JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Solar-Driven Disturbances in the heliosphere and very local interstellar medium

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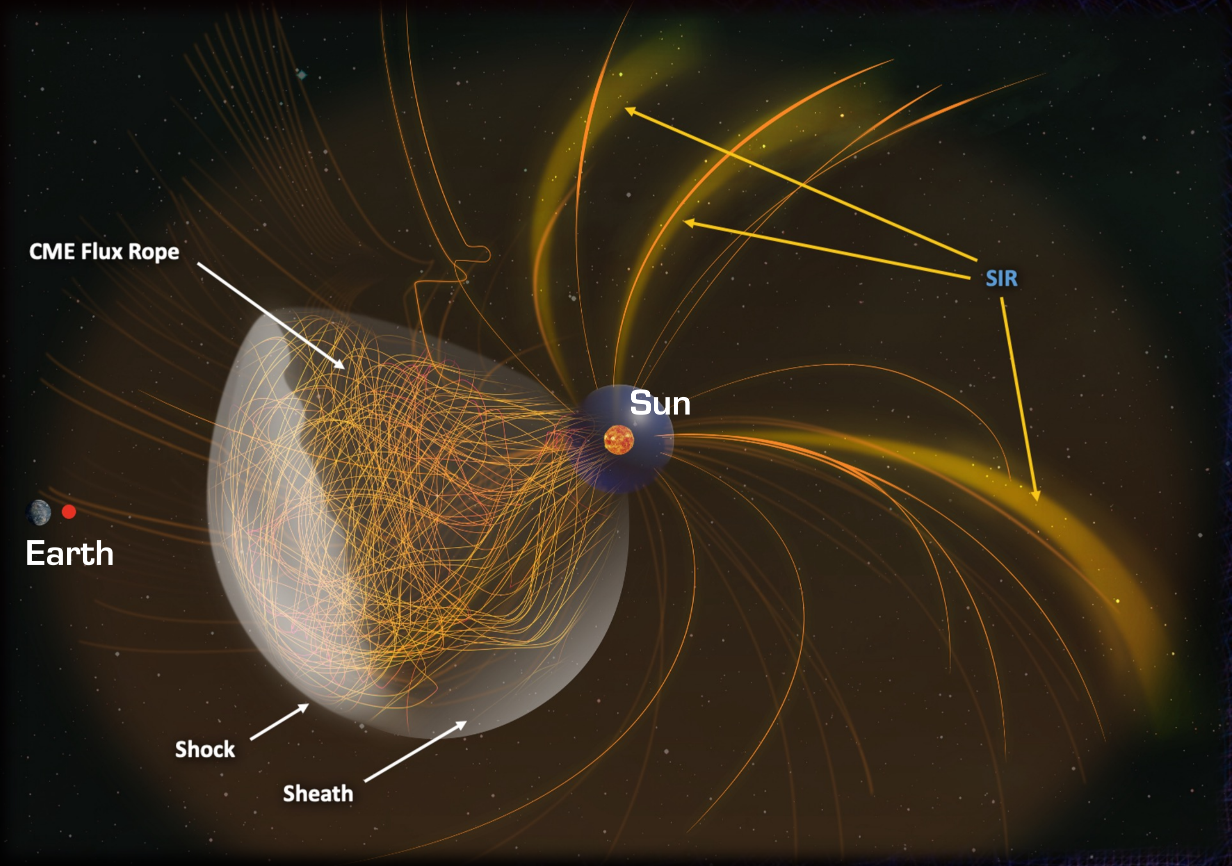
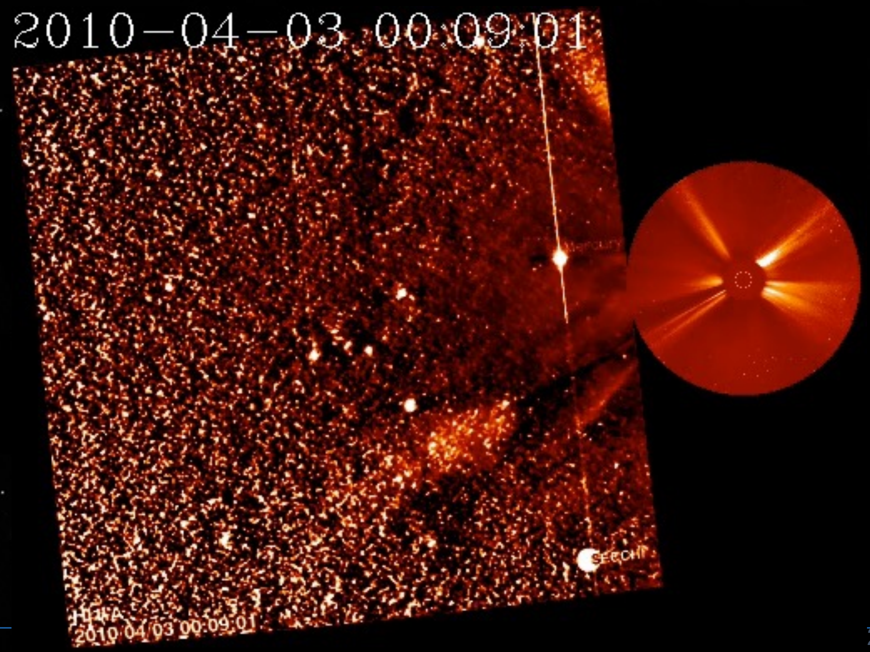
Outline

- Multi-scale structures in the solar wind
- Corotating Interaction Regions from inner to outer heliosphere
- Coronal Mass Ejections forming global disturbances (MIRs)
- Beyond the heliosphere: Shocks in the very local interstellar medium
- Interaction of the interstellar and interplanetary dust with solar wind structures

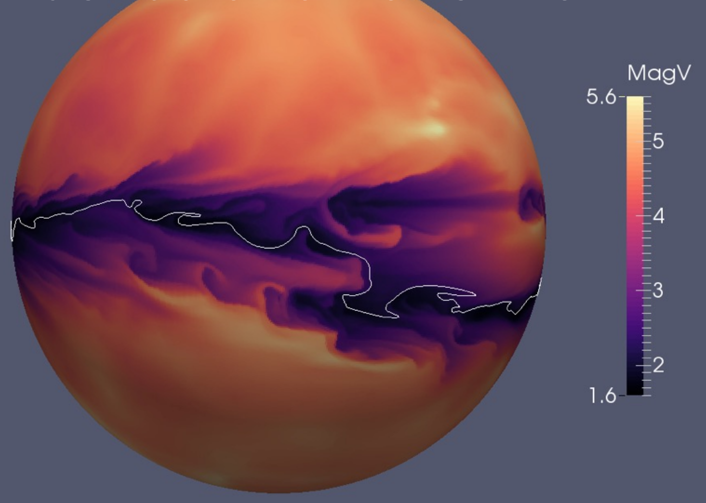


Multi-scale structure of the solar wind

- Large-scale disturbances in the solar wind (>10^7 km)
  - Coronal Mass Ejections (CMEs)
  - Corotating Interaction Regions (CIRs)
- Mesoscale structures (~10^4-10^6 km) in the solar wind:
  - Magnetic flux tube meandering, small-scale magnetic flux ropes, density fluctuations, CME and CIR substructures
- Small ion-kinetic scale (<10^3 km): MHD and kinetic waves

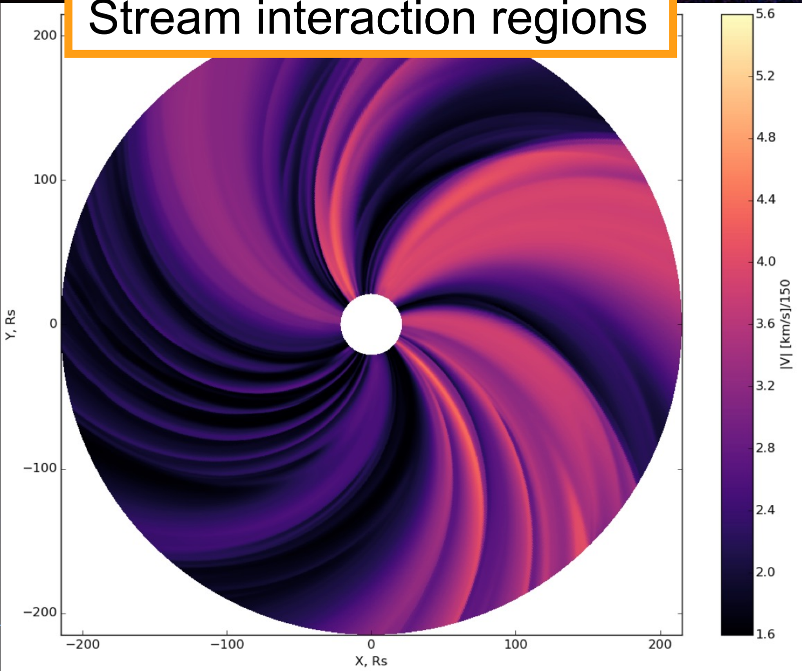


Resolving mesoscales in global solar wind simulation for the first time



GAMERA-Helio (Mostafavi et al. 2022)

Stream interaction regions



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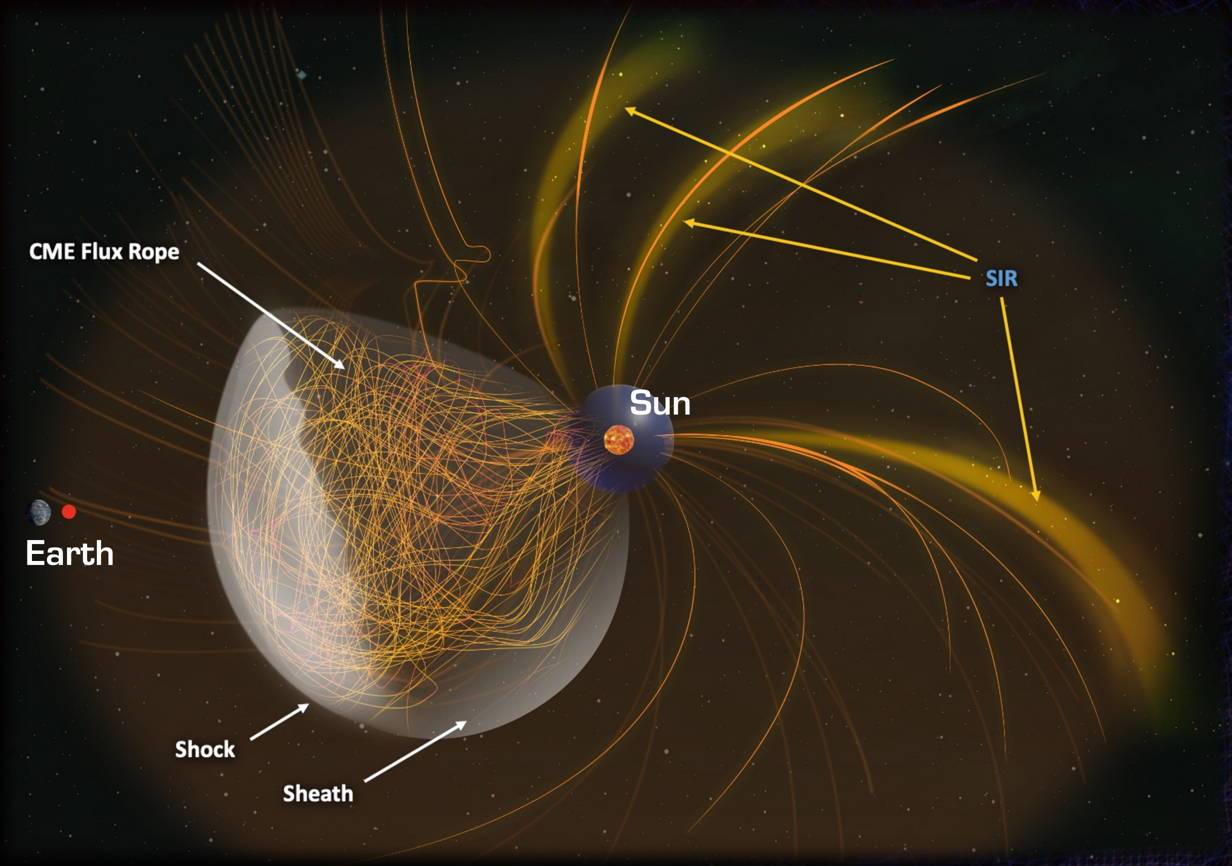
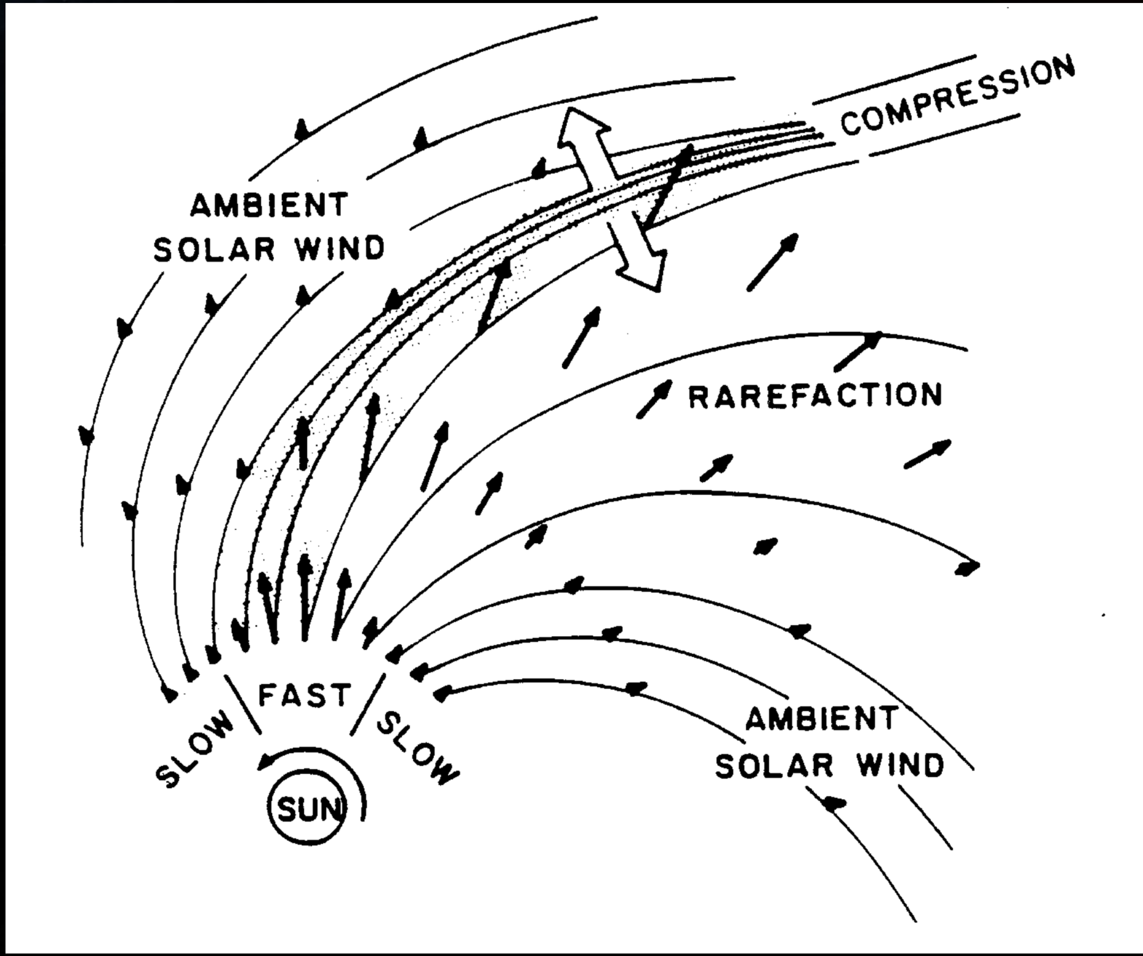
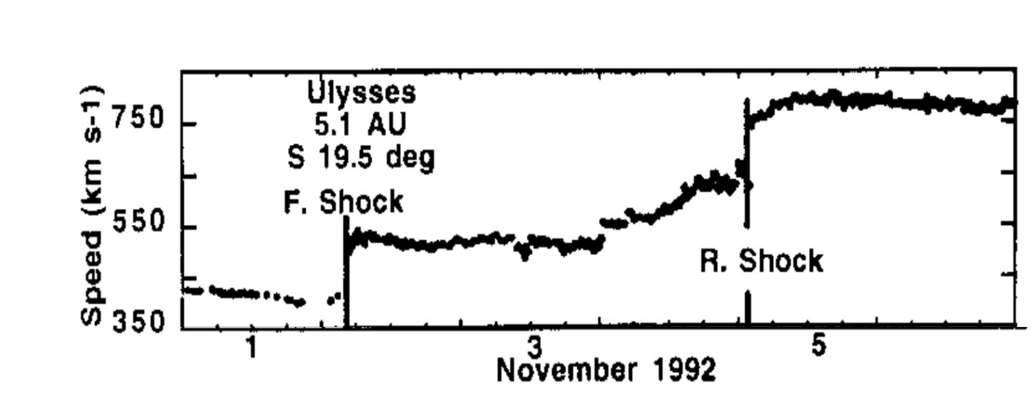


Corotating Interaction Regions



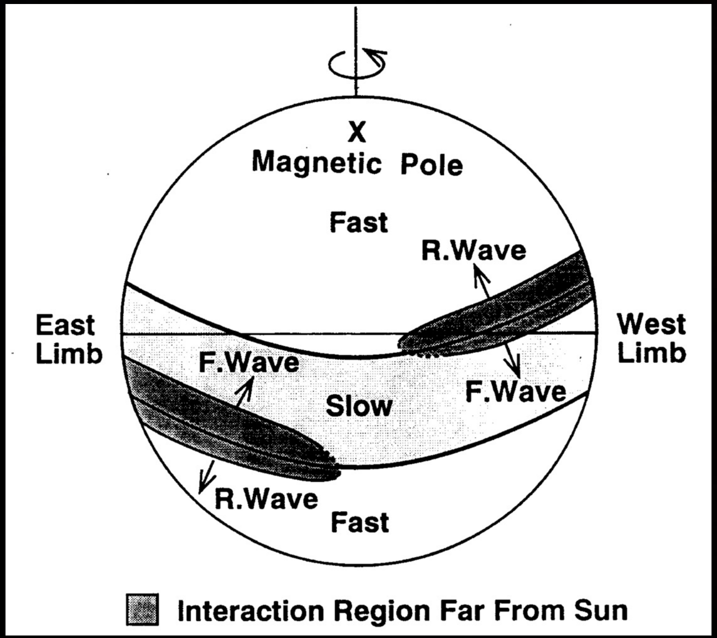
Gosling and Pizzo 1999

- Region with high plasma density, pressure, magnetic field
- Forward-reverse shocks form at distances 2-8 AU from the Sun
- Measured in-situ by L1 observatories, Ulysses, Voyagers, Pioneer

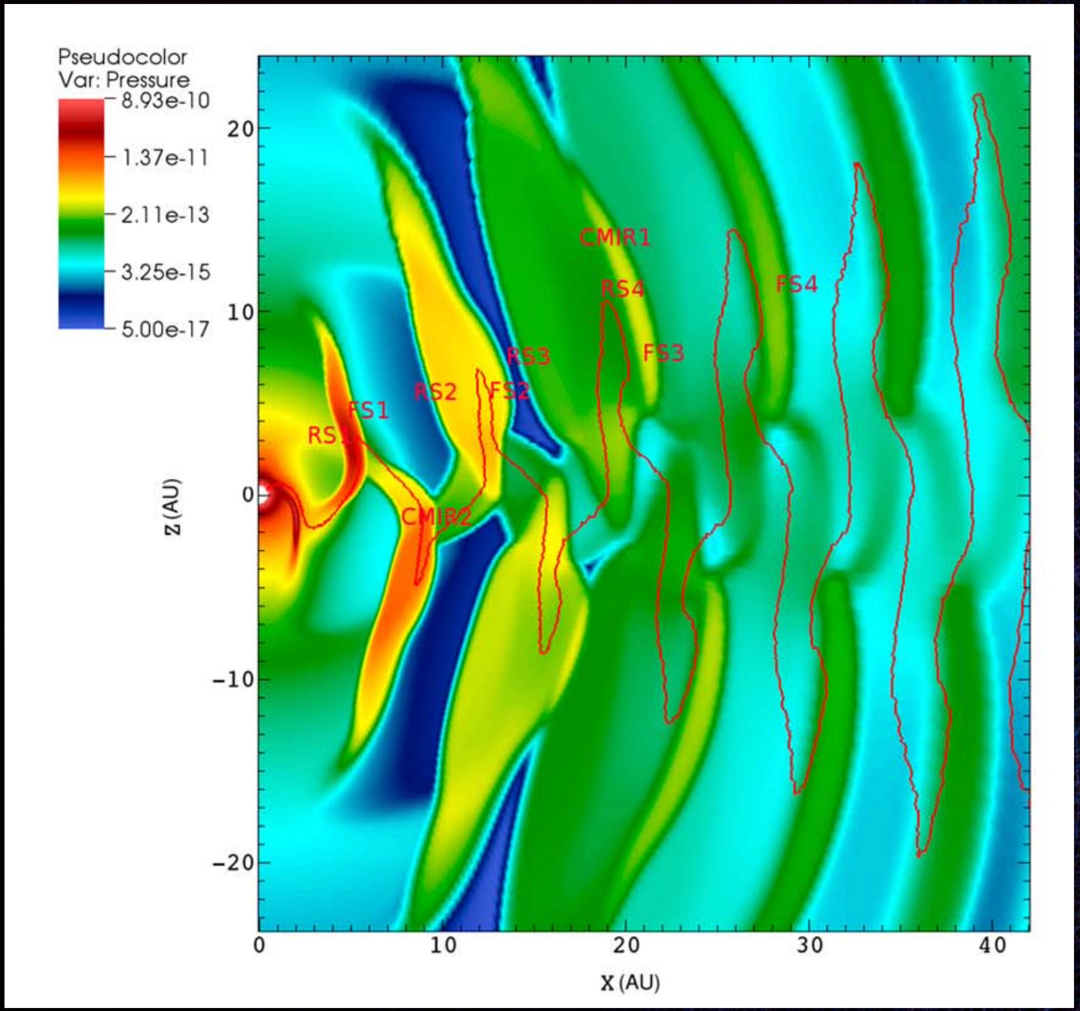


CIRs are complex long-lived 3D structures

Schematic view



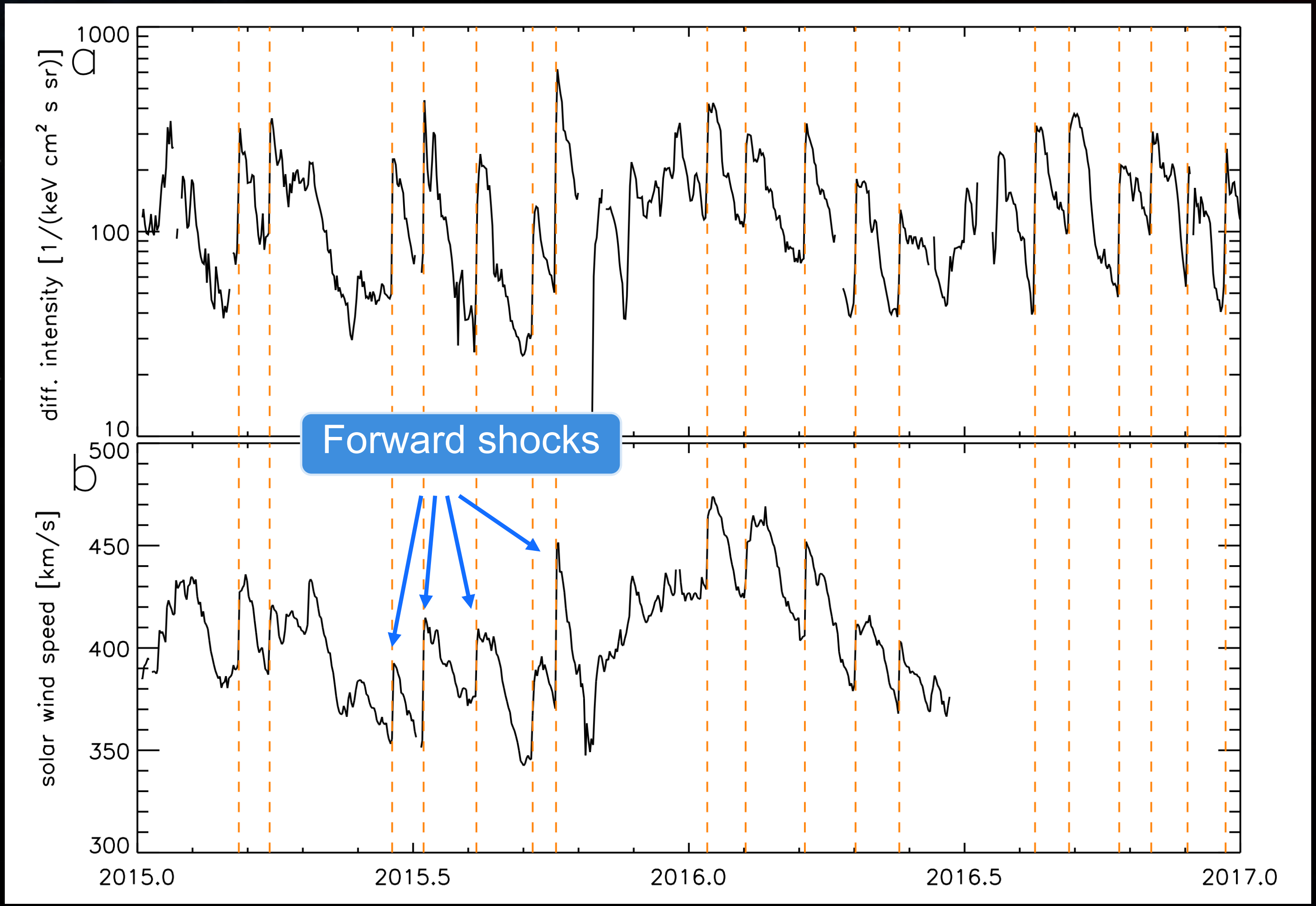
Gosling and Pizzo 1999



Guo and Frorinski 2014

- Forward shocks propagate toward the equator
- Reverse shocks propagate toward the poles
- Ulysses:
  - More forward shocks at low heliolatitudes (<10º)
  - More reverse shocks at higher heliolatitudes (>30º)
  - Both forward and reverse shocks at mid latitudes

New Horizons observed successors of CIRs at 30-35 AU

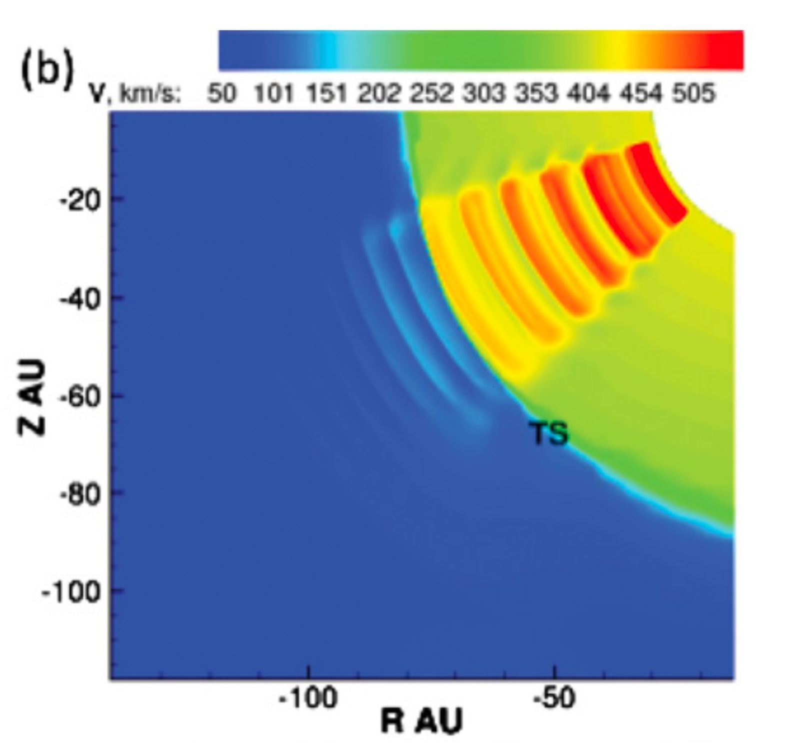


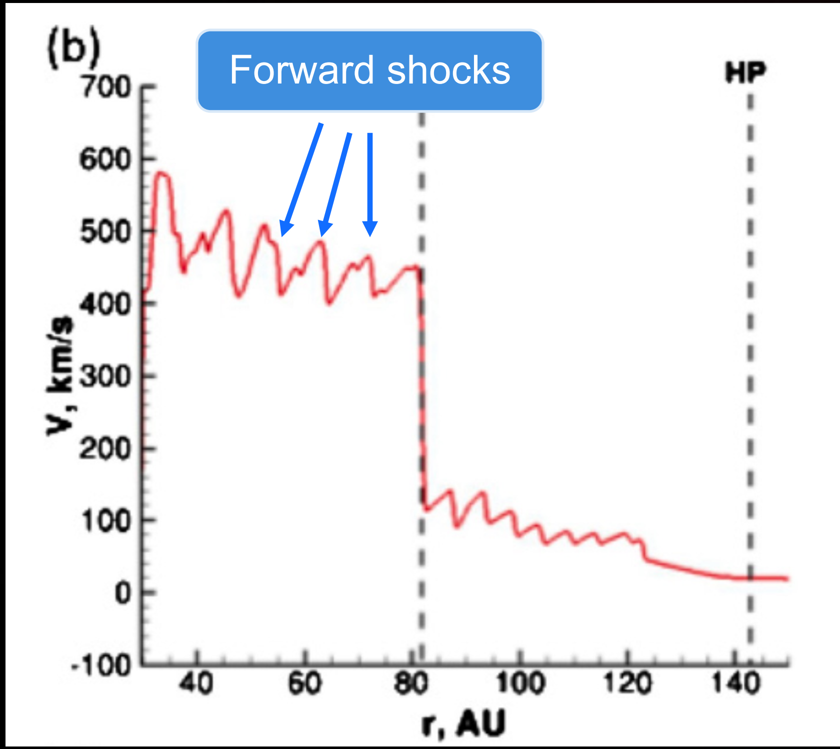
- Interpreted at forward shocks associated with CIR remnants
- Similar plasma structures were detected by Voyager 2 at 45 AU *(Lazarus et al. 1999)*
- What processes led to a lack of reverse shocks at these heliocentric distances?
  - 3D evolution: reverse shocks are dominant at higher latitudes
  - Reverse shocks become weak in CIR merging process?

Kollmann+ 2019

Weakening of CIR shocks in the heliosphere

BU Global Model





Simulation of CIR plasma structures
(Provornikova et al. 2012)

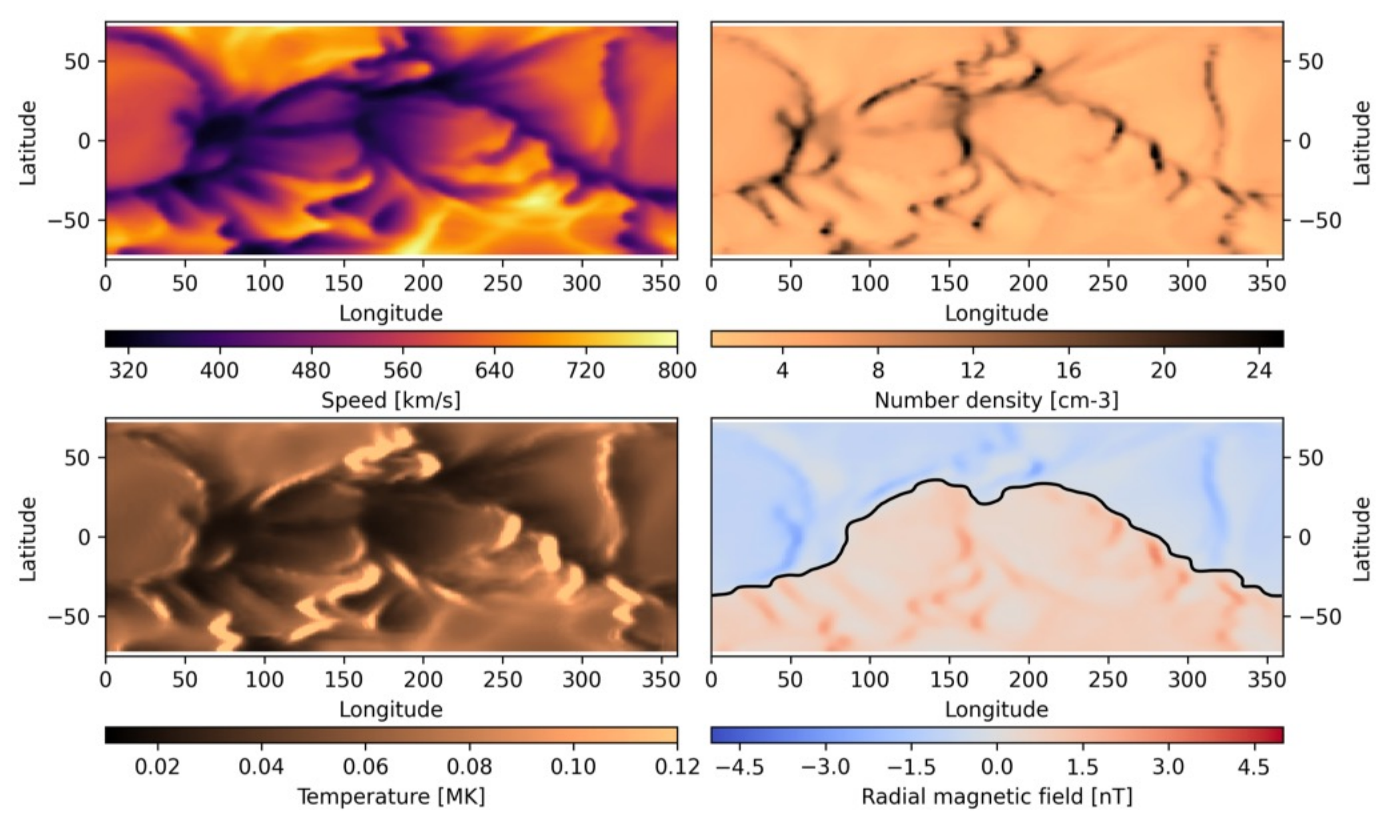
- Reverse shocks weaken and disappear due to interaction with rarefaction waves behind the CIRs in the solar wind.
- Forward shocks are left but weaken
- Fast magnetosonic waves propagate in the heliosheath
- Qualitatively agrees with solar wind speed profiles observed by SWAP/New Horizons

Simulations of complex 3D solar wind structure

GAMERA-Helio model 0.1-10 AU

- Solar wind driven by conditions in the solar corona 0.1 AU
- GAMERA-Helio model (Merkin+2011, Merkin+2016, Mostafavi+2022)
- Very complex structure of the solar wind
- Future work – to extend beyond to New Horizons distances

Latitude-longitude maps of the solar wind at 0.1 AU
Declining phase

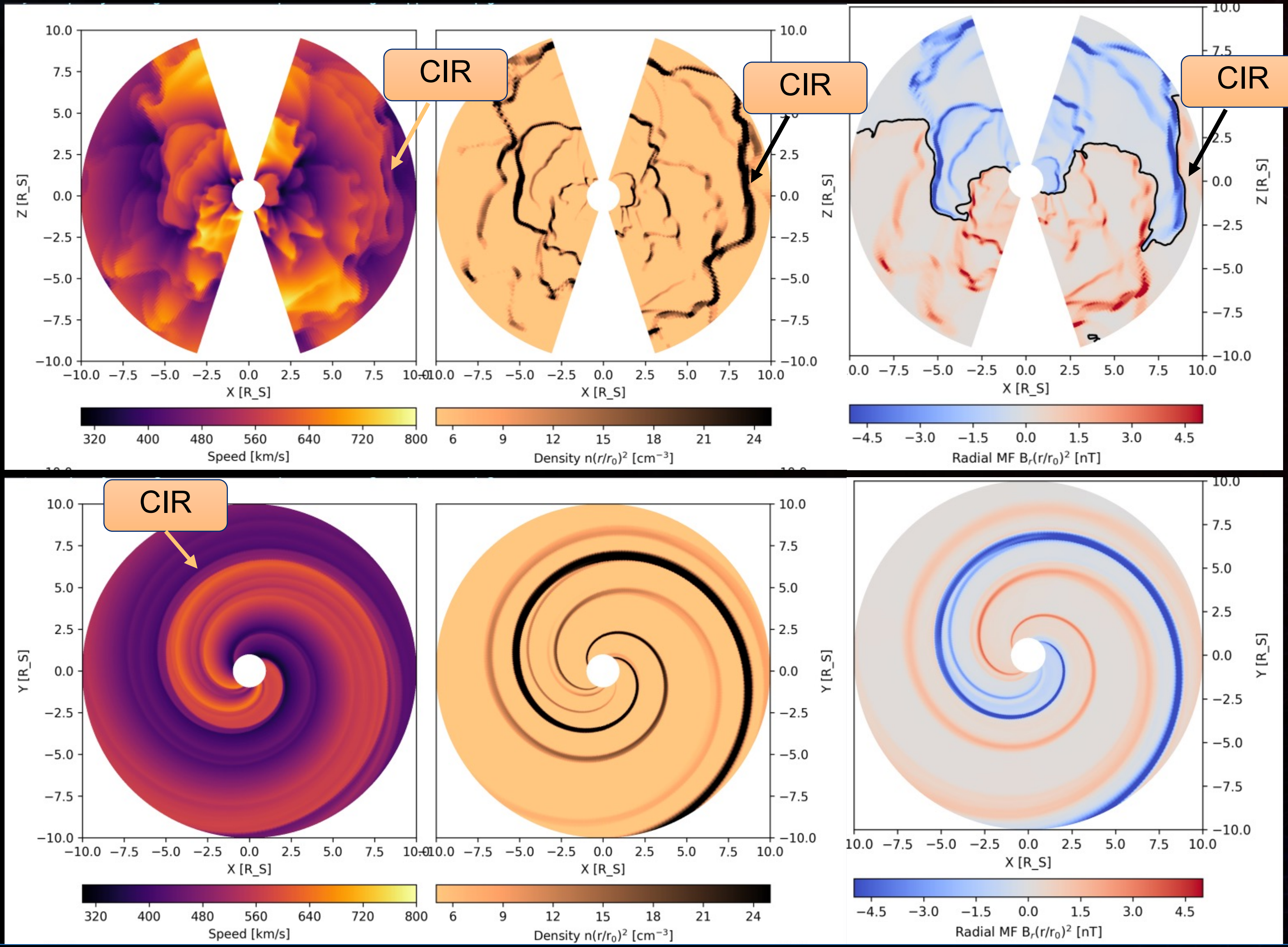


Simulations of complex 3D solar wind structure

GAMERA-Helio model 1-10 AU

Meridional plane

Solar Equatorial plane



Solar wind structure is much more complex than in simplified models

Future work: To extend the model to New Horizons location and beyond, compare to SWAP

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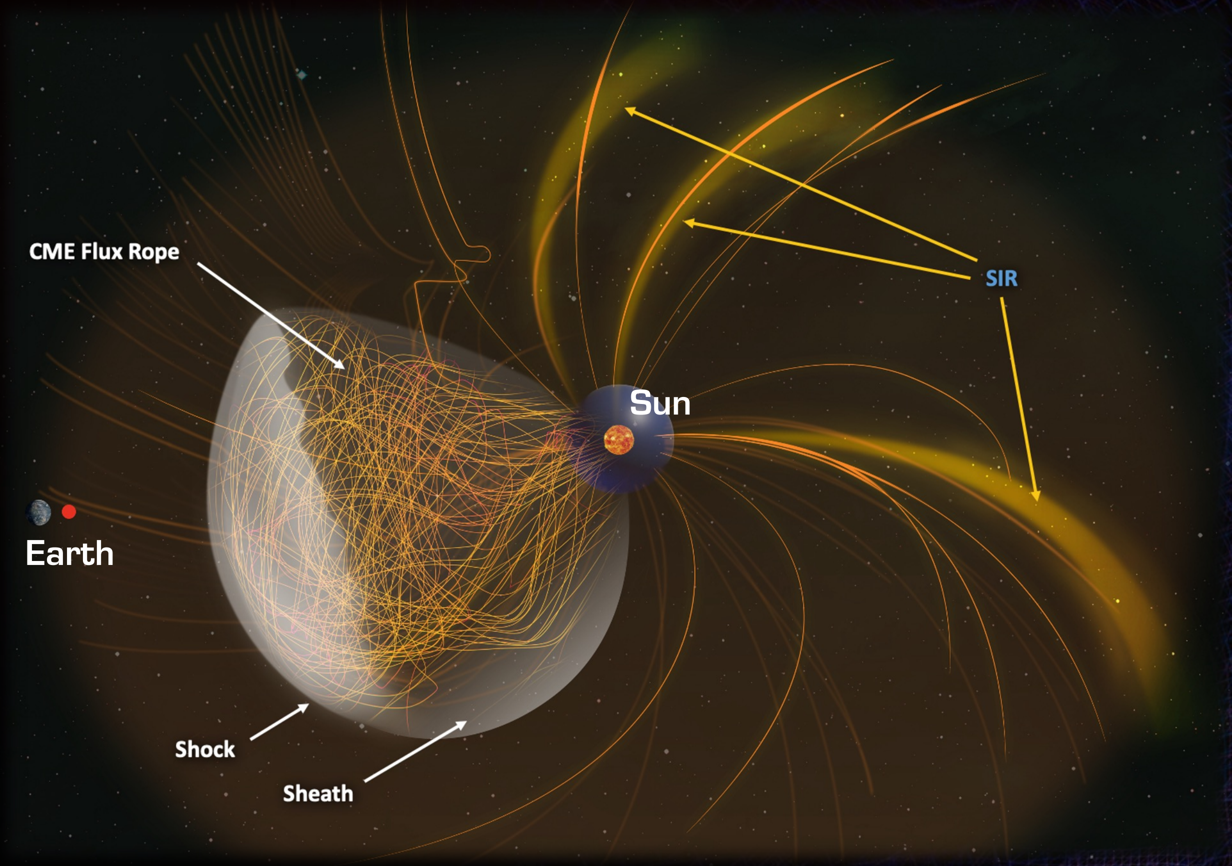
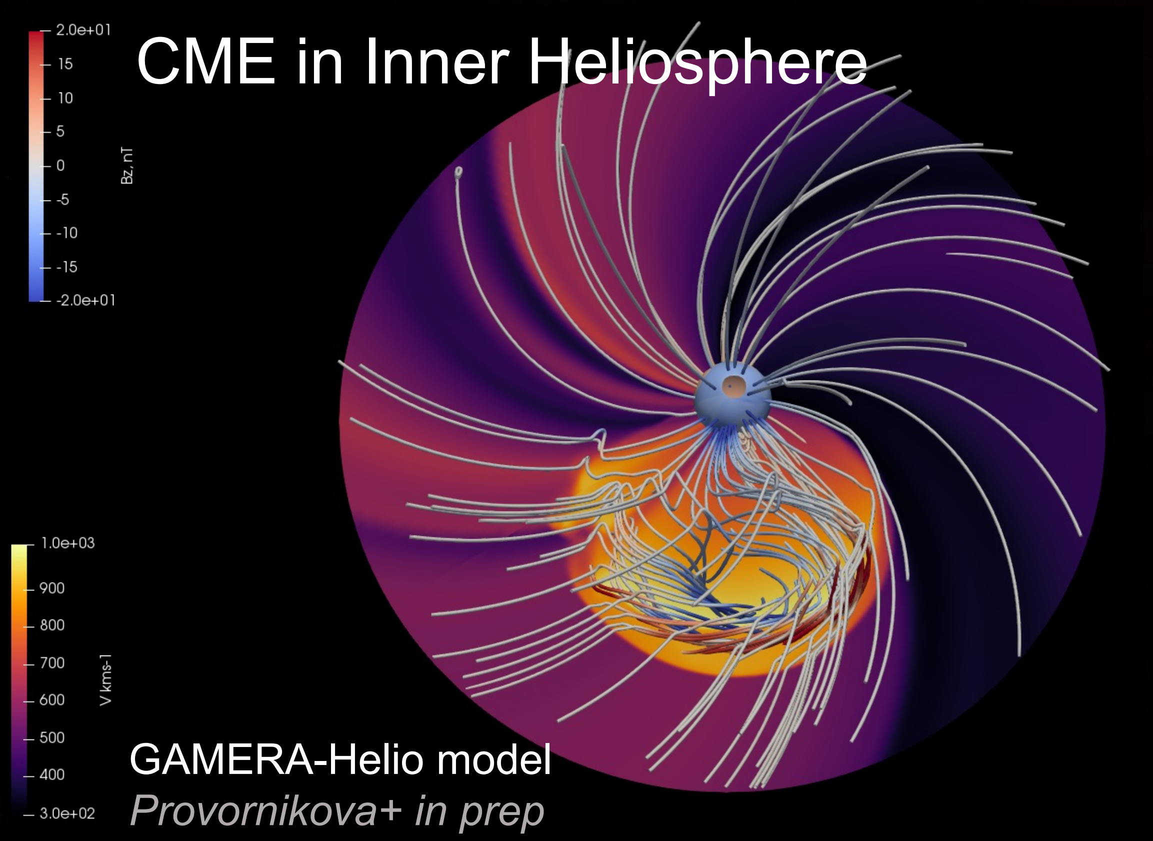
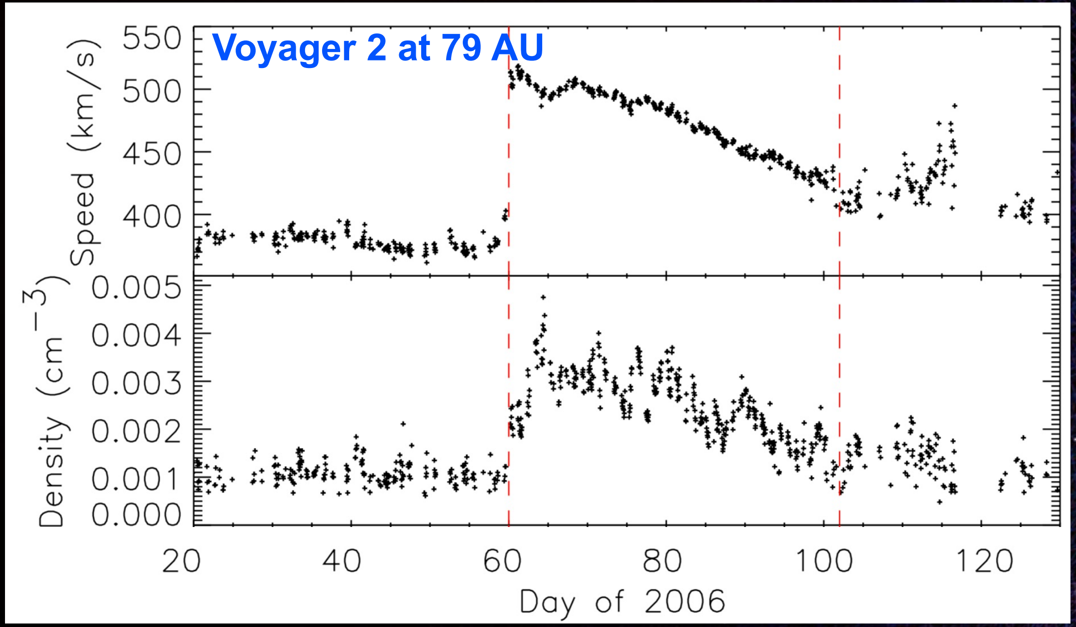


Solar Coronal Mass Ejections and MIRs

Magnetized clouds of plasma released from the Sun, merge in the heliosphere and produce large-scale disturbances in the solar wind and in the VLISM



MIR in Outer Heliosphere

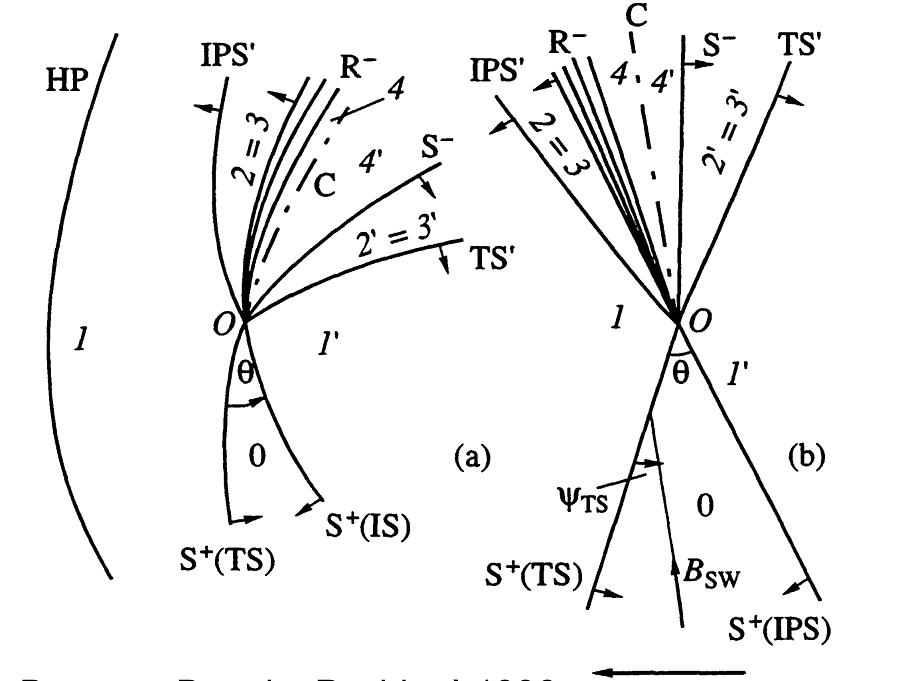


Richardson et al 2006

- CMEs expand, merge forming MIRs
- Drive shocks in outer heliosphere
- Significant change in solar wind parameters
- Modulate transport of cosmic rays

MIRs in transit through heliospheric boundaries

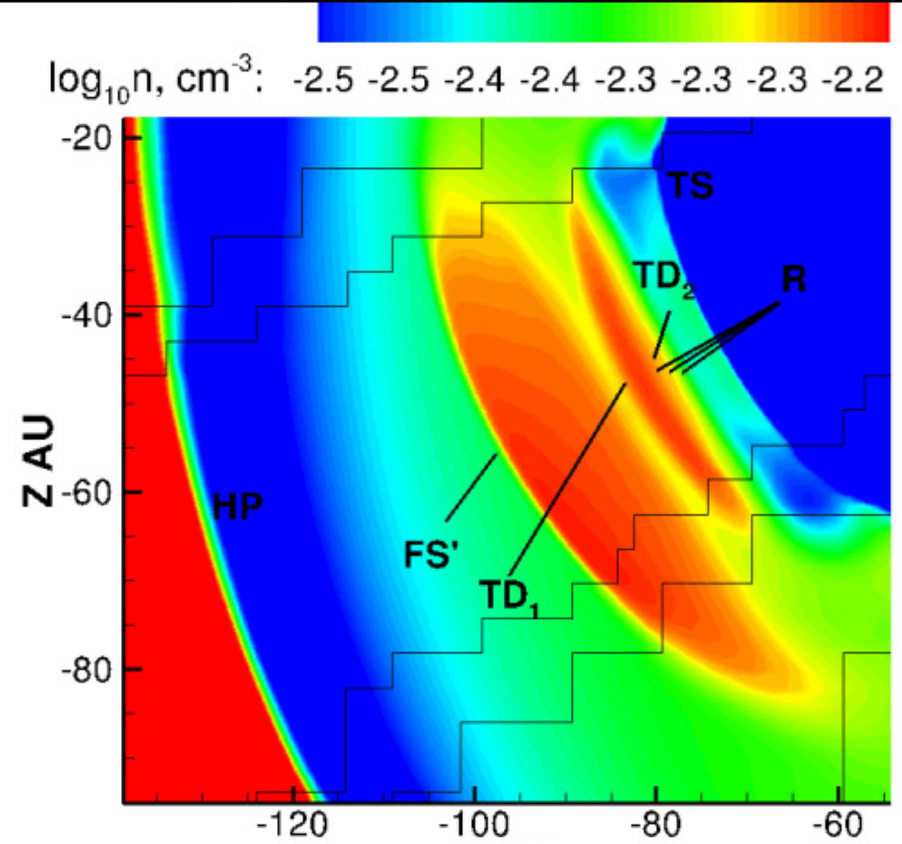
Two-dimensional MHD interaction of two shocks



Baranov, Barmin, Pushkar` 1996

- Five dimensionless parameters define the flow after shocks' interaction
- Shocks, other type discontinuities and waves arise in interaction

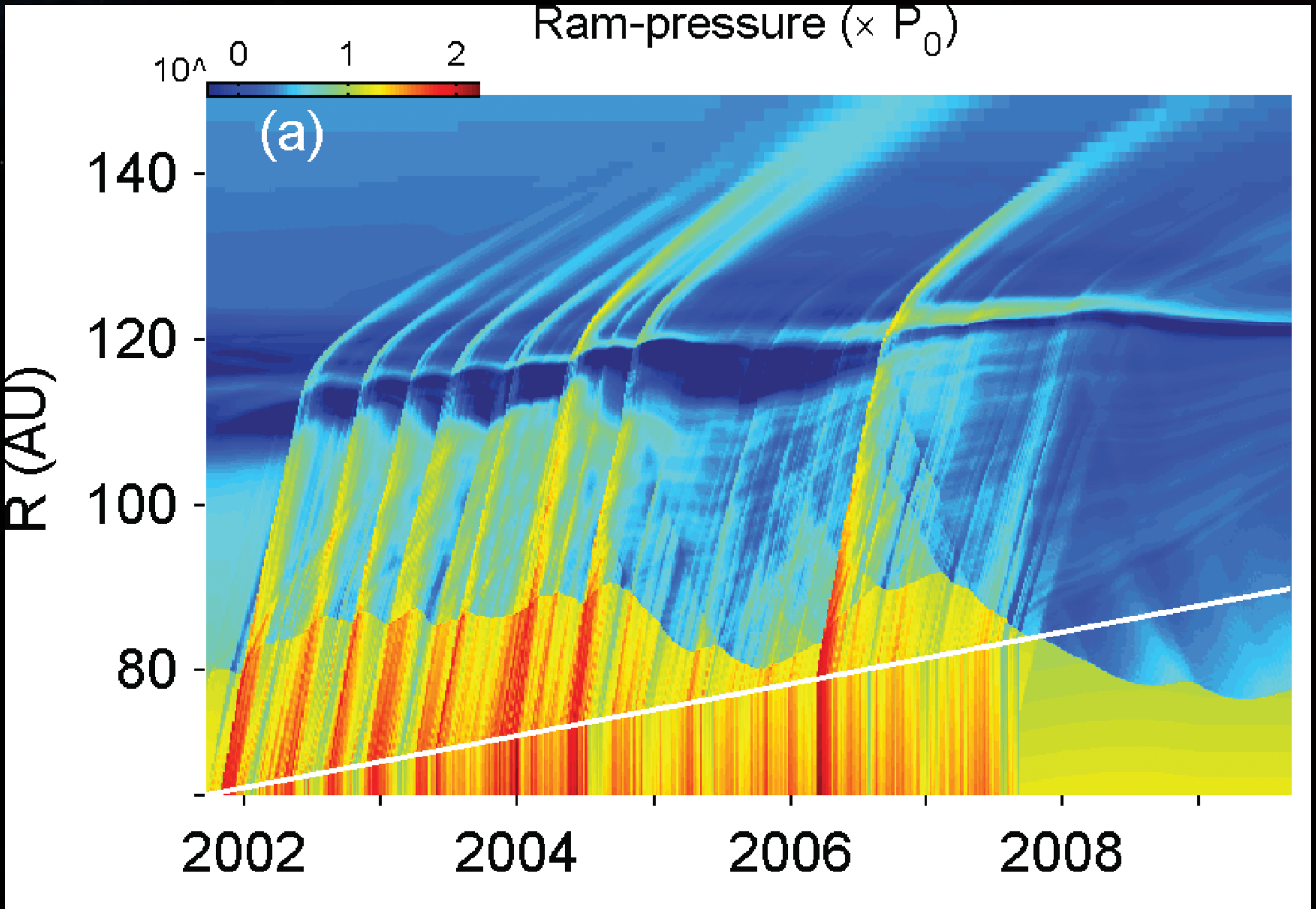
3D simulation of MIR-driven shock interaction with the Termination Shock



Provornikova et al. 2013

- Large fluctuations of solar wind due to shock-shock interaction
- Highly variable plasma in heliosheath

Reflection of waves inside the heliosheath



Washimi et al. 2011

- Shocks and pressure pulses bounce to heliopause moving it outward
- Magnetosonic waves reflect from the heliopause (or plasma depletion layer?) back inside heliosheath
- Reflected waves bounce to termination shock and move it inward

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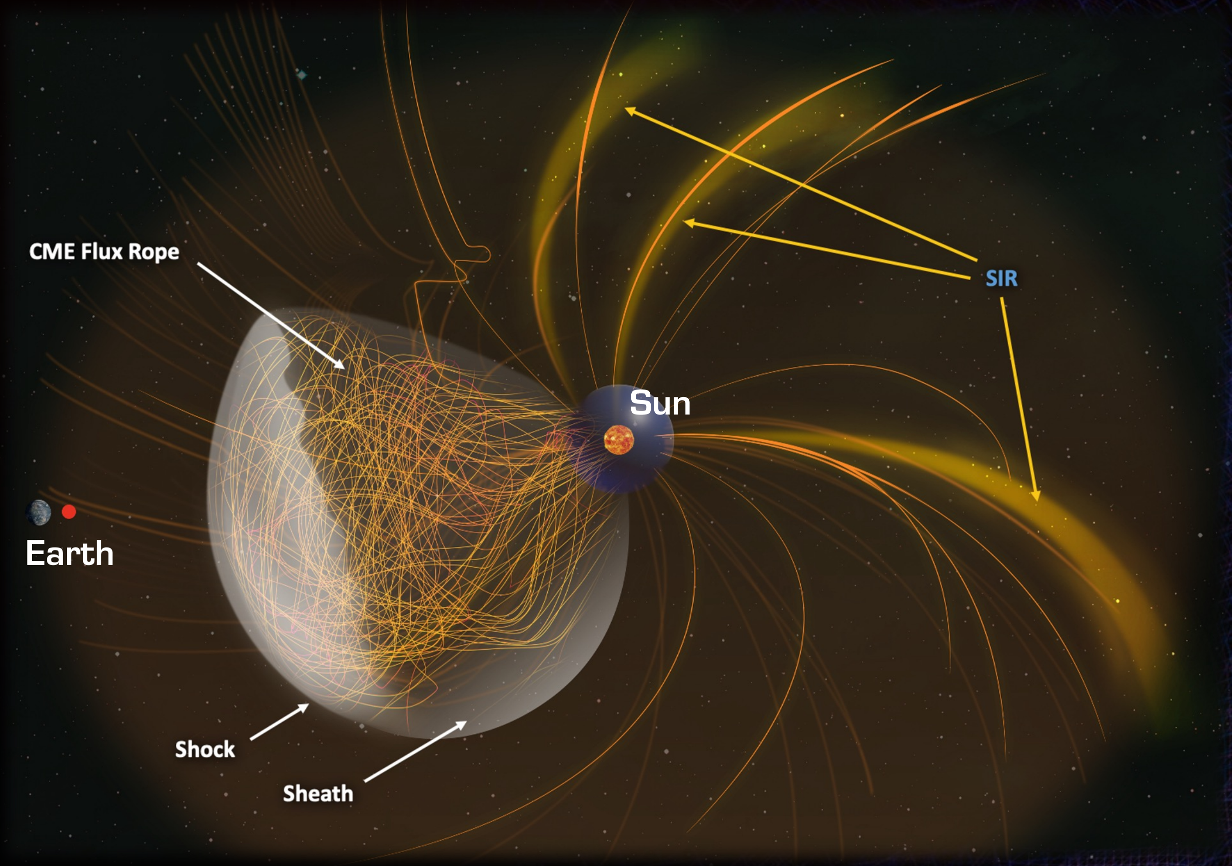
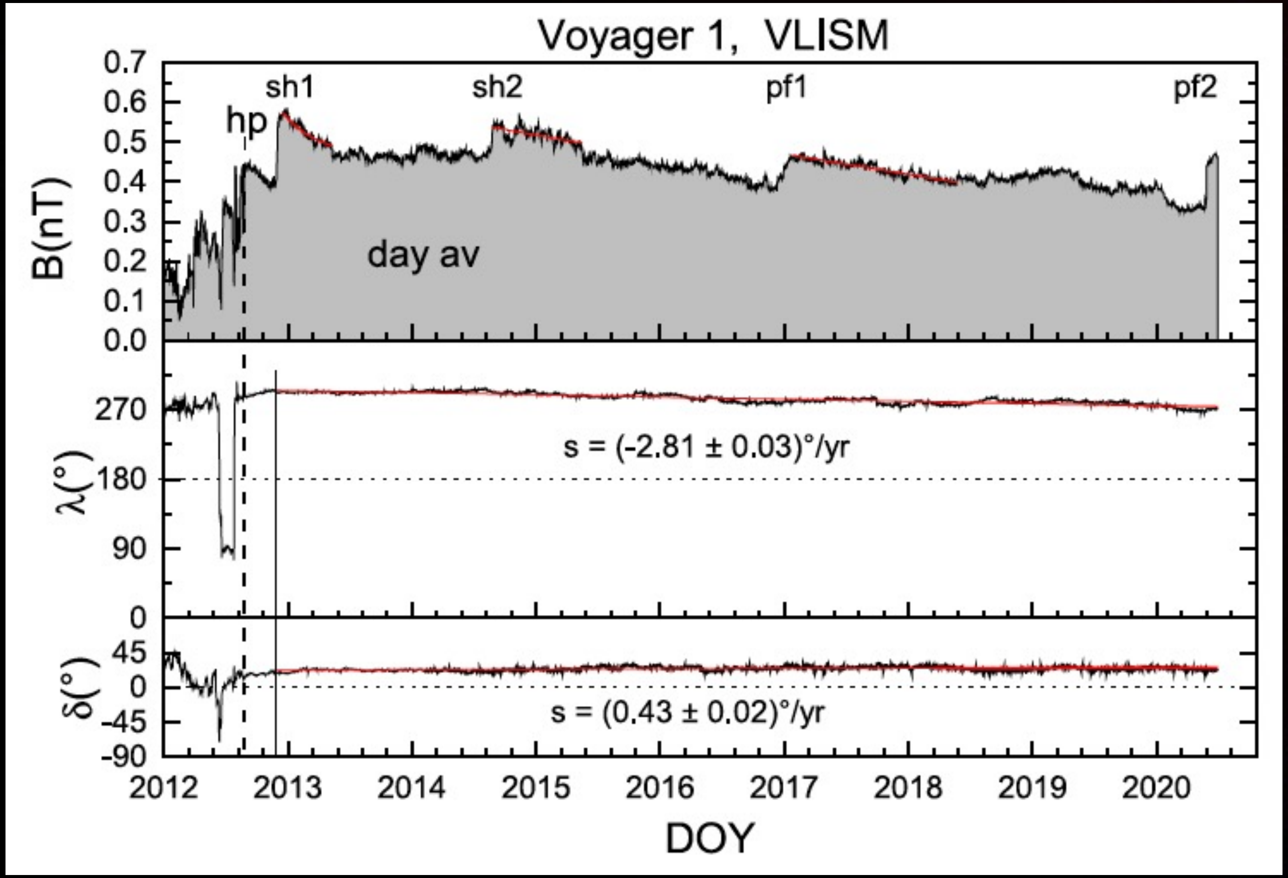


Voyager 1 observations beyond the Heliopause

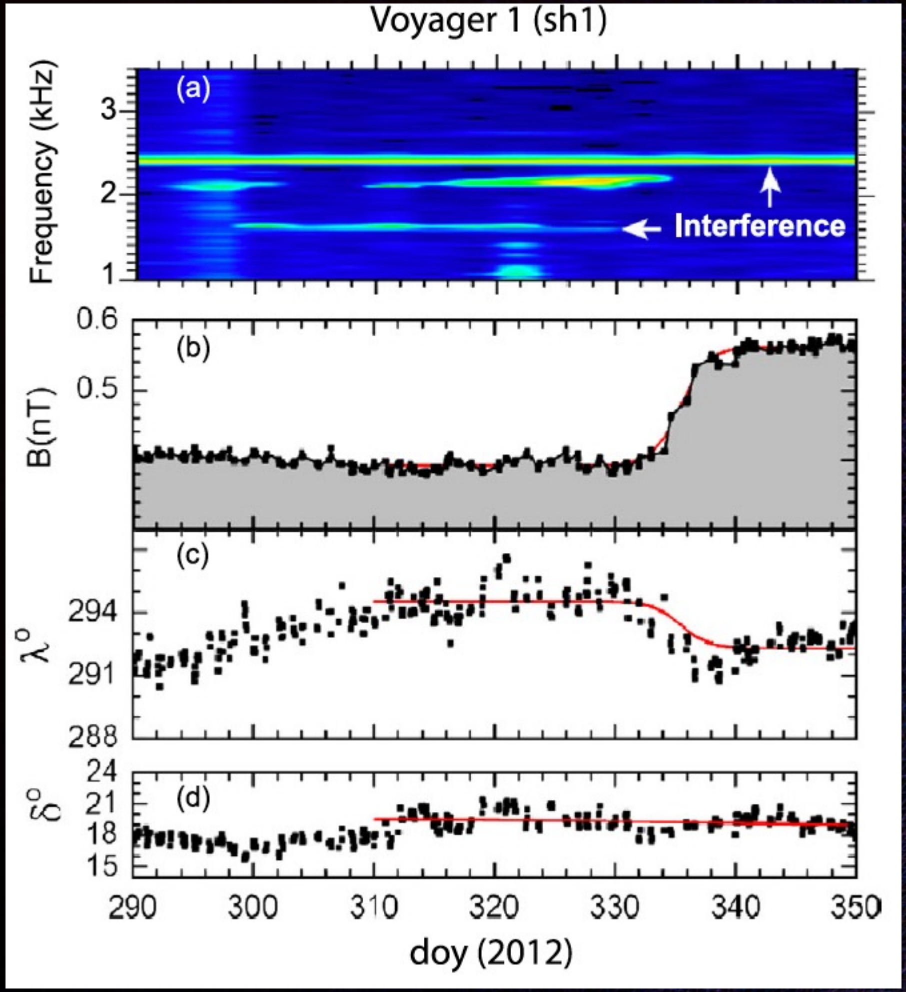


Burlaga et al. (2021)

Voyager 1 observations: 2 shocks and 2 pressure fronts

Voyager 1 observations (sh1)

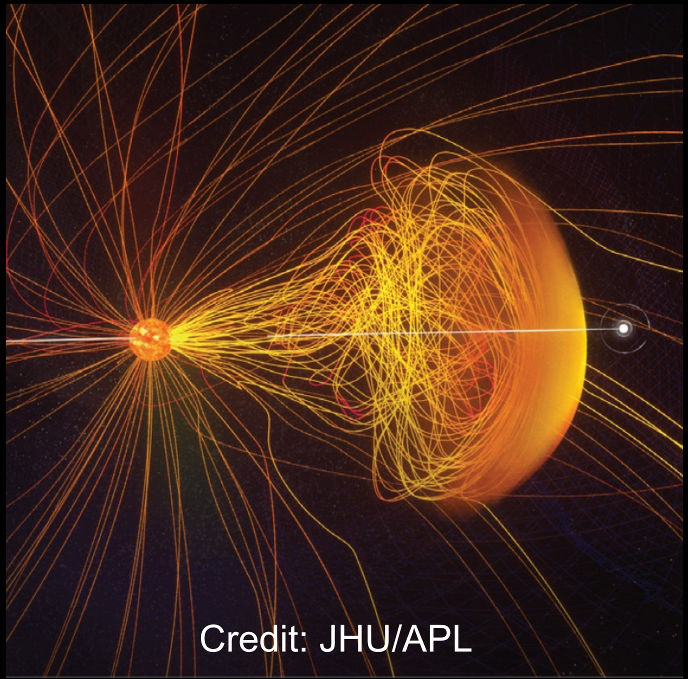
- Shock 1 (sh1):
- In situ observations of plasma oscillations that were generated by electrons accelerated by a shock.
- Also an increase in B.
- Weak MHD shock: $B_2/B_1 = 1.4$
- Laminar, subcritical, resistive, quasi-perpendicular shock.
- Shock thickness = 8.7 days
- ~10^4 broader than a shock with similar properties at 1 au. (30-60s).



Burlaga et al. (2013)

What is the origin of shocks in VLISM?

- Driven by disturbances originated near the Sun (CMEs, CIRs, GMIRs). They evolve as they propagate.
- Shocks can merge and generate stronger shocks.



Credit: JHU/APL

- The interaction of a shock and HTS and HP is a very complicated problem.
- Different model of shock propagation:
- Whang & Burlaga; Story & Zank; Washimi et al; Provornikova et al., Washimi et al., … : shock propagation, collision of shock with HTS and HP. Movement of HTS and HP and propagation of shocks in the VLISM.
- Kim et al. (2017): 3D data-driven time-dependent model can predict the arrival of disturbances and corresponding radio emissions to V1 in the VLISM with reasonable accuracy.

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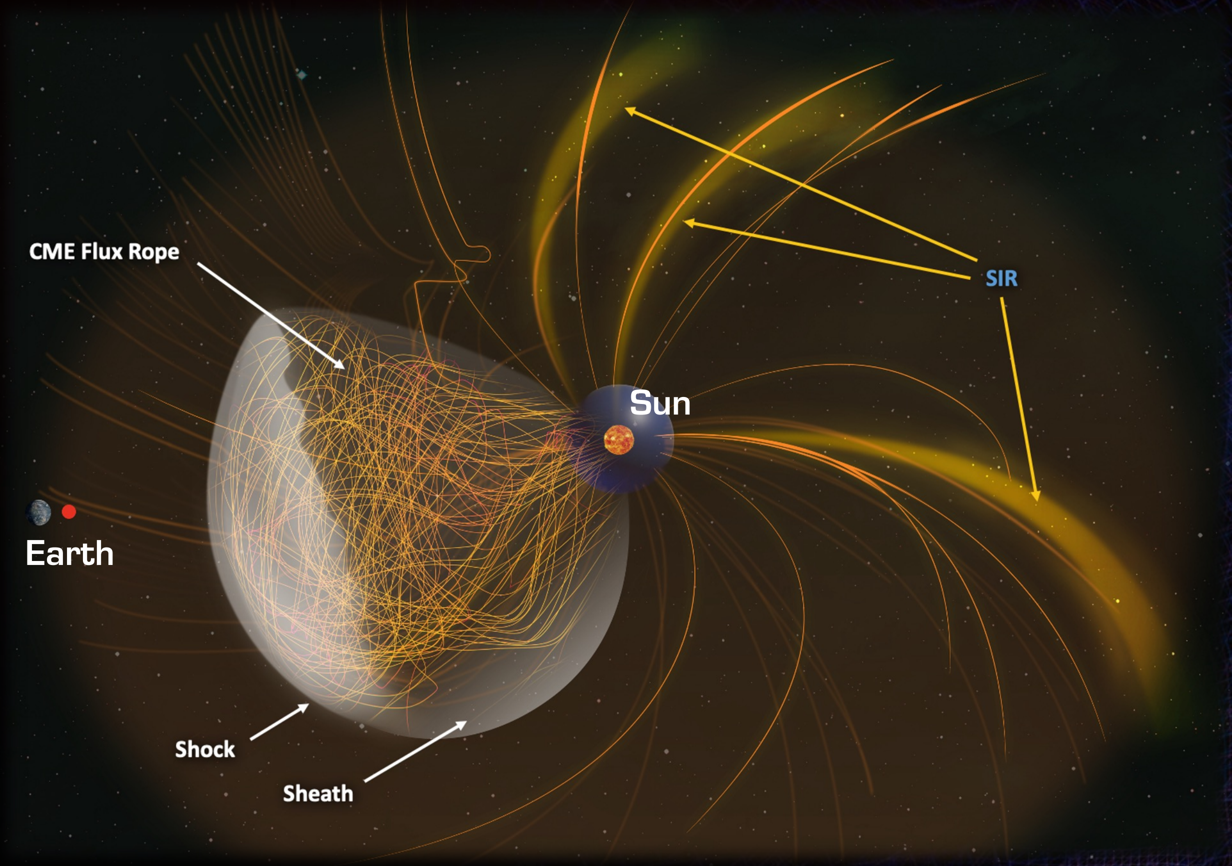
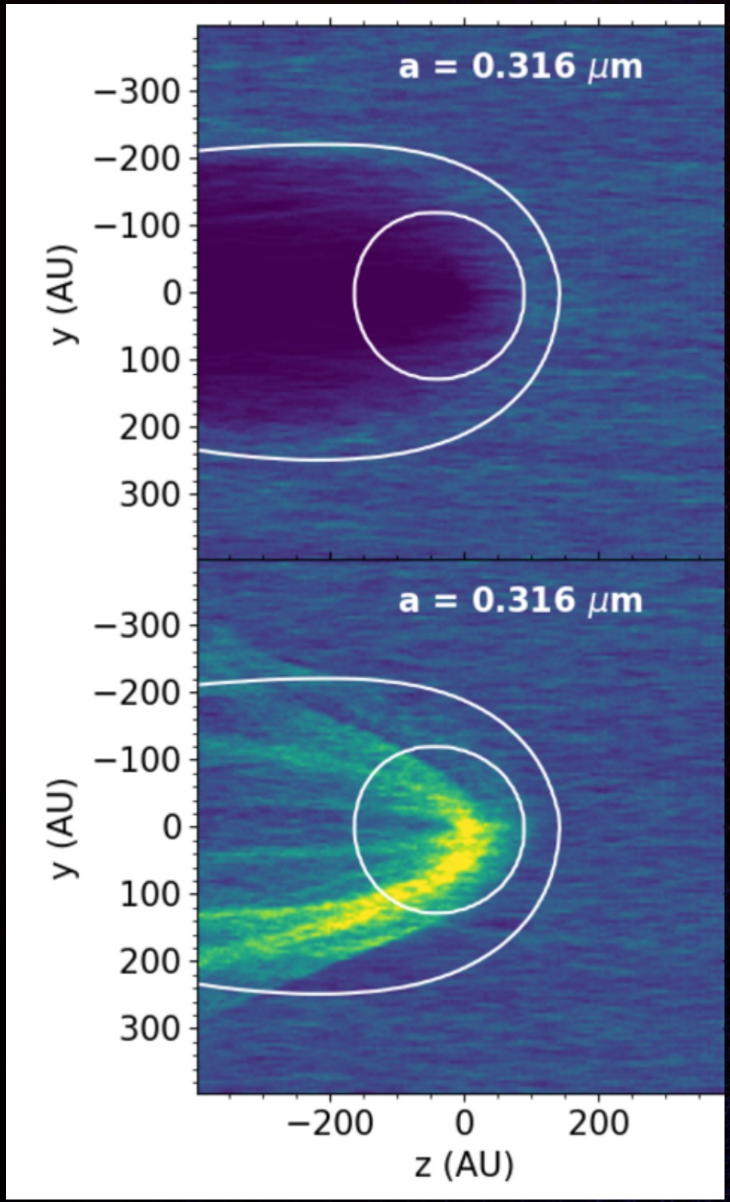


Interaction of interstellar dust with solar wind structures

- Focusing and defocusing of the interstellar dust in the heliosphere is the effect of the global static magnetic field configuration
- *Do large-scale disturbances in the solar wind like GMIRs affect propagation of interstellar dust?*
- For small particles gyroradii is larger or comparable with the scales of GMIRs – dust scattering?

Slavin+2012, Alexashov et al. 2016, Sterken+2022



Summary

- Lack of reverse shocks observed by SWAP/New Horizons may be a result of their weakening in the interaction with the rarefaction regions
- Merged CIRs and CMEs drive large-scale disturbances in the distant solar wind and heliosheath, cause displacements of the TS and HP
- Modeling solar wind structures with GAMERA-Helio model at the New Horizons location is in progress

Open Questions

- What will New Horizons observe with an increasing number of CMEs (seen by Parker Solar Probe) as we are transitioning to solar maximum?
- How are solar wind structures measured by New Horizons at large distances linked to the solar corona structure and dynamics?
- What processes control evolution of structures and shocks through the vast region between inner heliosphere observatories and New Horizons?
- Are there effects of large scale solar wind structures on motion of small dust particles?