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The Sun at solar minimum: North - south asymmetry of the polar coronal holes

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[1] Data from the Solar Wind Ion Composition Spectrometer (SWICS) on Ulysses and synoptic charts derived from Kitt Peak magnetograms are used to compare the south and north polar coronal holes which existed during the declining/minimum phase of the solar activity cycle from 1992 to 1997. The kinetic properties of the solar wind emanating from the two polar coronal holes, as represented by solar wind speed, do not differ significantly. However, the electron temperature in the two coronal holes inferred from ionic charge composition data, namely the O^{7+}/O^{6+} ratio, show consistent differences, with the south polar hole being 10 to 15% hotter. The ground-based magnetograms show that the north polar coronal hole covers a larger part of the solar surface than the southern one. The total magnetic flux and, specifically, the flux density of the north polar coronal hole is considerably lower for the whole interval of time between 1992 and 1997. This strongly indicates that the difference in coronal hole temperature between the southern and northern coronal hole is intrinsic and is not due to the fact that the Ulysses observations in the south and north coronal hole streams were made at different phases of the solar cycle. Thus the differences found represent a real north-south asymmetry during this time period. *INDEX TERMS:* 7511 Solar Physics, Astrophysics, and Astronomy: Coronal holes; 2162 Interplanetary Physics: Solar cycle variations (7536); 2164 Interplanetary Physics: Solar wind plasma; 7509 Solar Physics, Astrophysics, and Astronomy: Corona

1. Introduction

[2] The magnetic field in interplanetary space during solar minimum conditions is dominated by the near-equatorial current sheet and open field line regions at higher latitudes. The boundary between these two regions maps to about 60° solar latitudes at the Sun [see e.g., the review by *Schwenn*, 1990]. The current sheet is associated with the slow solar wind belt. The open field line regions are associated with the polar coronal holes (PCH), from which fast solar wind streams emanate [*Krieger et al.*, 1973; *Phillips et al.*, 1994]. This overall configuration can be described to first approximation by combining an azimuthally symmetric equatorial current sheet with an axisymmetric dipole or multipole field [*Banaszkiewicz et al.*, 1998]. Possibly existing north-south asymmetries bear important implications for the global structure of the Sun's magnetic field and models describing it. An opportunity to investigate the symmetry is provided by the Ulysses spacecraft which observed the solar wind expanding from the PCHs and the interplanetary magnetic field convected with it. Ulysses observed the southern PCH stream from 1992 to 1994 during the declining phase of the solar cycle and the northern PCH stream from 1995 to 1997 during the minimum phase of the solar cycle.

[3] So far, the existence of a north-south asymmetry could not be deduced. An investigation of basic solar wind parameters, such as velocity and temperature showed that only marginal differences in the few percent range exist between the average values estimated for the northern and southern PCH solar wind streams [*McComas et al.*, 2000]. Other parameters like the scaled proton density showed a difference of about 20%. However the fast transition of Ulysses from the south into the north PCH in 1994/95 allowed a study of the southern and northern PCH streams separated in time by only a few weeks which minimizes a possible bias from solar cycle variations. Essentially no differences between the south and north coronal holes were found for these adjacent time periods. It was therefore concluded that the apparent differences of the long term averages could be attributed to solar cycle effects. However, possible rather short-term temporal variations during the fast latitude scan inferred from magnetic field observations [*Smith et al.*, 2000b] might question this conclusion.

[4] The magnetic field observations on Ulysses likewise did not show an unambiguous north-south asymmetry of the magnetic field magnitude [*Forsyth et al.*, 1996; *Erdös and Balogh*, 1998; *Smith et al.*, 2000a]. However, uncertainties introduced e.g. by possible geometric asymmetries like a southward displacement of the current sheet [*Smith et al.*, 2000b] naturally complicates a direct comparison of the intrinsic field strengths of the north and south polar regions.

[5] In preliminary studies of the charge-state distributions of minor solar wind ions a possible difference between the south and north PCH was noted [*von Steiger et al.*, 2000; *Ko et al.*, 1999], although again solar cycle variations could not be ruled out as the cause of the differences.

[6] In this study, we investigate in detail the O^{7+}/O^{6+} charge state ratio measured with the Solar Wind Ion Composition Spectrometer SWICS in the solar wind streams emanating from the north and south PCH. The Ulysses observations are complemented by basic parameters like the PCH area, and coronal hole magnetic flux and density derived from magnetograms recorded from the ground.

2. Observations

[7] Data from the Solar Wind Ion Composition Spectrometer SWICS aboard Ulysses are used to derive the solar wind proton speed and the charge-state ratio of O^{7+}/O^{6+} as a proxy for the coronal temperature. The study is based on data collected between 1992 and 1997. The SWICS instrument is described in detail by *Gloeckler et al.* [1992], a method to derive the O^{7+}/O^{6+} ratio including instrumental errors by *von Steiger et al.* [2000]. Systematic errors for the data presented here are well below 10%, statistical uncertainties are reduced even below that by using long accumulation times.

[8] In general, charge-state distributions of minor solar wind ions can be used to estimate the so-called freezing-in temperatures which are related to coronal temperatures in the source region of the solar wind [for a detailed discussion see *Bürgi and Geiss*, 1986]. Specifically, in the fast coronal hole streams charge-state

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ratios are a well-suited indicator of coronal temperatures [*Geiss et al.*, 1995; *von Steiger et al.*, 2000].

[9] Synoptic charts constructed from magnetograms and He I 1083 nm observations recorded at Kitt Peak are used to estimate the coronal hole area, coronal hole magnetic flux and flux density.

[10] The synoptic maps were constructed from strips along the central meridian of daily maps of the Sun. The original observations were made with 1 arc sec pixels and then converted to daily, low resolution maps in a Carrington longitude vs. sine latitude format. Each of the synoptic maps represents one Carrington rotation of the Sun. The following corrections are applied to the magnetic synoptic charts. 1. On the generally made assumption that the fields are perpendicular to the solar surface, the observed fields are divided by the cosine of the latitude. 2. The magnetograph signal very close to the poles can be very noisy or is even missing (when the pole in question is tilted away from Earth). In these cases we replaced the measured signal by a cubic spline fit to valid values in the polar regions. Coronal hole boundaries are identified on the He I 1083 nm synoptic maps, from which the polar coronal hole areas are estimated. Within the coronal hole boundaries the total magnetic flux and average flux density are derived from the magnetic synoptic maps.

[11] The heliographic latitude range scanned by Ulysses from early 1992 to mid-1997 and the variation of solar activity represented by the sunspot number is shown in Figure 1a. During the declining phase of the solar cycle Ulysses was at southern heliographic latitudes. After leaving the ecliptic plane at aphelion in 1992, Ulysses reached a highest southern latitude of 80° in 1994. The fast latitude scan in 1994/1995 at perihelion took Ulysses in just a few months from the south into the north polar regions of the Sun. During the minimum phase of the solar cycle Ulysses descended again from high northern latitudes towards the ecliptic which was reached in late 1997.

[12] Figure 1b gives an overview of the O^{7+}/O^{6+} charge-state ratio and the solar wind proton speed measured by SWICS in the south and north PCH streams. Values averaged over Carrington rotations are shown for times when Ulysses is permanently immersed in the southern or northern streams (south PCH 08.1993 to 01.1995; north PCH 03.1995 to 08.1996). For mid-latitude observations (06.1992 to 07.1993 and 09.1996 to 02.1997), when Ulysses encountered the polar streams once per rotation for a limited time, one 12-hour-average per rotation comprising the core of the stream is displayed. Characteristically for solar wind from the PCHs the speed in the southern as well as in the northern stream is at a high level of 700 to 800 km/s, compared to typical values of 400 km/s in the streamer belt. South and north PCH speeds are about equal. As already reported by *McComas et al.* [2000] based on Ulysses/SWOOPS data, values averaged over the whole southern, respectively northern polar stream intervals agree within a few percent. For both PCH streams the speed is not constant throughout the respective coronal hole intervals but exhibits clear variations. The variations could be of temporal nature or could reflect a dependence on latitude. The fact that the solar wind speed peaks at highest latitudes in the center of the coronal hole and decreases towards its edges consistently for both coronal hole supports the conclusion derived in previous studies [*Neugebauer et al.*, 1998; *McComas et al.*, 2000] of a latitudinal rather than a temporal or solar cycle dependence.

[13] The O^{7+}/O^{6+} ratio (same averaging procedure as for the speed) is at a low level, which is typical for the solar wind from the PCHs and indicative for low coronal temperatures in the coronal holes [e.g., *von Steiger et al.*, 1997]. It ranges from about 0.007 to 0.025, which converts to a freezing-in temperature of about 1 MK to 1.2 MK. This should be compared to values typically larger than 0.1 in the streamer belt (freezing-in temperature >1.5 MK). The ratio is about 0.02 in the center of the south PCH. It remains roughly constant throughout the entire coronal hole stream interval without any indication for variation with time or latitude. In the center of the north PCH the charge-state ratio is around 0.015, i.e., significantly lower compared to the south PCH. Moreover, the pronounced difference exists even for the adjacent south and north PCH time intervals during the fast latitude scan. In contrast to the south PCH the northern one shows a clear variation of the ratio, which either reflects a latitudinal dependence or a temporal evolution. However, as for the speed the ratio peaks at highest

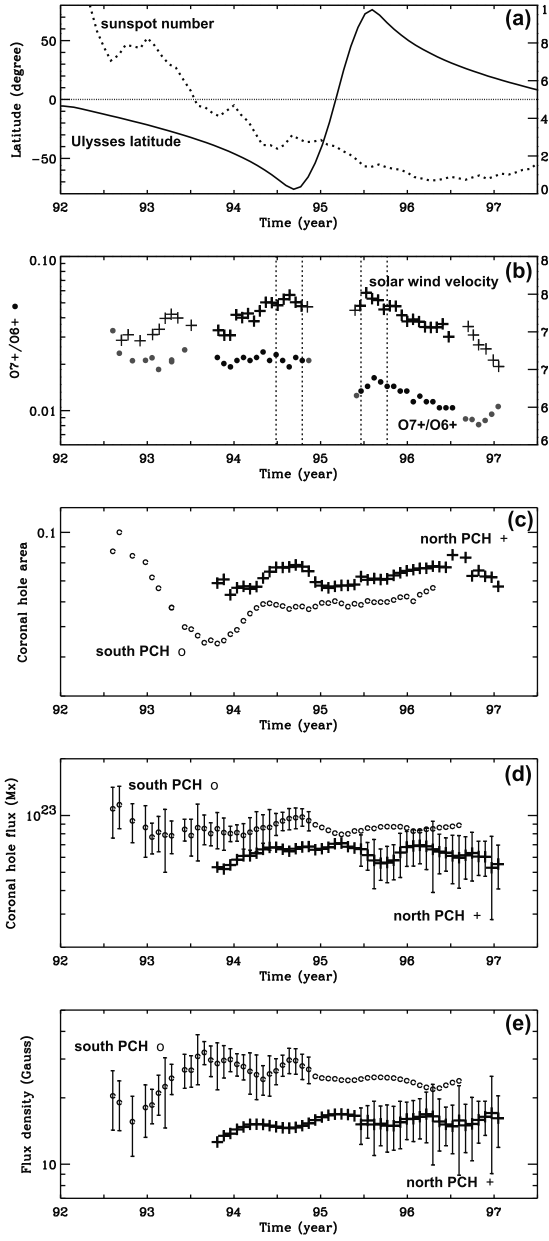

Figure 1. Selected solar wind and polar coronal hole parameters during 1992 to 1997. (a) Heliographic latitude of Ulysses and sunspot number; (b) O^{7+}/O^{6+} ratio and solar wind speed as measured by SWICS/Ulysses from 1992 to 1997 (heavy symbols denote pure PCH stream observations, light symbols observations from the mid-latitude fast-slow wind interface regions); (c) area of the south PCH (o) and north PCH (+) estimated from Kitt Peak He I 1083 nm synoptic maps as fraction of the solar surface; (d) magnetic flux of the south (north) PCH derived from Kitt Peak synoptic maps, error bars are included for the south (north) PCH values over the south (north) Ulysses PCH stream intervals; (e) same as in (d) but for magnetic flux density.

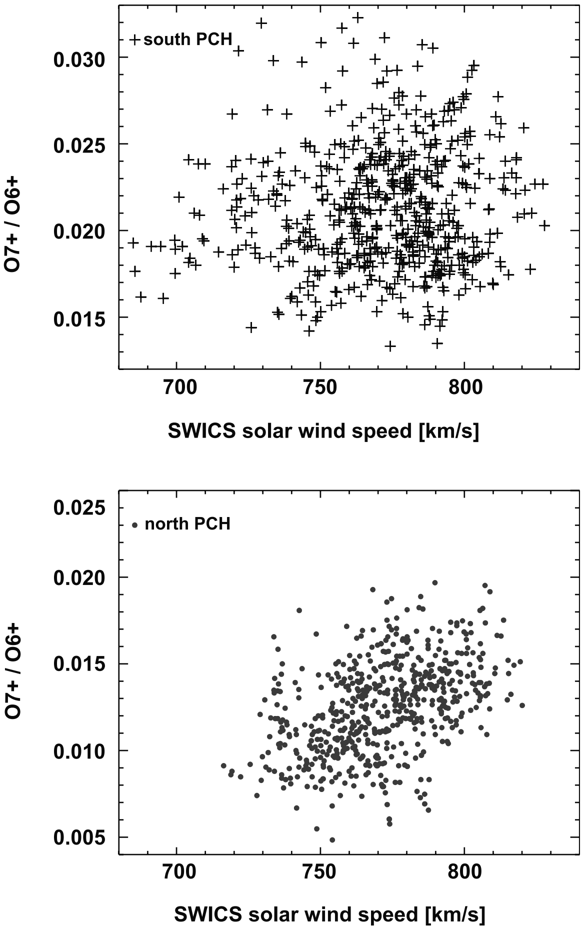

Figure 2. O^{7+}/O^{6+} versus solar wind speed as measured in the south (top) and north (bottom) PCH solar wind streams.

latitudes, thus we tend to favor a latitudinal dependence as the cause of the variations.

[14] The coronal hole area, coronal hole flux and flux density as deduced from synoptic charts are shown in Figures 1c to 1e. The north PCH area is somewhat larger compared to the south PCH area. This is persistently the case. The magnetic flux of the north PCH is slightly lower compared to the south PCH. The coronal hole flux densities differ significantly, the flux density in the south PCH being nearly twice as large as in the north PCH.

[15] The differences persist for multiple years throughout the period in which Ulysses observes the PCH streams. A dependence of these differences on the solar activity cycle is not apparent, although the PCH areas do evolve with time. The small-amplitude variations with one-year periodicity superimposed on the otherwise stable levels of the studied parameters are possibly an artifact introduced by the changing Earth-Sun viewing angle due to the inclination of the Sun's rotation axis with respect to the ecliptic. The amplitude of these variations is considerably smaller than the difference of the mean north and south polar values.

[16] In Figure 1b a clear variation of the charge-state ratios and solar wind speed with latitude (and/or time) is seen in the north PCH stream, whereas the dependence is less pronounced or even absent in the south PCH stream. Figure 2 emphasizes this difference. Scatter plots of 15 h averaged O^{7+}/O^{6+} ratios versus solar wind speed for both polar coronal holes are shown. A weak correlation between O^{7+}/O^{6+} and solar wind speed is observed in the north PCH, the correlation coefficient being 0.44. No correlation is seen in the south PCH (correlation coefficient 0.07).

[17] In summary, the north and south PCHs differ geometrically and in their physical properties. The north PCH is somewhat larger. It is cooler and its magnetic flux density is lower.

3. Discussion

[18] The observations presented here confirm the findings of *McComas et al.* [2000] in that the velocity of the south and north PCH streams do not differ significantly. Likewise other solar wind parameters studied by *McComas et al.* [2000] did not reveal any significant difference in the two PCH streams, at least not to a degree that solar cycle effects could be excluded. Thus these parameters do not point to north-south asymmetries in the structure of the corona.

[19] However, most of the parameters studied by *McComas et al.* [2000] refer to the kinetic properties of the solar wind and are sensitive to modification during solar wind expansion and propagation to the spacecraft. Similarly, the absence of a significant north-south asymmetry in the magnetic field strength deduced from Ulysses [*Forsyth et al.*, 1996; *Smith et al.*, 2000a] is not surprising in view of the fact that a stronger field at the solar surface is expected to expand more rapidly until approximately equal field strengths are achieved. In contrast, the ionic composition as measured in interplanetary space is already established in the solar corona and most probably not altered to a large extent during propagation from the Sun to the observation point. Thus it is a good proxy for the physical conditions in the solar corona, namely for the electron temperature and its profile.

[20] The O^{7+}/O^{6+} ratios differ between the two PCHs on average by several 10% compared to just a few percent difference in the solar wind kinetic properties. This translates into a coronal electron temperature that is about 10% lower in the north PCH. Moreover, large north-south differences were observed for closely aligned time intervals during the fast latitude scan. We can thus exclude that all the differences are produced by solar cycle variation and can conclude that they at least partly reflect a real asymmetry of the two PCHs.

[21] For the north PCH a correlation between the O^{7+}/O^{6+} ratio and the solar wind speed is found. This correlation most likely reflects a latitude dependence of both parameters. The ionic composition as well as the solar wind speed increase with latitude within this PCH, so that the highest values are observed in the center of the PCH, lowest values at the edges. A similar correlation is not seen for the south PCH. Whereas the speed does show a similar, though somewhat less pronounced, latitude dependence as in the north PCH, the O^{7+}/O^{6+} ratio does not. The latter remains roughly constant throughout the coronal hole interval. It is not readily understandable why the two coronal holes should behave differently. We suggest that, although the main difference of the freezing-in temperatures in the south and north PCH are not due to solar activity variation, the coronal temperature may nevertheless depend weakly on the solar activity cycle. If so, the strong decline of the solar activity in 1993 to 1994 would have actually led to a slight decrease of the coronal temperature in this period. This decrease would have compensated the increase which would arise due to Ulysses descending from the ecliptic towards the south polar region. The result is a freezing-in temperature apparently independent on latitude. This explanation is supported by the strong increase in the area of the south PCH during the second half of 1993 and the first half of 1994 (Figure 1c). Another possible explanation could be that the south PCH, during the declining phase of the solar cycle, was aligned less well with the solar rotation axis than the north hole was around solar minimum. Indeed, a stronger wobble (or more inclined current sheet) was observed when entering the south hole in 1992/93 as compared to leaving the north hole in 1996. This wobble could have contributed to smearing out the signal in the south PCH.

[22] The existence of a north-south asymmetry inferred from in-situ observations in interplanetary space is corroborated by variations in solar surface parameters deduced from Kitt Peak magnetograms. Throughout the declining/minimum phase of the solar cycle the north PCH covered approximately 20% more of the solar surface than the southern one. Despite its smaller area, the magnetic flux passing through the south PCH was somewhat larger than through the north PCH. The flux density in the south PCH was twice as large as in the northern one. Unfortunately, the Kitt Peak synoptic charts are not suited to investigate latitudinal variation of the magnetic flux density within the polar coronal holes. Thus we cannot deduce whether the latitudinal variations of solar wind speed and freezing-in temperature are associated with variations of the flux density.

[23] At present we cannot address the important question whether the observed asymmetry is specific to the investigated solar cycle or whether it is present every solar cycle and possibly reverses in alternate cycles. However, the observations made on the second orbit of Ulysses around the Sun combined with synoptic charts derived from magnetograms may answer this question.

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