Effects of the solar cycle variations on the solar wind flows in the outer heliosphere and global dynamics

Elena Provornikova (JHU APL), Merav Opher (Boston University), John Richardson (Kavli Institute for Astrophysics and Space Research, MIT), Vladislav Izmodenov (Space Research Institute of Russian Academy of Sciences), Pontus Brandt (JHU APL)
Sun launches disturbances of various scales to heliosphere

- Variations of the solar wind dynamic pressure over 11-year solar cycle
- Large-scale solar wind structures:
  - CMEs evolving into Merged Interaction Regions (MIRs) and Global MIRs (GMIRS) (Burlaga et al. 1993)
  - CIRs evolving into periodic structures observed in the solar wind and energetic particle enhancements (Lazarus et al. 1999, Hill et al. 2020)
- Mesoscale structures in the solar wind: flux ropes, density fluctuations (Kepko et al. 2019)
- Small scale: MHD and kinetic waves, turbulence (Usmanov et al. 2011)
11-year solar cycle effects: Global heliosphere simulations with the realistic boundary conditions at 1 AU

- 3D global multi-fluid model developed in Boston U group (Opher et al. 2009, Provornikova et al. 2014)
- Solar wind varies in time and latitude
- Boundary conditions inferred from Lyman-alpha data (Quemerais et al. 2006; Lallement et al. 2010) and IPS data

Provornikova et al. 2014
Comparison of global simulations with the Voyager 2 plasma data
Motion of the heliosphere boundaries

Solar wind dynamic pressure at 1 AU

Termination Shock motion

Heliopause motion

Termination shock distances agree with actual Voyager crossings.

In simulations heliopause (140-170 AU) is too far from the Sun compared to Voyager crossings at ~120 AU.
Corotating Interaction Regions in the outer heliosphere

- Long-lived structure (Ulysses: 30 solar rotations!)
- CIRs are efficient particle accelerators in the heliosphere (ions and electrons)
- In local ISM quasi-periodic B-fluctuations with period \( \sim 28 \text{ days} \approx \text{solar rotation} \)
- Mechanism for fluctuations is unknown! CIRs?

- CIRs are dominant structures in heliosphere during declining phase of the solar activity
- CIRs shocks form at >2 AU

Voyager 2 45 AU

Voyager 1 in ISM

Lazarus et al 1999

Burlaga et al 2016
Solar Coronal Mass Ejections evolving into MIRs

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

Voyager 2 at 79 AU

Richardson et al. 2006

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

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

Provornikova et al. 2013
Summary and challenges

• Solar minimum conditions drive inward motions of the heliosphere boundary
• Heliopause is less sensitive to solar wind variations, displacements are smaller than of termination shock
• Signatures of CIRs are observed in the distant solar wind (40 AU) and beyond the heliosphere boundary in the ISM but evolution is not understood
• CMEs drive formation of shocks, rarefactions and tangential discontinuities in the heliosheath
• How disturbances evolve from the Sun throughout the heliosphere is an open question demanding new data and advances in simulations
• The major simulation challenge is to track evolution of CIRs and CMEs from the Sun to the heliosphere boundary with realistic boundary conditions in the model