How similar are time series of elemental abundances of different low first ionization potential elements? B23

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Abstract

The elemental abundance of the solar wind is determined in the solar atmosphere and is in particular different in different types of solar wind. The abundance of heavy elments in the solar wind is specific for the respective source region and solar wind type. Therefore, the upcoming Solar Orbiter mission aims to identify the source regions of the slow solar wind with coordinated observations of low first ionization potential (FIP) elements with in-situ and remote sensing instruments. However, this relies on the assumption that time series of these elements, typically Fe, Mg, and Si, are indeed well correlated on all relevant time scales. Here, we scrutinize this assumption and investigate the Spearman ranking correlation and mutual information between time series of elemental abundances measured by the Solar Wind Ion Composition Spectrometer (SWICS) onboard the Advanced Composition Explorer (ACE). We then repeat this analysis for time scales corresponding to the size of individual solar wind flux tubes, the typical length of solar wind streams, and longer times scales up to a few Carrington rotations.

Solar wind elemental abundances from ACE/SWICS

We consider ten years of data from the Solar Wind Ion Composition Spectrometer (SWICS) on ACE ([3]). The solar wind proton plasma parameters are taken from the Solar Wind Electron, Proton and Alpha Monitor (ACE/SWEPAM) ([9]) and magnetic field observations from the magnetometer ACE/MAG ([11]).

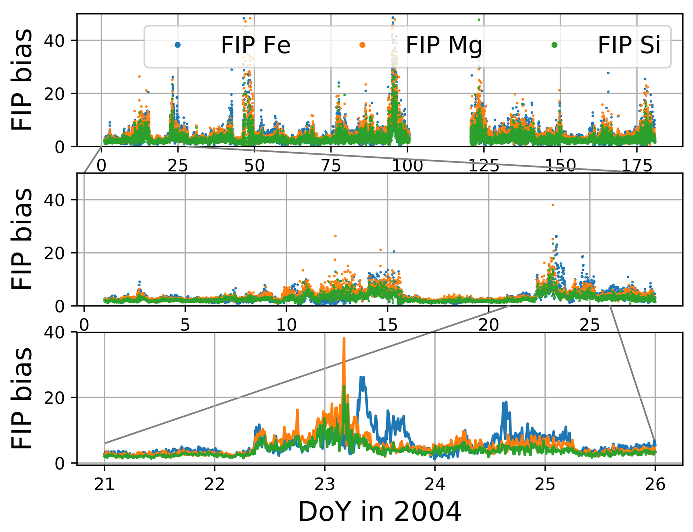
The ionic composition is derived from the SWICS Pulse Height Analysis (PHA) words as described in [1]. The elemental abundance of He, O, Mg, Si, and Fe is taken as the sum of the respective most prominent ion species, namely He^{2+}, O^{6+}, O^{7+}, Mg^{7+}, Mg^{8+}, Mg^{9+}, Mg^{10+}, Si^{7+}, Si^{8+}, Si^{9+}, Si^{10+}, Si^{11+}, Fe^{7+}, Fe^{8+}, Fe^{9+}, Fe^{10+}, Fe^{11+}, Fe^{12+}, Fe^{13+}. To reduce statistical noise, we require for each element a minimum of ten counts distributed over all respective ions.

To characterize the solar wind type, we rely on the Xu & Borovsky [12] 4-type solar wind categorization scheme. This heuristic scheme distinguishes between coronal hole wind, two types of slow solar wind, sector-reversal plasma and helmet streamer plasma, and ejecta plasma. Interplanetary coronal mass ejections (ICMEs) are excluded following the [7, 6] and [10] ICME list instead of the ejecta category. We refer to the union of the two slow solar wind types (sector reversal and helmet streamer plasma) as "all slow" solar wind.

FIP bias time series

The ratio of the abundance of an element X with density n_X relative to O in the solar wind $(n_X/n_O)_{sw}$ divided by the respective photospheric ratio $(n_X/n_O)_{photo}$ taken from [4] is called the X

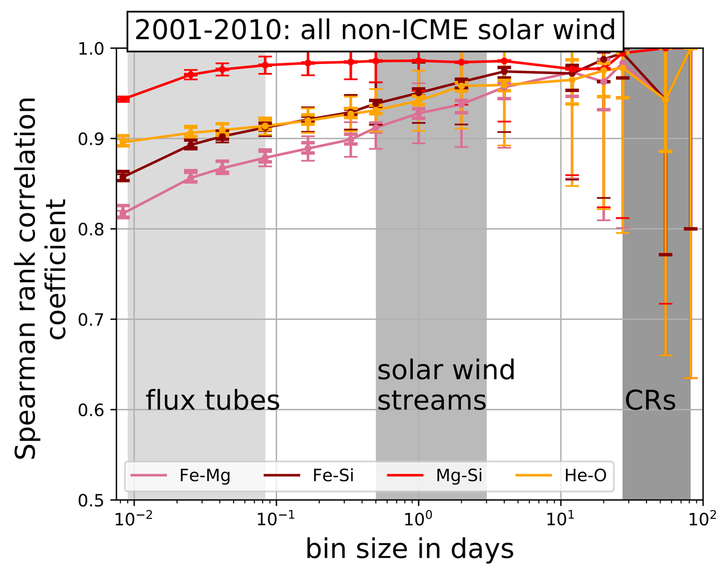
$$\text{FIP bias } f(X) = \frac{\left(\frac{n_X}{n_O}\right)_{sw}}{\left(\frac{n_X}{n_O}\right)_{photo}}.$$



Time series of FIP ratios for Fe, Mg, and Si. Are these always well correlated?

Spearman ranking correlations on different time scales

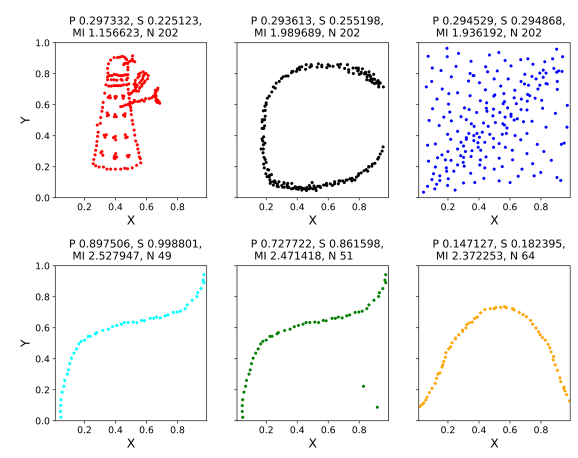
We start with the native time resolution of ACE/SWICS and rebin the ten year time series of Mg, Si, Fe, O, and He into bin sizes of: 12 min, 36 min, 1h, 2h, 4h, 8h, 12h, 1d, (2d, 4d, 12d, 20d, 27.24 d (≙ 1 Carrington rotation), 2CRs, 3CRs).



Spearman rank correlation coefficients between ten year time series of count rates of Fe vs Mg, Fe vs Si, Mg vs Si, and He vs O. Two types of error bars are included: Thin error bars: statistical error of Spearman rank correlation coefficient based on sample size. Thick error bars: Influence of an individual CR.

The shorter the time scale, the lower are the Spearman rank correlation coefficients. Nevertheless, for all considered time scales Mg and Si are well-correlated. For times scales in the order of flux tubes (time the spacecraft travels through an individual flux tube based on [2]), the correlations between Fe and Mg degrade.

Is the Spearman ranking coefficient answering the right question?



Mutual information

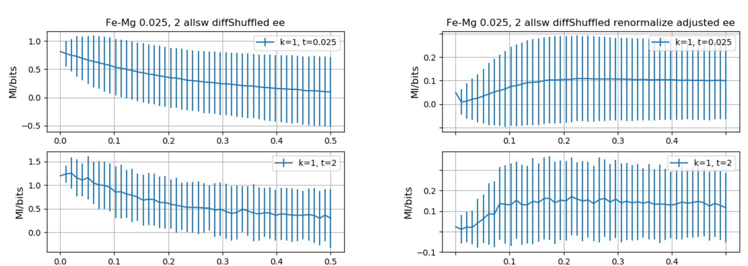
The mutual information I of two random variables X and Y can be expressed in terms of the entropy ($H(X)$ and $H(Y)$) of each random variable and their joint entropy $H(X,Y)$:

$$I(X,Y) = H(X,Y) - H(X|Y) - H(Y|X)$$

In pratice, two questions need to be answered:

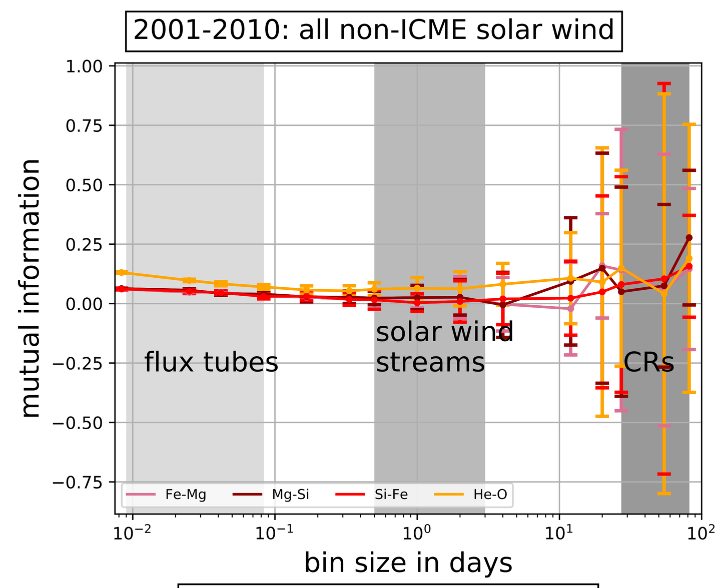
1. How to estimate the distributions $p(X)$, $p(Y)$, $p(X,Y)$?
2. How to normalize the mutual information such that different samples sizes are comaprable?

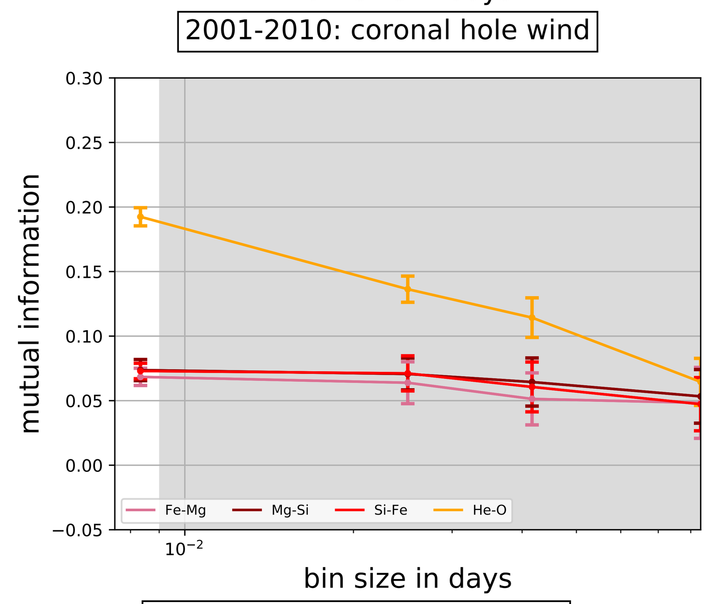
Stability of mutual information score depending on sample size [5]

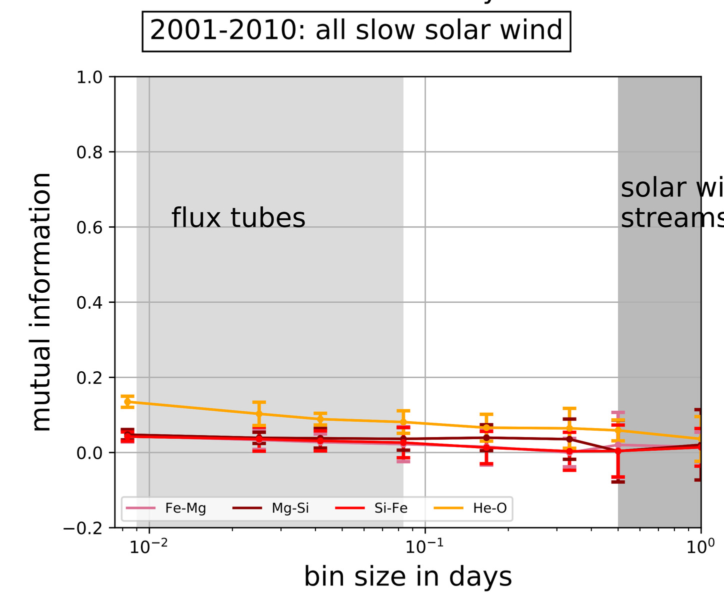


Errorbars are derived in a similar way: a cross-validation error is computed for different subsample sizes and extrapolated to the full sample size. The mutual information has been computed with `https://github.com/gregversteeg/NPEET`. Here, the distributions are estimated with a k nearest-neighbor approach ([8]), with $k = 1$. "diff-Shuffled" refers to randomly shuffling X and Y 20 times, and then using the median of the mutual information computed on the shuffled data sets as an estimator for the expected mutual information. In addition, in the "adjusted" case, the mutual information is also normalized by $\text{mean}(H(X), X(Y))$.

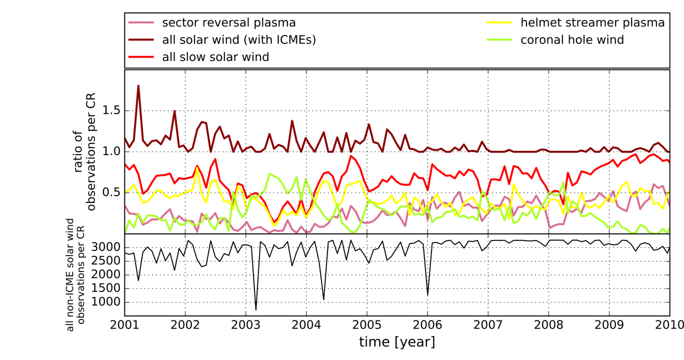
Mutual information of elemental abundances on different time scales





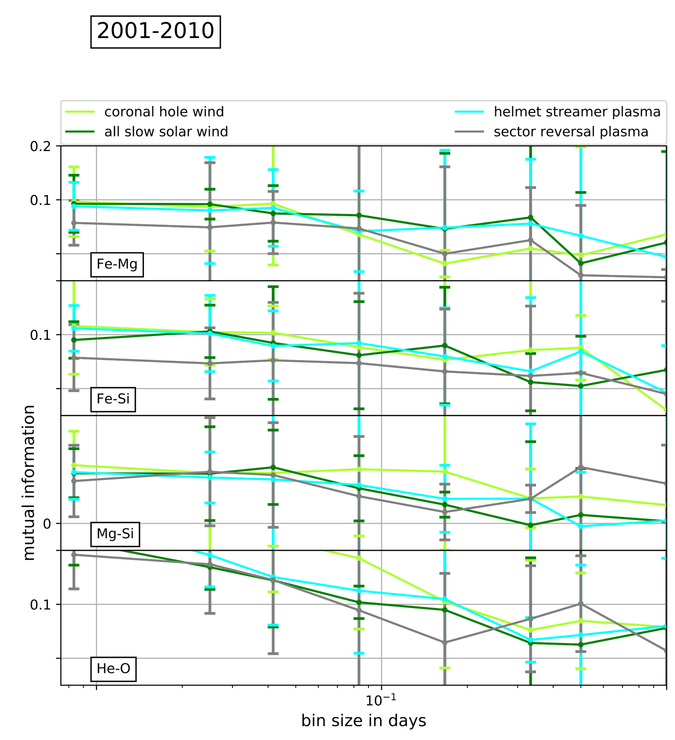


Solar wind type mix



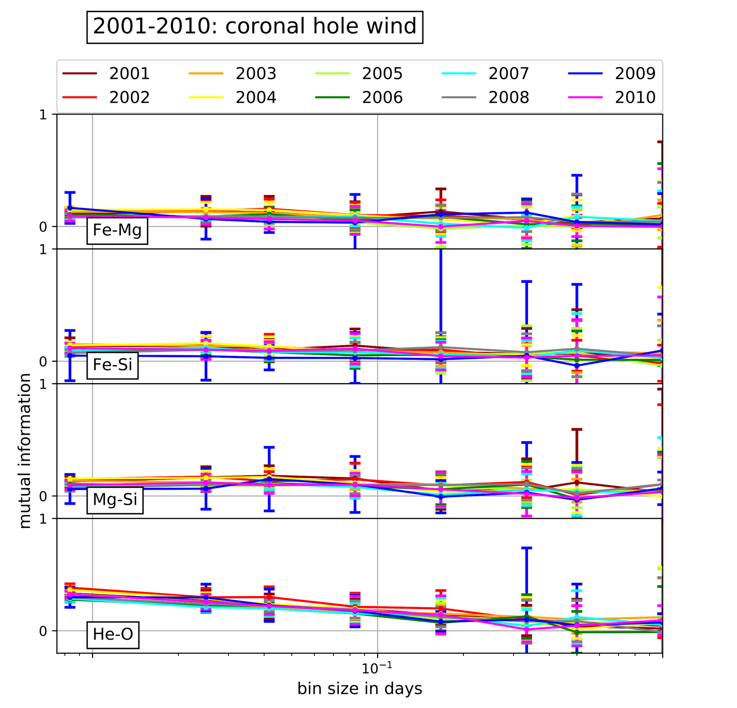
Ratio of observations of solar wind types (modified [12] scheme) relative to all solar wind (without ICMEs) over time. 2009 contains very few coronal hole wind observations, whereas in 2003 coronal hole wind was observed most frequently.

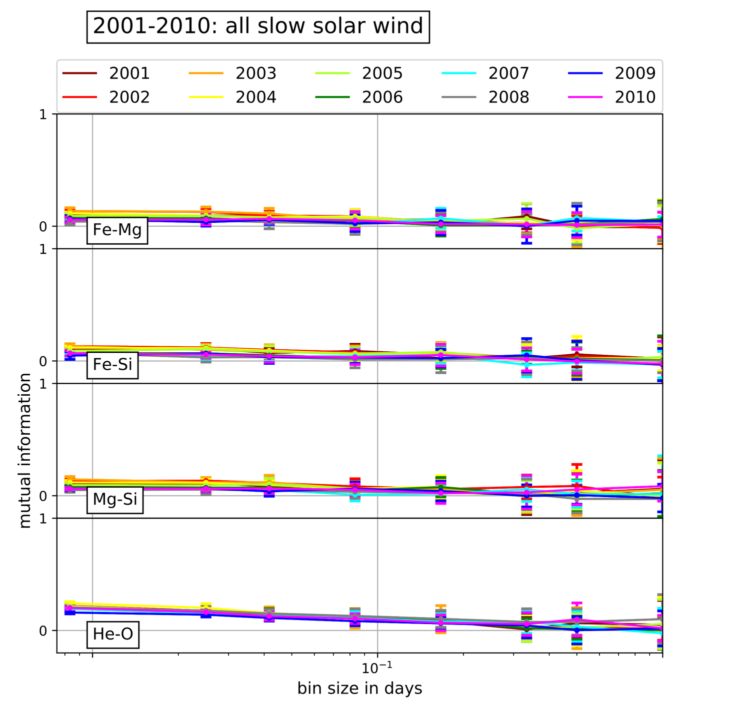
Solar wind type dependency



Solar cycle dependency

Mutual information for each ion pair per year and solar wind type (top: coronal hole wind, bottom: all slow solar wind). Both slow solar wind types show a weak solar cycle dependence.





Conclusions

- ▶ The Spearman ranking coefficient shows with decreasing time scale always a decreasing correlation for all considered pairs of elements. The mutual information score shows a weak opposite trend.
- ▶ Under the mutual information score, the difference between the different low FIP elements are small. However, also for short time scales, the adjusted mutual information score is low (< 0.2). For Solar Orbiter this implies that the low FIP elements Fg, Mg, and Si are not interchangable.
- ▶ The mutual information score is higher during solar activity maximum than during solar activity minimum in part because of a different mix of coronal hole and slow solar wind.
- ▶ On average, higher mutual inforamtion scores for coronal hole wind than for slow solar wind are observed.

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