Large-scale and small-scale turbulence: particles and fields

Daniel Verscharen

Mullard Space Science Laboratory, University College London; UK
and Space Science Center, University of New Hampshire; USA

Acknowledgements: Chris Chen, Jiansen He, George Nicolaou, Chris Owen, Rob Wicks, Honghong Wu

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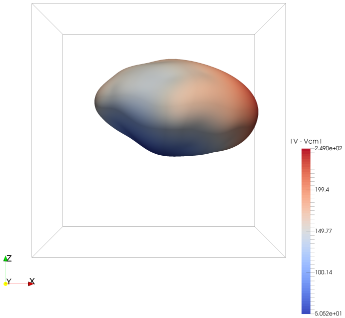
@DVerscharen

Collisionless plasma conditions
Non-thermal particle distributions



Non-thermal features in particle distributions form and survive:

- Temperature anisotropies
- Multi-temperature
- Beams/drifts
- ...

$\Rightarrow$ A (low-moment) fluid description becomes highly problematic!

Alternative:
kinetic description!

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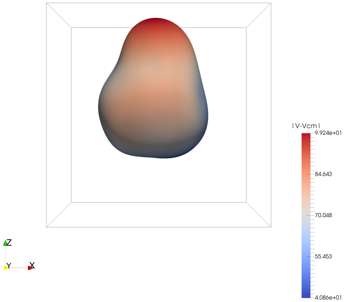

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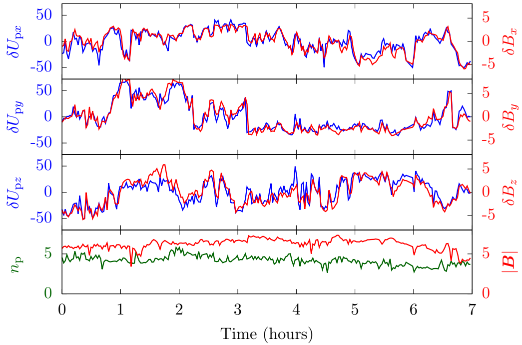
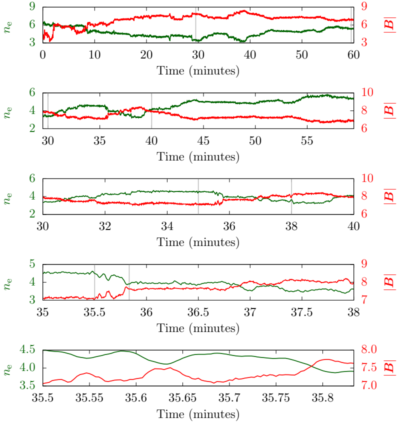
Solar-wind turbulence is mostly Alfvénic



- Wind measurements
- Solar-wind turbulence has mainly Alfvén-wave-like polarisation
- Non-compressive component with (anti-)parallel $\delta \boldsymbol{v}$ and $\delta \boldsymbol{B}$

(Verscharen et al., 2019)

Compressive turbulence in the solar wind



(Verscharen et al., 2019)

- Cluster measurements at 1 au
- Anti-correlation between δn_e and $\delta|\boldsymbol{B}|$
- Slow-mode-like polarisation (and pressure balance?)

Fluctuations in the distribution function

In kinetic theory, a plasma wave is associated with fluctuations in the distribution function:

$$f_\mathrm{p} = f_{0\mathrm{p}} + \delta f_\mathrm{p}.$$

The time-dependent perturbation δf_p leads to fluctuations in the plasma bulk parameters. For example:

$$\delta n_\mathrm{p} = n_{0\mathrm{p}} \int \delta f_\mathrm{p} \mathrm{d}^3 v, \qquad \text{density}$$

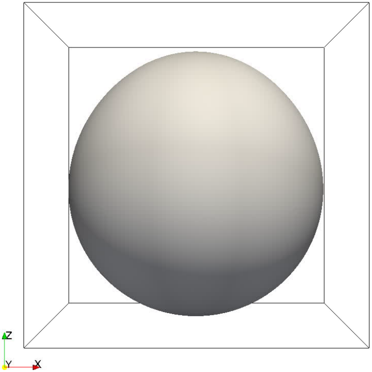
$$\delta U_{\parallel\mathrm{p}} = \int \delta f_\mathrm{p}\, v_\parallel \mathrm{d}^3 v, \qquad \text{bulk speed}$$

$$\delta p_{\perp\mathrm{p}} = \frac{n_{0\mathrm{p}} m_\mathrm{p}}{2} \int \delta f_\mathrm{p}\, v_\perp^2 \mathrm{d}^3 v, \qquad \text{perpendicular thermal pressure}$$

$$\delta p_{\parallel\mathrm{p}} = n_{0\mathrm{p}} m_\mathrm{p} \int \delta f_\mathrm{p} v_\parallel^2 \mathrm{d}^3 v. \qquad \text{parallel thermal pressure}$$

Fluctuations in the distribution function

Slow Mode with $\theta = 88^\circ$, $\beta_\mathrm{p} = \beta_\mathrm{e} = 1$, $k_\parallel v_\mathrm{A}/\Omega_\mathrm{p} = 0.001$, $\delta B_z/B_0 = 0.1$

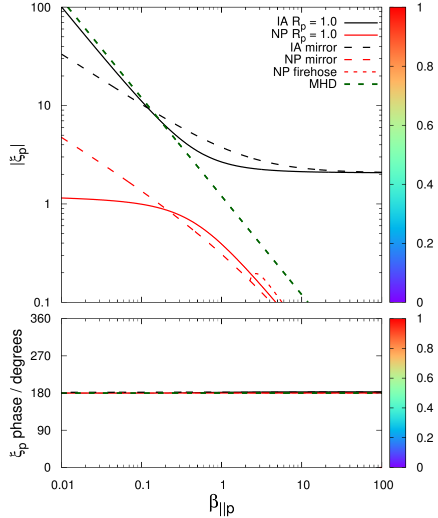


(Verscharen et al., 2016)

- These signatures are different for each plasma mode.
- On the following slides: Predict behaviour of the three lowest velocity moments in large-scale fluctuations (using analytical gyrokinetic theory).
- Compare with observations.

How fluid-like is small-scale turbulence?

Compressive turbulence: fluid and kinetic theory



$$\frac{\delta n_{\rm p}}{n_{0\rm p}} = \xi_{\rm p} \frac{\delta B_{\parallel}}{B_0}$$

(Verscharen et al., 2017)

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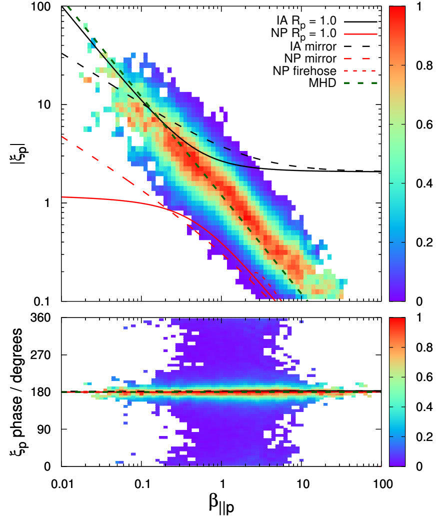

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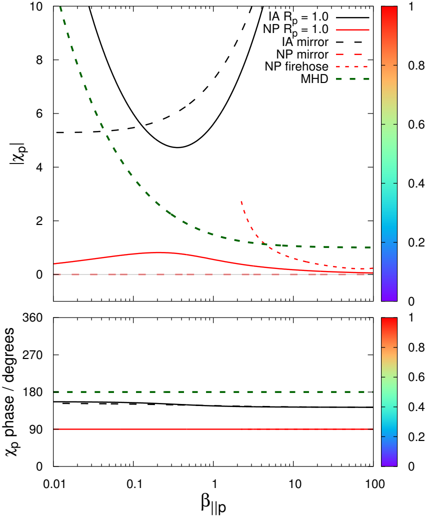

$$\frac{\delta U_{\|\mathrm{p}}}{v_{\mathrm{A}}} = \chi_{\mathrm{p}} \frac{\delta B_{\|}}{B_0}$$

(Verscharen et al., 2017)

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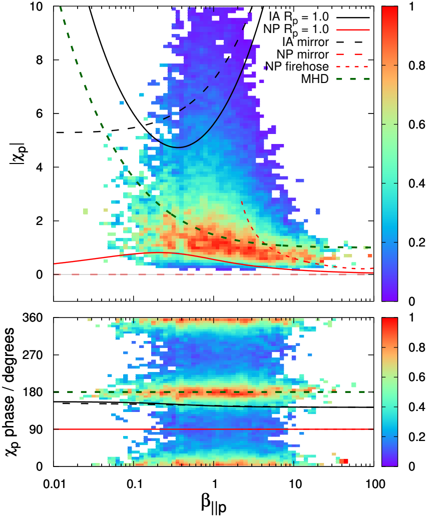

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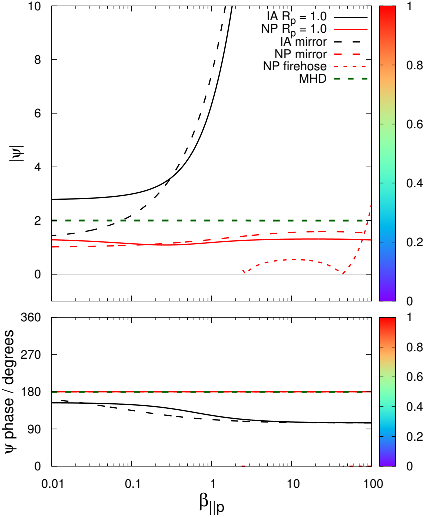

$$\frac{\delta p}{p_{B0}} = \psi \frac{\delta B_{\parallel}}{B_0}$$

(Verscharen et al., 2017)

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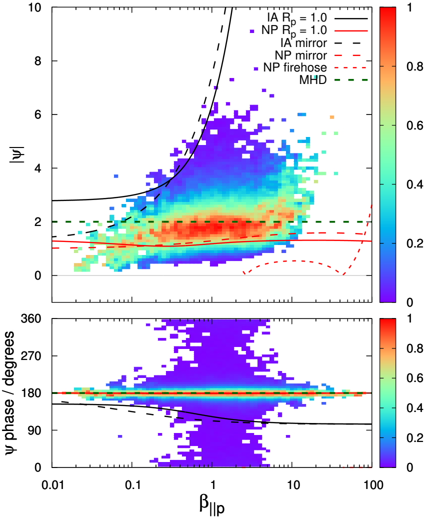

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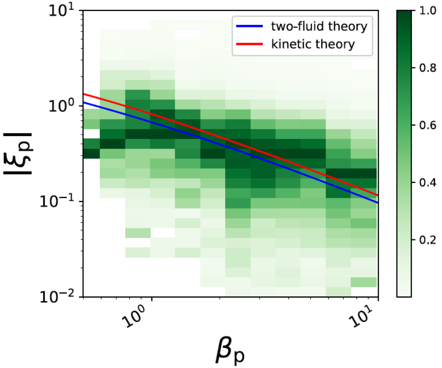
How fluid-like is small-scale turbulence?

Kinetic-Alfvén turbulence at $k_\perp \rho_\mathrm{p} \approx 2$: two-fluid and kinetic theory

MMS magnetosheath measurements



(Wu, DV, et al., 2019)

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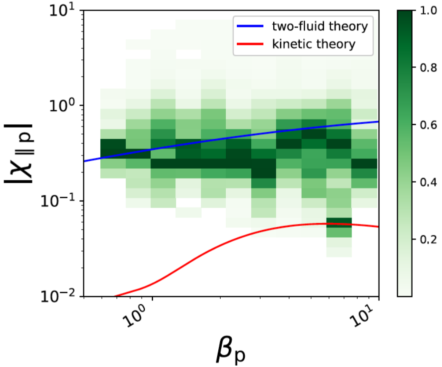

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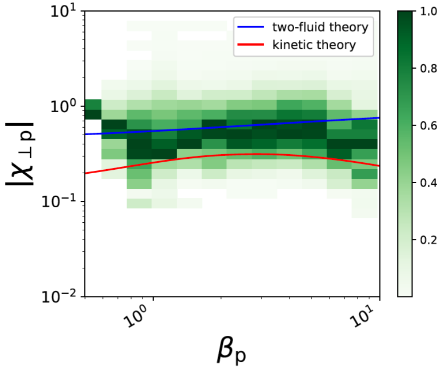

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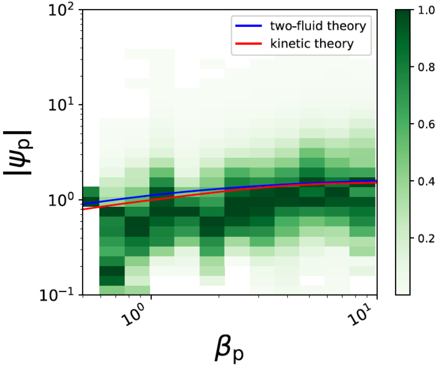
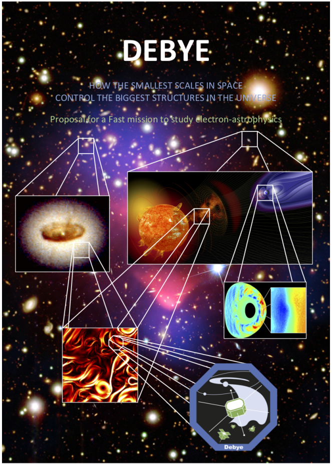


$$\frac{\delta p_\mathrm{p}}{p_{B0}} = \psi_\mathrm{p} \frac{\delta B_\perp}{B_0}$$

(Wu, DV, et al., 2019)

Exploring the smallest scales
ESA F-class proposal *Debye*

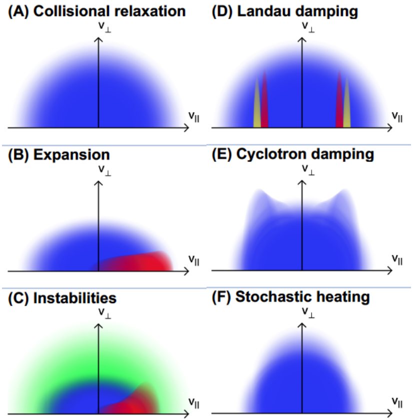


- *Debye* is a UCL-led proposal for ESA's F-class programme.
- Main spacecraft will measure electric/magnetic fields, electron distributions, proton properties.
- 3 deployable spacecraft will measure high-frequency magnetic-field fluctuations.
- Science goal: *How are electrons heated in astrophysical plasmas?*
- Scale coverage: 300 m to 3,000 km.
- Full proposal now under review.

Exploring the smallest scales

ESA F-class proposal *Debye*

The first dedicated electron-astrophysics mission!

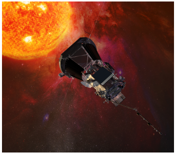


- SWA/EAS heritage: electron pitch-angle distributions with 50 ms cadence.
- Multi-point and multi-baseline SCM measurements.
- JAXA/NASA collaboration on DSC.

Follow us on Twitter: @DebyeMission

Conclusions

- Plasma waves and turbulence are associated with characteristic fluctuations in distribution functions and velocity moments.
- Polarisation of compressive fluctuations (large and small scales) is in better agreement with fluid than with kinetic predictions.
- Some yet unknown process (e.g., fluctuating-moment effects or anti-phase-mixing) makes the plasma behave more fluid-like.
- Solar Orbiter and Debye will explore field and particle fluctuations at small scales in great detail.



(Credit: NASA)

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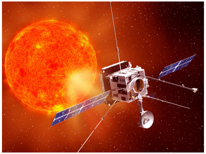

(Credit: ESA)

Literature

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Closure of the moment hierarchy

What's the difference?

Recipe for MHD: Add proton and electron moment equations, assume quasi-neutrality, define bulk parameters!
For example, momentum equation:

$$\frac{\partial}{\partial t}(\rho \boldsymbol{U}) + \nabla \cdot (\rho \boldsymbol{U}\boldsymbol{U}) = -\nabla \cdot \boldsymbol{P} + \frac{1}{c}\boldsymbol{j} \times \boldsymbol{B}$$

This equation is exact as long as quasi-neutrality and $\mathcal{C} f_j = 0$ are fulfilled!

The only problem is the combined pressure tensor $\boldsymbol{P} = \boldsymbol{P}_{\mathrm{p}} + \boldsymbol{P}_{\mathrm{e}}$.

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Easiest closure: $\boldsymbol{P}$ is isotropic and adiabatic, so that we can write $\nabla \cdot \boldsymbol{P} = \nabla p$ with $p \propto \rho^{\gamma}$

(similar assumptions apply to Ohm's law etc.)

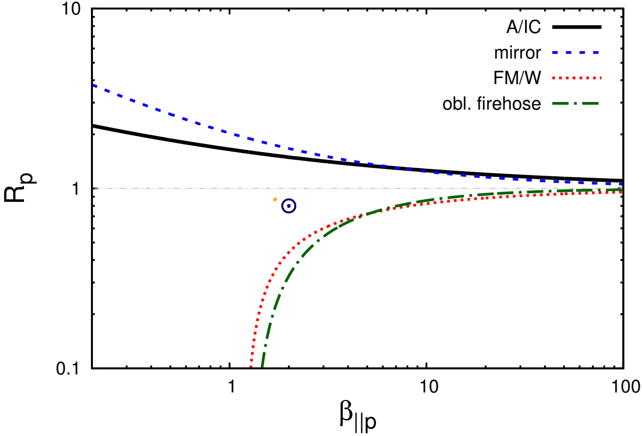
Closure of the moment hierarchy
The key question

Which collisionless processes lead to an adiabatic closure for the pressure tensor?

- Equivalently: Which processes suppress higher moments (especially heat flux) in the distribution function?
- **Important:** The main differences between large-scale kinetic theory and MHD are due to the moment-closure problem!

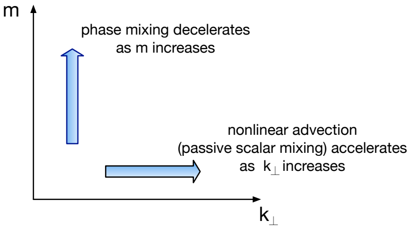
A possible explanation: fluctuating-moment effects

IA wave with $\delta|\boldsymbol{B}|/B_0 = 0.028$



$R_{\rm p} = \frac{T_{\perp \rm p}}{T_{\| \rm p}}$ (Verscharen et al., 2016)

Another possibility: anti-phase-mixing



(Credit: B. Chandran)

- Schekochihin et al. (2016) discuss “anti-phase-mixing”.
- Turbulence cascades to larger $k_\perp$.
- Phase mixing leads to cascade of VDF to larger Hermite-moment orders m.
- Stochastic echo creates flux of energy from larger m to smaller m.
- Comparison of timescales shows that distribution stays at low m.