Observational Evidence of universal kappa distributions and the implications for the Interstellar Boundary Explorer

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Abstract

Emerging from decades of interplanetary measurements of the solar wind and other space plasmas is the conclusion that kappa distributions, not Maxwellian, characterize the suprathermal ion population and power law tail. More recent research by Fisk and Gloeckler has demonstrated that there is a particular distribution function with a specific kappa number ~ 1.5 that emerges universally in the speed range from ~2-10 times the solar wind speed and the spatial range between ~2-5 AU. The implications of these observational results are explored in several different regimes along with the importance of utilizing these functions to describe space plasmas. The Interstellar Boundary Explorer (IBEX) will image energetic neutral atoms (ENAs) of energies 0.01 keV to 6 keV originating from a population of shocked solar wind ions. Using two different MHD models of the termination shock (TS), synthetic IBEX images are generated for Maxwellian and κ distributions. The suprathermal tails are found to significantly impact the expected ENA flux compared to a thermal population for the IBEX mission. While the microphysics that creates the suprathermal tail is unknown, observationally the power law tail strengthens after disturbances such as shocks. CLUSTER has recently made it possible to make detailed observations of reconnection which is known to occur in turbulent and disturbed plasma. Using 3 spacecraft's observations, the tail is found to strengthen to ~ the 1.5 κ number during a reconnection event. This result, in combination with mounting evidence for reconnection as a universal process, emphasizes the importance of including the suprathermal population in discussions of the solar wind. This poster brings together the observational evidence for the universality of the κ distribution and explores the implications for the heliosheath and the IBEX mission.

I. Empirical evidence of universal κ distributions motivates description for solar wind plasma throughout Heliosphere

$$f(v)=\frac{n\Gamma(\kappa+1)}{\omega_o^3\pi^{3/2}\kappa^{3/2}\Gamma(\kappa-1/2)}\left[1+\frac{(|v-v_{SW}|)^2}{\kappa\omega_o^2}\right]^{-\kappa-1} \quad \text{where} \quad \omega_o=\sqrt{\frac{2T}{m_p}\frac{(\kappa-3/2)}{\kappa}}$$

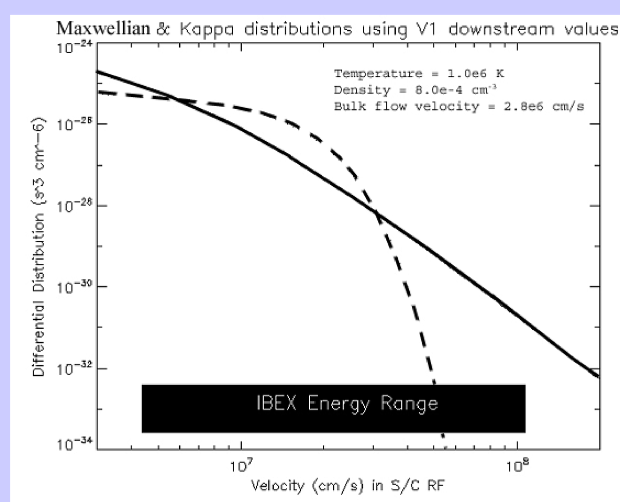
κ distribution characteristics

•Describes empirical power-law suprathermal tail. (Above)

• As κ → ∞, $f(v)$ → Maxwellian. The lower the κ number, the more pronounced the suprathermal tail.

• Thermal core tends to have a higher κ than higher energies

• Same bulk values produce different differential distributions. (Right: using Voyager 1 TS crossing values - solid is κ = 1.6, dashed is Maxwellian.)



Empirical Evidence

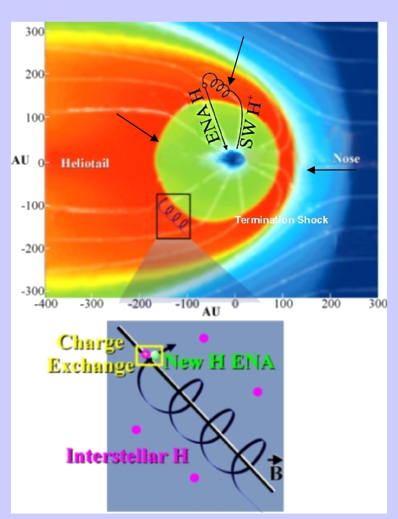
Location	V Range	Type of Plasma	Result	Mission & Reference
1 AU	< $2v_{sw}$	Fast and slow solar wind	κ = 2.4-4.7	WIND, Collier *et al.* (1996)
1 AU	< $2v_{SW}$	Corotating Interaction Regions	κ = 3.0-4.2	WIND, Chotoo *et al.* (2000)
1 to 5.4 AU	$2v_{SW}$ - $8v_{SW}$	Quiet time solar wind	**universal κ ~ 1.5**	ACE and Ulysses, Gloeckler (2003), Fisk & Gloeckler (2006)
94 AU	>>v_{SW}	Heliosheath (downstream TS)	κ = 1.6	Voyager 1, Decker *et al.* (2005)

II. IBEX background and distribution function relevance

•Will observe Heliosheath ENAs (Right)

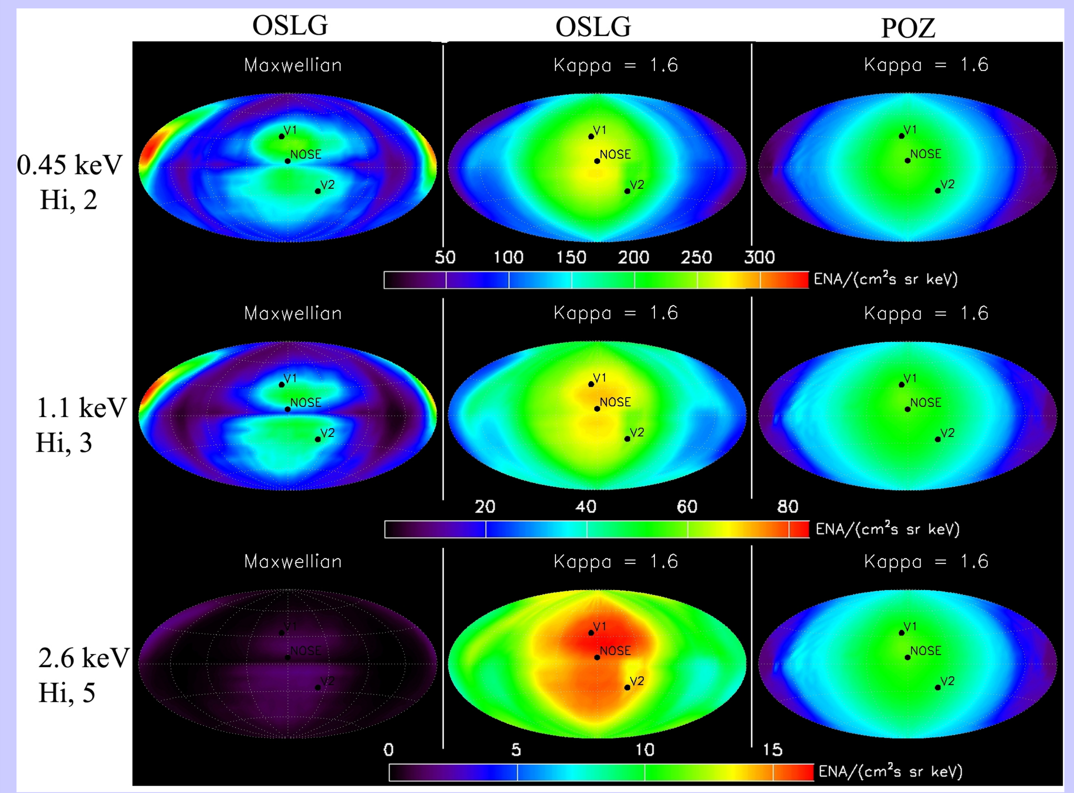
•Measure global properties (location, strength, etc.) of TS from ENA population

•Energy dependent H ENA flux at Earth (j_{ENA}): number density of neutrals (n_A), distribution function of solar wind protons (f), charge exchange cross section (σ), survival probability against reionization (P) (Below)



$$j_{ENA}(E)\left[\frac{\#}{\text{cm}^2\ \text{s sr keV}}\right]=\int_{R_0}^{\infty}\frac{2E}{m_p^2}n_A(r)f(n_p(r),E)\sigma(E)P(E,R_0)dr$$

III. Implications of κ distributions for IBEX: What impact do they have on synthetic ENA flux images?



• **κ distributions significantly increase synthetic ENA flux** (2nd and 3rd columns) **from Maxwellian** (1st column)

• Bigger effect at higher E where suprathermal tail more significant

Left: All-sky H ENA flux maps using a Hammer-Aitoff projection in HSEa coordinates for IBEX energies. One model is based on an adaptation of the ideal MHD BATS-R-US code by Opher, Stone, Liewer, and Gombosi (OSLG) (Opher *et al.*, 2006) and the other is based on work by Pogorelov *et al.* (2006), referred here as the POZ model. The first two columns correspond to the OSLG model using a Maxwellian and the Voyager 1 κ value of 1.6. The third column shows the POZ model using κ = 1.6. Also shown for reference are the positions of V1, V2, and the nose of the TS in the MHD models. Flux is derived using Gruntman *et al.*(2001)'s discussion of j_{ENA} and IBEX geometric factors.

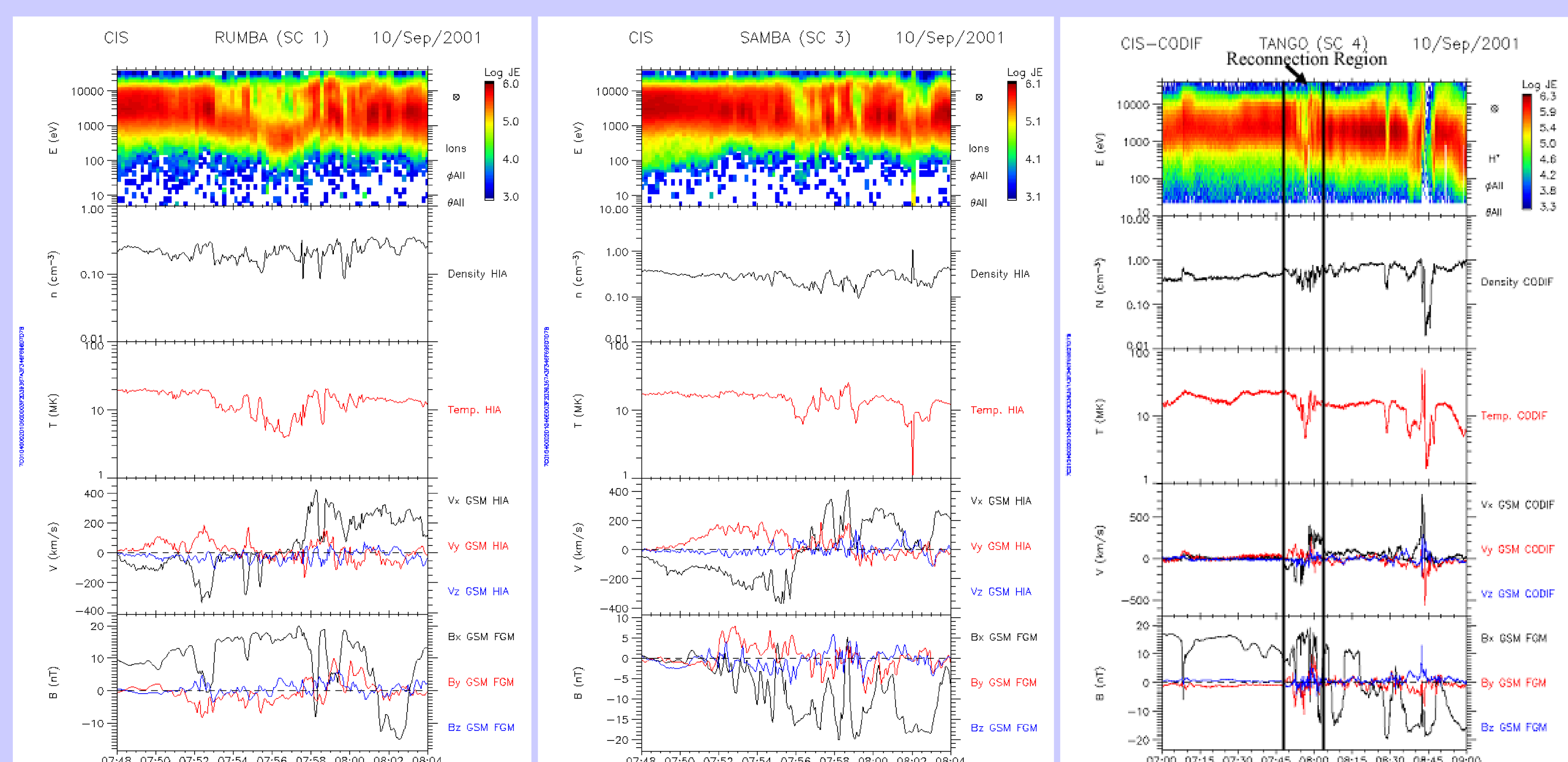
IV. A CLUSTER case study: Is Reconnection linked to the universal process that generates ~ 1.5 κ distributions?

Study Motivation

•CLUSTER reports the first direct evidence that reconnection occurs on small scales such as the turbulent solar wind (Retinò, *et al.*, 2007)

•Suprathermal tail strengthens during disturbances (shocks and CIRs) during which boundary Reconnection is likely to occur

•No study done before examines proton distribution evolution during Reconnection



10/Sept/01 Event Specifics

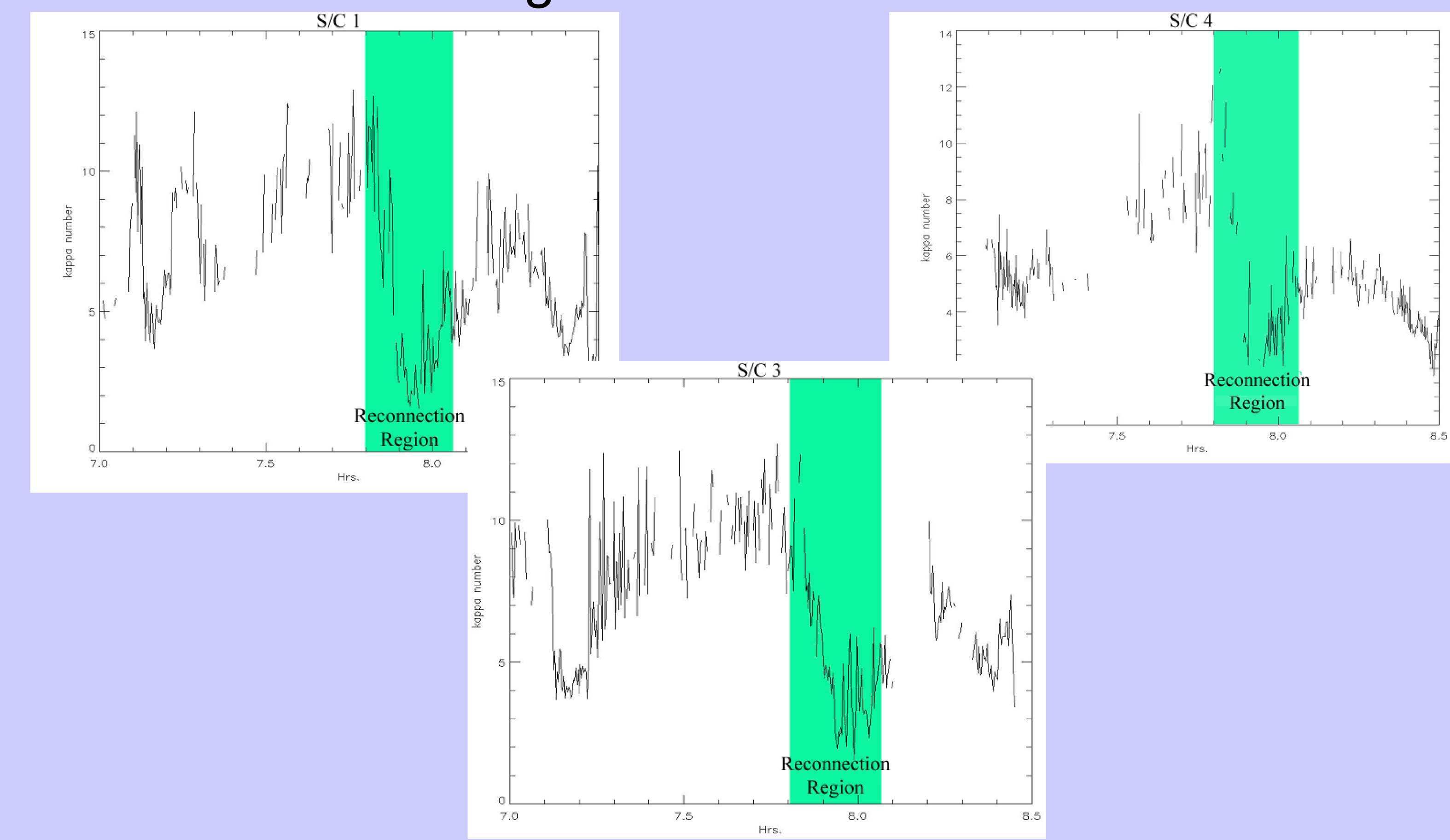
•CLUSTER crossing magnetosphere current sheet; Reconnection 07:48-08:04

•S/C 1 and 4 on opposite side of current sheet than S/C 3 (See Bx direction Above)

• 1 event out of 13 identified by CLUSTER team, but only one with low enough T to observe suprathermal tails with CIS

•Reconnection characterized by B → 0 and V changing directions as plasmoid and x-line pass by

V. Results from 3 CLUSTER space craft; κ distribution fits during a Reconnection Event



All three spacecraft observe a decrease in κ number during the Reconnection event, minimizing at κ~1.5

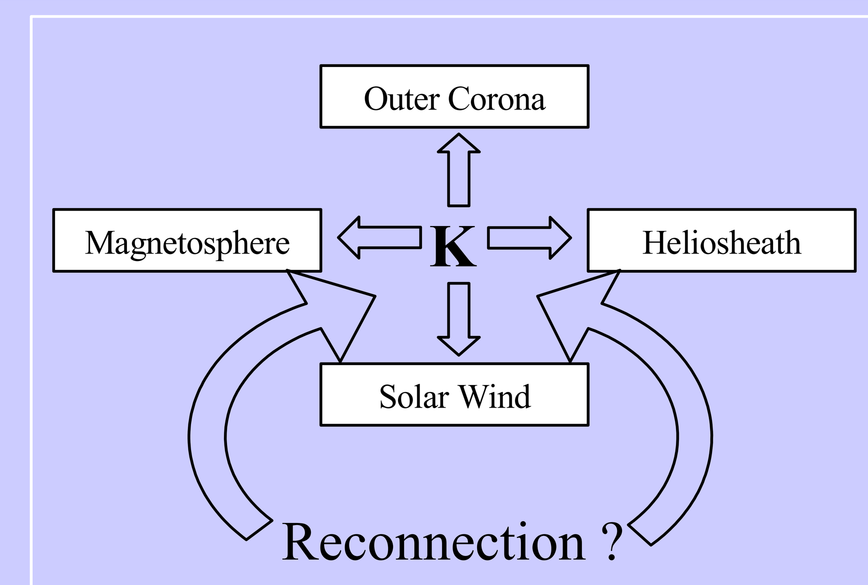
Conclusions and Future Work

• Empirical evidence, including Voyager 1's recent crossing of the TS, shows **κ~1.5 is an inherent characteristic of the outer Heliospheric solar wind**.

• The **κ distribution significantly alters synthetic IBEX ENA images** from thermal distributions and therefore is an important physical piece for interpolating IBEX's data set.

• In a CLUSTER case study, all three space craft observe **κ minimizes to ~1.5 during a Reconnection Event**.

•**Further studies of κ evolution** during reconnection events should be done to find a statistical representation of this phenomena.



Does Reconnection give us another clue to the universal process that generates the suprathermal tail?

Acknowledgements & References

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