THE 3-D HELIOSPHERE FROM THE *ULYSSES* AND ACE SOLAR WIND ION COMPOSITION EXPERIMENTS

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Abstract. The source region of solar wind plasma is observed to be directly reflected in the compositional pattern of both elemental and charge state compositions. Slow solar wind associated with streamers shows higher freeze-in temperatures and larger FIP enhancements than coronal hole associated wind. Also, the variability of virtually all compositional parameters is much higher for slow solar wind compared to coronal hole associated wind. We show that these compositional patterns persist even though stream-stream interactions complicate the identification based on in situ plasma parameters.

1. Introduction, Interpretation of Solar Wind Composition Parameters

The first orbit of *Ulysses* has presented us with a rather simple picture of the 3-D heliosphere. It is filled with two types of solar wind: Fast and steady wind emanating from large polar coronal holes dominates the regions poleward of about ±30°; slow and variable wind from the coronal streamer belt dominates within ±20° from the equator. The two solar wind types were shown to be distinctly different not only in their kinetic properties, but also in their elemental and charge state compositions. The latter signatures can not only be used to identify the stream types and in particular the boundaries between them (Geiss *et al.*, 1995; Wimmer-Schweingruber *et al.*, 1997, 1999; Burton *et al.*, 1999), but also to infer the processes and conditions at the respective source regions (e.g., von Steiger, 1998). The same compositional signatures have been observed in equatorial coronal holes (Zurbuchen *et al.*, 1999). Interspersed with the two quasi-stationary stream types are transient events that may or may not differ radically from them, namely the coronal mass ejections, which occur at a rate that varies with the solar activity cycle. The majority of these events show the presence of high charge states, indicating a high source temperature. Many CMEs (but by no means all of them) show a moderate to strong enhancement of alpha particles, and some rare events show a freak composition with strong enhancements of heavy elements up to iron (Gloeckler *et al.*, 1999). Only the new, rare class of high-latitude CMEs discovered by Gosling *et al.* (1995) is virtually indistinguishable from the surrounding high-speed stream if only compositional signatures are considered (Neukomm, 1998).

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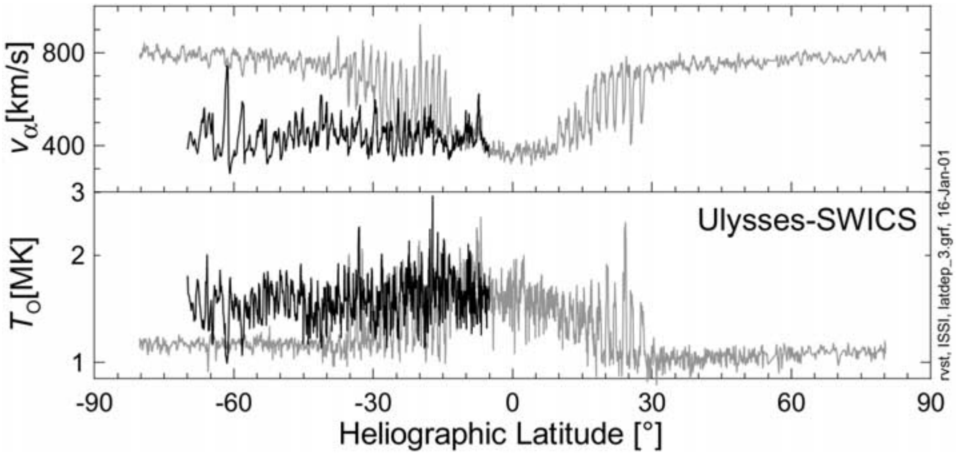

Figure 1. Overview of two solar wind parameters obtained by SWICS as a function of heliographic latitude: speed of alpha particles (which represents the bulk speed to better than 0.5%), and oxygen freezing-in temperature. The solar wind during the first polar orbit (gray) looks quite different from the second one (black), but compositional signatures indicate that both are made up from the same two quasi-stationary types that only are much more intertwined during the latter period.

Thus heavy ion charge states are a very useful tool for identifying stream types, and we routinely use the freezing-in temperature from the O^{7+}/O^{6+} charge state ratio as an indicator of fast streams and the average iron charge state as an indicator for CMEs. Both parameters can now be obtained at a time resolution of 3 hours from the *Ulysses* data system at ESTEC (http://helio.estec.esa.nl/ulysses/archive/expt/swics/swics.htm).

2. 3-D Structure of the Heliosphere, Conclusions

The compositional signatures of the two quasi-stationary solar wind types around solar minimum activity were described in detail in von Steiger *et al.* (2000). With the rise to solar maximum, during *Ulysses*' second polar orbit, we obtain a quite different picture of the 3-D heliosphere, as also discussed in this meeting by McComas *et al.* (2001). Figure 1 shows an overview of two parameters obtained with SWICS as a function of heliolatitude. The difference between the data from the first and the second polar orbits are obvious. The large fast polar streams that dominated the first orbit at high latitudes have completely vanished, and there is no sign even of a regularly alternating stream pattern during the second orbit such as the one at mid-latitudes during the first orbit. Only the most recent data, obtained at latitudes $\gtrsim$60°, clearly show the presence of several fast streams (high v_α and low T_O), although only one of them attains the high speed of the polar fast stream during the first orbit. This is, of course, the result of the shrinking and fragmenting polar coronal holes with the increase of the solar activity level and the corresponding reversal of the magnetic dipole. It is in fact not expected that *Ulysses*

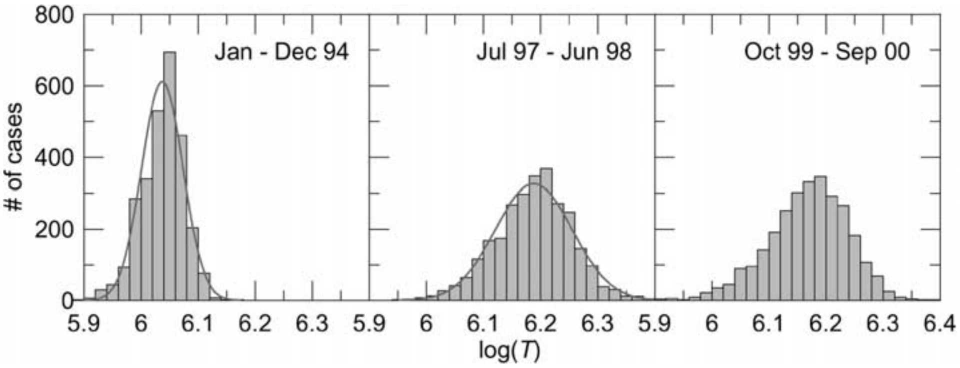

Figure 2. Histograms of 3-hr averages of the oxygen freezing-in temperature obtained during periods of a pure fast stream (left) and slow solar wind (middle), which both are log-normals, and a mixture of the two (right). The parameters of the fits are $\log T_{\mathrm{O,fast}}\,[\mathrm{K}] = 6.037 \pm 0.036$ and $\log T_{\mathrm{O,slow}}\,[\mathrm{K}] = 6.188 \pm 0.068$.

will encounter a persistent fast stream except perhaps at its highest latitudes as a result of the increasing tilt of the coronal magnetic neutral line that outruns *Ulysses* on its way to the deep south (Balogh and Smith, 2001). In line with this picture we also observe, with ACE-SWICS at 1 AU and near the solar equatorial plane, the presence of an increased number of small fast streams of either polarity that persist for 2 or 3 solar rotations, stemming from the low-latitude, fragmented coronal holes (Zurbuchen *et al.*, 2001).

The question arises whether the recent *Ulysses* observations show a new class of solar wind or whether the notion of two quasi-stationary classes interspersed with CMEs remains sufficient. The following argument should provide evidence for the latter possibility, based on the charge-state temperature of oxygen. This parameter indicates the presence of a high-speed stream even if its bulk speed does not reach the range of 700–800 km s^{-1} observed in the polar streams, or the absence thereof even if the speed is high due to a transient CME. In Figure 2 we show three histograms of 3-hr samples of T_{O}, each of which was accumulated over one year. The left and middle samples represent pure fast and slow solar wind, respectively, and both can be well approximated by log-normal distributions (Burlaga and Lazarus, 2000), but with distinctly different mean temperatures of 1.09 MK (fast) and 1.54 MK (slow). Unfortunately, the two histograms have some overlap in the region around 1.25 MK, which makes T_{O} not absolutely sufficient to tell the two stream types apart. The right panel shows the most recent data, which consists of predominantly slow wind with a small number of clearly identifiable fast streams embedded (Figure 1). The histogram of this period shows a shoulder at low temperatures, and a quantitative analysis shows that the shoulder accounts for 5% of the cases, quite in agreement with the superficial impression one obtains from Figure 1. Moreover, the right histogram also shows a lack of high temperatures as compared to the middle one. This can be explained by the distinctly ($\sim$50%) lower occurrence rate of CMEs at *Ulysses* in 1999–2000 as compared to 1997–1998 (Figure 2 of McComas *et al.*, 2001). CMEs embedded in slow wind have an average temperature of $\log T_\mathrm{O}$ [K] $= 6.3 \pm 0.05$ (Neukomm, 1998), which matches quite well with the missing shoulder. In summary, we think that the mixed solar wind observed in recent times at *Ulysses* can be well explained by the presence of the same two quasi-stationary types plus transient CMEs as was the case during the first polar orbit, but that they are now mixed on much smaller scales and may have their kinetic properties altered by stream-stream interactions, whereas the compositional signatures remain largely unchanged.

In conclusion, the labels ‘fast streams’ and ‘slow solar wind’ are therefore not applicable throughout the solar cycle. Instead, ‘coronal hole associated, cool source’ and ‘streamer-belt associated, hot source’ seem to be much more successful in classifying the two solar wind types throughout the solar cycle. It is important to note that the composition provides us with a powerful, if not invaluable tool for identifying the sources of the solar wind.

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References

Balogh, A. and Smith, E. J.: 2001, ‘The Heliospheric Magnetic Field at Solar Maximum: *Ulysses* Observations’, *Space Sci. Rev.*, **97**, 147–160 (this issue).

Burlaga, L. F. and Lazarus, A. J.: 2000, ‘Lognormal Distributions and Spectra of Solar Wind Plasma Fluctuations: Wind 1995–1998’, *J. Geophys. Res.* **105**, 2357–2364.

Burton, M. E., Neugebauer, M., Smith, E. J., Crooker, N. U., and von Steiger, R.: 1999, ‘Identification of Trailing Edge Solar Wind Stream Interfaces: a Comparison of *Ulysses* Plasma and Composition Measurements’, *J. Geophys. Res.* **104**, 9935–9932.

Geiss, J., Gloeckler, G., and von Steiger, R.: 1995, ‘Origin of the Solar Wind From Composition Data’, *Space Sci. Rev.* **72**, 49–60.

Gloeckler, G., Fisk, L. A., Hefti, S., Schwadron, N. A., Zurbuchen, T. H., Ipavich, F. M., Geiss, J., Bochsler, P., and Wimmer-Schweingruber, R.-F.: 1999, ‘Unusual Composition of the Solar Wind in the 2–3 May 1998 CME Observed with SWICS on ACE’, *Geophys. Res. Lett.* **26**, 157–160.

Gosling, J. T., Bame, S. J., McComas, D. J., Phillips, J.-L., Balogh, A., and Strong, K. T.: 1995, ‘Coronal Mass Ejections at High Heliographic Latitudes: *Ulysses*’, *Space Sci. Rev.* **72**, 133–136.

McComas, D. J., Goldstein, R., Gosling, J. T., and Skoug, R. M.: 2001, ‘*Ulysses*’ second orbit: Remarkably Different Solar Wind’, *Space Sci. Rev.* **97**, 99–103 (this issue).

Neukomm, R. O.: 1998, ‘Composition of Coronal Mass Ejections Derived with SWICS/*Ulysses*’, Ph. D. thesis, Universität Bern.

von Steiger, R.: 1998, in C. Fröhlich, M. C. E. Huber, S. Solanki, and R. von Steiger (eds.), ‘Composition Aspects of the Upper Solar Atmosphere’. *Solar Composition and Its Evolution – From*

Core to Corona, Vol. 5 of *Space Sciences Series of ISSI*, Kluwer Academic Publishers, Dordrecht, Holland, pp. 407–418.

von Steiger, R., Schwadron, N. A., Fisk, L. A., Geiss, J., Gloeckler, G., Hefti, S., Wilken, B., Wimmer-Schweingruber, R.-F., and Zurbuchen, T.-H.: 2000, ‘Composition of Quasi-stationary Solar Wind Flows from *Ulysses*/SWICS’, *J. Geophys. Res.* **105**, 27 217–27 236.

Wimmer-Schweingruber, R. F., von Steiger, R., and Paerli, R.: 1997, ‘Solar Wind Stream Interfaces in Corotating Interaction Regions: SWICS/*Ulysses* Results’, *J. Geophys. Res.* **102**, 17 407–17 417.

Wimmer-Schweingruber, R. F., von Steiger, R., and Paerli, R.: 1999, ‘Solar Wind Stream Interfaces in CIRs: New SWICS/*Ulysses* Results’, *J. Geophys. Res.* **104**, 9933–9945.

Zurbuchen, T. H. *et al.*: 2001, in preparation.

Zurbuchen, T. H., Hefti, S., Fisk, L. A., Gloeckler, G., and von Steiger, R.: 1999, ‘The Transition Between Fast and Slow Solar Wind From Composition Data’, *Space Sci. Rev.* **87**, 353–356.