The FIP Effect on Individual Charge State Abundances

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Main Questions

Remote sensing spectrometers and in-situ ion mass spectrometers can be used to study the elemental abundances of the solar corona and the source of the solar wind. These two observational methods measure different ranges of particle ionization states, which are used to calculate total abundance ratios.

- Do the individual ion charge state ratios measured give a different First Ionization Potential (FIP) bias than their aggregate counterparts in in-situ observations?
- What does this mean regarding the linking back of in-situ structures to their solar counterparts?

Our Findings

- Abundance ratios vary depending on specific ion ratios and can display different ordering of slow and fast wind than the aggregate ratio.
- FIP bias of individual charge state ratios can be much larger than the FIP bias of the aggregate elemental abundance ratio.
- Difference depends on the relative abundance of individual charge states, and this difference is present in solar cycle and wind type characterization.
- Care must be taken when relating remote measurements with in-situ measurements of FIP bias. Minor charge states may not be suitable for aggregate estimation.

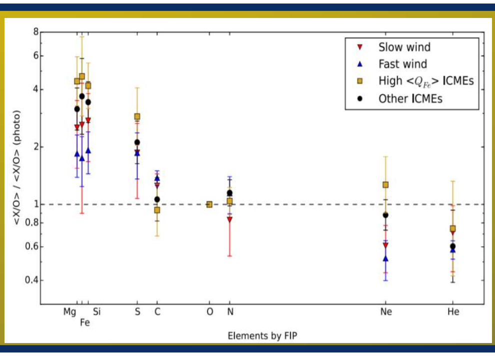

Figure 1. FIP bias from ACE/SWICS. Slow and ICME related solar wind are characterized by an overabundance of low FIP elements (in-situ) when compared to photospheric abundances. Similar abundances have also been observed in large coronal loops and within active regions, indicating a common source for the material (From Zurbuchen et al. 2016).

Background: Elemental Composition and Charge State

- Heavy ions (>He) make up trace amounts of solar wind particles. Temperatures and densities in the corona are reflected in the varying ion charge states observed for each element.
- Elemental composition and charge state abundances of solar wind samples transport information on properties of where the plasma originates in solar corona (Laming 2015).

Data from the Advanced Composition Explorer (ACE)

- Solar Wind Ion Composition Spectrometer (SWICS) is used for charge state and abundance ratios for oxygen, magnesium, iron, silicon, carbon, and neon. In-situ elemental abundance ratios are calculated by summing over all available charge states for elements.
- Magnetic Field & Solar Wind Electron Proton Alpha Monitor (SWEPAM) is used for wind speed.
- Separated by solar max: 2000-2002, and solar min: 2008-2009.
- ICMEs from Richardson & Cane list: removed samples from 1 day before reported ICME start time up to 1 day after ICME end time (Richardson and Cane, 2010).
- Photospheric abundances are from von Steiger et al (2000).

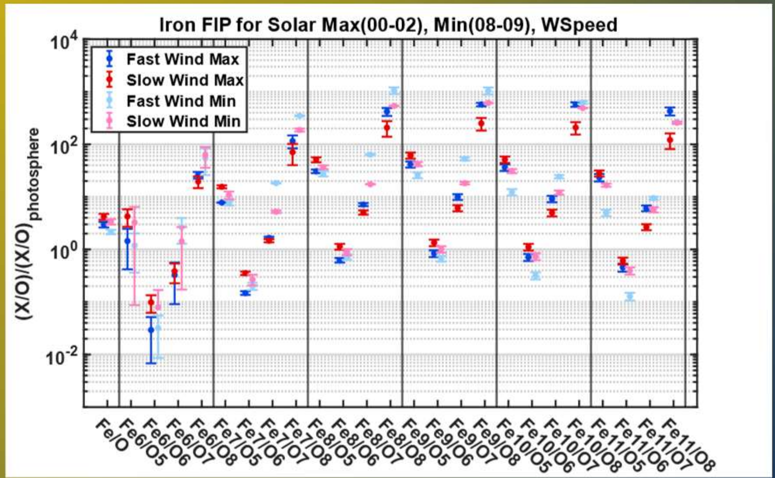

Figure 2. Permutations of iron and oxygen charge states, averaged over phase of solar cycle. The aggregate Fe/O abundance is shown to the left. Vertical bars group common iron charge states. Error bars that represent 1 standard deviation of the data (adjusted to $\log_{10}$ scale).

Abundances

- We separated fast and slow solar wind by speed, von Steiger & Zurbuchen 2010, Zhao et al. 2009, and Zhao et al. 2017 schemes, but the results were generally robust to our selection. The results are shown in Figure 2.
- Slow wind dominates fast wind for O^{5+} and O^{6+} states (like the aggregate Fe/O) while fast wind dominates slow for O^{7+} and O^{8+}.
- The solar minimum averages tend to be lower for O^{5+} and O^{6+} states and higher for O^{7+} and O^{8+} states, suggesting that SWICS sees more lower oxygen states in solar maximum than in solar minimum. This is to be expected if the equatorial coronal holes as a fast wind source are absent in solar minimum; however, there must be a factor caused by the iron states as well.
- The variance in Fe^{6+} states seems to be quite large, which warrants future examination.

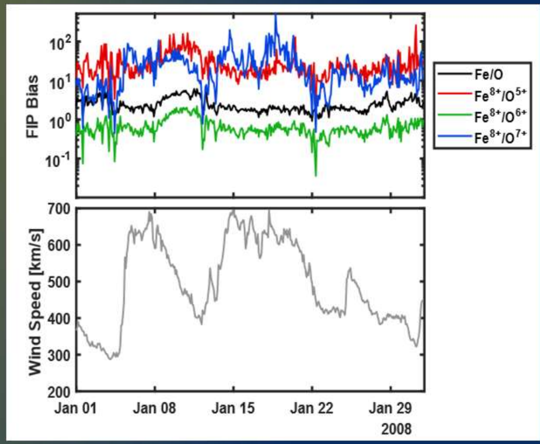

Figure 3. Time series of Fe/O and select charge states (top) and wind speed (bottom).

Time Series

- We show the wind speed, aggregate abundance, and charge state distributions against time in Figure 3.
- O^{6+} is roughly more than 90% of the oxygen species. O^{7+} is typically around 5% and is strongly anticorrelated with the ambient wind speed.
- The Fe^{8+}/O^{6+} charge state ratio is well correlated with the aggregate abundance and is closest match for magnitude.
- It is well known that O^{7+} is strongly anti-correlated with the solar wind speed; by dividing out by it, the charge state ratio seems to have a strong positive correlation with the bulk wind speed.

Future Work

- Expand dataset and permutations to lower charge states and high latitude coronal wind.
- Examine connections between remote and in-situ measurements by leveraging ionization models.
- Work closely with remote sensing teams to connect their measured FIP fractionation with this work, preparing for Solar Orbiter SPICE and HIS collaboration.

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