Pick-up Ion Ring Stability in the Outer Heliosheath

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Structure of the Heliosphere/ISM Boundary

- **Supersonic Solar Wind**
- **Inner Heliosheath**
- **Outer Heliosheath (OHS)**
- **Interstellar Medium (ISM)**

Diagram showing the boundary between the Sun's magnetic field and the interstellar medium.
Interstellar Boundary Explorer (IBEX)

- mapping the boundary between the heliosphere and the true interstellar space by detecting fast moving energetic neutral atoms of hydrogen (ENAs) produced at the heliosheath
Energetic Neutral Atoms

- an energetic solar wind ion (proton) 'steals' charge from a slow moving neutral atom originating, e.g., from interstellar space to become an Energetic Neutral Atom (ENA)

- the ENA leaves the charge exchange region in a straight line with the velocity of the original plasma ion
IBEX ribbon - plausible explanation

- Intergalactic magnetic field shapes the heliosphere as it drapes over it; the ribbon appears to trace the area where the magnetic field is most parallel to the surface of the heliopause, i.e., perpendicular to solar wind particles' velocity.

**Scenario:**
- IBEX ribbon formed by so-called "secondary" ENAs:
  - Primary ENAs are born from charge exchange between solar wind protons and ISM neutrals in the heliosphere and propagate away from the Sun.
  - Primary ENA charge-exchange in the OHS to become the Pick-up Ions (PUIs); due to magnetic field orientation PUIs form a ring distribution in the velocity space.
  - PUI charge-exchange again to produce secondary ENAs that have trajectories leading to back to the heliosphere (can be seen by IBEX).

**Essential condition:**
- PUI ring distribution must not scatter considerably before PUIs become secondary ENAs - PUI distribution must remain stable for several years.
Pick-up Ion Ring Stability in the OHS

**Question:**
- under what conditions PUI rings remain long-time stable in the OHS?

**Methods:**
- linear analysis
- hybrid Particle-In-Cell simulations
- full Particle-In-Cell simulations
Method of Particle-In-Cell Simulations

- **Particle-In-Cell** simulations - an *ab-initio* model of *collisionless* plasma:
  - integration of Maxwell’s equations on a numerical grid
  - integration of relativistic particle equations of motion in collective self-consistent EM fields

- Full PIC simulations: dynamics of both electrons and ions resolved
- Hybrid PIC simulations: only ion dynamics resolved, electrons modeled as a fluid (as in MHD)
Hybrid and full PIC simulations

**Hybrid PIC simulations (1D)**
- realistic physical parameters, e.g., ring-to-ambient density ratio of $10^{-4}$
- grid size: 1024 cells with size $0.5 \lambda_{si}$
- simulation time: 1000 ion orbits (61 h in the OHS) equiv. to $100,000\pi$ time steps ($\Delta t = 0.02\Omega^{-1}$)
- particle statistics: $N_{ppc} = 1000,000$
- 1h with a 1000 CPU-core simulations (1D)

**Full PIC simulations with physical $m_i/m_e=1826$ (1D)**
- need to resolve $\sqrt{m_i}$ smaller spatial and temporal scales than hybrid PIC
- grid size: 44,000 cells
- simulation time: 75 billion time steps ($\Delta t = 0.0625\omega_{pe}^{-1}$)

**Our full PIC simulations (2D3V)**
- scaled physical parameters, e.g., ring-to-ambient density ratio $2.5\times10^{-2}$, $m_i/m_e = 50$
- grid size: 6000x192 cells
- simulation time: up to 2,5 million time steps (10 CPU-days with $N_{proc} = 4800$)
- particle statistics: $N_{ppc} = 2500$
  (up to 25,000; typical in shock physics $N_{ppc} = 10$)

- Pleiades (NASA, SGI ICE X, 211,872-core, Haswell, Ivy Bridge,…, 4.09 PFlop/s)
Linear analysis

- parallel broadening leads to stable rings but second instability (Alfven Ion Cyclotron) appears for even broader rings

- AIC instability, albeit slowly growing, cannot be stabilized by temperature effects
Importance of particle statistics - hybrid PIC simulations of finite-temperature rings

Pitch-angle spread for a stable ring of finite width

Cold ring after 1000 orbits

- for low $N_{ppc}$ scattering is due to statistical noise, not an instability
1D hybrid PIC simulations of finite-temperature rings

- low temperature (cold) rings take several years to scatter onto an isotropic shell ($\langle \mu^2 \rangle = 1/3$), allowing ample time for charge exchange that produces a ribbon
- initially broad rings unstable and scatter toward isotropy on much shorter time scales
- what is the actual width of PUI distribution in the OHS?
Realistic initial ring distributions

- **realistic** distribution from MHD-MC global heliosphere modeling of atomic hydrogen (Heerikhuisen et al. 2014)
• good agreement between full PIC and hybrid PIC simulations for the same parameters
• all rings unstable, although the growth rate decreases for broader rings
• scaling to 1D hybrid results with physical parameters suggests that realistic distributions can be stable for about 21 days
Conclusions

• PUI distributions in the outer heliosheath can be stable and produce the IBEX ribbon unless parallel ring temperatures fall in the AIC unstable region

• this may be the case for realistic PUI distributions derived from primary ENAs

• careful and detailed studies of these distributions needed to see whether it is possible to prevent significant growth of the PUI instability

Results of full PIC simulations show that:
• electron dynamics is unimportant for the problem of the PUI rings stability

• the system is essentially one-dimensional and 1D hybrid kinetic modeling can accurately model the relevant physics
Dziękuję za uwagę

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