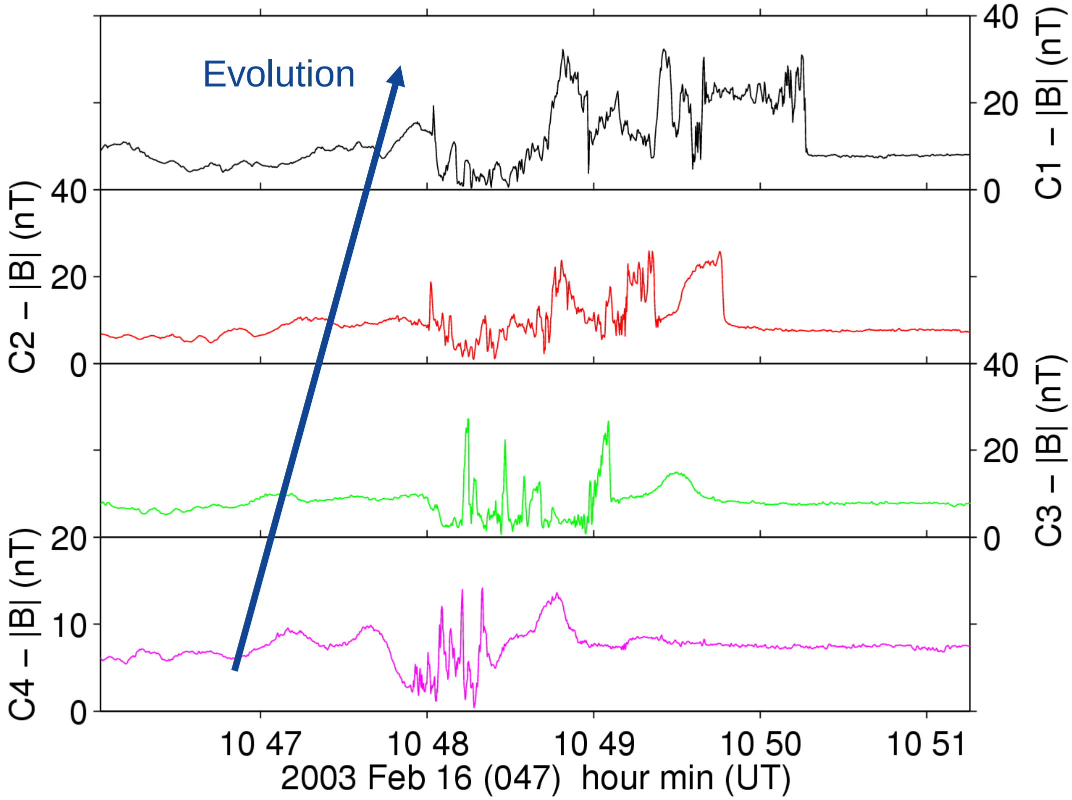
April 2 2002: HFA 2 ion distributions

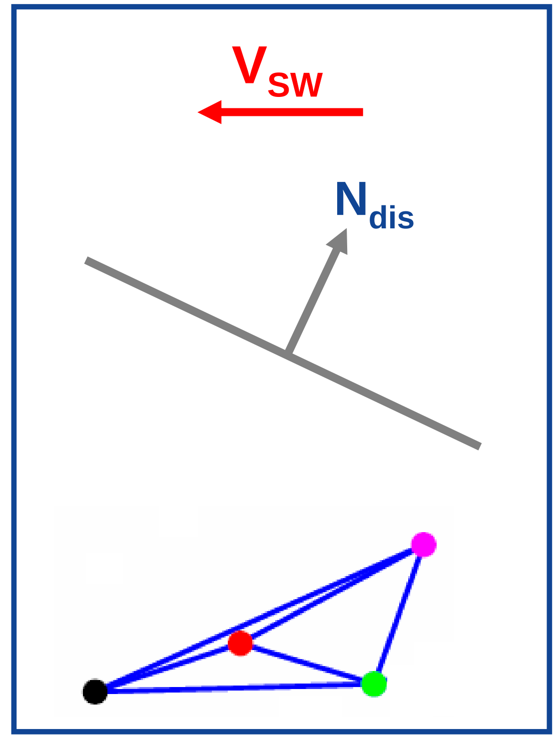


- Older, more well developed HFA
- Single ion population
- Motion superposition of
  - Convection northward across bow shock
  - Rapid expansion perpendicular to discontinuity plane (north then south)
- Entry normal parallel to discontinuity orientation
  - HFA extended parallel to discontinuity
  - Mechanism for injecting energised particles far upstream of bow shock

[Lucek et al, JGR, 109, A6, 2004]

February 16 2003: HFA evolution





- Shock steepens over ~1 minute between Cluster 4 and **Cluster 1**
- **Cluster 1**: single hot ion distribution, moving southwards; low wave power
- Cluster 3: more complex ion distribution; higher wave power

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Summary

Shape and size	Expanding sheet centred on discontinuity Thickness ~ 3000 km
Motion	Signatures of convection and expansion Bounded by shocks
Ion distributions	Two: solar wind + reflected ions → young HFA Single: hot population → more evolved HFA
Time evolution	Wave power, shocks, ion distributions evolve over ~ 1 minute

What next: ISSI working group

Multi-mission data	Cluster – Wind – Double Star Evolution over longer time/spatial scales?
Simulations	Dependence of HFA signature on discontinuity properties?
Particle characteristics	Energy dependence on cavity size? Energisation rate?
Broader implications	Generic particle energisation mechanism?