The Solar Wind Abundance Mystery

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Abstract

By analyzing in situ measurements of the fast solar wind, we have found a systematic decrease in the abundance of Helium (measured by Wind) and the degree of Iron fractionation (measure by ACE and Ulysses) during the recent extended solar minimum relative to the previous minimum. These observations were also temporally accompanied by a decrease in the supergranular network emission length scale (measured by SOHO), signaling a reduction in the strength of the magnetic field and the scale over which mass and energy are transported into the quiet solar atmosphere. Together, these findings reveal that a significant change in the heating process likely took place during the recent minimum. Additionally, a decay in the helium abundance has been observed over multiple solar cycles, possibly indicative of long- term changes in the background magnetic field and energy input into the solar wind.

Introduction

The solar wind abundance mystery can be described in two parts: (1) The composition of the solar wind is observed to change with time. (2) The overabundance of heavy atoms (including Iron, Silicon and Magnesium) compared with their photospheric abundance, which is a result of an unknown physical process termed *fractionation*. Understanding these is an essential part of understanding the heating processes taking place in the lower solar atmosphere, an outstanding challenge in the solar physics community. Capturing particles coming from fast solar wind streams enables us to essentially probe this region and thus, these processes, without adding complications that arise from heating and cooling of plasma in closed loops. By analyzing compositional changes in the fast wind, we take a first step in understanding energy and mass release into the solar corona and solar wind.

Data Sources

- The Faraday Cup (FC) instrument on the *Wind* spacecraft
  - Launched in 1994 - Located at L1
  - Used for analysis the Helium abundance, A_{He}
- The Solar Wind Ion Composition Spectrometer (SWICS) on the ACE (Advanced Composition Explorer) spacecraft
  - Launched in 1997 - Located at L1
  - Used for analysis of heavy ions, specifically Fe/O
- The SWICS and the Solar Wind Observations over the Poles of the Sun (SWOOPS) instruments on the Ulysses spacecraft
  - Launched in 1990 - In a polar orbit about the Sun
  - Used for analysis of both A_{He} (SWOOPS) and Fe/O (SWICS)
- The OMNI data set
  - Multi-source data set spanning the time period from 1963 to the present
  - Data from spacecraft located at L1 and/or near-Earth, geocentric spacecraft

The helium abundance, A_{He}, is defined as the relative abundance of helium to hydrogen by number density, $(n_{He}/n_H) \times 100$.

References

Kasper, J. et al. (2011) *ApJ*, "Evolution of the relationships between helium abundance, minor ion charge state, and solar wind speed over the solar cycle" (in press)

McIntosh, S. et al. (2011a) *ApJ*, 730, L3.

Acknowledgements

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Helium Abundance Variations

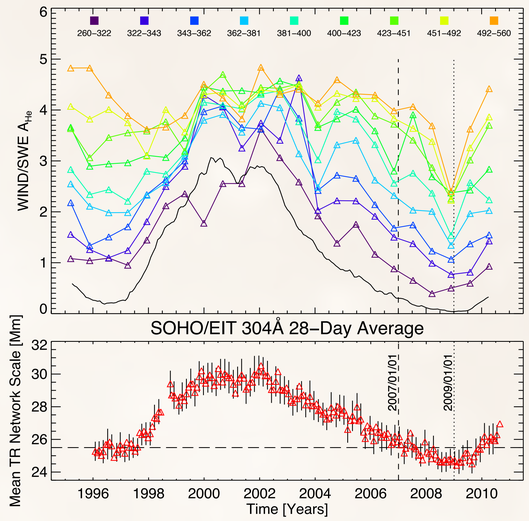

FIGURE 1 — Combining the analysis of the *Wind* Helium abundance as a function of the solar wind speed in 250-day averages in the top panel (from Kasper et al. 2011) with the 28-day running average of the transition region (supergranular) network length scale from *SOHO* (from McIntosh et al. 2011a). The solid black trace in the top panel shows the variation in the smoothed monthly sunspot number over the same time period. The dashed vertical line marks January 1 2007 as an approximate date when the network scale falls below the mean value of the 1996 solar minimum. The time of minimum scale and Helium abundance occur coincidently close to January 1, 2009.

Key Findings

- As seen in Figure 1, a significant decrease in A_{He} occurred during the extended solar minimum following cycle 23. This decrease, which was observed for all wind speeds, was simultaneously accompanied by the minimum in the supergranular length scale, the scale of which mass and energy transport take place.
- Through comparison of the two panels in Figure 2, the degree of iron fractionation in the fast solar wind was reduced during the last minimum relative to the previous minimum. As observed outside of the ecliptic plane by the *Ulysses* spacecraft, the abundance of Fe/O approached photospheric values.
- In reference to Figure 3, the decrease in Fe/O in the fast solar wind, with values again approaching unity, was also observed by the ACE spacecraft which is located in the ecliptic plane.
- Additionally in Figure 3, a steady reduction in the mean Iron charge state is noted in the fast wind during the declining phase of cycle 23, reaching a minimum coinciding with the minima in A_{He} and the supergranular length scale (see Fig. 1).
- When the abundance of Helium is analyzed over multiple solar cycles (Figure 4), a general decay in A_{He} is noted in addition to the known solar cycle variation.

Conclusions

The observational results described above are consistent with a decrease in the amount of energy supplied in the lower solar atmospheric which heats the fast wind. During the last solar minimum, the heating process appeared to be less efficient. Furthermore, the long-term reduction in A_{He} seems to imply that the background magnetic field has been slowly decaying over multiple solar cycles, resulting in a decrease in both energy and mass release.

Iron Variations In and Out of the Ecliptic Plane

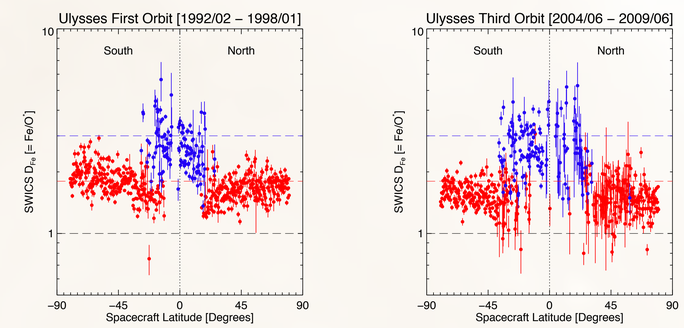

FIGURE 2 — Comparing the degree of Iron fractionation (D_{Fe}, the ratio of the Iron and Oxygen densities normalized by the expected photospheric value of 0.035) measured over the first (left) and third (right) orbits of *Ulysses* by SWICS as a function of the heliographic latitude of the spacecraft. These orbits spanned the minima of cycle 22 into 23 and that of cycle 23 into 24, respectively. We have isolated the fast (V_{sw} > 500km/s) and slow (V_{sw} < 400km/s) wind and plotted in 0.5 degree bins of latitude. The horizontal dashed lines indicate values of D_{Fe} = 1 (black), D_{Fe} = 1.8 (red), and D_{Fe} = 3 (blue).

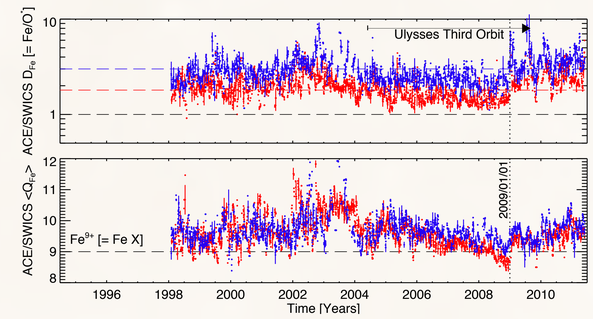

FIGURE 3 — Comparing the daily averages in the degree of Iron fractionation (D_{Fe} ; top) and the average Iron charge state ($<Q_{Fe}>$; bottom) in the fast (V_{sw} > 500km/s) and slow wind (V_{sw} < 400km/s) through the 2009 solar minimum as measured by *ACE*/SWICS in the ecliptic plane. January 1, 2009 is indicated by a vertical dotted line. In the upper panel the horizontal dashed lines indicate values of D_{Fe} = 1 (black), D_{Fe} = 1.8 (red), and D_{Fe} = 3 (blue) and an arrow is drawn to illustrate the duration of the third orbit of *Ulysses* through the declining phase of cycle 23. In the bottom panel a horizontal dashed line is drawn at $<Q_{Fe}>$ = 9 for the reference of the reader.

Long-term Helium Abundance Variations

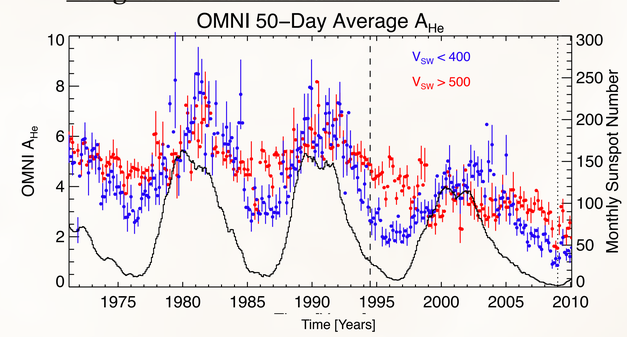

FIGURE 4 — Using the OMNI database to extend 50-day averages of the Helium abundance measure shown in Fig. 1 back through other cycles for fast (V_{sw} > 500km/s) and slow (V_{sw} < 400km/s) wind. Again, January 1, 2009 is indicated by a vertical dotted line while June 1, 1994 is indicated by a vertical dashed line to mark the start of the *Wind* measurements shown in Fig. 1. The solid black trace shows the variation in the smoothed monthly sunspot number.