Solar Wind Characteristics from Soho-Sun-Ulysses Quadrature Observations

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Abstract. Coronal and solar wind observations of the same plasma, first observed remotely in the corona and later, in situ, provide the best way to determine the evolution of plasma as it is being accelerated from the corona out to interplanetary distances. We have used this technique to derive solar wind characteristics from the analysis of data acquired by SOHO and Ulysses when the SOHO-Sun-Ulysses included angle is 90 degrees: that is, when SOHO, the Sun and Ulysses are in quadrature. We summarize here the results obtained from the study of the December 1998 quadrature, when we focussed on the behavior of slow wind from low-latitude regions, and anticipate some results from the June 2000 quadrature, which focussed on establishing a relationship between coronal and wind abundances of different elements and whose analysis is in progress. We conclude by illustrating briefly the objectives of future quadrature studies.

INTRODUCTION

In the pre-SOHO era, the only possibility to observe the same plasma first remotely in the corona and, later, in situ, occurred when the Helios 1 and 2 probes were moving away from the Earth, and conveniently located with respect to the P78 coronagraphs [1]. Today, when SOHO, the Sun and Ulysses are in quadrature, that is, when the SOHO-Sun-Ulysses included angle is 90 degrees, we have the opportunity of again making observations of the same plasma parcel at different positions as it moves from the corona to the interplanetary medium.

We have made several SOHO-Sun-Ulysses quadrature campaigns and plan to make more in future. These occur twice a year, with the latitude of the radial to Ulysses, at the time of the quadrature, depending on the position of Ulysses along its orbit. Hence, the position of Ulysses dictates the scenario of the campaign, and, in part, its objective: slow/fast wind analyses depending on whether Ulysses is at low/high latitudes. Making observations over several years, we also have a means of studying the variation, with solar cycle, of the characteristics of the slow (high) speed streams. Figure 1 shows when past, and planned, quadrature campaigns occur and the quadrant and latitude of Ulysses, as a function of the phase of the solar cycle.

A quadrature campaign relies heavily on SOHO LASCO and UVCS coronal observations. LASCO provides the overall coronal context above 2 solar radii and the UVCS spectrograph acquires data over a limited range of altitudes, usually between ≈ 1.5 and 4.5 solar radii. The UVCS slit is set normal to the solar radius, with the radial to Ulysses crossing through its center. The grating positions, as well as the spatial and spectral resolution, are chosen to fit the objective of the campaign. Coronal parameters are derived from data of these two experiments and in situ parameters are provided by Ulysses SWOOPS and SWICS experiments. Data from other sources, SUMER and CDS on SOHO or Sacramento Peak National Observatory FeXIV maps and Wilcox Solar Observatory magnetic field maps, or the Ulysses magnetometer, have been occasionally used to complement the UVCS/LASCO and SWOOPS/SWICS data sets.

At the time of this writing, we have led 8 quadrature campaigns, making observations at latitudes ranging from 10 to ≈ 80 degrees, sampling both low and high latitude coronal plasma. In the next section we illustrate the results we obtained from observations made in 1998, at a latitude of 17 degrees, as an example of the opportunities offered by quadrature data. After this, we anticipate a few results from the June 2000 campaign which focussed on elemental abundances in the corona and solar wind, at a time when the radial to Ulysses was crossing through an evolving streamer complex. A brief description of anticipated results from upcoming campaigns concludes the paper.
**SLOW WIND FROM THE FALL 1998 QUADRATURE CAMPAIGN**

The 1998 quadrature occurred when the radial to Ulysses, at a southern latitude of 17.4 degrees, crossed through a small coronal hole, before being immersed in a streamer complex for the rest of the campaign. At Ulysses, the speed of the solar wind was low, as expected from low-latitude streams, but connecting the *in situ* to the coronal plasma allowed us to separate the coronal hole wind from the wind emerging from the streamer complex. We were able to derive the plasma (and heavy ion) outflow speed, at 3.5 and 4.5 $R_\odot$, from spectra taken by UVCS for both the coronal hole and streamer sources.

We used Doppler dimming to compute the values of the outflow speed that allowed us to reproduce both the observed ratio of the intensities of the O vi 1032 and 1037 Å doublet lines (which can be considered a crude proxy for the heavy ion speed: [2]) and the individual O vi line intensities, as well as the intensity of the H Lyman-\(\alpha\) line. We refer the reader to [3] for a detailed description of the method. Here it suffices to note that the line intensities depend on the electron density and temperature, the proton (or ion) outflow speed, the parallel and perpendicular temperature of the ion originating the line, the heavy ion abundance and the intensity of the exciting chromospheric radiation. Electron densities were derived from pB LASCO measurements, perpendicular temperatures were derived from line widths, electron temperatures were been taken from literature, and disk intensities during the quadrature were either available or extrapolated from measurements made at other times.

We want to point out, however, that the parallel temperature cannot be inferred from observations and that the value of the abundance of heavy elements is usually assumed *a priori*. Moreover, the interplay between the element abundance and the poorly-known electron temperature (higher abundances leading to higher line intensities, higher electron temperatures leading to lower line intensities) introduces an ambiguity that usually cannot be resolved. The role of Ulysses data has been crucial in constraining the values of these parameters by providing values of mass flux and Oxygen abundances in the solar wind: that is, by providing us with more conditions that need to be satisfied.

The outflow speeds we derived are shown in Figure 2. The proton and heavy ion speeds in plasma emerging from low latitude regions is lower than the polar plasma speed. Moreover, independent of the region where it originates, low-latitude plasma is accelerated at greater heights and through a more extended region than fast wind from large coronal holes. For the small, low-latitude hole we analyze, the ratio between polar and low latitude wind speed at 1 AU is about 1.5. The same ratio at coronal levels is on the order of 2.5, implying that equatorial wind accelerates throughout a more extended altitude range than polar wind.

The fall 1998 quadrature also gave some indication on another issue, still not well understood. It has long been known that the slow wind is highly variable, but the reason for this is not yet clear. When UVCS was traversing the small coronal hole, the plasma speed turned out to be slightly higher than the plasma speed measured when the wind was emerging from the streamer complex. This is illustrated in Figure 2, which shows that a 20% variability in the speed of slow wind can be ascribed to the presence of open field regions interspersed amidst streamers. These could be responsible for the fastest wind.
FIGURE 2. Outflow speed at 3.5 and 4.5 $R_\odot$ for: full symbols -proton flow speed for the low latitude streamer and coronal hole observed during the 1998 fall quadrature; full symbols, diamonds -as above, for O VI ions; open symbols, squares -proton flow speed for the low latitude streamer speed, are also given.

QUADRATURE OBSERVATIONS AND ELEMENTAL ABUNDANCES

Elemental abundances play a key role in studies aimed at relating coronal and solar wind plasmas. Similar coronal and wind abundances provide a clue in the search for the site where solar wind originates. This has been used by [6], for instance, to suggest that slow wind originates from streamer boundaries. Quadrature observations, where the source of the solar wind may be easily identified, offer an unique opportunity for checking on the coronal vs. solar wind elemental abundances. As a further benefit the distribution of element abundance vs. altitude in the corona, or the temporal fluctuations of element abundances at a given location in the corona may be tested with quadrature data.

A quadrature campaign, using SUMER, CDS and UVCS, was held in June 2000, with the purpose of analyzing elemental abundances. At that time, the radial to Ulysses crossed through an evolving streamer complex. The sub-Ulysses point skimmed along the neutral line for the Wilcox Solar Observatory source surface map for several days. This provides only a crude indication, however, because of the rapid changes in the coronal configuration over the campaign. At Ulysses, the solar wind speed was typically around 350 km/s. Ulysses was at about 3.25 AU, so it took the plasma about 17-18 days to reach the spacecraft. Hence, data taken on 20 to 6 of July are representative of the coronal plasma at the time of our observations.

UVCS took spectra that include lines from many ions, including O v i, Si xii, Fe x, xii and xiii, Ar xii, plus H Lyman-$\alpha$, Lyman-$\beta$ and Lyman-$\gamma$ lines, at altitudes ranging from 1.6 to 2.2 $R_\odot$. Absolute Oxygen abundances can be derived once the collisional and radiative components of the H and of the O v i 1032 and 1037 A lines are identified, under the assumption that plasma is in ionization equilibrium ([6]). In a streamer complex, at the altitudes we consider, this hypothesis is tenable. The Fe absolute abundance can be calculated from the predicted vs. observed ratio of the iron lines to the collisional components of H lines. This way one gets an estimate of the Fe/O ratio in the corona, that may be compared with in situ values of the same quantity.

It is well known that fast and slow wind plasma have different FIP effect. Being Fe and O, respectively, low and high FIP elements, a measure of the Fe/O ratio is a proxy for the plasma FIP effect and may offer a further clue in the quest for the slow wind origin. Preliminary estimates of Fe/O along the radial to Ulysses, at 1.6 $R_\odot$, for three days of the campaign, lead to coronal values that are within 10% of those measured by Ulysses. The same ratio, when measured by the ACE spacecraft shows a high variability that was not seen during the quadrature either in SWICS or UVCS data. This, however, may be ascribed to different factors, including the long integration time for SWICS, to derive good values of the ratio, and both the long integration time and the line-of-sight effect for UVCS. However, the agreement between the coronal and the in situ abundance ratios seems to imply that whatever mechanism is responsible for FIP effects is ineffective beyond $\approx$ 1.5 solar radii and that the precise connection between coronal and interplanetary FIP measurements can be made.

PLANS AND ANTICIPATED RESULTS FROM FUTURE CAMPAIGNS

As to what we can expect from future studies, we refer to Figure 1. The first 8 quadratures campaigns are completed. The next one, in fall 2002, with Ulysses at low latitude (≈ 26 degrees) will focus on the study of variations in the physical parameters of the corona and solar wind, as a consequence of flares. The low latitude of the spacecraft, and the phase of the activity cycle, not so distant from maximum, leave hope for a flare occurrence during the two week campaign interval. SOHO-Ulysses data will then be complemented by HESSI data.

As to future studies, we list a couple of issues. We haven’t analyzed, yet, CME data. Some CMEs have al-
ready been observed in past campaigns (e.g. campaigns 4, 5, 7 and 8) and we may expect more in the next quadratures. We expect to be able to correlate abundance variation in the CMEs with abundances measured in situ and to analyze the temperature changes and the ensuing variations in the ion populations at those times. Another topic is the boundary crossing between streamers and coronal holes. Ulysses analyses have shown that composition changes abruptly across the boundary (see, e.g. [7]); but not much has been done on this subject at coronal levels. Whether we will really have the opportunity to measure this depends entirely on the unpredictable solar morphology at the time and position of future quadratures.

In this brief report we meant to give an instance of the kind of research activity that quadrature configurations have allowed us to pursue and plan. For the December 1998 campaign this meant the results that smaller coronal holes have delayed solar wind acceleration compared to large polar coronal holes and that a precise connection can be made between the FIP effect in the solar wind and at 1.6 solar radii. We like to end the report by thanking the Ulysses and SOHO community for the support given throughout the campaigns we lead: without their collaboration we would have been unable to work on the exciting data we had the privilege to collect.

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