The ribbon of the rings: the stability of the rings

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Abstract. The astounding result of the Voyager 1 observations in the outer heliosheath region is the Kolmogorov-like spectrum of magnetic fluctuations, consistent with the ambient spectrum of interstellar turbulence deduced from remote sensing. Such quiet conditions appear to be incompatible with the ionization of the neutral solar wind hydrogen atoms by charge exchange, which would generate abundant turbulent fluctuations due to an instability of the resulting proton ring. Here we revisit the problem of stability of ring and shell distributions embedded in a warm plasma characteristic of the outer heliosheath. We show that ion rings with parallel velocity dispersion between a few km/s and the core thermal speed are stable, while those outside these bounds are subject to magnetic-fluctuation-producing left- and right-handed instabilities. Wave generation by the instability is too efficient to be transported to shorter scales and converted into heat by the turbulent cascade.

1. Introduction
One of the most surprising results of the IBEX mission was the discovery of a circular band in space emitting large quantities of energetic neutral atoms or ENAs [12]. A number of possible explanations for the band, dubbed the IBEX ribbon, were proposed in the following years. Theories and models placing the ribbon source outside the heliopause (mainly in the outer heliosheath, OHS) and using charge exchange of pickup ions (PUIs) of solar-wind origin on interstellar hydrogen atoms [7] have been very successful in explaining the observed properties of the ribbon. In these models the ribbon (a vast ring in space) is produced by ring-like distributions of protons gyrating in place in directions where the magnetic field is normal to the line of sight from IBEX and waiting for a chance to capture an electron from a passing interstellar hydrogen atom (hence the title).

The outstanding problem with these models is the requirement to maintain anisotropic ring- or shell-like distributions of pickup protons for several years, long enough to undergo a charge transfer collision. Such distributions are though to be unstable, having the tendency to scatter onto an isotropic spherical shell and excite magnetic fluctuations in large quantities [5, 11]. No magnetic fluctuations of pickup-ion origin were observed in the OHS by Voyager 1 [1]. We note, however, that Voyager 1 is not located in the ribbon, and the fluctuations could still exist in other directions.

Summerlin and co-workers [16] proposed that a ring distribution could be stabilized by a warm proton core. We will show here that this stabilization only occurs in a relatively narrow range of ring parallel temperatures, while outside this range the rings and shells are still unstable. Models show that the proton distributions generated from ENAs of solar-wind origin could be hotter than the upper limit of the stability range. The situation is exacerbated by the presence...
of the second population of PUIs produced from inner heliospheric ENAs that have very high temperatures.

In this report we summarize the plasma physics of the instability generated by a warm gyrating proton ring. We also employ kinetic (hybrid) plasma simulations to study the scattering of proton rings injected into a warm plasma characteristic of the OHS. The simulations do confirm the existence of a region of stability in between two unstable regions. Finally, we argue that the existence of unstable ring population in the OHS is not compatible with Voyager 1’s observations of the interstellar turbulence spectrum.

2. Stability analysis

Charge transfer collisions between interstellar H atoms and solar-wind protons generate a stream of energetic hydrogen atoms called neutral solar wind (NSW). These atoms can undergo a second charge-exchange interaction outside the heliopause, producing a gyrating population of pickup protons. Suppose the NSW has a Maxwellian distribution with a bulk radial speed \( v_{sw} \) (the solar-wind speed) and thermal velocity spread \( \delta v = (2k_BT_{SW}/m_p) \), where \( T_{SW} \) is the temperature of the solar-wind protons, \( m_p \) is the proton mass and \( k_B \) is the Boltzmann constant. Because NSW atoms are produced over a range of heliocentric distances, from a few AU all the way to the termination shock, their actual distribution in the OHS would be a superposition of Maxwellsians with different temperatures. Observations show that the core solar wind proton temperature decreases between 1 and 10 AU, and afterwards remains roughly constant at \( \sim (1 - 2) \times 10^4 \) K until the termination shock because of turbulent heating by PUI-excited waves [15]. The effective temperature of the entire NSW distribution therefore will be in the tens of thousands of K, and generally higher in the fast solar wind.

The distribution of secondary PUIs produced from NSW hydrogen by electron capture is obtained by transforming the atoms’ velocities into the OHS plasma rest frame and averaging over the gyrophase. For perpendicular pickup, the resulting ring distribution is easily shown to be

\[
fr(v_{\parallel}, v_{\perp}) = \frac{n_r}{\pi^{3/2} \delta v^3} I_0 \left( \frac{2v_{\perp} v_{sw}}{\delta v^2} \right) \exp \left( -\frac{v^2 + v_{sw}^2}{\delta v^2} \right),
\]

where \( n_r \) is the number density of the ring protons, and \( I_0 \) is the modified Bessel function. Generally, in the solar wind \( \delta v \ll v_{sw} \), in which case the expression (1) is very similar to the Gaussian toroid of [16], which is mathematically tractable.

Consider now a Gaussian toroidal distribution of pickup protons with the major radius \( v_{sw} \). We take \( v_{sw} = 450 \) km s\(^{-1}\), the core plasma temperature in the OHS of 20,000 K, the OHS magnetic field of \( B_0 = 3 \mu \)G, and the ratio of the PUI density to the core density of \( 10^{-4} \). From linear Vlasov theory, the normal modes \( \omega(k) \) are the eigenvalues of the Maxwell tensor

\[
\Lambda_{ij} = (\omega^2 - k^2 c^2) \delta_{ij} + c^2 k_i k_j + 4\pi i \omega \sigma_{ij},
\]

where \( k \) is the wavevector, and \( \sigma_{ij} \) is the conductivity tensor which depends on the properties of the particles’ distribution function. For a Gaussian toroid the expressions for \( \sigma_{ij} \) for arbitrary wave propagation angles may be found in [6].

Figure 1 shows the imaginary part of the complex frequency as a function of wavenumber for the Alfvén-ion cyclotron (AIC) wave propagating in the direction of \( B_0 \) (it may be shown that maximum growth is attained for \( k \times B_0 = 0 \) for \( \delta v = 10 \) km s\(^{-1}\), 22.5 km s\(^{-1}\), 50 km s\(^{-1}\), and 100 km s\(^{-1}\), corresponding to solar wind temperatures of \( 6 \times 10^3 \) K, \( 2.4 \times 10^4 \) K, \( 1.5 \times 10^5 \) K, and \( 6 \times 10^5 \) K, respectively. Growing modes are obtained when the PUI ring effective temperature (proportional to the minor radius of the toroid) exceeds the temperature of the core OHS plasma. In that case the ring excites waves in the low-\( k \) range where there are few resonant core protons and the cyclotron damping is weak. The ring is also unstable at very low temperatures, below a
few hundred K [16, 6]. However, this is well below the range of temperatures in the solar wind, and we will not discuss the cold ring instability here.

For oblique pickup angles the resulting ring-beam distribution can resonate with the magnetosonic-whistler wave, in addition to the Alfvén wave. As shown in [6], both of these resonances are associated with instabilities. Generally, the former instability has the higher growth rate of the two when the temperature of the ring is lower than the temperature of the core; otherwise the Alfvén mode is the dominant instability. In the direction of Voyager 1 the pickup angle is close to 70° [2] and the PUI ring-beam may be shown to be always unstable thus generating magnetic fluctuations [6]. The apparent absence of such fluctuations in the Voyager 1 magnetometer measurements [1] remains an unsolved puzzle. We will return to this topic in Section 4.

3. Particle-mesh simulations

Recently [13] performed two sets of numerical kinetic simulations of a tenuous but energetic proton ring distribution embedded in a warm plasma characteristic of the OHS. The first set used a hybrid model, which uses a fluid-like approximation for the electron component, in one dimension along the mean magnetic field. The second set used a particle description for both species and two spatial dimensions. The two sets of simulation had nearly identical wave growth and PUI scattering rates, which demonstrates that including only ion dynamics and fluctuationa traveling along $B_0$ is sufficient to properly model the relevant instabilities. For this reason, we only use the hybrid simulations here, since they are much less computationally expensive.

To test the linear stability conclusions of the preceding section, we performed two numerical simulations of proton rings and toroids using the 1D hybrid code. The first had a small, but finite temperature $T_{\|} = T_{\perp} = 200$ K, and the second had a large parallel temperature $T_{\|} = 125,000$ K with $T_{\perp} = 17,500$ K. The two simulations used $10^6$ and $10^5$ particles per cell, respectively. Both were run for 1000 proton Larmor orbital periods (about 2.5 days).

Figure 2 compares the time evolution of the magnetic fluctuation intensity $\langle (B - B_0)^2 \rangle$ and the pitch-angle width $\langle \mu^2 \rangle$ ($\mu$ is the pitch angle cosine) for the two cases. The 200 K ring appears to have a very short wave growth period, but the fluctuation intensity barely rises
above the statistical noise level. The thin ring undergoes some minimal scattering initially (this is unavoidable in kinetic simulations with finite numbers of particles), but remains essentially cold at the end of the run. By contrast, the 125,000 K toroid generates intense fluctuations for the first few hundred Larmor periods after which the instability saturates (the exponential wave growth interval is a telltale sign of an instability in case of the hot distribution). The warm toroid spreads in pitch angle even more; by the end of the run it has reached $\langle \mu^2 \rangle \sim 0.1$ (for comparison, an isotropic distribution has $\langle \mu^2 \rangle = 1/3$).

![Figure 2. Pitch angle variance $\langle \mu^2 \rangle$ (solid lines) and magnetic fluctuation intensity $\langle (B - B_0)^2 \rangle$ (dashed lines) as functions of time for initial $T_\parallel = T_\perp = 200$ K (blue) and $T_\parallel = 125,000$ K, $T_\perp = 17,500$ K (red). The cold ring is stable and the hot ring is unstable.](image)

The numerical model results shown here are in agreement with the linear theory predictions. The 200 K is nominally unstable [16], but this type of instability is very quick to saturate and the resulting turbulence does not scatter the ring ions appreciably. The 125,000 K ring, however, is strongly unstable (cf. the 150,000 K curve in Figure 1), and the turbulence it generates is significant. While this result might appear counter-intuitive, it has been obtained using two completely different methods, and its veracity is not in doubt. As we discuss below, it has profound implications for the IBEX ribbon models.

In addition to toroids, [6] analyzed partial shell proton distributions away from the ribbon direction, i.e., at oblique pickup angles. These shells consist of ions with pickup angles larger than the local pickup angle that travel along the magnetic field lines from the direction of the ribbon. A simple model with straight magnetic field lines and zero temperature NSW yields the PUI distribution function at a heliocentric distance $r$ as

\[
f_r(v, \mu) = \frac{n_{\text{NSW}} n_p \sigma r}{4\pi v_{\text{SW}}^2 \mu (1 - \mu^2)} \exp \left[ n_H \sigma r \left( \frac{1 - \mu}{\mu} \sqrt{\frac{1 - \mu^2}{1 - \mu_0^2}} \right) \right] \delta(v - v_{\text{sw}}) H(\mu_0 - \mu),
\]

(3)

where $\sigma$ is the charge exchange cross-section, $\mu_0$ is the local pickup angle, $n_H$ and $n_p$ are the number densities of interstellar neutral and ionized hydrogen, respectively, $n_{\text{NSW}}(r)$ is the
number density of the neutral solar wind, and \( H \) is the Heaviside step function. For the Voyager 1 direction (\( \mu_0 = 69^\circ \)) the distribution (3) is unstable and tends to scatter toward a half-shell [6]. The ENAs generated from the half-shell PUI distribution are not directed toward Earth and therefore do not contribute to the distributed flux. However, the level of magnetic fluctuations in the hybrid simulation was some three orders of magnitude above the background inferred from Voyager 1 observations. If indeed the instability is operating in the OHS, an efficient sink of magnetic fluctuation is required to dissipate the wave energy released by the PUI scattering process.

4. Discussion

According to [16], a pickup proton ring with a temperature in excess of a few hundred K is stable in the OHS plasma. This, however, ignores the second instability that has a temperature threshold close to the core plasma temperature in the OHS, \( \sim 15,000 – 25,000 \) K, based on MHD models [17]. The stable region therefore extends roughly from 200 K to 20,000 K. [13] have found, using Monte Carlo simulations of the neutral solar wind, that the latter is generally hotter than the upper limit on stability. Exacerbating the problem is the second PUI population produced from heliosheath ENAs. That population is significantly denser than the NSW, and has a toroidal-like velocity distribution with a temperature of several million degrees K. According to [13], adding the heliosheath PUI population doubles the wave growth rate in the particle-mesh simulations. Therefore, contrary to the conclusions of [5] and [16], ribbon PUI stability requires low, and not high, ion ring temperatures.

Models have appeared recently where scattering is a beneficial factor concentrating ENA emissions in the ribbon direction [14, 9]. These models are compatible with our results for high-temperature toroids. The problem is that observations show extremely low magnetic fluctuation levels in the OHS that all but rule out a strong local source of turbulence in the direction of Voyager 1 [1]. PUI signature waves are also rarely seen in the solar wind as a consequence of rapid spectral transfer to smaller scales by the turbulence cascade [3]. However, we found [6] that for the OHS conditions the rate of energy spectral transfer is much smaller than the rate of energy production by the instability. The ratio can be estimated as

\[
\frac{\dot{E}_{\text{turb}}}{\dot{E}_{\text{prod}}} \approx \frac{2 k^{-5/2}}{\eta_{\text{NSW}} \sigma_{\text{SW}} n_{\text{SW}}^2} \left( \frac{du^2}{dk} \right)^{3/2}
\]

for a Kolmogorov cascade, where \( \eta \sim 0.01 – 0.02 \) is the fraction of the PUI energy transferred to the waves [6], \( n_{\text{NSW}} \) is the number density of NSW atoms [8], and \( u^2 \) is the turbulent energy per unit mass [1]. Using the published numbers, one arrives at a ratio of only 0.01. It must accepted, therefore, that the ambient turbulent cascade in the OHS is not the mechanism responsible for the absence of the waves.

If the OHS ENA model of the IBEX ribbon is correct, one must choose between two possibilities. The first is that the ion rings are stable and the waves are not generated. Then the PUIs either scatter very slowly or not at all (the ribbon’s properties in that case could be explained by focusing effects from magnetic field draping around the heliopause [4] or the large scale magnetic irregularities that are part of the ambient wave spectrum in the LISM [10]). The second possibility is that there is efficient scattering on self-excited fluctuations [14, 9], but the waves are removed by turbulent processes and eventually dissipated as heat. Given the above estimate of the dissipation rate, the first possibility appears to be more realistic. In a follow up publication we will show that the NSW could be cold enough to prevent the Alfvén wave instability from operating in the OHS.
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References

[1] Burlaga L F, Florinski V and Ness N F 2015 Astrophys. J. Lett. 804 L31
[2] Burlaga L F and Ness N F 2014 Astrophys. J. 784 146
[3] Cannon B E, Smith C W, Isenberg P A et al. 2014 Astrophys. J. 787 133
[4] Chalov S V, Alexashov D B, McComas D et al 2010 Astrophys. J. Lett. 716 L99
[5] Florinski V, Zank G P, Heerikhuisen J, Hu Q and Khazanov I 2010 Astrophys. J. 719 1097
[6] Florinski V, Heerikhuisen J, Niemiec J and Ernst A 2016 Astrophys. J. in press
[7] Heerikhuisen J, Pogorelov N V, Zank G P, et al. 2010 Astrophys. J. Lett. 708 L126
[8] Heerikhuisen J, Zirnstein E, Funsten H, Pogorelov N V and Zank G P 2014 Astrophys. J. 784 73
[9] Isenberg P A 2014 Astrophys. J. 787 76
[10] Giacalone J and Jokipii J R 2015 Astrophys. J. Lett. 812 L9
[11] Liu K, Möbius E, Gary S P and Wüske D 2012 J. Geophys. Res. 117 A10102
[12] McComas D J, Allegrini F, Bochsler P, et al. 2009 Science 326 959
[13] Niemiec J, Florinski V, Heerikhuisen J and Nishikawa K-I 2016 Astrophys. J. in press
[14] Schwadron N A and McComas D J 2013 Astrophys. J. 764 92
[15] Smith C W, Isenberg P A, Matthaeus W H and Richardson J D 2006 Astrophys. J. 638 508
[16] Summerlin E J, Viñas A F, Moore T E, Christian E R and Cooper J F 2014, Astrophys. J. 793 93
[17] Zank G P, Heerikhuisen J, Wood B E et al 2013 Astrophys. J. 763 20