

# The solar wind composition throughout the solar cycle: A continuum of dynamic states

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Received 16 August 2001; revised 11 January 2002; accepted 17 January 2002; published 15 May 2002.

[1] Variations in the speed and elemental and ionic charge composition of the solar wind are reported throughout the solar cycle, as observed by the SWICS instrument on Ulysses. The apparent bimodal nature of the solar wind during the solar minimum does not persist throughout the solar cycle. Rather, with increasing solar activity, a continuum of solar wind speeds and charge states is observed. The exception is the elemental composition which is noticeably less enhanced in elements with low first ionization potential (FIP) in material from coronal holes throughout the solar cycle. These observations are consistent with theories in which the solar wind originates from coronal loops that reconnect with open magnetic field lines. *INDEX TERMS:* 2162 Interplanetary Physics: Solar cycle variations (7536); 2169 Interplanetary Physics: Sources of the solar wind; 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162)

## 1. Introduction

[2] The Solar Wind Ion Composition Spectrometer (SWICS) on the Ulysses mission has observed the solar wind continuously since launch in 1990, and thus throughout almost an entire solar cycle and over a full range of heliographic latitudes ( $\pm 80^\circ$ ). SWICS provides not only basic solar wind flow parameters such as speed and density, but also, for the first time, comprehensive measurements of the elemental and charge composition of the solar wind.

[3] The first pass of Ulysses over the poles of the Sun was at solar minimum conditions. As has been reported elsewhere, e.g. Phillips *et al.* [1995], the solar wind appears to be bimodal, with a steady and relatively fast solar wind (speed  $\sim 760$  km/s) from the well-established polar coronal holes, and a more variable, slower ( $\sim 400$  km/s) wind from lower latitudes [see, also, McComas *et al.*, 2000a]. As reported by Geiss *et al.* [1995], the composition appears to be similarly bimodal. The charge composition is determined in the solar corona as the solar wind density declines and the charge states freeze in. The freeze-in temperature for the fast solar wind is  $\sim 1.2 \times 10^6$  K and relatively constant, whereas in the slow wind it is variable and  $\sim 1.7 \times 10^6$  K. The elemental composition is enhanced in elements with low first ionization potential (FIP), FIP-enhanced, in the slow wind, and noticeably less so in the fast wind.

[4] It is the purpose of this paper to extend the discussion of the observations of the solar wind composition throughout the solar

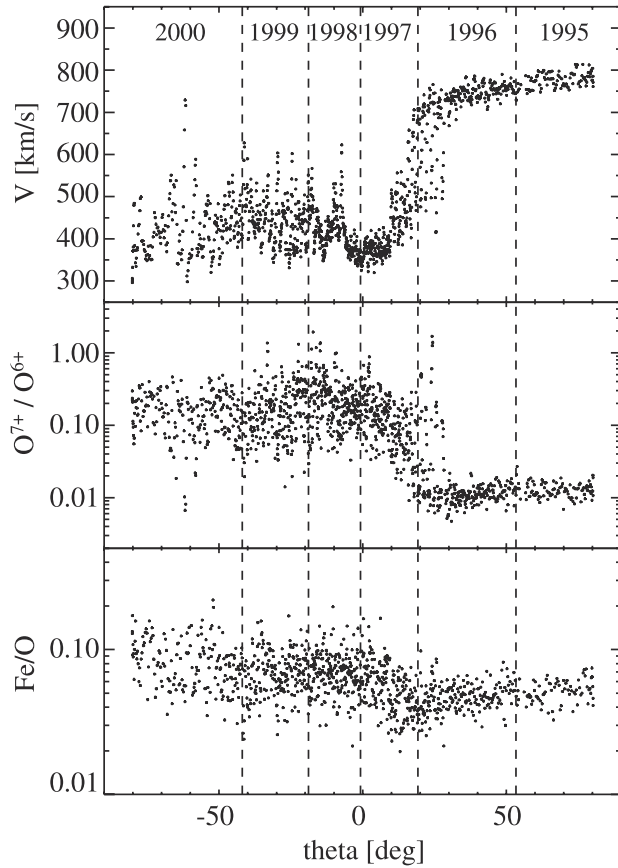
cycle, and to point out that the apparent bimodal nature of the solar wind at solar minimum is not a feature of the entire solar cycle. Rather, with increasing solar activity, a continuum of solar wind speeds and freeze-in temperatures, as determined from the charge states, is observed. The observed average FIP enhancements remain rather bimodal, with noticeably lower FIP enhancements observed from material that originates in coronal holes throughout the solar cycle.

## 2. Observations

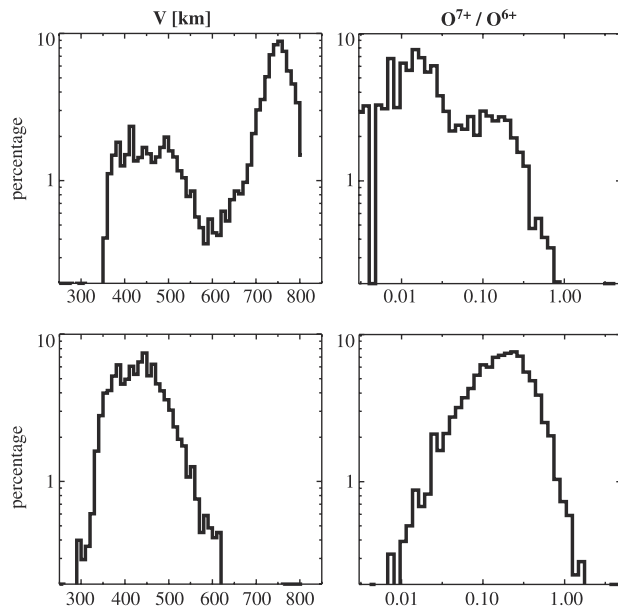
[5] We use Ulysses SWICS data during its transition from highest northern latitudes in 1995 to highest southern latitudes in 2000. This time interval is ideally suited to compare solar minimum and maximum conditions. Figure 1 shows the solar wind speed, the oxygen charge state ratio  $O^{7+}/O^{6+}$ , and the elemental abundance ratio of Fe/O as a function of heliographic latitude. All quantities are plotted with a time resolution of six hours. The vertical dashed lines indicate the year when the measurements were taken. Naturally, Ulysses spends more time at low latitudes, close to the apogee of its orbit, and transverse the highest latitudes at faster speed. All quantities shown in Figure 1 are independent of the radial distance if stream-stream interactions are neglected in the cases of the solar wind speed  $V$ . They are therefore ideally suited to investigate the evolution of the solar wind source regions.

[6] The dramatic differences of  $V$  from solar minimum to maximum have been described by McComas *et al.* [2000b]. During solar minimum a large part of the heliosphere is dominated by solar wind emerging from stable polar coronal holes. Transient coronal holes still significantly contribute to the solar maximum solar wind. However, the solar wind speed is typically slower. This slower speed is clearly a property of the transient coronal holes and not a signature of stream-stream interaction in the heliosphere [Nolte *et al.*, 1976; Miralles *et al.*, 2001]. The oxygen charge state ratio  $O^{7+}/O^{6+}$  has been shown to be a good measure of the solar wind source region because of its relatively fast freeze-in process in the low corona [Bürge and Geiss, 1986; Zurbuchen *et al.*, 2000]. A low  $O^{7+}/O^{6+}$  is observed to be a very good signature of a coronal hole associated with a solar minimum [Zurbuchen, 2001]. Also, note the very low variability in coronal-hole-associated wind during activity minimum in 1995. Coronal-hole-associated wind during solar maximum typically has a higher  $O^{7+}/O^{6+}$ . Only one single fast stream showed a  $O^{7+}/O^{6+} < 0.02$ , which is typical of coronal holes at solar minimum. However, it can be shown that time periods of  $O^{7+}/O^{6+} < 0.1$  are associated with coronal hole solar wind [von Steiger *et al.*, 2001]. Most solar wind during solar maximum lies within  $0.1 < O^{7+}/O^{6+} < 1.0$ , the typical range of slow solar wind associated with streamers. The  $O^{7+}/O^{6+}$  composition of this wind is highly variable, as discussed by Zurbuchen *et al.*

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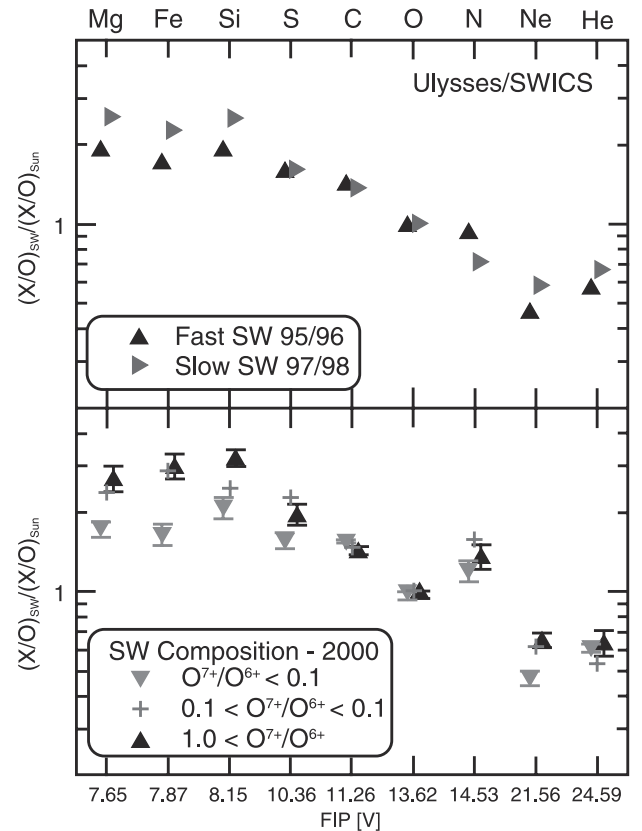
**Figure 1.** Solar wind speed, the oxygen charge state ratio  $O^{7+}/O^{6+}$ , and the abundance ratio of Fe/O from SWICS-Ulysses from the highest northern latitude reached in 1995 to the highest southern latitude in 2000. During solar maximum all quantities are more highly variable than at solar minimum. For a detailed discussion refer to the text.



**Figure 2.** Histograms of solar wind speed  $V$  and  $O^{7+}/O^{6+}$  during the solar cycle. The solar minimum case is shown at the top, the solar maximum case is shown at the bottom. The bimodal character common for  $V$  and  $O^{7+}/O^{6+}$  during solar minimum is replaced by single peaked distribution.

[2000]. Note also that there are a number of time periods with a  $O^{7+}/O^{6+} > 1$ . These time periods of unusually hot charge states are typically associated with coronal mass ejections (CMEs) [Lepré *et al.*, 2001; Henke *et al.*, 2001]. The elemental abundance ratio Fe/O is a good measure for the FIP effect described before. There is a clearly lower Fe/O in the solar minimum coronal hole, but the Fe/O variability dramatically increases during activity maximum. The experimental uncertainties of Fe/O and  $O^{7+}/O^{6+}$  are determined by the counting statistics. They contribute most importantly to Fe/O because of the relatively low density of Fe and the small variability of Fe/O of only a factor of  $\sim 2$  from coronal-hole-associated wind to solar wind from streamers.

[7] Figure 2 compares histograms of solar wind speed  $V$  and of  $O^{7+}/O^{6+}$  during two time periods of two years each in solar minimum and maximum. The time periods of 730 days have been chosen such that Ulysses penetrates a similar latitude range in both solar minimum and solar maximum cases. The time interval for solar minimum is from July 31, 1995 to July 30, 1997, covering a solar latitude range from  $80.2^\circ$  to  $7.0^\circ$ . The time interval for solar maximum is from November 24, 1998 to November 23, 2000, covering a solar latitude range from  $-80.2^\circ$  to  $-17.0^\circ$ . Solar minimum is shown on the top, solar maximum on the bottom. In both  $V$  and  $O^{7+}/O^{6+}$  there is a clearly bimodal distribution during solar minimum. Note that because of the large variability of  $O^{7+}/O^{6+}$  for slow solar wind, the second maximum is not as high as the equivalent peak slow speeds. The high-latitude wind during solar maximum is no longer bimodal. The distributions of  $O^{7+}/O^{6+}$  and



**Figure 3.** Elemental composition during solar minimum and solar maximum ordered according to the first ionization potential. The solar maximum is split into three parts according to the  $O^{7+}/O^{6+}$  ratio. Cool solar wind ( $O^{7+}/O^{6+} < 0.1$ ) is associated with coronal holes, hot ejecta ( $O^{7+}/O^{6+} > 1.0$ ) are associated with interplanetary CMEs. The error estimate is given by the symbol size, or by error bars for values of relatively large statistical uncertainties.

**Table 1.** FIP Fractionation of Low-FIP Elements Relative to O, for the Data in Figure 3<sup>a</sup>

	FIP Fractionation, $f_0$
Minimum: Fast SW	$1.87 \pm 0.11$
Minimum: Slow SW	$2.79 \pm 0.34$
Maximum: $O^{7+}/O^{6+} < 0.1$	$1.82 \pm 0.24$
Maximum: $0.1 < O^{7+}/O^{6+} < 1.0$	$2.57 \pm 0.27$
Maximum: $0.1 < O^{7+}/O^{6+}$	$2.98 \pm 0.27$

<sup>a</sup>For detailed definition of  $f_0$  refer to von Steiger *et al.* [2002].

V remain very broad because of the admixture of coronal-hole-associated wind, as discussed above.

[8] Figure 3 shows the elemental composition of the solar wind during solar minimum (top) and maximum (bottom) for a number of elements from low-FIP metals to He. The elements in Figure 3 are ordered according to their FIP. The solar minimum values have been determined by von Steiger *et al.* [2000] using two time intervals that are characteristic of coronal-hole-associated wind (July 1995–April 1996), and slow, fractionated wind at very low levels of solar activity during the ascending phase of the solar cycle (July 1997–April 1998). Following von Steiger *et al.* [2000], the elemental abundance ratios are normalized with photospheric abundance values from Grevesse and Sauval [1998].

[9] It is useful to analyze the solar maximum data in three different groups according to the solar wind  $O^{7+}/O^{6+}$  ratio. This analysis is limited to the entire year 2000, a time period comparable in length with the intervals studied by von Steiger *et al.* [2000], and very close to solar maximum conditions. The transitions between the three groups are somewhat arbitrary, as discussed in Figure 2. The time periods of  $O^{7+}/O^{6+} < 0.1$  are closely associated with time periods of solar wind from coronal holes. Slow solar wind from streamers is identified by  $0.1 < O^{7+}/O^{6+} < 1.0$ , and unusually hot ejecta, with  $O^{7+}/O^{6+} > 1.0$ , are discussed separately. Note that there were only very small contributions of such ejecta during the July 1997–April 1998 time period discussed in the upper panel. The statistical error bars in Figure 3 are shown, where they are larger than the symbol size. Note that there are large systematic abundance variations, particularly in slow solar wind, that by far exceed these statistical error bars, as discussed elsewhere [e.g., Zurbuchen *et al.*, 2000; von Steiger *et al.*, 2000]. Table 1 summarizes the FIP enhancement factors, as defined by von Steiger *et al.* [2000] in Equation (5), for the data in Figure 3.

[10] It is clear from Figure 3 and Table 1 that there is no significant difference between the ejecta time periods and times of predominantly slow solar wind. This indicates a common source of plasma associated with CMEs and slow solar wind. Conversely, the elemental abundance of the relatively cool periods is clearly different from the slow solar wind abundance. Within the error bars, the elemental composition during these time periods is equivalent to the composition of polar coronal holes. The elemental composition of coronal-hole-associated wind is therefore much less variable than the kinetic properties and the freeze-in temperature as measured by  $O^{7+}/O^{6+}$  and remains roughly constant during the entire solar cycle.

### 3. Discussion

[11] The bimodal nature of the solar wind near solar minimum, in its speed and elemental and charge composition, argues strongly for distinct origins for the two flows. This argument is particularly strong for the elemental composition. FIP enhancements must be imparted when the ions are first ionized. Thus, the presence of a FIP enhancement in the slow wind, and its relative absence in the fast wind, demands that the two flows connect to different conditions or different processes in the chromosphere.

[12] Fisk [1996] argued that there should be large-scale motions of open magnetic flux (the magnetic flux that opens into the heliosphere) across the polar coronal holes at solar minimum. The motions result from the interplay among differential rotation of the Sun, the non-radial expansion of the solar wind, and the offset of the polar coronal holes from the solar rotation axis. Fisk *et al.* [1999a] argue that there need to be motions in the open flux through the regions of primarily closed magnetic flux outside of the polar coronal holes to avoid a build-up in the open flux. The motions are thought to result from a diffusive process in which open field lines reconnect with closed magnetic loops and make a series of random jumps in location. Fisk *et al.* [1999b] argue that a similar diffusive process should occur in the polar coronal holes, but with open field lines reconnecting with small emerging magnetic loops. The Poynting and mass flux that results from the reconnection is consistent with observations of the fast solar wind. Note, however, that the convective transport of magnetic flux within coronal holes clearly dominates the diffusive transport in these holes, as discussed by Zurbuchen *et al.* [1999]. In Schwadron *et al.* [1999] a mechanism for developing FIP enhancements on loops is proposed in which wave heating on the loops preferentially heats elements with low ionization potential, increasing their scale height and thus their relative composition on the loops.

[13] The bimodal nature of the solar wind near solar minimum can thus be due to the bimodal nature of coronal loops near solar minimum. Feldman *et al.* [1999] observe that outside of the polar coronal holes at solar minimum there is a canopy of overlying loops with temperatures  $\sim 1.4 \times 10^6$  K and dimensions from  $2 \times 10^4$  to  $4 \times 10^5$  km. Inside coronal holes only smaller, cooler loops occur. Moreover, Feldman *et al.* [1998] observe that the larger loops can be FIP-enhanced, whereas the smaller loops in coronal holes are not. The fast wind thus results from the reconnection of open field lines with the small emerging loops in coronal holes; the resulting high speed is consistent with this process [Fisk *et al.*, 1999b]. The slow wind originates from the reconnection of open field lines with the distinctively larger, pre-existing loops outside of coronal holes, and derives its FIP-enhanced composition from the composition of the loops.

[14] As solar activity increases, similar processes should occur. Fisk and Schwadron [2001] argue that the open magnetic flux of the Sun should tend to be constant. Throughout the solar cycle the open flux is organized into two regions of uniform polarity separated by a single current sheet [Smith *et al.*, 2001]. Open flux can be reduced only if open flux of opposite polarity reconnects, a process that can occur only at the current sheet and may be unlikely. Thus, the reversal in polarity of the open magnetic flux during the solar cycle must be accomplished by a rotation of the current sheet and the open flux that it separates through 180 degrees, as Ulysses observations appear to confirm [Smith *et al.*, 2001]. This transport of open flux at solar maximum should occur by the same diffusive process as at solar minimum, in which open field lines reconnect with closed magnetic loops. At solar maximum there is more variety in the distribution and properties of loops. Coronal holes are smaller and more transient, and can still contain underlying loops; outside of coronal holes, loops of various sizes and properties occur. Thus, a continuum in the states of the resulting solar wind flow will occur, as is observed.

[15] Fisk (Motions of open magnetic flux in the solar corona and the acceleration of the solar wind, *J. Geophys. Res.*, submitted, 2002) takes the diffusion process in which open field lines reconnect with closed loops and relates it to the acceleration of the solar wind, and finds that the final speed of the solar wind depends primarily on the temperature on the loops. Gloeckler and Zurbuchen (Correlation between solar wind speed and coronal temperature: New insight on the acceleration of the slow and fast solar wind, *J. Geophys. Res.*, submitted, 2002) identify the loop temperature as the freeze-in temperature of solar wind ions, and



from observations of the speed and charge states of the solar wind from Ulysses, find that the relationship of speed to loop temperature is well confirmed.

[16] The bimodal nature of the elemental composition throughout the solar cycle requires additional consideration. Feldman *et al.* [1998] find that only the largest and longest-lived loops exhibit significant FIP enhancements. This suggests that although there may be a continuum of loop properties that give rise to a continuum of solar wind speed and charge states, there is a threshold value for FIP enhancements. Loops below a certain size and lifetime in coronal holes do not have time to develop significant FIP enhancements, whereas larger, longer-lived loops outside of coronal holes have sufficient time.

#### 4. Concluding Remarks

[17] We have observed that, although there is a bimodal solar wind near solar minimum, there is a continuum of states in the solar wind when viewed over the solar cycle, particularly near solar maximum. This continuum is consistent with theories in which the solar wind originates from closed magnetic loops that reconnect with open field lines. These observations are not consistent with some other theories. The bimodal nature of the solar wind at solar minimum, in particular the bimodal nature of the elemental composition, is inconsistent with theories in which all of the solar wind originates from the polar coronal hole, with slower wind resulting from an over expansion of the flow [Bravo and Stuart, 1997]. Also, theories for the acceleration of the solar wind in which the source of energy is processes associated with the network of magnetic flux in the photosphere are unlikely to be correct, e.g. nano-flares or reconnection within the network [McKenzie *et al.*, 1998]. The network appears the same everywhere on the Sun, whereas to explain the continuum of states of the solar wind there must be conditions and processes that occur both in the corona and in the region of first ionization that are systematically different. Coronal loops provide these differences. They have a distinctive pattern on the Sun—large loops outside of coronal holes and smaller loops within; and they vary in the extent to which they are FIP enhanced.

[18] **Acknowledgments.** This work was supported, in part, by NASA contracts NAG5-2810 and NAG5-7111 and JPL contract 955460.

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