Pick-up Ion Scattering in the Outer Heliosheath - Implications for IBEX and Voyager 1 Observations

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Introduction

- Ribbon seen by IBEX is thought to be produced by secondary energetic neutral atoms (ENAs) in the outer heliosheath by a secondary pickup ion ring from solar-wind primary ENAs.
- A key feature in this mechanism is wave-particle scattering of PUIs before they charge-exchange to become secondary ENAs; enhanced ENA fluxes are expected from regions with $\mathbf{B} \cdot \mathbf{r} = 0$.
- Recent Voyager 1 observations reveal a very low level of magnetic fluctuations in the region beyond the heliopause.
- Narrow sharply defined PUI ring distributions are always unstable in linear theory through resonant interactions with RH polarized waves; hybrid simulations showed that m.f. turbulence quickly scatters initial ring toward an isotropic shell.

**Aim of this work:**
- Investigate long-time stability of two different classes of PUI ring distributions using 1D hybrid and 2D PIC simulations.
- Concentrate on rings with 90° pick-up angle.
Initial ring distributions

- warm **finite-temperature** toroidal distribution (Summerlin et al. 2014)

\[
f(v) = \frac{1}{\pi^{3/2} \delta v_T^2 \delta v_{II}} \left\{ \exp \left( -\frac{v_{II}^2}{\delta v_{II}^2} \right) + \frac{\sqrt{\pi} v_{II} \, \text{erfc} \left( -\frac{v_{II}}{\delta v_{II}} \right)}{\delta v_{II}} \right\}^{-1} \\
\times \exp \left[ -\left( \frac{v_{II} - v_{II0}}{\delta v_{II}} \right)^2 \right] \exp \left( -\frac{v_T^2}{\delta v_T^2} \right)
\]

- flat rings spread in perpendicular velocity are always unstable (Florinski et al. 2010)
- parallel broadening leads to stable rings
Initial ring distributions

- **realistic** distribution from MHD-MC global heliosphere modeling (Heerikhuisen et al. 2014)
Hybrid simulations of finite-temperature rings

- improvements to the 2010 1D code (Florinski et al. 2010): implicit advance for particle and fields, parabolic spline shape function; $\Delta x = 0.5 \ c/\omega_i$, $N_{ppc} = 1\,000,000$
Hybrid simulations of finite-temperature rings

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**Pitch-angle spread for a stable ring of finite width**

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

- $N_{ppc}=1000,000$

- resonance relations for ions ($\pm \Omega_i$) at the edges of the broadened ring
2D Particle-In-Cell simulations

- realistic parameters not computationally feasible for 2D PIC simulations
- approximate model assumes the scaling for frequencies in the OHS plasma:

\[ \omega_{pe} \gg \omega_{pi} \gg \Omega_e \gg \Omega_i \]

- for ion-to-electron mass ratio \( m_i/m_e = 50 \) we choose: \( \omega_{pe}/\Omega_e = 20, \omega_{pi}/\Omega_i \sim 141.42, \omega_{pi}/\Omega_e \sim 2.83 \)

- other parameters:
  - plasma beta: \( \beta = v_{i,th}^2/v_A^2 = 1 \)
  - solar wind speed: \( v_{SW} = 0.1c \simeq 14v_A \)
  - ion ring-beam to background density ratio: \( N_{\text{ring}}/N_i = 0.025 \)
  - \( N_{\text{ppc}} = 2500 \)

- results converge for \( N_{\text{ppc}} \) above 250

*for real mass ratio \( m_i/m_e = 1836 \) and \( \omega_{pi}/\Omega_i = c/v_A = 1.74 \times 10^4 \)
these scalings are numerically: \( \omega_{pe}/\Omega_e \sim 406, \omega_{pi}/\Omega_e \sim 9.48 \)
2D Particle-In-Cell simulations

Cold (narrow) ring

- Cold ring at $t=0$
- Cold ring at $t=25/\Omega$

Energy vs. time ($\text{Energy}/(\text{Energy}_0) \times 100$)

- Blue: cold
- Red: finite temp. ($v_{\text{th}}=v_x$)
- Green: realistic
- Yellow: thermal plasma

$B_z$ at $t=3.75/\Omega$ (top) and $t=25/\Omega$ (bottom)
2D Particle-In-Cell simulations

Realistic ENA distribution

- modes strongly damped up to $\sim 50/\Omega_i$
- growth rate about 40 times slower than for the cold ring
- PUI distribution at near-saturation at $t_0 \sim 150/\Omega_i$ only weakly scattered
- simple scaling suggests that this distribution should be stable for at least 10 days

By at $t\Omega_i = 31.25, 62.6, 100.0, 143.75$ (from top to bottom)
2D Particle-In-Cell simulations

Finite-temperature distribution with $\delta v_{\parallel} = \delta v_{\perp} = v_{i,th}$

Finite-temp $v_{i,th}$ at $t=0$ and $t=25/\Omega_i$

Bz at $t=6.25/\Omega_i$ (top) and $t=25/\Omega_i$ (bottom)
2D Particle-In-Cell simulations

Finite-temperature distribution with $\delta v_\parallel = \delta v_\perp = 3v_{i,\text{th}}$

By at $t=6.25/\Omega_i$ (top) and $t=25/\Omega_i$ (bottom)
Summary

- the stability of two different classes of pick-up ion ring distributions that serve as parent ions of the ribbon ENA has been investigated with 1D hybrid and 2D (scaled) Particle-In-Cell simulations.
- PIC modeling shows that realistic broadened ring+halo distribution derived from simulations of neutral atoms in the heliosphere is the most stable, exhibiting no scattering for at least 10 days.
- Hybrid simulations show that warm toroidal distributions broadened in velocity parallel to the mean magnetic field can be stable over 1000 orbits.
- Hybrid modeling also suggests that even cold narrow rings can be stabilized in the nonlinear stage once cold PUI loose resonance with the waves generated by the edges of the initially broadened ring.
- Such distributions may thus remain stable long enough for charge-exchange to take place and generate ENAs that would be detected by IBEX.
- In such case the absence of magnetic fluctuations at Voyager 1 is naturally explained.