Capabilities of the wave telescope for multi-scale spacecraft configurations using a Vlasiator simulation

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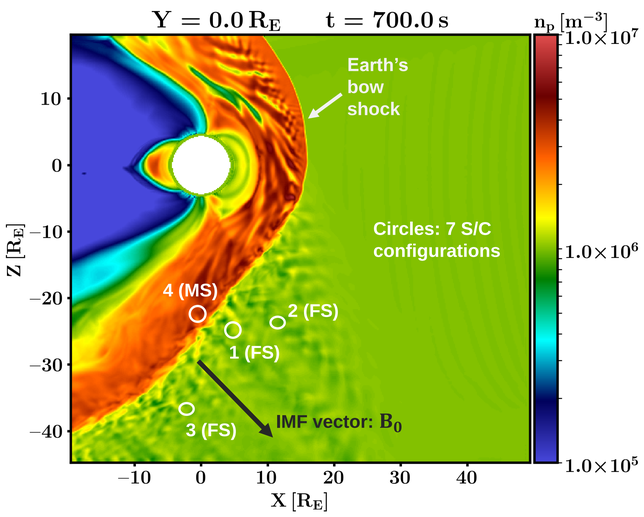
Why the wave telescope and multi-scale spacecraft configurations?

- Wave telescope: Analysis method applied to multi-spacecraft data: Allows estimation of **k**-space spectra quantifying wave vectors (Motschmann et al. 1996) → Needed for understanding of formation mechanisms and behavior of plasma waves
- Has been used for 4-spacecraft (S/C) configurations (Cluster, MMS)
- Multi-scale S/C configurations (meaning > 4 S/C) are planned: HelioSwarm (9 S/C), Plasma Observatory (7 S/C)
- Possibility for improvement in resolution, detection range and general performance of the wave telescope

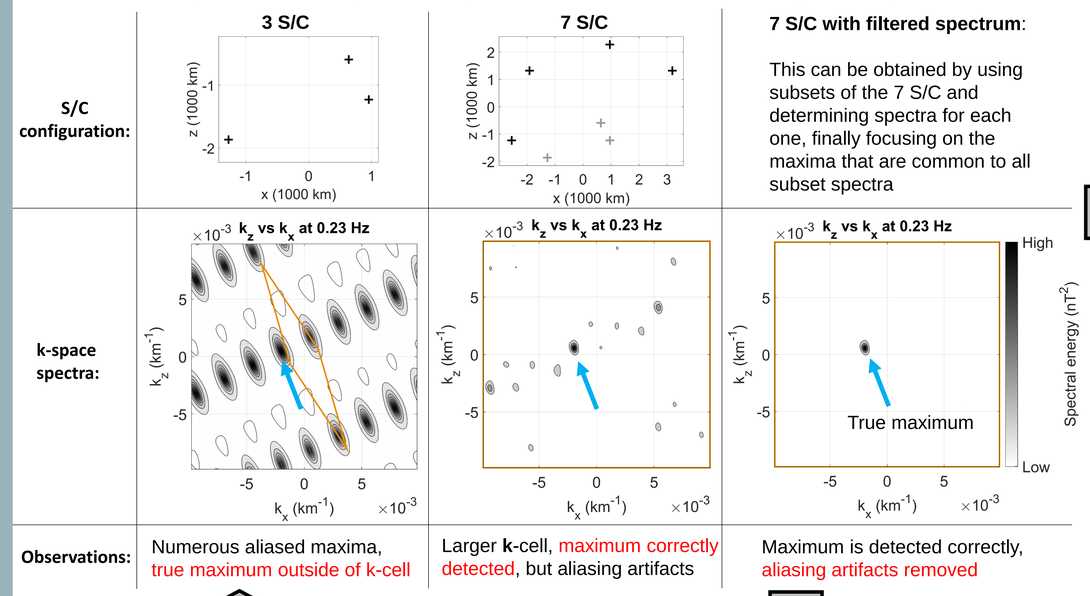
Vlasiator as a probing ground

- Currently, no multi-scale mission in space → Use of simulations to test (improved) capabilities of wave telescope
- Vlasiator: Hybrid-Vlasov plasma simulation (Palmroth et al. 2018)
- Use of one Vlasiator run with interplanetary magnetic field (IMF) cone angle of 45° with a clock angle close to 180° → Foreshock in southern hemisphere
- Probing of 3 foreshock (FS) and 1 magnetosheath (MS) positions with 2 different multi-spacecraft configurations (7 S/C)
- For simplicity: 2D configurations, extension to 3D is no problem



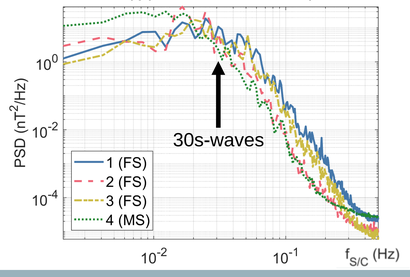
Advantages of multi-scale S/C: Improved k-space spectra

- **k**-space spectra obtained for each peak in PSD separately using the wave telescope
- Spatial aliasing due to S/C positioning limits detection range (**k**-cell, orange parallelogram); see Schulz et al. 2023
- Here: Correct maximum cannot be detected using 3 S/C, but can with 7 S/C, due to increased detection range
- However, many false detections (local maxima) in 7 S/C spectrum → spectrum filtering necessary



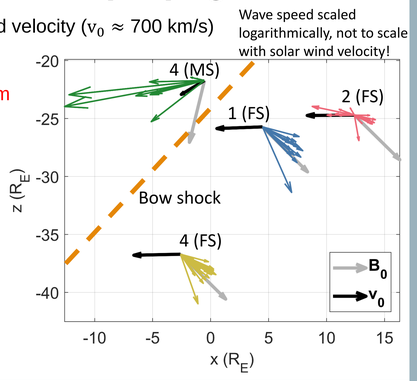
Frequency spectra

- Power spectral density (PSD) determined via Fourier transform of **B**-field time series
- Among others revelation of low frequency 30s-waves (typical for Foreshock)



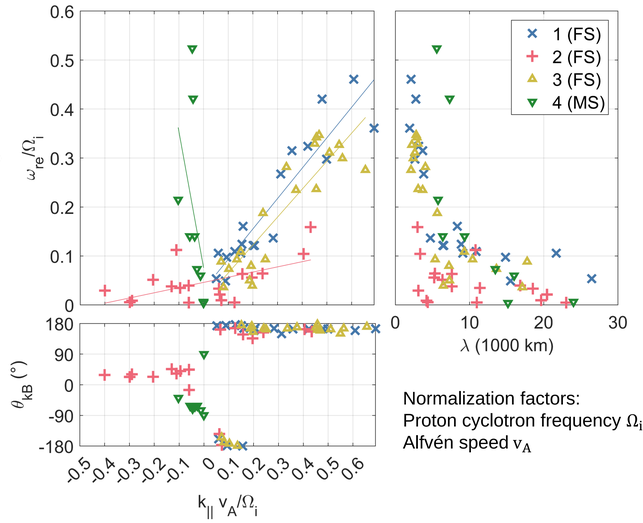
Results: Wave propagation

- Fast solar wind velocity ($v_0 \approx 700$ km/s)
- FS: waves move upstream along $\mathbf{B_0}$
- MS: waves move downstream
- Wave speed: FS waves in the order of Alfvén speed; MS waves slightly above



Results: Dispersion and wave characteristics

- Frequencies in S/C frame and wave vectors obtained from spectra
- Conversion to plasma rest frame via $\omega_{re} = 2\pi f_{S/C} - \mathbf{k}\mathbf{v_0}$
- Yields rest frame wave velocity (see lower mid-right panel) via $\mathbf{v_{ph}} = \omega_{re}\mathbf{k}/k^2$, wavelength λ, angle θ_{kB} between **k** and $\mathbf{B_0}$



Normalization factors:
Proton cyclotron frequency Ω_i
Alfvén speed v_A

- FS: Typical 30s-waves due to backstreaming ions; observed properties show basic agreement with literature:
  - Dispersion slopes (Narita et al. 2003, 2004, 2007)
  - Wavelength in the order of Earth's radius (Eastwood et al. 2005)
  - Wave vectors parallel or antiparallel to IMF (Narita et al. 2004)
- MS: Also agreement with literature:
  - Waves seem to be partly 'transmitted' through the bow shock (see Turc et al. 2022), but with changed direction
  - Wave vectors perpendicular to $\mathbf{B_0}$ (Narita et al. 2016)

Conclusions

- Vlasiator produces realistic foreshock environment to study waves
- Wave telescope offers huge capabilities for wave analysis, which can be largely enhanced by use of multi-scale S/C configurations
- Basic agreement of wave type, dispersion, propagation and wavelength with literature → Further evaluation ongoing

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EGU24-8122 | ST2.1

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VLASIATOR

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