Anomalous Behavior of Carbon, Oxygen charge states in a Population of Interplanetary Coronal Mass Ejections

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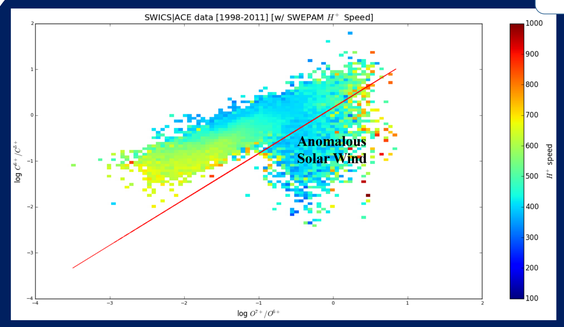
1. Background

- Interplanetary Coronal Mass Ejections [ICMEs] are brilliant solar eruptions that impact Space Weather and can be severely geoeffective. Their ability to be disruptive to human infrastructure makes an accurate understanding of ICMEs crucial. Significant efforts to further our understanding of the charge state composition of ICMEs has been made in the past decade.
- Charge state composition is an effective tool to study the origin and evolution of ICMEs, because as ICMEs travel away from the sun the electron density decreases to the point of shutting down plasma ionization and recombination processes. Hence the charge state composition measured in the heliosphere can be used to study the formation and early evolution of CMEs.
- Oxygen & Carbon freeze in a similar region above the solar corona. Hence, we expect the behavior of $^{O^{7+}}/_{O^{6+}}$ and $^{C^{6+}}/_{C^{5+}}$ to correlate well past their freeze-in region. However, anomalous behaviour is observed with regions of low and uncorrelated $^{C^{6+}}/_{C^{5+}}$ density ratios. [Figure 1]
- **This study focuses on a subset of the ICMEs where this anomalous behavior of the Carbon charge states is found, in order to determine what has caused them and what they can tell us of the origins of ICMEs.**

2. The Depleted I.C.M.E.

Figure 1



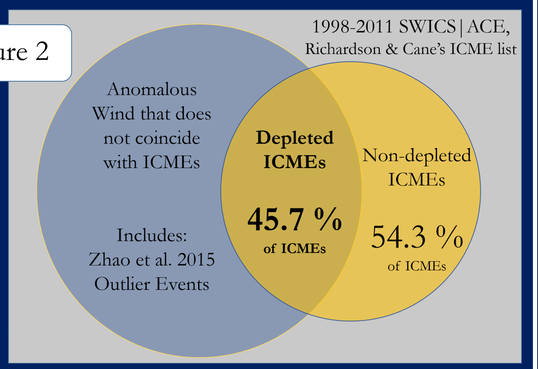
- A Threshold Sensitivity Analysis technique is employed to identify the most effective threshold for anomalous wind isolation.
- Wind with abnormally low $\frac{nC^{6+}}{nC^{5+}}$ ratio is isolated using a threshold defined as follows:

Threshold = $<\log \frac{nO^{7+}}{nO^{6+}} / \frac{nC^{6+}}{nC^{5+}}> + 2*\sigma[\log \frac{nO^{7+}}{nO^{6+}} / \frac{nC^{6+}}{nC^{5+}}]$

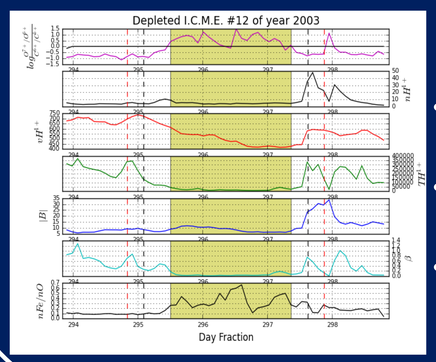
[Calculated for each year and averaged over entire mission.

- Figure 2 shows intersections of the anomalous solar wind with Richardson & Cane's ICME list.
- Zhao et al. 2015 discussed observations of the non-ICME 'Outlier' slow wind, finding they constitute 11% of the slow wind.
- 45.7% of ICME observations coincide with anomalous solar wind. We call these **Depleted ICMEs.**

Figure 2



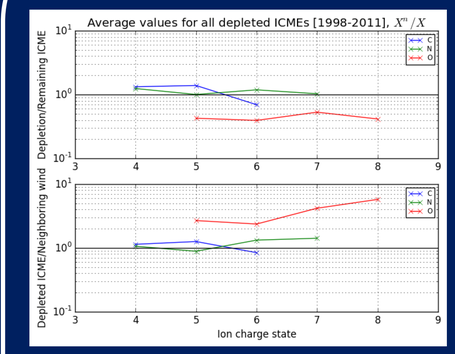
A total of 156 depleted I.C.M.Es from 1998-2011 are identified. 44 charge states of 10 ions are investigated. The figure below shows a depleted ICME from the Halloween Storm months of 2003.

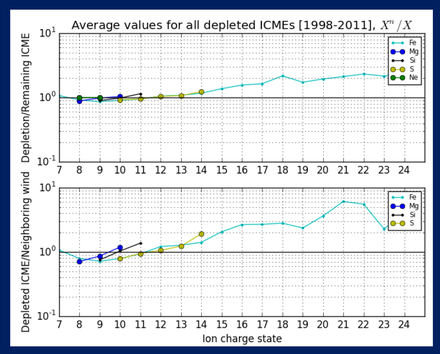


- **Proton Properties:** Depleted ICMEs typically have lower speeds & significantly lower temperature than the surrounding solar wind.
- **Magnetic Properties:** The Plasma Beta is significantly lower in the depleted ICME.
- Occurrence rate of Depleted ICMEs is **solar cycle dependent.**
- **Depletion occurs only in part of the ICMEs** however, there is no trend for the location or duration of depletion within the ICME.

3. Findings

Composition of charge states of Heavy Ions:





Ion densities of:	Depleted ICME compared to surrounding wind	Depletion region compared to remaining depleted ICME
C6+, N7+ [Fully Stripped]	Depleted in ~ 70% of 156 events	Depleted in ~ 70% of 156 events
O8+ [Fully Stripped]	Depleted in ~ 75% of 156 events	Enhanced in ~80% of 156 events
Fe18+ to Fe24+	Enhanced in ~80% of 156 events	Enhanced in ~80% of 156 events
Si10, Si11	Enhanced in ~70% of 156 events	Enhanced in ~90% of 156 events
S13+,S14+	Enhanced in ~70% of 156 events	Enhanced in ~80% of 156 events
Ne9+	Enhanced in ~65% of 156 events	Enhanced in ~75% of 156 events

- ❖ The portion of the ICME which is depleted shows enhancements in the high charge states of O, Fe, Si, S, Ne, Mg relative to the rest of the CME and the surrounding wind.
- ❖ Significant depletion in the average charge state of Carbon is noted across all events.
- ❖ Densities of fully-stripped ions of C, O, N are depleted in a significant population of the depleted ICMEs.

4. Interpretation

Wind-Ion & Energetic Proton interactions can be classified as follows:

Impact Ionization	✗	No Bound Electron
Impact Excitation	✗	
Charge Exchange w/ H+	✗	
Coulomb Collision	✓	Significant transfer of momentum

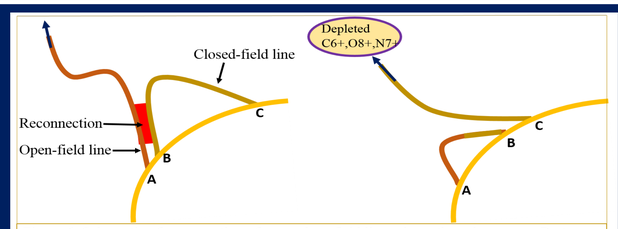


Figure 6: Schematic of reconnection of open-close field lines above the solar corona. Proton jets accelerate the fully-stripped ions away from the depleted ICME wind observed at 1 AU.

- Momentum exchange in proton-ion collisions preferentially accelerate fully stripped ions away, while proton-ion collisions involving ions with bound electrons result in ionization and excitation rather than Coulomb-collisions.
- This process takes place near the corona, at a height near the freeze-in region.

5. Conclusions

Anomalous behavior in $^{C^{6+}}/_{C^{5+}}$ ratio led us to identifying unique heavy-ion composition characteristics of a substantial subset of Interplanetary Coronal Mass Ejections. We call these Depleted ICMEs.

- We interpret this depleted ICME wind to be the direct product of a magnetic-reconnection in the current sheet that trails the CME, occurring near the freeze-in region above the solar corona. It is theorized that this depleted ICME wind is a signature of acceleration by energetic proton jets produced through reconnection.
- Furthermore, this study expands on the Zhao et al. 2015 study of 'Outlier' slow wind, with our discovery of a new subset of solar wind showcasing this novel, anomalous charge-state composition behavior.