Observations and simulations of foreshock waves during magnetic clouds

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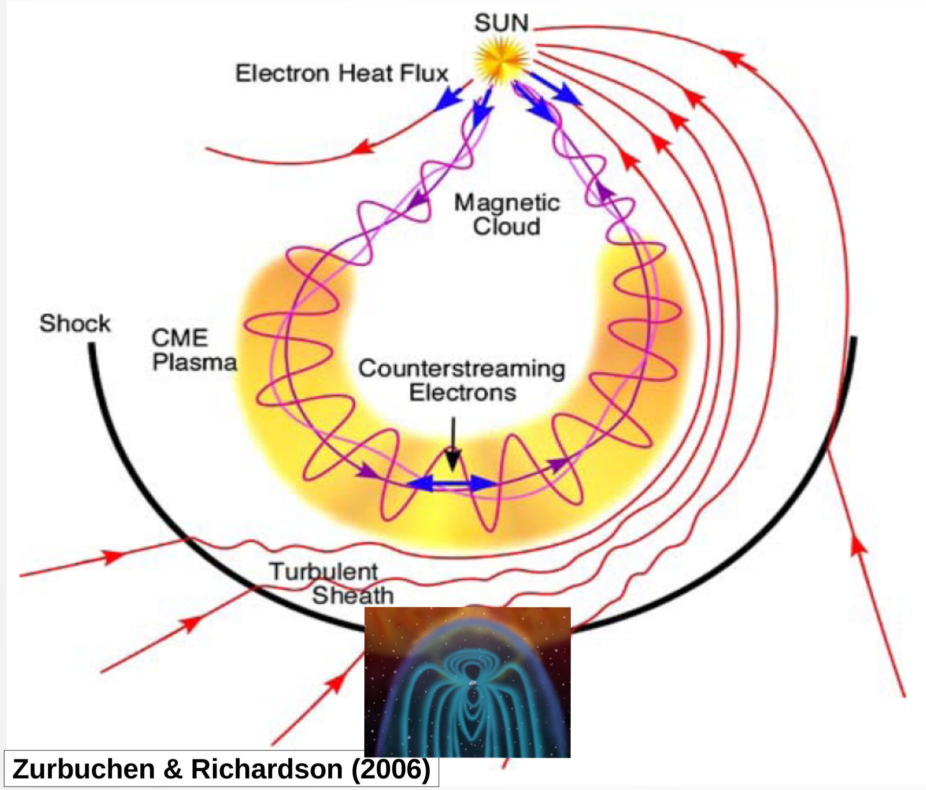
MAGNETIC CLOUDS DRIVE THE MOST INTENSE DISTURBANCES AT EARTH



Zurbuchen & Richardson (2006)

Magnetic clouds = subset of coronal mass ejections

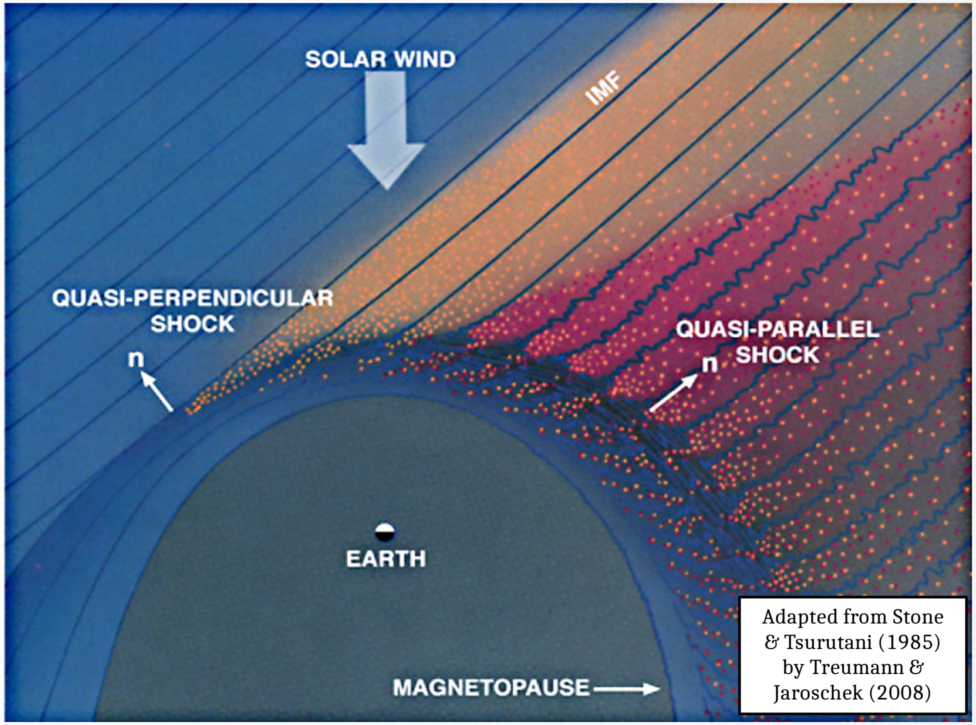
Properties in the interplanetary space [Burlaga et al., 1981]:

- Enhanced magnetic field
- Smooth rotation of the magnetic field direction

Because of their strong geoeffectivity, it is important to understand the details of their interaction with near-Earth space

WHAT HAPPENS WHEN MAGNETIC CLOUDS CROSS THE EARTH'S FORESHOCK?

The **foreshock** is the sunward-most extent of geospace, populated by **backstreaming particles**, and hosting a variety of **waves**



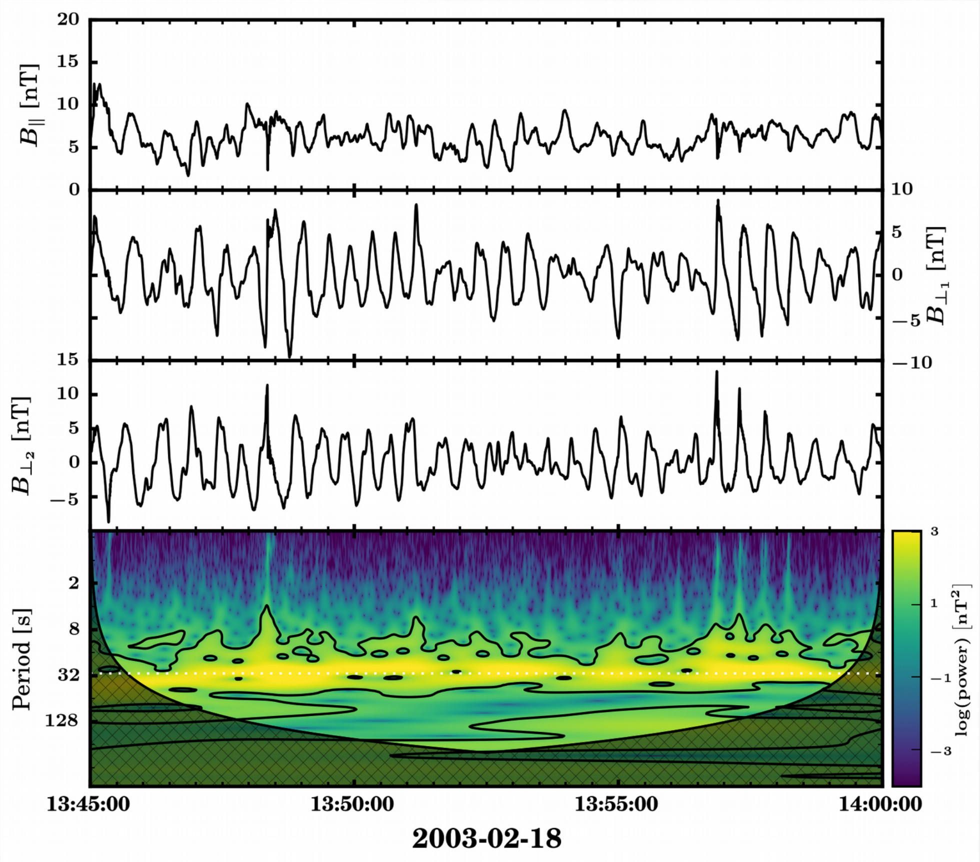
Adapted from Stone & Tsurutani (1985) by Treumann & Jaroschek (2008)

First region crossed by incoming solar wind and magnetic clouds

WE FOCUS ON THE MOST COMMON FORESHOCK WAVES

- Foreshock mainly populated by waves with a period around 30 s [e.g., Eastwood et al., 2005]

- Fast magnetosonic waves generated through the ion-ion beam right-hand instability



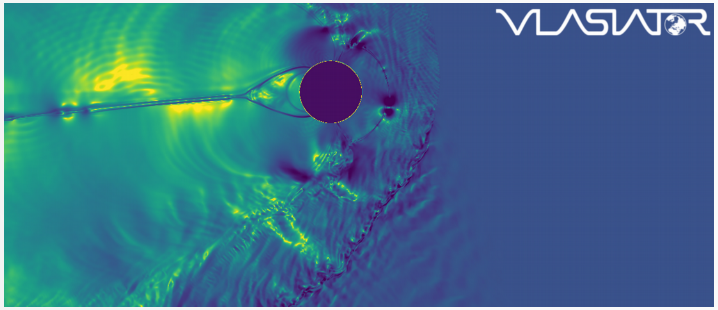
30 s foreshock waves observed by the Cluster spacecraft

HOW CAN WE STUDY THE FORESHOCK PROPERTIES?

Numerical approach

Global kinetic simulations of near-Earth space performed with the Vlasiator code

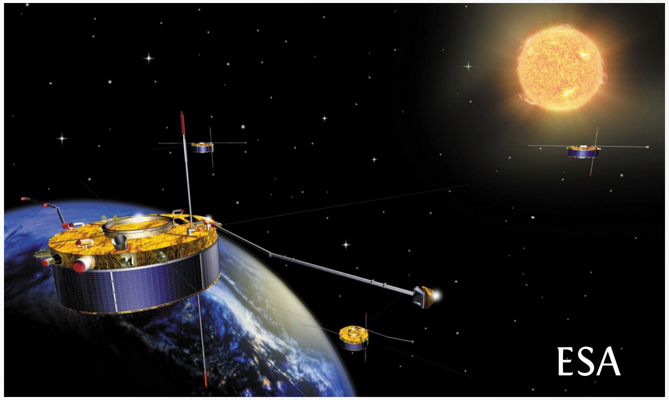
→ global view of the foreshock
→ small-scale features



Observational approach

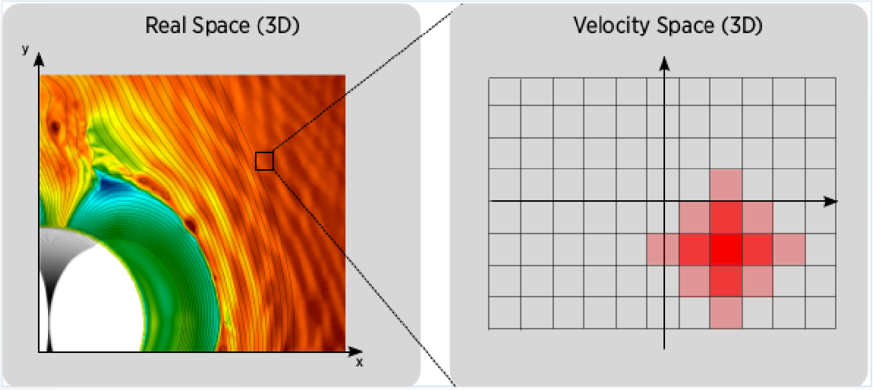
Observations from ESA's four-spacecraft Cluster mission

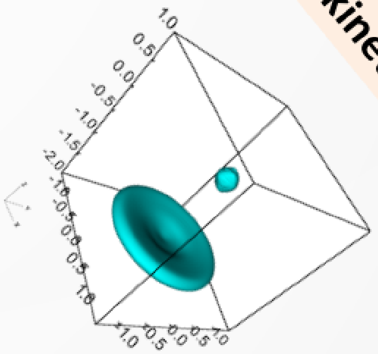
→ accurate determination of the foreshock wave properties



PI: **Minna Palmroth** (minna.palmroth@helsinki.fi)

- Hybrid-Vlasov model designed for global magnetospheric simulations
- Ions treated as velocity distribution functions, electrons are a charge-neutralizing fluid
- Most runs are currently 5D – 3D in velocity space and 2D in ordinary space
- Full description of the model: Palmroth et al., 2018





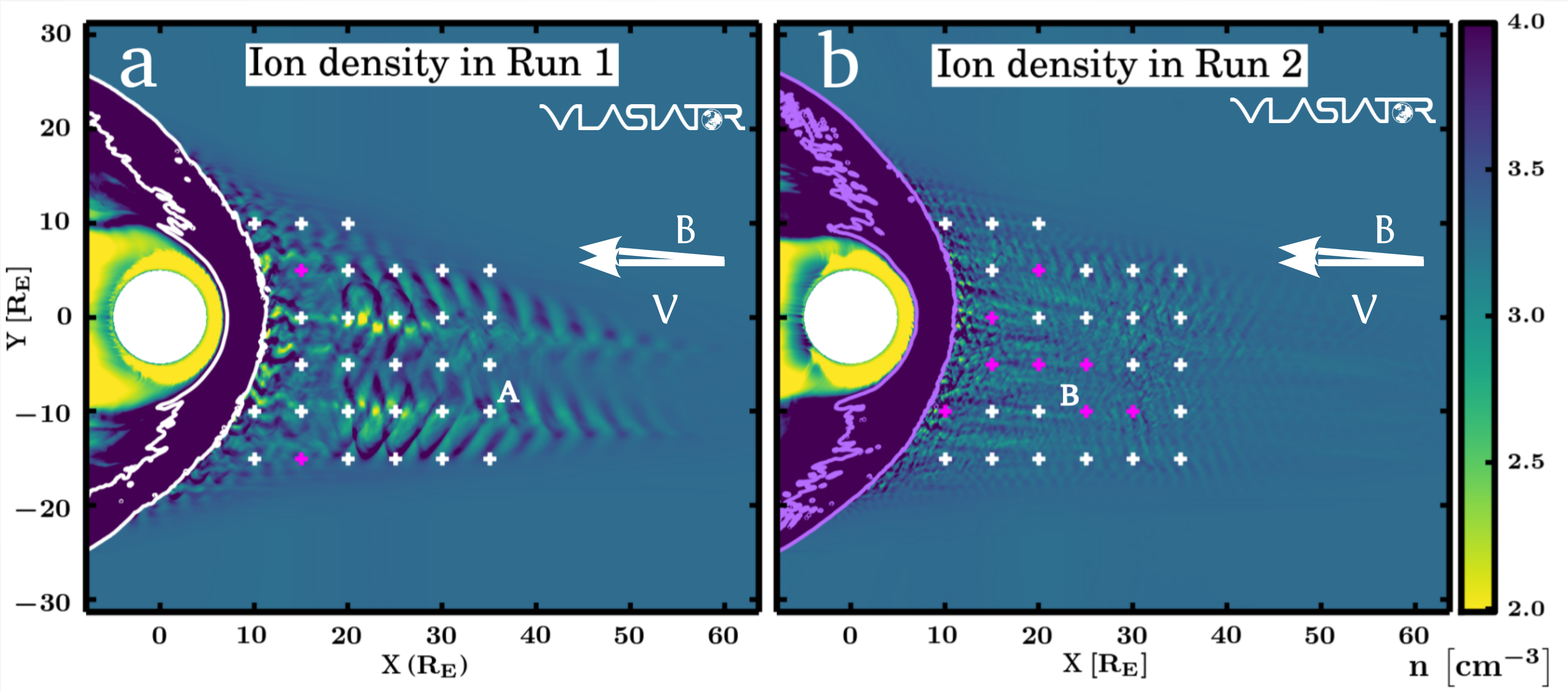
Noise-free multi-temperature kinetic physics!

VLASIATOR RUNS USED IN THIS WORK

- Run set-up:
  - Equatorial plane
  - Quasi-radial interplanetary magnetic field (IMF) (cone angle = 5°)
  - Solar wind parameters: V = 600 km/s ; n = 3.3/cc ; T = 500 kK
- **Run 1**: typical IMF strength (5 nT) → M_A = 10 [Palmroth et al., 2015]
- **Run 2**: enhanced IMF strength (10 nT) → M_A = 5 (”magnetic cloud-like” conditions)

→ **Effects of the enhanced interplanetary magnetic field strength on foreshock properties**

AN ENHANCED MAGNETIC FIELD MODIFIES THE LARGE-SCALE STRUCTURE OF THE FORESHOCK

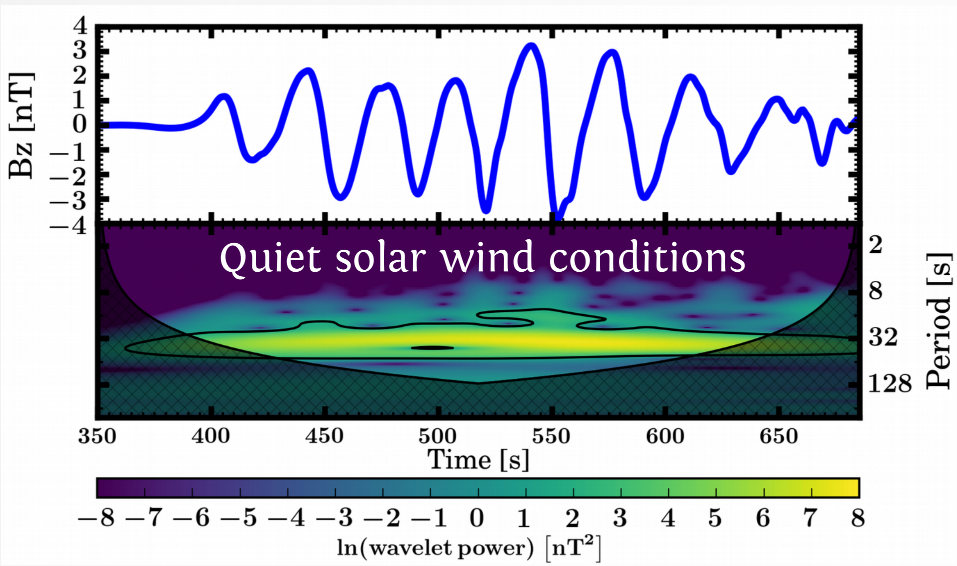


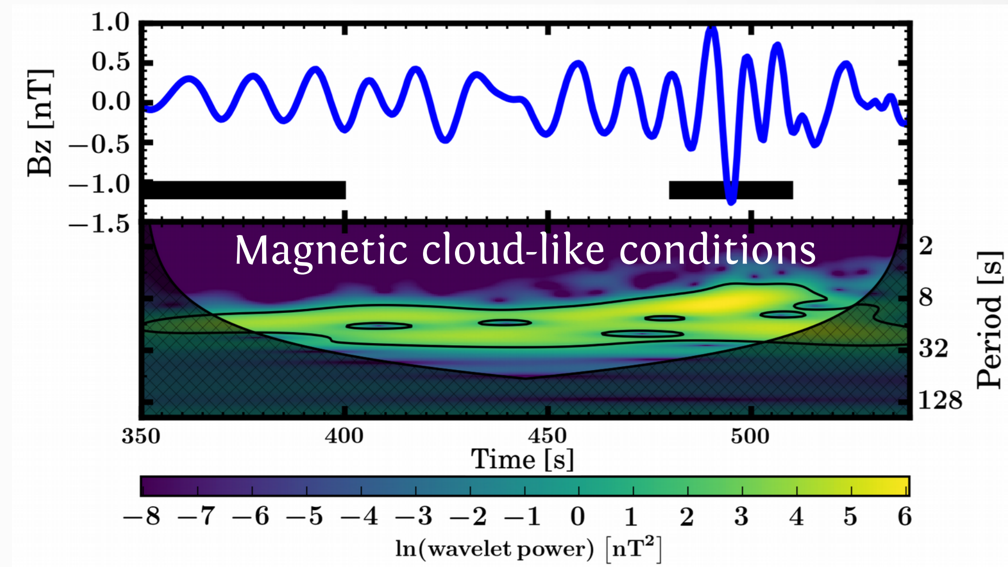
Quiet solar wind conditions

Magnetic cloud-like conditions

Turc et al., 2018, *JGR*

AN ENHANCED MAGNETIC FIELD CHANGES THE FORESHOCK WAVE PROPERTIES





Turc et al., 2018, *JGR*

During magnetic clouds, we find:

- A shorter foreshock wave period

  Consistent with previous works [Takahashi et al., 1984; Le & Russell, 1996]
- A more complex wave activity

FORESHOCK OBSERVATIONS DURING MAGNETIC CLOUD EVENTS ARE SCARCE

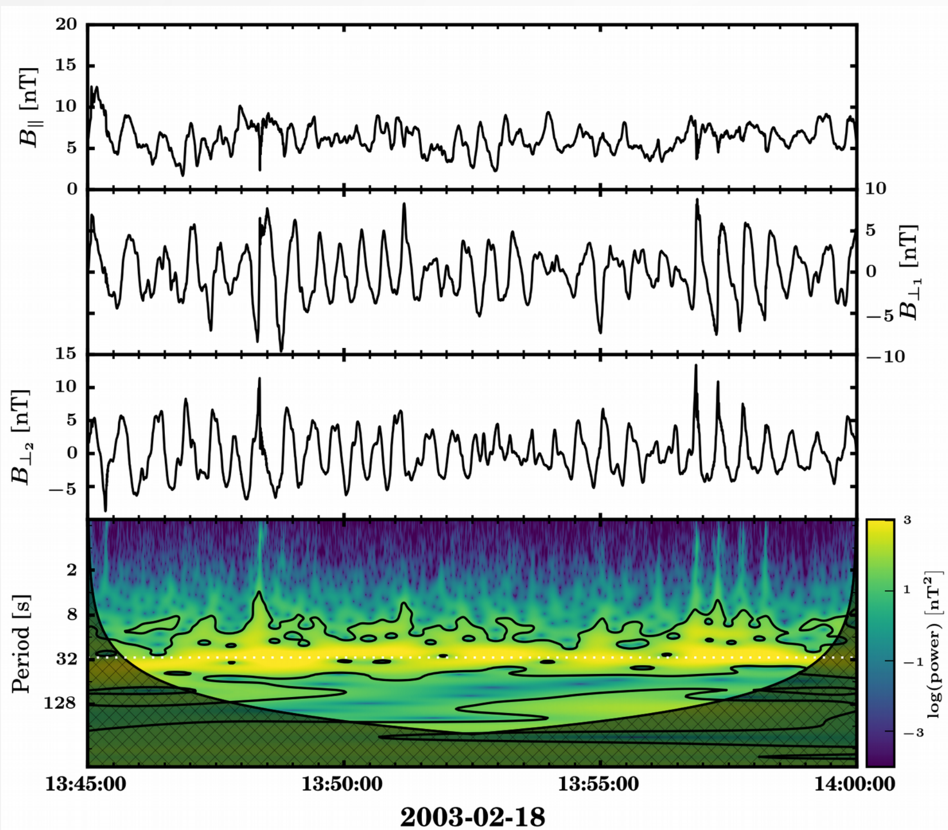
- Magnetic clouds are observed about 2% of the time at Earth [Yermolaev et al., 2012]
- Cluster is only sporadically located in the foreshock
- Spacecraft separations similar to the waves characteristic size mostly in the early phase of the mission
- 6 magnetic cloud events with left-handed foreshock waves

4 magnetic cloud events with confirmed 30 s waves

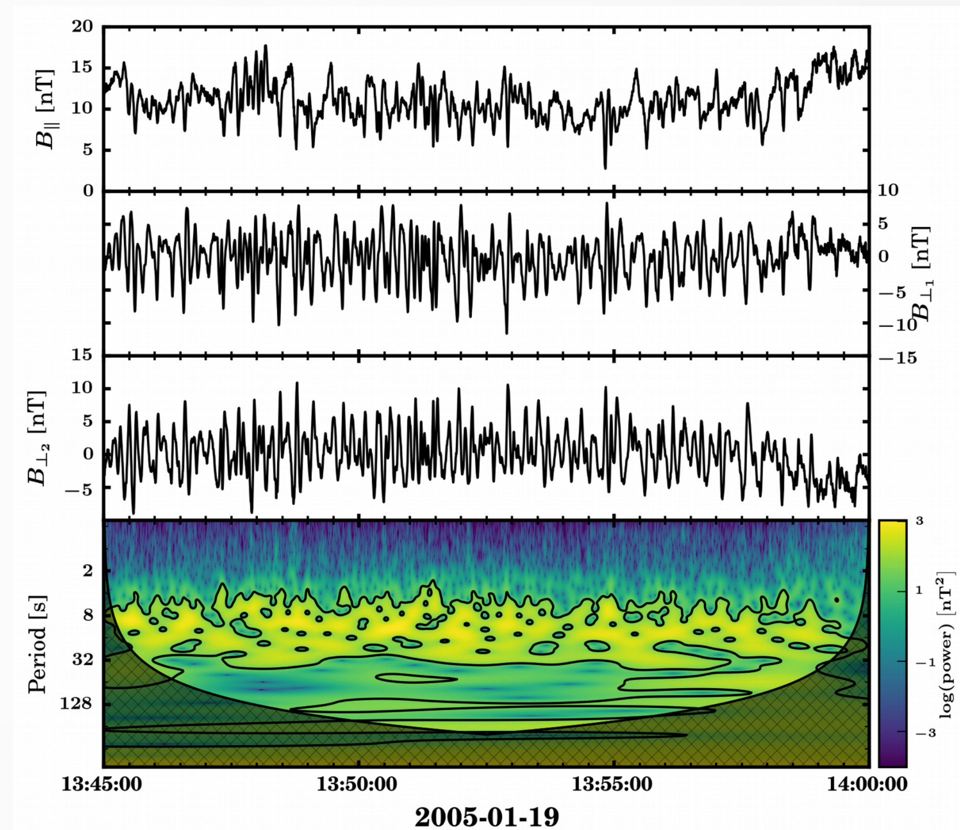
FORESHOCK WAVE ACTIVITY BECOMES MORE INTRICATE DURING MAGNETIC CLOUDS

Turc et al., 2019, *GRL*

Quiet solar wind conditions



Magnetic cloud



MULTI-SPACECRAFT ANALYSIS CONFIRMS THAT THE WAVES ARE FAST MAGNETOSONIC

Determination of the wave properties

- **Multi-point signal resonator technique** [Narita et al., 2011] (variant of k-filtering/wave telescope method [Pinçon & Lefeuvre, 1991; Motschmann et al., 1996]) → ideal for cases with several wave modes
- **Timing analysis** [e.g., Eastwood et al., 2005] applied on bandpass-filtered data (to separate the co-existing periods) → easier to apply to a large number of intervals

→ superposition of fast magnetosonic waves at different periods

FORESHOCK WAVE ACTIVITY BECOMES MORE INTRICATE DURING MAGNETIC CLOUDS

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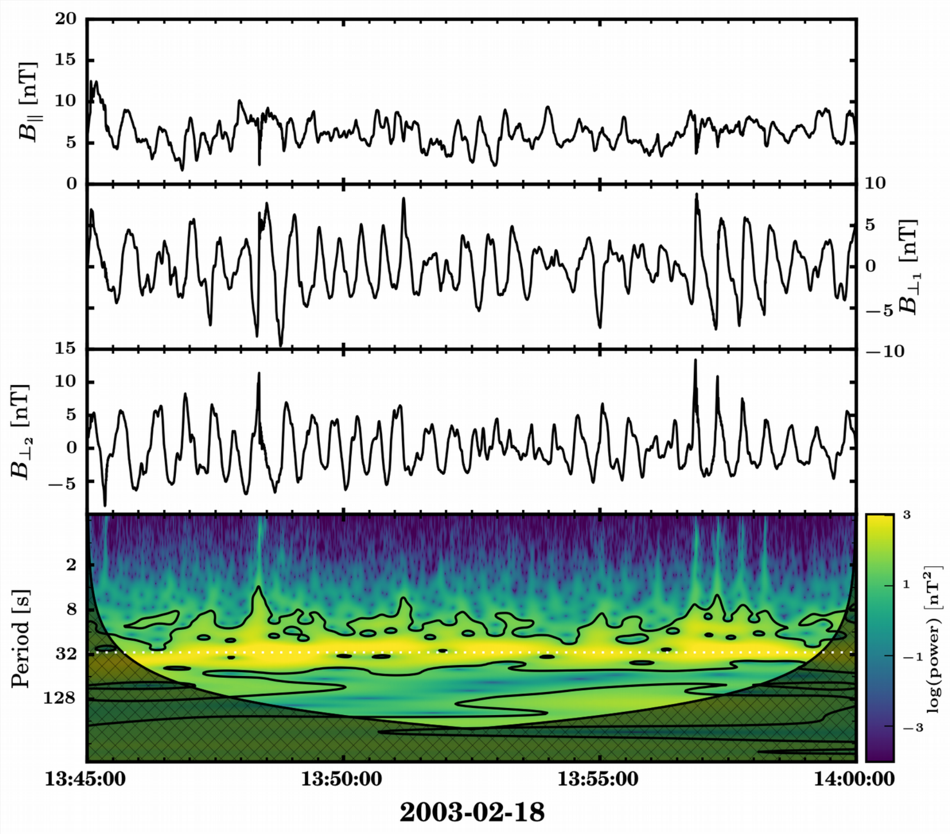
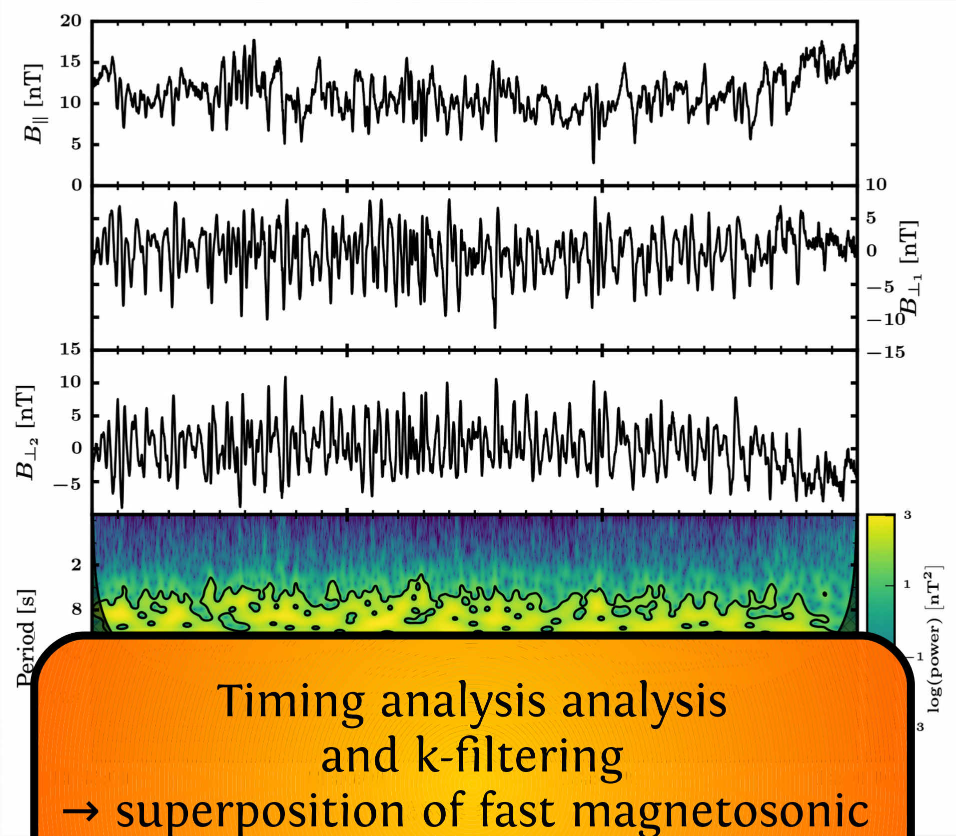
Quiet solar wind conditions



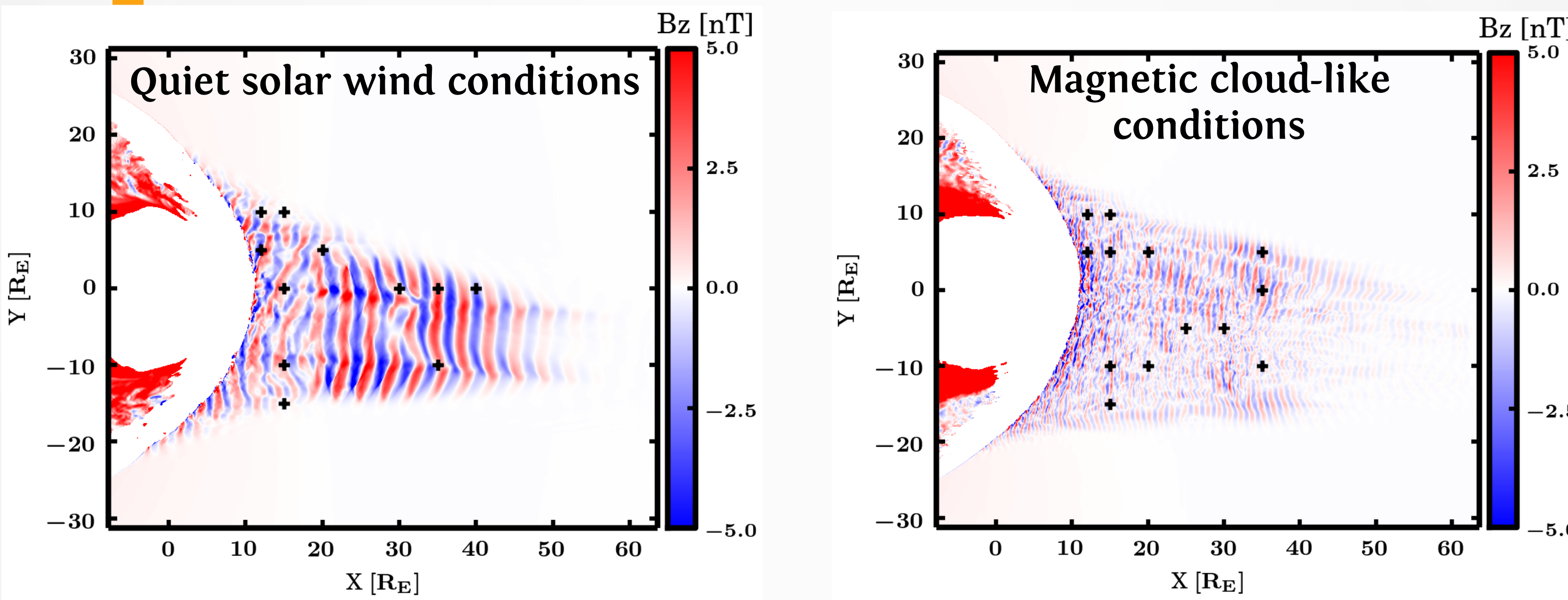
Magnetic cloud



Timing analysis analysis
and k-filtering
→ superposition of fast magnetosonic
waves at different periods

THE WAVE FRONTS ARE MUCH SMALLER DURING MAGNETIC CLOUDS

Turc et al., 2019, *GRL*



Transverse extent (from multi-spacecraft analysis technique [Archer et al., 2005])

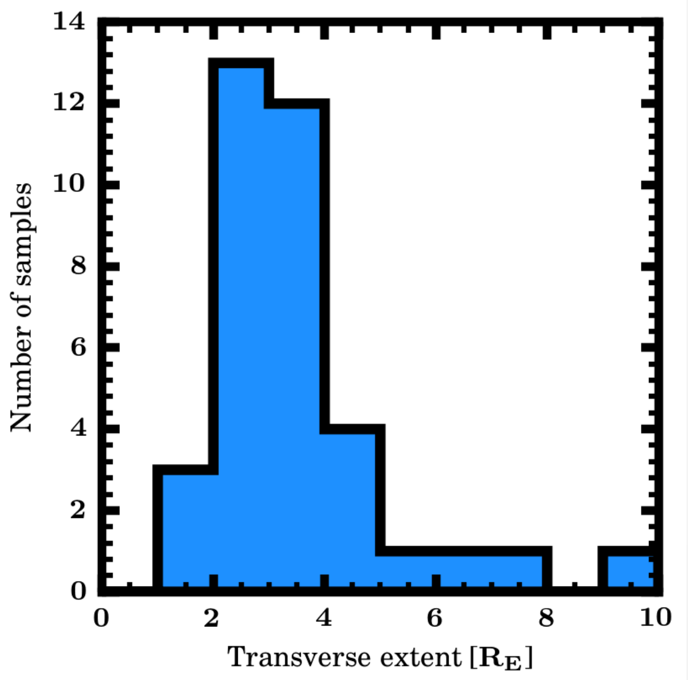
- Quiet solar wind conditions: **3-11 R_E (average: 7 R_E)**
- Magnetic cloud-like conditions: **2-6 R_E (average: 4 R_E)**

THE WAVE FRONTS ARE MUCH SMALLER DURING MAGNETIC CLOUDS

Cluster observations in the foreshock during 4 magnetic clouds

35 2-min intervals with fast magnetosonic waves during which we determine reliably the transverse extent of the wave fronts

→ **1-10 R_E (average = 3.5 R_E)** < 8-18 R_E [Archer et al. 2005]



Turc et al., 2019, *GRL*

CONCLUSIONS

Magnetic clouds modify significantly the foreshock wave field

Both **Vlasiator simulations** and **multi-spacecraft observations** consistently show that during magnetic clouds, the foreshock is characterised by:

- a lower wave period
- the coexistence of fast magnetosonic waves at different periods
- smaller wave fronts

This could strongly affect the regions downstream:

- bow shock properties
- waves in the magnetosphere
- …

ACKNOWLEDGEMENTS

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Visit https://www.helsinki.fi/en/researchgroups/vlasiator

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