

Heavy ion abundances evolve with solar activity

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ABSTRACT

Context. When observed at 1 AU, solar wind traveling at slow speeds ($v_{\text{sw}} \lesssim 500 \text{ km s}^{-1}$) is typically considered to have originated in source regions with magnetic topologies that are intermittently open to the heliosphere. Solar wind with fast speeds ($v_{\text{sw}} \gtrsim 500 \text{ km s}^{-1}$) is generally believed to have originated in source regions that are continuously open to the heliosphere, such as coronal holes. The evolution of the solar wind helium abundance (A_{He}) with solar activity is likely driven by the evolution of different solar wind source regions. The change in the gradient of A_{He} and heavier elements with increasing v_{sw} can be used to identify characteristic speeds at which the dominant source of solar wind transition from source regions that have intermittently to continuously open magnetic topologies. However, these observations are typically limited to slow and intermediate speed solar wind ($\lesssim 600 \text{ km/s}$) because slow wind is observed in the ecliptic more often than fast wind.

Aims. We aim to increase the maximum speed above which such analyses of the association between solar wind abundances and solar activity can be performed, extending it up to 800 km s^{-1} . This stands as a rough upper limit on non-transient solar wind speeds when observed near 1 AU. We also aim to characterize the evolution of heavy element abundances $(X/H):(X/H)_{\text{photo}}$ with solar activity. This analysis provides insight into the evolution of solar wind source regions with solar activity.

Methods. We separate the solar wind into “fast” and “slow” for each element’s abundance based on the characteristic speed previously derived for it. We analyzed the evolution of helium and heavy element abundances with solar activity using ACE/SWICS observations in each speed interval and correlated these abundances with solar activity, as indicated by the 13-month smoothed sunspot number and a normalized version that accounts for the sunspot number’s amplitude in each cycle. We normalize the sunspot number to its maximum in each solar cycle to convert it to an amplitude-independent clock for timing the phase of solar activity. Finally, a comparison of the SWICS abundances with A_{He} derived from Wind/SWE observations offers a validation of our work.

Results. We show that (1) A_{He} is strongly correlated with sunspot number in the slow and fast wind; (2) the average non-transient solar wind A_{He} is limited to 51% of its photospheric value; (3) slow-wind heavy element abundances (with the exception of C) do evolve significantly with solar activity; (4) fast-wind heavy element abundances do not evolve with solar activity to a significant extent; (5) the correlation coefficient with sunspot number of elemental abundances for species heavier than He monotonically increases with increasing mass; and (6) the correlation coefficients between the in situ observations and the normalized sunspot number are stronger than those using the unnormalized sunspot number. We also report that the minimum in heavy element abundances may be closer to the rapid depletions and recoveries of A_{He} that precede and predict sunspot minima (i.e. the helium shutoff). However a higher time-resolution analysis is necessary to properly characterize this signature.

Conclusions. We infer that (1) the sunspot number is indeed a clock timing the solar cycle, but not a driver of the physical process underlying the evolution of A_{He} and heavy element abundances with solar activity; (2) this underlying process is likely related to the energy available to accelerate the solar plasma from the chromosphere and transition region or low corona into the solar wind; and (3) the differences between the evolution of slow and fast solar wind A_{He} and heavy element abundances are similarly related to the energy available to accelerate the elements at these heights above the Sun’s surface.

Key words. Sun: abundances – Sun: activity – Sun: heliosphere – solar wind

1. Introduction

Broadly, there are two classes of solar wind sources on the Sun. Solar wind originating from sources with magnetic fields that are continuously open to interplanetary space such as coronal holes (Phillips et al. 1994; Geiss et al. 1995b) tends to be accelerated to faster speeds and carry significant non-thermal features (Kasper et al. 2006, 2008, 2017; Tracy et al. 2015, 2016; Stakhiv et al. 2016; Alterman et al. 2018; Berger et al. 2011; Klein et al. 2021; Verniero et al. 2020, 2022; Āurovcová et al.

2019). Sources with magnetic fields that are intermittently open to interplanetary space, such as helmet streamers, pseudostreamers, the boundaries between pseudostreamers and coronal holes (CHs), and the separatrix or S-Web (Fisk et al. 1999; Subramanian et al. 2010; Antiochos et al. 2011; Crooker et al. 2012; Abbo et al. 2016; Antonucci et al. 2005), tend to accelerate a slower wind that is more thermalized (i.e. displaying non-thermal features are smaller or non-existent).

Due to the difficulty in measuring absolute densities of heavy elements, solar wind abundances are often considered to be the ratio of the densities of two elements. In this paper, we consider solar wind abundances of helium (He) and

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heavier elements referenced to the hydrogen (H) number density (n_X/n_H for element X). We denote such abundances as X/H . These abundances are often normalized to their photospheric values $(X/H):(X/H)_{\text{photo}}$ because they are set below the sonic critical point in the chromosphere and/or transition region (Laming 2015, 2004, 2009; Schwadron et al. 1999; Geiss 1982; Geiss et al. 1995a; Rakowski & Laming 2012; Lepri & Rivera 2021; Rivera et al. 2022a). In the case of the helium abundance, we denote it as A_{He} when it is not normalized to its photospheric value for consistency with the terminology used in previous works (e.g. Aellig et al. 2001; Kasper et al. 2007, 2012; Alterman et al. 2021). The slow and fast wind have distinct fractionation patterns that reflect differences in their source regions (von Steiger et al. 2000; Geiss et al. 1995a,b; Zhao et al. 2017, 2022; Xu & Borovsky 2015; Fu et al. 2017, 2015; Brooks et al. 2015; Weberg et al. 2015; Zurbuchen et al. 2016; Ervin et al. 2024a; Rivera et al. 2025). As such, these abundances trace the source region features and can map in situ observations back to their sources. Several key results have been derived in this manner.

In the slow and intermediate speed wind, highly variable A_{He} evolves with solar activity (Feldman et al. 1978), which is typically quantified with the sunspot number (SSN) (SILSO World Data Center 2023), the number of optically dark spots on the Sun's surface. For solar wind speeds $v_{\text{sw}} \lesssim 500 \text{ km s}^{-1}$, the strength of the correlation between A_{He} and SSN is strongest in slower wind and decreases with increasing v_{sw} (Aellig et al. 2001; Kasper et al. 2007; Alterman & Kasper 2019). Over this speed range, the modulation of A_{He} is linear and A_{He} drops below detectable levels at the vanishing speed $v_v = 259 \pm 12 \text{ km s}^{-1}$ (Kasper et al. 2007). The modulation of A_{He} with solar activity lags SSN by 150–350 days, with a delay that increases with increasing SSN, and is likely tied to changes in the magnetic topology of solar wind source regions on the Sun (Alterman & Kasper 2019; Yogesh et al. 2021).

In contrast to the long duration evolution of A_{He} with solar activity, Alterman et al. (2021) observed a rapid depletion and recovery of the helium abundance that is concurrent in time across all $v_{\text{sw}} \leq 601 \text{ km s}^{-1}$. They refer to this as the “helium shutoff”. It precedes sunspot minima by 229–300 days and the uncertainty on this value is dominated by the 250-day averaging window. They argue that this process is driven by a physical mechanism in or below the chromosphere and transition region because it impacts A_{He} (which is set in these regions) irrespective of v_{sw} (which is set above these heights). They further posit that the driving mechanism is related to the cancellation of the equatorial component of the buoyant toroidal magnetic flux near the equator that cancels during the death of each solar cycle.

With these abundances, we can differentiate between the solar wind from different types of source regions in a manner that is more rigorous than speed alone (von Steiger et al. 2000; Geiss et al. 1995a,b; Zhao et al. 2022; Xu & Borovsky 2015; Fu et al. 2017, 2015; Lepri et al. 2013). Lepri et al. (2013) showed that heavy ion abundances referenced to H are depleted in fast and slow wind during solar minima with respect to solar maxima, with the depletion being more significant in the slow wind, rather than fast wind. The first ionization potential (FIP) bias is the enhancement with respect to photospheric values of elements with $\text{FIP} < 10 \text{ eV}$ above high $\text{FIP} > 10 \text{ eV}$ elements. Although both fast and slow abundances with respect to H are depleted during solar minima in comparison to solar maxima, the fast wind's FIP bias does vary with solar activity and that of the slow wind does not. Synthesizing these different observations, the authors inferred that average iron charge state ($\langle Q_{\text{Fe}} \rangle$)

observations suggest that these differences between the fast and slow wind are mainly generated in the low corona, “where C and O freeze-in, and then the two winds experience a similar evolution in the extended corona, where Fe freezes-in” (Lepri et al. 2013).

Observations of quiescent streamers suggest that neither the coronal electron temperature nor density vary with solar activity and, as such, the observed changes in charge state ratios must be related to changes above the heights at which the quiescent streamers are observed or in the efficiency of solar wind acceleration over the solar cycle (Landi & Testa 2014). As different solar wind source regions likely accelerate solar wind with different efficiencies, this latter inference could also indicate a difference in the frequency at which solar wind originating in different source regions is observed over the solar cycle. Kasper et al. (2007) proposed two sources for the slow wind:

1. active regions (ARs), which produce solar wind with slow speeds and helium abundances that resemble fast wind and are observed more often during solar maxima;
2. the streamer belt, which is highly variable, carries signatures of gravitational settling and is primarily observed during solar minima.

Models have shown that the coronal heat flux into the transition region modulates the solar wind speed by modifying coronal densities and electron heating in the transition region (Lie-Svendsen et al. 2001, 2002). Comparisons between (1) A_{He} , (2) the solar wind iron-to-oxygen ratio normalized to its photospheric value $(\text{Fe}/\text{O}):(\text{Fe}/\text{O})_{\text{photo}}$, and (3) $\langle Q_{\text{Fe}} \rangle$ along with the variation of these quantities with both solar activity and the transition region (TR) scale size (McIntosh et al. 2011) suggest that the decrease in A_{He} during solar minima is driven by the evolution of the coronal heat flux into the transition region with solar activity because changes in this heat flux impact the energy available the plasma at transition region depths. This coupling is likely related to the local magnetic topology, which also implies that it varies with source region (Alterman & D'Amicis 2025, Section 4.3 and references therein) and, therefore, changes in the solar wind acceleration efficiency across these regions.

To statistically quantify the relationship between composition and changes in v_{sw} for source regions with continuously and intermittently open magnetic fields, Alterman & D'Amicis (2025, hereafter *Helium Saturation Paper*) have characterized the change in gradient of A_{He} derived from the Wind Faraday cups (Ogilvie et al. 1995; Kasper et al. 2006) as a function of v_{sw} ($\nabla_{v_{\text{sw}}} A_{\text{He}}$) with a bi-linear fit. Here, v_{sw} is calculated as the bulk proton speed. Because $\nabla_{v_{\text{sw}}} A_{\text{He}}$ for speeds $v > v_s$ is approximately zero, they call this the helium saturation point $(v_{\text{sw}}, A_{\text{He}}) = (v_s, A_s)$ with the saturation speed, v_s , and saturation abundance, A_s . With this technique, Alterman & D'Amicis (2025) have derived the saturation speed ($v_s = 433 \text{ km s}^{-1}$) and abundance ($A_s = 4.19\%$) at which $\nabla_{v_{\text{sw}}} A_{\text{He}}$ changes from highly variable when $v_{\text{sw}} < v_s$ (slow wind) to fixed at $A_s \approx 4.19\%$ for speeds $v_{\text{sw}} > v_s$ (fast wind).

The normalized cross helicity, σ_c , is a measure of the correlation between fluctuations in the components of the solar wind's velocity and magnetic field. It is given by $\sigma_c = \frac{e^+ - e^-}{e^+ + e^-}$, where $e^\pm = \frac{1}{2} \langle (z^\pm)^2 \rangle$ are the energies in the Elsässer variables (Elsasser 1950; Tu et al. 1989; Grappin et al. 1991). The Elsässer variables are $z^\pm = v \pm \frac{1}{\sqrt{\mu_0 \rho}} b$ for velocity, v , magnetic field, b , mass density, ρ , and permeability of free space, μ_0 . The cross helicity can be used to quantify how Alfvénic solar wind fluctuations are (Tu & Marsch 1995; Bruno & Carbone 2013; Woodham et al. 2018; Alterman & D'Amicis 2025).

Quantifying how $\nabla_{v_{\text{sw}}} A_{\text{He}}$, and (v_s, A_s) change with $|\sigma_c|$, the [Helium Saturation Paper](#) argued that solar wind with speeds $v_{\text{sw}} < v_s$ observed at 1 AU predominantly originates in intermittently open source regions, while solar wind with speeds $v_{\text{sw}} > v_s$ predominantly come from continuously open sources. They drew this inference, in part, because A_{He} is set in the chromosphere and/or transition region (i.e., below the sonic critical point), while σ_c is modified by motion in the corona (e.g., interchange reconnection) until the solar wind crosses the Alfvén critical surface, above which $|\sigma_c|$ primarily decays during propagation through interplanetary space ([Marsch & Tu 1990](#)). Figure 2 from the [Helium Saturation Paper](#) is a cartoon illustrating how A_{He} and $|\sigma_c|$ are set at different heights above the solar surface, along with the relationship between these quantities and the solar wind speed.

The Alfvénic slow wind (ASW) is solar wind that is described as having characteristically slow speeds, but with other properties including a helium-to-hydrogen temperature ratios, non-zero He and heavy ion flow velocities in excess of H, and high levels of correlation between the H velocity and magnetic field that reflect the typical fast wind ([D’Amicis et al. 2021a,b, 2018, 2016, 2011](#); [D’Amicis & Bruno 2015](#); [Yardley et al. 2024](#); [Marsch et al. 1981](#); [Ervin et al. 2024b](#); [Rivera et al. 2025](#); [Helium Saturation Paper](#)). The [Helium Saturation Paper](#) characterized v_{sw} as a function of $|\sigma_c|$ and A_{He} , revealing that ASW is an exception to the classification of solar wind with speeds that are either slower or faster than v_s as coming from intermittently and continuously open source regions, respectively. This is because ASW is the slow speed extension of solar wind born in continuously open regions.

To characterize the dependence of (v_s, A_s) on the solar wind composition, [Alterman et al. \(2025, hereafter Composition Saturation Paper\)](#) applied the same bilinear or saturation fitting technique from the study of [Helium Saturation Paper](#) to heavy ion abundances X/H derived from observations carried out with the Advanced Composition Explorer (ACE, [Stone et al. 1998](#)) Solar Wind Ion Composition Experiment (SWICS, [Gloeckler et al. 1998](#)). We used the 12-minute H densities reported by SWICS, down-sampled to the heavy ion measurement cadence. Because they utilized heavy-ion composition observations, [Composition Saturation Paper](#) normalized their abundances to their photospheric values $(X/H):(X/H)_{\text{photo}}$. As in [Composition Saturation Paper](#), we denote the SWE helium abundance as A_{He} and the SWICS helium abundance as $(\text{He}/\text{H}):(\text{He}/\text{H})_{\text{photo}}$. The [Composition Saturation Paper](#) shows an agreement between the helium saturation point derived from both Wind and ACE observations. In the worst case, v_s is 15 km s^{-1} different between the two instruments and A_s differs by at most 0.019 percentage points between the two instruments, indicating the reliability of extending the analysis of the [Helium Saturation Paper](#) from Wind/FC observations to ACE/SWICS observations. These authors then showed that the gradient of heavy ion abundances as a function of v_{sw} is independent of M, Q, M/Q, FIP, and so on in the slow wind, suggesting that the processes that set heavy ion abundances in the slow wind do not include a preferential coupling to any element. In contrast, A_s in Figure 5 of the [Composition Saturation Paper](#) shows the fast solar wind dependence on FIP expected from [Zurbuchen et al. \(2016\)](#), which is likely due to fractionation in the chromospheric and transition region. The [Composition Saturation Paper](#) also reported several unexpected results. First, the saturation speed for elements heavier than He is $v_s = 327 \pm 2 \text{ km s}^{-1}$, independent of mass. From this, they inferred that some process preferentially couples with He, but not heavier elements. Then they showed that v_s values for helium are faster than those for the heavy ion

v_s by 63 km s^{-1} . From this, they inferred that He is impacted above the sonic critical point by an acceleration mechanism in a manner that heavy ions are not. Because the peak of the solar wind distribution at 1 AU separates the He and heavy v_s speeds, this observation may also be consistent with heavy elements being drawn out of the corona via collisional coupling with H, but with He being accelerated in a different fashion. Finally, they reported a heavy ion fractionation in fast solar wind that depends on average heavy ion charge state (Q) or (to a lesser extent) heavy ion mass (M), but not on the mass-per-charge ratio (M/Q). However, they did not provide an explanation for this.

In this Letter, we utilize the results of [Composition Saturation Paper](#) to split heavy ion abundances into solar wind predominantly from magnetically closed regions (slow solar wind) and magnetically open regions (fast wind). We then characterize how A_{He} and heavy ion abundances of He, C, N, O, Ne, Mg, Si, S, and Fe normalized to H evolve with solar activity. Solar activity is quantified by the 13-month smoothed sunspot number ([SILSO World Data Center 2023](#)) in the same manner as has previously been applied to A_{He} ([Aellig et al. 2001](#); [Kasper et al. 2007, 2012](#); [McIntosh et al. 2011](#); [Alterman & Kasper 2019](#); [Alterman et al. 2021](#)). To account for how the amplitude of SSN changes across solar cycles, we calculated a normalized SSN (NSSN) that scales SSN in each activity cycle to its maximum value ([Zhao et al. 2013](#)). By splitting each element into intervals that are faster and slower than its saturation speed, we are also able to extend the analysis of A_{He} to faster speeds. We report that $(X/H):(X/H)_{\text{photo}}$ and A_{He} from slow solar wind vary with solar activity. The variation of A_{He} in fast solar wind with SSN is also strong, but the correlation coefficients between fast wind $(X/H):(X/H)_{\text{photo}}$ and SSN are insufficiently significant to draw inferences. Comparing A_{He} observed by SWICS and SWE, we cannot rule out that low p -values derived with SWICS observations in fast wind may be due to the limited time period of observations. For the slow solar wind, the correlation between SSN and $(X/H):(X/H)_{\text{photo}}$ for elements heavier than He monotonically increases with increasing mass. In particular, these slow wind correlation coefficients increase from 0.49 for $(\text{C}/\text{H}):(\text{C}/\text{H})_{\text{photo}}$ to 0.81 for $(\text{Fe}/\text{H}):(\text{Fe}/\text{H})_{\text{photo}}$, which is as strong as $(\text{He}/\text{H}):(\text{He}/\text{H})_{\text{photo}}$. We interpret the increase of this correlation coefficient with increasing element mass as a signature of gravitational settling, while the strong correlation coefficient between $(\text{He}/\text{H}):(\text{He}/\text{H})_{\text{photo}}$ and SSN is more likely related to how helium is dynamically relevant for solar wind acceleration.

2. Observations

In this study, we used the same dataset as in the [Composition Saturation Paper](#). We combined observations of A_{He} from the Wind ([Acuña et al. 1995](#)) Solar Wind Experiment (SWE, [Ogilvie et al. 1995](#)) Faraday cups (FC) with heavy ion observations from the Advanced Composition Explorer (ACE, [Stone et al. 1998](#)) Solar Wind Ion Composition Spectrometer (SWICS, [Gloeckler et al. 1998](#)), a charge-resolving ion mass spectrometer. We used H and He observations available from the ACE Science Center ([Garrard et al. 1998](#)) using the same formulation as [Lepri et al. \(2013\)](#). A detailed discussion of the instruments are available in the cited papers. Both ACE and Wind observations are exclusively collected in the ecliptic plane. We used the 13-month smoothed sunspot number (SSN) to trace solar activity ([SILSO World Data Center 2023](#)). To calculate the normalized sunspot number (NSSN), we subtracted the minimum SSN during each cycle and then normalized this shifted SSN in a given cycle to its maximum value in that cycle. For

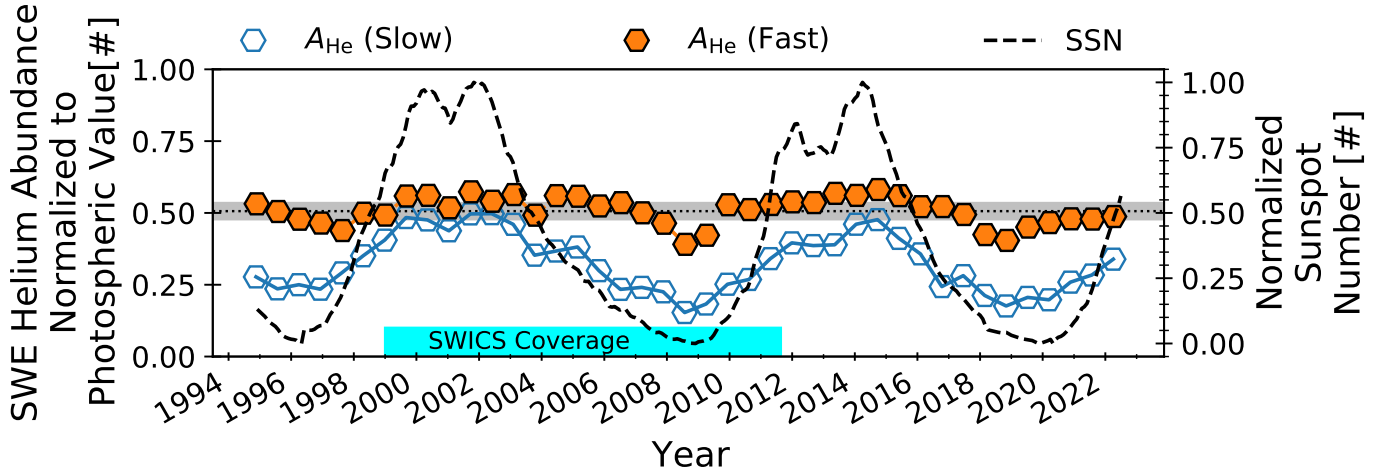


Fig. 1. SWE helium abundance in fast (filled marker) and slow (empty marker) wind intervals as a function of time, aggregated down to 250 days. The right axis plots the normalized 13-month smoothed sunspot number. The horizontal dotted line surrounded by the gray band indicating $A_{\text{He}} = 51 \pm 3\%$ of its photospheric value is the weighted mean of the 250-day binned values along with the weighted uncertainty, where the weights are calculated as the standard deviation of A_{He} in each 250-day bin.

solar cycle 25, we used a maximum SSN of 160.6, which is the prediction from NOAA's Space Weather Prediction Testbed¹.

3. Analysis

Figure 1 plots the SWE helium abundance as a function of time. The abundance has been split into fast and slow wind intervals, where the transition is defined by the speed $v_s = 420 \text{ km s}^{-1}$, at which the gradient of A_{He} as a function of v_{sw} changes (Composition Saturation Paper). The interval over which SWICS observations are available is indicated at the bottom of the panel. Over the full time period plotted, the correlation coefficients between the SWE abundances and SSN are 0.94 (slow wind) and 0.66 (fast wind), both with p -values < 0.05 . Using NSSN, we get 0.95 (slow wind) and 0.72 (fast wind) with p -values < 0.05 . When only considering the time period for which SWICS observations are available, the correlation coefficients change to 0.95 (slow wind) and 0.75 (fast wind), again with p -values of < 0.05 . Using NSSN, we get 0.95 (slow wind) and 0.76 (fast wind) with p -values < 0.05 . These results are summarized in Table 1.

In Figure 1, the horizontal dotted line indicates $A_{\text{He}} = 51 \pm 3\%$ with respect to the photospheric helium abundance, which is the weighted mean of the fast wind observations in the 250-day intervals. Here, the weights are calculated as the standard deviation of A_{He} in each 250-day interval and the gray band indicates the weighted uncertainty. The fast wind observations, which are predominantly from continuously open source regions, oscillate around half of the photospheric A_{He} . Slow wind A_{He} , which is predominantly from intermittently open source regions. It oscillates around a much larger range of values and reaches a maximum of this 51% level during solar maxima.

Figure 2 plots the SWICS abundances as a function of time in (a) fast and (b) slow wind. In Figure 1, we calculate A_{He} as the simple average over the interval. In Figure 2, we calculate the weighted mean and standard error of the weighted mean because SWICS observations are reported with a 2 h cadence, instead of 92s by SWE. A_{He} derived from SWE observations is normalized to its photospheric value and plotted to show consistency with SWICS He/H. The right axes indicate the normalized 13-month smoothed SSN. The vertical dotted lines indicate solar minimum 24. The vertical dash-dotted line indicate the helium shutoff preceding solar minimum 24. In general, there is a rough stratification in the abundances such that low FIP abundances are higher than high FIP abundances across the solar cycle. With the exception of slow wind S and fast wind Si, the observed minimum of fast wind $(X/H):(X/H)_{\text{photo}}$ precedes solar minimum 24 by 122 days and follows helium shutoff by 62 days.

Table 1. Correlation Coefficients between Abundances and SSN.

	Slow Wind			Fast Wind		
	SWE	SSN	NSSN	SWE	SSN	NSSN
SWE*	–	0.94	0.95	–	0.66	0.72
SWE	–	0.95	0.95	–	0.75	0.76
He	0.84	0.81	0.84	0.55	0.50	0.50
C	0.62	0.51	0.56	–	–	–
N	0.80	0.67	0.70	–	–	–
O	0.84	0.74	0.76	–	–	–
Ne	0.88	0.72	0.74	–	–	–
Mg	0.90	0.76	0.78	0.58	0.53	0.59
Si	0.90	0.79	0.81	0.62	0.53	0.58
S	0.91	0.77	0.78	0.52	–	0.48
Fe	0.93	0.82	0.84	0.72	0.59	0.66

Notes. Fast and slow wind correlation coefficients for the species identified in the first column. The columns labeled SWE provide the correlation coefficient between a given species and A_{He} observed by the SWE Faraday cups. Columns labeled SSN and NSSN give the correlation coefficient between a given abundance as SSN and NSSN, respectively. The row labels SWE* provides the correlation coefficients between A_{He} and SSN over the full time period plotted in Figure 1. The row labeled SWE provides the same correlation coefficients calculated over the time period when SWICS data is available. Only significant coefficients with p -values < 0.05 are shown.

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To characterize the evolution of these abundances with solar activity, we calculated the correlation coefficient between each abundance and NSSN. For the SWE abundance, this is limited to the same time period over which the SWICS abundances are available. We also calculated the correlation coefficient between

¹ <https://testbed.spaceweather.gov/products/solar-cycle-progression-updated-prediction-experimental>

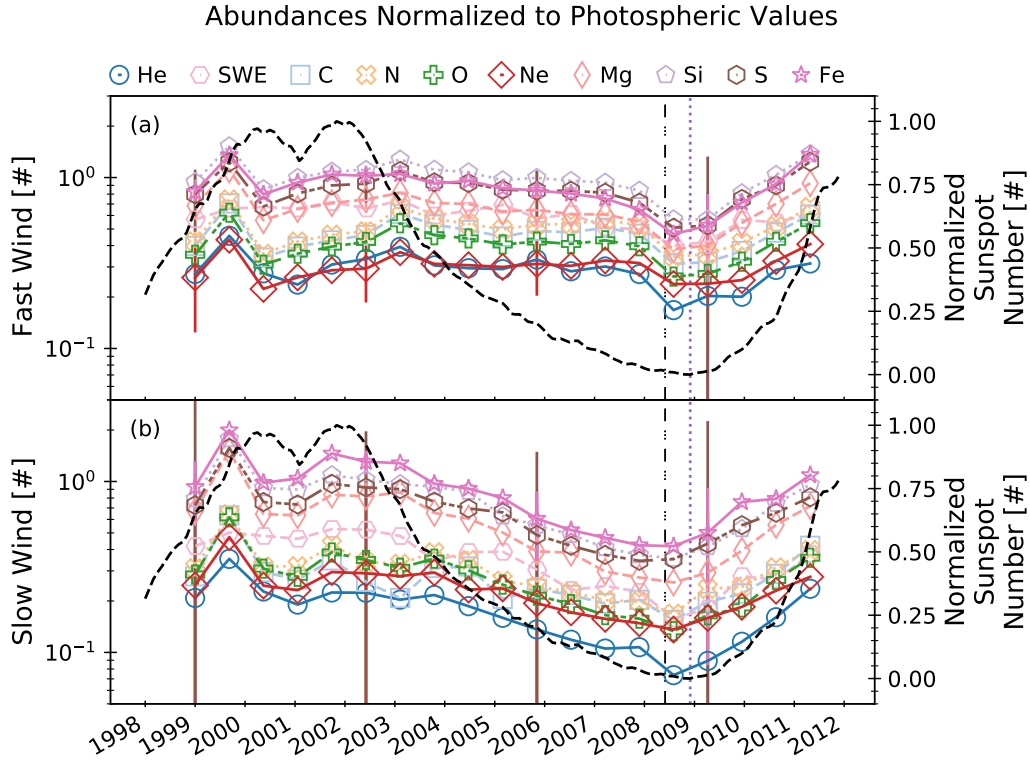


Fig. 2. SWICS abundances normalized to their photospheric values in (a) fast and (b) slow wind as a function of time, aggregated in 250-day intervals. The right axes plots the normalized 13-month smoothed sunspot number. The SWE abundances normalized to its photospheric values are plotted for reference. The vertical dotted lines indicate solar minimum 24. The vertical dash-dotted line indicates the helium shutoff (Alterman et al. 2021).

all SWICS abundances and the SWE abundance. These correlation coefficients are calculated for slow wind ($v_{sw} < v_s$) and fast wind ($v_{sw} > v_s$), where v_s is defined as in Composition Saturation Paper for each species. As the SWE and SWICS data have a different observation cadence, the boundaries of each data set's 250-day intervals do not necessarily overlap. As such, the SWE data have been interpolated to the SWICS observation time for this calculation. Table 1 summarizes these correlation coefficients for both slow and fast wind.

The SWE columns indicates the correlation coefficients between $(X/H):(X/H)_{photo}$ and A_{He} . The SSN columns indicate the correlation coefficients between a given abundance and SSN. Similarly, the NSSN column indicates the correlation coefficients between a given abundance and NSSN. Only significant correlation coefficients (p -value < 0.05) are shown. The correlation coefficient between fast and slow wind SWE abundances and SSN is stronger than the correlation between SWICS abundances and SSN. In general, the correlation coefficients derived for slow wind observations increase with increasing mass and (excluding C) all are strong (>0.6 for SSN and >0.7 for NSSN). In the fast wind, only four (SSN) or five (NSSN) of nine correlation coefficients using SWICS data are significant and none are strong (<0.6); the exception is the correlation coefficient between $(Fe/H):(Fe/H)_{photo}$ and NSSN, which exceeds 0.6 and is thus significant. With the exception of slow wind Fe, SWICS $(He/H):(He/H)_{photo}$ is larger than all other $(X/H):(X/H)_{photo}$ correlation coefficients with SSN. Slow wind Fe's correlation coefficient with SSN is larger to slow wind He; its correlation coefficient with NSSN in slow wind is equal to that of He. In fast wind, Fe exhibits the strongest correlation coefficient with SSN and NSSN. In the slow and fast wind, Fe exhibits the strongest correlation with A_{He} observed by SWE.

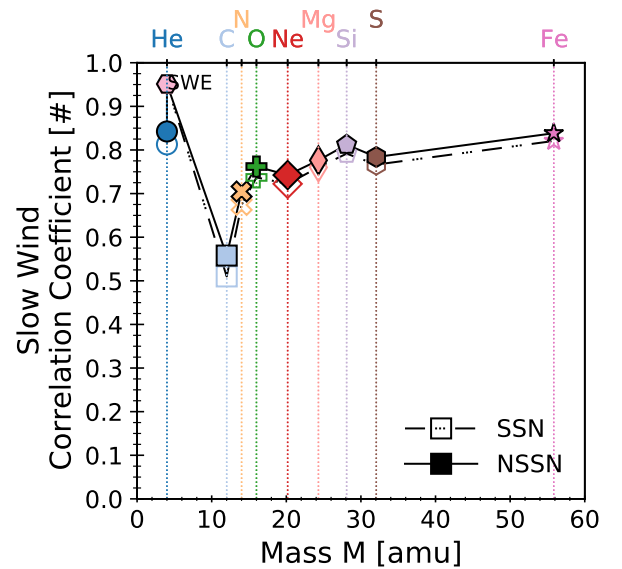


Fig. 3. Correlation coefficient between NSSN (solid line) or SSN (dash-dotted line) $(X/H):(X/H)_{photo}$ observed by ACE/SWICS along with A_{He} observed by Wind/SWE. With the exclusion of the helium abundances, the correlation coefficients monotonically increase with increasing M . All correlation coefficients using NSSN are stronger than those using SSN.

Figure 3 plots the slow wind correlation coefficients with NSSN (solid line) and SSN (dash-dotted line) as a function of element mass (M). Markers are connected to aid the eye. The top axis identifies each species in the color corresponding to the marker and a vertical dotted line in the same color connects this

label to the marker. The SWE abundance is labeled to differentiate it from the SWICS He/H. As in Table 1, the correlation coefficients using NSSN are stronger than those using SSN. For elements heavier than He, we also observe a monotonic increase in the correlation strength with increasing mass. An ordering by charge state (Q), M/Q, and FIP is less apparent.

4. Discussion

Elemental abundances are set in the chromosphere and transition region. Because such quantities are fixed by the time the coronal plasma enters the solar wind, they serve as tracers of solar wind source regions and the physical processes active there. As such, the evolution of these abundances with solar activity is driven by the evolution of their solar sources. This work applies methods that have long been used to study the evolution of the solar wind helium abundances with solar activity (Aellig et al. 2001; Kasper et al. 2007, 2012; Alterman & Kasper 2019; Alterman et al. 2021; Yogesh et al. 2021) to heavy ion composition observations. To achieve sufficient statistical reliability in the observations, we did not split the observations into ten quantiles of v_{sw} as has been done in prior work. Instead, we have split the solar wind into “slow” and “fast” regimes, where the different regimes are defined by speeds slower and faster than each species’ v_s . This “saturation speed” (v_s) is the speed at which the gradient of a given abundance as a function of v_{sw} changes. The [Composition Saturation Paper](#) calculated v_s values for heavy ion abundances observed by ACE/SWICS. When comparing v_s for heavy abundances and A_{He} , we have noted them $v_{s;Heavy}$ and $v_{s;He}$, respectively, to differentiate between the two. The [Helium Saturation Paper](#) applied the same method to Wind/FC observations of A_{He} . Based on the evolution of v_s and the abundance at this speed (the saturation abundance A_s) with normalized cross helicity, the [Helium Saturation Paper](#) argued that “fast” wind ($v_{sw} > v_s$) primarily comes from polar solar source regions with magnetic topologies that are continuously open to the heliosphere and “slow” wind ($v_{sw} < v_s$) primarily comes from equatorial solar source regions with magnetic topologies that are only intermittently open to the heliosphere. The [Composition Saturation Paper](#) showed that (1) the gradient of $(X/H):(X/H)_{photo}$ and A_{He} for speeds $v_{sw} < v_s$ are indistinguishable; (2) the heavy element saturation speeds is $v_{s;Heavy} = 327 \pm 2 \text{ km s}^{-1}$ across all elements heavier than He; (3) $v_{s;Heavy} > v_{s;He}$ by $63 \pm 4.5 \text{ km s}^{-1}$; and (4) there is a mass- or charge-state- dependent fractionation of $(X/H):(X/H)_{photo}$ for speeds $v_{sw} > v_s$. From the first observation, the [Composition Saturation Paper](#) inferred that heavy element and He abundances are driven by the same process over speeds $v_{sw} < v_s$. From the second and third observations, they inferred that the process impacting $(X/H):(X/H)_{photo}$ and A_{He} for speeds $v_{sw} < v_s$ takes place below heights at which v_{sw} is established. Therefore, this is likely to occur in the chromosphere and/or transition region. These authors have argued that both of these results are consistent with gravitational settling. From the fourth observation, they identified a mass- or charge-state- dependent fractionation process that becomes increasingly significant with increasing speed; however, they provided no justification for this empirical observation.

4.1. SWE abundances

Figure 1 plots the solar wind helium abundance in two speed intervals: faster and slower than v_s . The correlation coefficient

between A_{He} and SSN in both speed intervals is high (>0.6 or better). Alterman & Kasper (2019) analyzed A_{He} ’s evolution with SSN across ten speed quantiles. The data in each quantile were aggregated into 250-day intervals. The slow wind interval defined in this work covers their seven slowest speed quantiles. Over these quantiles, the correlation coefficient between A_{He} and SSN exceeds 0.8. The fast wind interval defined in this work covers the three fastest speed intervals from Alterman & Kasper (2019) along with faster wind. This allowed us to extend the range of this analysis from a maximum of $v_{sw} \approx 600 \text{ km s}^{-1}$ to $v_{sw} \approx 800 \text{ km s}^{-1}$ (Aellig et al. 2001; Kasper et al. 2007, 2012; Alterman & Kasper 2019; Alterman et al. 2021). In these faster speed quantiles, the correlation coefficient between A_{He} and SSN markedly drops to below 0.7. These correlation coefficients likely exceed those reported by Kasper et al. (2007) across all speeds and those reported by Kasper et al. (2012) in faster quantiles because longer time intervals reduce the impact of fluctuations when calculating the correlation coefficients between two time series. This is, for example, why the two solar cycles of activity reported by Alterman & Kasper (2019) enabled the authors to characterize the v_{sw} -dependent phase lag in the response of A_{He} to changes in the SSN. As such, although the speed intervals reported in this paper are markedly larger than those reported by Alterman & Kasper (2019), Kasper et al. (2007, 2012) and speeds $v_{sw} < v_s$ aggregate over the speed-dependent phase lag between A_{He} and SSN (Alterman & Kasper 2019), the larger speed intervals in this paper are less sensitive to fluctuations in the aggregated values. This is likely why the correlation coefficient between A_{He} and SSN for speeds $v_{sw} < v_s$ is closest to the strongest correlation coefficients reported for observations with speeds near the peak of the distribution of v_{sw} observed near 1 AU (Kasper et al. 2007, 2012; Alterman & Kasper 2019). Regarding the speeds $v_{sw} > v_s$, the probability density of the distribution of v_{sw} observed near 1 AU drops by nearly an order of magnitude from peak over the speed range 343 to $\sim 650 \text{ km s}^{-1}$. Further dividing solar wind observations into smaller speed intervals increases the significance of random fluctuations in aggregated quantities. By aggregating across a wide range of speeds, we reduced the impact of such statistical fluctuations. This is why we are able to determine that A_{He} with speeds $v_{sw} > v_s$ (and, thus, predominantly coming from source regions that are continuously open to the heliosphere) also evolves with solar activity. The fact that the correlation coefficients derived with NSSN exceed those derived with SSN in both the slow and fast wind indicates that the sunspot number is tracking the evolution of solar activity and not necessarily the physical process driving the evolution of A_{He} with it.

The photospheric helium abundance is $8.25 \pm 0.2\%$ (Asplund et al. 2021). For speeds $v_{sw} > v_s$, solar wind A_{He} oscillates around $51 \pm 0.3\%$ this value. During solar maximum, when solar wind sources with continuously open magnetic topologies (e.g., as coronal holes) are not confined to the Sun’s polar regions, solar wind A_{He} with speeds $v_{sw} < v_s$ reaches a maximum during of 47.7% (maximum 24) to 49.7% (maximum 23) of its photospheric value. Given that coronal mass ejections (CMEs) release solar plasma from deep within the solar atmosphere and are known to be enhanced in heavy element abundances and A_{He} (e.g. Yogesh et al. 2022; Rivera et al. 2022b; Song et al. 2022), coupled with the fact that slow wind A_{He} is depleted from its fast wind values, we infer that the mechanism limiting non-transient solar wind A_{He} to $\sim 50\%$ of its photospheric value occurs at heights near or below the chromosphere and transition region.

4.2. SWICS abundances

Per the [Helium Saturation Paper](#) and the [Composition Saturation Paper](#), solar wind observations at 1 AU with $v_{\text{sw}} > v_s$ predominantly come from source regions with magnetic field topologies that are continuously open to the heliosphere. In contrast, $v_{\text{sw}} < v_s$ identifies solar wind that is predominantly from intermittently open source regions. We have divided $(X/H):(X/H)_{\text{photo}}$ observations into intervals with speeds above and below v_s , where v_s is calculated independently for each species ([Composition Saturation Paper](#)). Figure 2 plots each $(X/H):(X/H)_{\text{photo}}$ as a function of time aggregated in 250-day intervals. In this plot, we label $v_{\text{sw}} > v_s$ as “fast wind” and $v_{\text{sw}} \leq v_s$ as “slow wind”. As expected, low FIP abundances are higher than high FIP abundances across the solar cycle.

According to Table 1, the correlation coefficients between SSN and these abundances is strong (>0.6) and significant (p -value < 0.05) for all species in solar wind from intermittently open source regions. The [Composition Saturation Paper](#) showed that the gradients of $(X/H):(X/H)_{\text{photo}}$ as a function of v_{sw} for $v_{\text{sw}} < v_s$ are consistent across all species. This allows us to infer that the underlying physical mechanism is not preferentially coupled to any element. With the exception of He, Figure 3 shows that the correlation coefficient between SSN and $(X/H):(X/H)_{\text{photo}}$ with slow speeds from intermittently open source regions monotonically increases with increasing M .

It is unsurprising that He does not follow the trend in Figure 3. The [Helium Saturation Paper](#) argued that He is dynamically relevant for solar wind acceleration in both continuously and intermittently open source regions. This is likely why the correlation coefficient between A_{He} and SSN is strong and significant for both the $v_{\text{sw}} < v_s$ and $v_{\text{sw}} > v_s$ speed ranges. In contrast, heavy element abundances are likely too small to be dynamically relevant to the solar plasma’s overall acceleration into the solar wind.

The similarity in the correlation coefficients of SSN with $(X/H):(X/H)_{\text{photo}}$ and A_{He} for $v_{\text{sw}} < v_s$ suggests that one or more processes drive the long term evolution of these abundances in similar ways. This is reflected in the correlation coefficients between A_{He} and $(X/H):(X/H)_{\text{photo}}$ in that they are (with the exception of C) strong and significant in slow wind with $v_{\text{sw}} < v_s$ and either weak (<0.6) or insignificant (high p -value > 0.05) in fast wind with $v_{\text{sw}} > v_s$. The fact that the correlation coefficients derived with NSSN exceed those derived with SSN further suggests that the sunspot number is a “clock” for timing solar activity, but it does not trace the underlying process driving the evolution of $(X/H):(X/H)_{\text{photo}}$.

Gravitational settling is one process that governs abundances in closed loops that is coupled to elements based on their mass, not their charge state, FIP, Q/M , and so on ([Vauclair & Charbonnel 1991](#); [Borrini et al. 1981](#); [Hirshberg 1973](#); [Weberg et al. 2015](#); [Alterman & Kasper 2019](#)). Such loops are longer lived during solar minima, leading to more depleted abundances. This mechanism does not affect solar wind from continuously open source regions where such closed loops are absent. As such, we infer that the difference between the evolution with solar activity of solar wind abundances from continuously and intermittently open source regions may be driven by gravitational settling in such regions.

That the correlation coefficient between slow wind A_{He} and SSN is higher than the heavier elements may signify that the evolution of helium with solar activity is driven by additional processes (e.g., the [Helium Saturation Paper](#), and references therein) that do not couple to heavier elements. Figure 7 in the

[Composition Saturation Paper](#) shows that $v_{s;\text{He}} = v_{s;\text{Heavy}} + 63 \text{ km s}^{-1}$ and these two speeds are separated by the peak of the solar wind speed distribution, further suggesting that some other process is accelerating He to faster speeds than heavy elements. However, we cannot rule out that the 2-h duration of SWICS measurements means that we cannot separate solar wind by speed when $v_{\text{sw}} \sim v_s$ for SWICS observations with the same precision as we can for SWE observations and that only one solar cycle of SWICS observations means that statistical fluctuations have a more significant impact on our SWICS observations than our SWE observations for $v_{\text{sw}} > v_s$.

4.3. Composition shutoff

The time between the observed minimum in fast wind $(X/H):(X/H)_{\text{photo}}$ and the helium shutoff preceding solar minimum 24 ([Alterman et al. 2021](#)) is half as long as the time between the minimum in fast wind $(X/H):(X/H)_{\text{photo}}$ and solar minimum 24. However, both of these intervals are within the 250-day averaging window and the 229-day uncertainty in the helium shutoff. As such, any inference from this observation requires higher time resolution analysis.

4.4. Drivers of the helium and heavy element abundances

[McIntosh et al. \(2011\)](#) studied how the relationship between A_{He} , the iron-to-oxygen ratio (Fe/O), average iron charge state ($\langle Q_{\text{Fe}} \rangle$), and characteristic scale size in the transition region evolve with solar activity in slow ($v_{\text{sw}} < 400 \text{ km s}^{-1}$) and fast ($v_{\text{sw}} > 500 \text{ km s}^{-1}$) solar wind. They argue that the drop in A_{He} during solar minima is consistent with a decrease in the energy available to accelerate coronal helium into the solar wind during this phase of solar activity. They suggested that this is consistent with a decrease in the transition regions scale size during solar minima, which also implies less energy available to heat the solar wind at these heights, resulting in a reduced number density ([McComas et al. 2008](#)) and $\langle Q_{\text{Fe}} \rangle$. This depletion in available energy is consistent with observations of solar wind $\text{O}^{7+}/\text{O}^{6+}$ and $\text{C}^{6+}/\text{C}^{5+}$ charge state ratios that evolve with SSN and drop during solar minima ([Kasper et al. 2012](#)). Given that coronal electron temperatures and densities likely do not change with solar activity ([Landi & Testa 2014](#)) and that the efficiency of solar wind acceleration likely varies with source regions, the evolution of these parameters with solar activity likely reflects the evolution of the frequency at which solar wind from different source regions is sampled at 1 AU.

In the case of fast wind, the solar wind originates from continuously open source regions with radial magnetic fields. In such solar wind, A_{He} and heavy ion abundances do not vary significantly because the solar wind primarily originates from a single class of source region.

In the case of slow wind, [Kasper et al. \(2012\)](#) attributed the variability of A_{He} to the occurrence of two different sources. One is ARs, the edge of which recent studies suggest may be consistent with sources of the Alfvénic slow wind ([Baker et al. 2023](#); [Yardley et al. 2024](#); [Ervin et al. 2024b](#)). The other is the streamer belt. [Alterman & Kasper \(2019\)](#) argued that the v_{sw} -dependent phase lag in the response of A_{He} to changes in SSN for speeds $v_{\text{sw}} \leq 574 \text{ km s}^{-1}$ is consistent with a He filtration mechanism. When set in the context of the results from the [Helium Saturation Paper](#), such a filtration mechanism may be related to the energy available to accelerate coronal helium into the solar wind, which varies with the source region ([Hansteen et al.](#)

1997; Endeve et al. 2005). Such an inference is consistent with Yogesh et al. (2021), who argued that this filtration mechanism is related to the topology of the Sun’s magnetic field. If the heat flux mediated coupling between the corona and transition region is significant for determining the energy available to accelerate the solar wind or, equivalently, the acceleration efficiency (Lie-Svendsen et al. 2001, 2002), such an inference is also consistent with differences between fast wind being “generated in the low corona, where C and O freeze-in, and then the two winds experience a similar evolution in the extended corona, where Fe freezes-in” (Lepri et al. 2013). If this is indeed the case, the highly variable X/H in solar wind with $v_{sw} < v_s$ also reflects the energy available to accelerate heavy ions from the solar plasma into the solar wind. The v_{sw} -dependent filtration mechanism may be related to helium’s dynamic role in solar wind acceleration (Hansteen et al. 1997; Endeve et al. 2005; Alterman & D’Amicis 2025), for which heavy element abundances are too small.

5. Conclusion

We have observed the evolution of the solar wind helium abundance and heavy element abundances with solar activity. The helium abundance observations cover approximately 22 years of Wind/SWE operations, while the abundances of heavier elements are limited to approximately 12 years during ACE/SWICS operations prior to the detector degradation. Using the solar wind helium abundance, we have made the following observations:

1. A_{He} observed in slow and fast wind is strongly correlated with the Sun’s activity cycle, as observed in SSN data.
2. The correlation coefficients derived with the normalized SSN (NSSN) are stronger than those derived with SSN, indicating that the sunspot number is a “clock” timing the evolution of solar activity, not the underlying physical process that modulates A_{He} .
3. Solar wind helium in fast wind, which is predominantly from continuously open magnetic sources, oscillates around 51% of its photospheric value.
4. In slow wind from intermittently open source regions, A_{He} is highly variable below 51% and only reaches this maximum value during solar maxima when continuously and intermittently open source regions are not confined to the Sun’s polar regions.

Using heavy ion abundances from ACE/SWICS, we have made the following observations:

1. In slow wind, the abundance of all heavy elements except C is strongly correlated with SSN.
2. In fast wind, $(X/H):(X/H)_{photo}$ abundances do not evolve significantly with solar activity. However, the more periods of oscillation observed, the less significant the impact any random fluctuations would have on the correlation coefficient. Because (a) we have more than two solar activity cycles from A_{He} observations and our observations of $(X/H):(X/H)_{photo}$ cover a time period slightly longer than one solar activity cycle and (b) fast wind oscillations are smaller in amplitude than slow wind oscillations, we cannot conclusively state that this is because $(X/H):(X/H)_{photo}$ in fast wind does not evolve with solar activity. Alternatively, the result could be due to the limited duration of our heavy ion observations.
3. The correlation coefficients derived between $(X/H):(X/H)_{photo}$ and NSSN are stronger than those derived with SSN, further indicating that the sunspot number

is tracking solar activity, but not the underlying process that drives the evolution of the abundances.

4. Unsurprisingly, the strong correlation between A_{He} and SSN along with $(X/H):(X/H)_{photo}$ and SSN is reflected in a strong correlation between A_{He} and $(X/H):(X/H)_{photo}$. That these correlation coefficients are weaker is unsurprising because we use the 13-month smoothed SSN and neither the 250-day average A_{He} nor $(X/H):(X/H)_{photo}$ are smoothed.
5. The correlation coefficients between $(X/H):(X/H)_{photo}$ and SSN monotonically increase with increasing element mass. We infer that this is a signature of gravitational settling in slow wind, which is consistent with the gradient of $(X/H):(X/H)_{photo}$ over speeds $v_{sw} < v_s$ being indistinguishable across the heavier elements (Composition Saturation Paper).
6. The helium shutoff is a precipitous depletion and recovery in A_{He} that precedes SSN minima by approximately 229 days (Alterman et al. 2021). The largest source of uncertainty on this observation is the 250-day averaging window. The minimum $(X/H):(X/H)_{photo}$ we observed precedes SSN minima by 122 days, but follows the helium shutoff by only 62 days. In other words, the time between the minimum in $(X/H):(X/H)_{photo}$ and the helium shutoff is half as long as the time between the minimum $(X/H):(X/H)_{photo}$ and SSN minima. However, the difference between these two times is smaller than the 229-day uncertainty on helium shutoff and the 250-day averaging window. As such, higher time-resolution analysis is necessary to determine if the depletion of $(X/H):(X/H)_{photo}$ during solar minima coincides with helium shutoff.

We attribute the differences between the evolution of A_{He} and $(X/H):(X/H)_{photo}$ in slow wind with solar activity to helium’s dynamic involvement in solar wind acceleration (Helium Saturation Paper, and references therein). These differences are also reflected in the difference between v_s for He and heavier elements derived in the Composition Saturation Paper. The differences in fast wind are either also related to how helium is dynamically relevant for solar wind acceleration or simply driven by the lower SWICS data volume with respect to SWE. More broadly, we infer that the variation in both A_{He} and $(X/H):(X/H)_{photo}$ with solar activity is driven by the energy in the chromosphere and transition region or low corona, which is also related to the topology of the magnetic field in the solar wind’s source regions. This suggests that the evolution of slow wind A_{He} and $(X/H):(X/H)_{photo}$ with solar activity observed at 1 AU may be due to changes in the frequency of observing solar wind from different source regions.

In closing, we note that both ACE’s and Wind’s orbits are in the ecliptic plane. Given that the occurrence rate and heliographic latitude of different solar source regions changes with solar activity, long-duration out-of-ecliptic observations are necessary to fully understand the relationship between source region and in situ abundances. Furthermore, recent results show that Alfvén wave energy deposition (Rivera et al. 2025; Alterman 2025) and thermal pressure gradients (Rivera et al. 2024) accelerate the solar wind in transit through interplanetary space. This means such out-of-ecliptic observations need to be either collected over a long duration and at a single radial distance or the relevant in situ acceleration mechanisms must be well understood so that radial gradients in v_{sw} can be properly accounted for; for instance, with observations from Ulysses/SWICS (Gloeckler et al. 1992; von Steiger et al. 2000). This approach would allow us to properly trace in situ observations back to their source regions and

such observations are a critical component of future missions (Rivera & Badman 2025).

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