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The wide skirt of the bashful ballerina: Hemispheric asymmetry of the heliospheric magnetic field in the inner and outer heliosphere

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[1] We reanalyze the observations of the heliospheric magnetic field (HMF) made by the Pioneer 10 and 11 and Voyager 1 and 2 heliospheric probes since 1972, and calculate the HMF sector occurrence ratios and tangential component strengths in the different regions of the heliosphere. Observations at the distant probes and at 1 AU show a very consistent picture of the HMF sector structure in the entire heliosphere, and even beyond the termination shock. HMF observations by the probes also support the southward shift of the heliospheric current sheet (the bashful ballerina phenomenon), which is observed earlier at 1–2 AU by the Ulysses probe and Earth-orbiting satellites, and verify the HCS shift over a wide range of radial distances until the distant heliosphere. Pioneer 11 and Voyager 1 show that the development of northern polar coronal holes was very systematic and active during all the four solar minima since mid-1970s, while Voyager 2 observations show a less systematic and delayed development of southern coronal holes in 1980s, 1990s and 2000s. This delay in the evolution of southern coronal holes with respect to the rapid and systematic evolution of northern coronal holes leads to a larger extent of northern coronal holes and the southward shift of the HCS for a few years in the late declining phase of each solar cycle. Although evidence for the connection between the different evolution of polar coronal holes and the bashful ballerina phenomenon is obtained here only for three solar cycles, this may be a common pattern for solar coronal hole evolution since the southward shift of the HCS has occurred at least since solar cycle 16.

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1. Introduction

[2] The heliospheric magnetic field is the extension of the solar coronal magnetic field, flowing radially outwards from the Sun with solar wind plasma. The heliospheric current sheet is the continuation of the solar magnetic equator from the corona into the heliosphere, and divides the HMF into the away (A) and toward (T) sectors (polarities), i.e., the northern and southern magnetic hemispheres. The first satellite missions around the ecliptic studied the HMF structure at 1 AU, observing the average 45° spiral angle and sector polarities alternating with the solar rotation period [*Rosenberg and Coleman*, 1969]. Subsequent missions beyond the Earth's orbit found that the equatorial HMF sector structure further out from the Sun closely follows the structure at 1 AU [*Slavin et al.*, 1984; *Burlaga et al.*, 1984]. The Ulysses mission covered the solar cycles 22 and 23 and, for the first time, almost all heliographic latitudes, giving a more global view of the large scale HMF structure [*Smith and Balogh*, 1995]. Ulysses data verified that during solar maximum times, due to a large HCS tilt angle with respect to heliographic equator, both sector polarities can appear at any latitude, while during solar minima unipolar regions cover a large range of latitudes due to a small HCS tilt angle [*Smith et al.*, 2001].

[3] Cosmic ray fluxes during the first Ulysses pole-to-pole fast latitude scan in 1994–1995 showed for the first time that the average location of the HCS was, at least momentarily, shifted southwards by about ten degrees from the heliographic equator [*Simpson et al.*, 1996]. (Actually, the proper term is "coning", but "shift" is by now in common practice). Ulysses HMF observations during the same period found that the HMF intensity is larger in the southern hemisphere, supporting the southward shifted HCS at this time [*Smith et al.*, 2000]. Subsequently, using the HMF observations at 1 AU since 1960s, it was verified that such a southward shift is a general long-term pattern, now called the bashful ballerina [*Mursula and Hiltula*, 2003]. According to this pattern, the HMF sector prevalent in the northern heliographic hemisphere dominates the sector occurrence around the equator for about three years in the late declining to minimum phase of the solar cycle (SC). However, the long-term (several solar cycles) averaged HCS shift was found to be smaller, only a few degrees [*Mursula and Hiltula*, 2003] than the momentary value observed during Ulysses. Coronal magnetic field predictions using the measured photospheric magnetic field and the potential field source surface model

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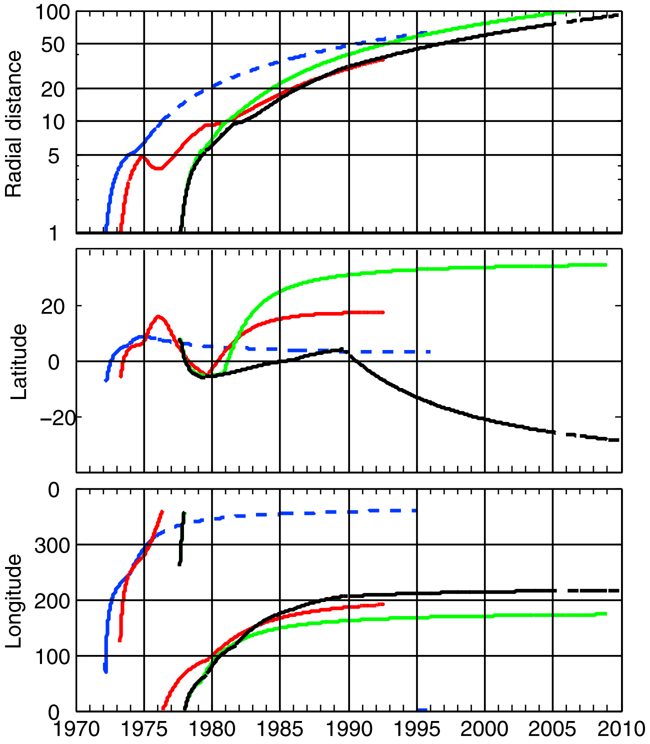

Figure 1. The radial distances, HGI latitudes and longitudes of Pioneer 10 (blue), Pioneer 11 (red), Voyager 1 (green), and Voyager 2 (black). Dashed line indicates missing HMF data.

also verified the larger area and the weaker intensity of the northern polarity field, leading to the average HCS southward shift by a few degrees [*Zhao et al.*, 2005]. In addition to satellite data, the daily averaged HMF sector polarities, extracted from ground-based geomagnetic field observations, were used to show that the HCS was shifted southward even during earlier times, at least since solar cycle 16 [*Hiltula and Mursula*, 2006]. More recently, when reanalyzing the Ulysses HMF observations, it was shown [*Virtanen and Mursula*, 2010; *Erdős and Balogh*, 2010] that during both the two solar minimum time fast latitude scans in 1994–1995 and 2007 the average HCS shift was about 2°, despite the very different solar polar field intensities during these times. We have also noted that the southward shift of the HCS could not be unambiguously measured at 1 AU during SC 23 because of the exceptionally thick HCS region due to the weak polar fields during this cycle [*Virtanen and Mursula*, 2010; *Mursula and Virtanen*, 2011].

[4] The aim of this paper is to study the hemispheric asymmetry in the HMF intensity, sector occurrence and HCS location at different distances of the heliosphere from 1 AU to the termination shock (TS), and even beyond, using magnetic field observations by the Voyager 1 and 2 and Pioneer 10 and 11 probes. We will compare these observations with each other and with the HMF observations at 1 AU collected in the OMNI database (http://omniweb.gsfc.nasa.gov/). We will show that the hemispherical asymmetries around solar minimum times are a global phenomenon appearing in the whole heliosphere. We study the relative occurrence of the T and A-sectors and the intensity of the tangential HMF component separately in the two HMF sectors and discuss their differences. The paper is organized as follows. Section 2 presents the orbits and HMF data of Pioneer 10 and 11 and Voyager 1 and 2 probes, and the HMF data of the OMNI database. Section 3 presents the HMF sector occurrence ratios measured by the probes and at 1 AU, and Section 4 the corresponding results for the intensity of the tangential (B_t) HMF component. In Section 5 we discuss the obtained results and in Section 6 give our final conclusions.

2. Probe Trajectories and Data

[5] We use here the magnetic field data of the Voyager 1 and 2 and Pioneer 10 and 11 probes available in the National Space Science Data Center COHOWeb database (http://cohoweb.gsfc.nasa.gov/). Figure 1 shows the radial distance and the heliographic (HGI) latitude and longitude of the four probes as a function of time. The abrupt changes in probe orbits, in particular in the latitude, are due to the gravity effects when passing by various planets. None of the probes reached very high latitudes, but Voyager 1 and 2 are now located roughly at 30° above and below equator respectively.

[6] For most of the time the longitudinal coverage is rather poor, since Pioneer 11, Voyager 1 and Voyager 2 have closely similar longitudes after 1980. Pioneer 10 moved in a roughly opposite direction but, unfortunately, the probe's magnetometer was only working until November 1975. Pioneer 11 magnetometer data extended until 1993, but the magnetometers aboard the two Voyager probes are still operating. However, these probes no longer yield new HMF data since Voyager 1 reached the termination shock at the end of 2004 and Voyager 2 in the middle of 2007 [*Stone et al.*, 2005, 2008].

[7] We also use here HMF observations in the NSSDC OMNI database, a collection of hourly solar wind and HMF data from satellites orbiting the Earth or located at the L1 point. The OMNI data are scaled to the radial distance of 1 AU. Following the Earth's orbit, the heliographic (HGI) longitude and latitude of OMNI data vary between 0° and 360° and between −7.4° (northern hemisphere Spring) and +7.4° (Fall), respectively, during one year.

[8] Figure 2 shows the availability and coverage of hourly magnetometer data for Voyager 1 and 2 and Pioneer 10 and 11 probes, and OMNI database in consecutive 27-day intervals. There is one long data gap in Voyager 2 in 2004–2006 which needs to be taken into account. During its last years of operation in 1990s, Pioneer 11 had a rather low data coverage of about 10%. However, even when the low coverage is due to small random data gaps (and not due to a small number of long gaps), it is still possible to reliably determine the relative fraction of HMF sectors [*Mursula and Hiltula*, 2003]. For example, the hemispheric asymmetry of the order of a couple of degrees, as found by WSO and Ulysses measurements, can be reliably determined when the data coverage is more than about 3%. Accordingly, as seen in Figure 2, all the four probes have sufficient data coverages for the present study throughout their lifetimes.

[9] The reliability of the measurement of magnetic field intensity at large distances is also of concern. Since the HMF field intensity decreases with distance, the probe's magnetic

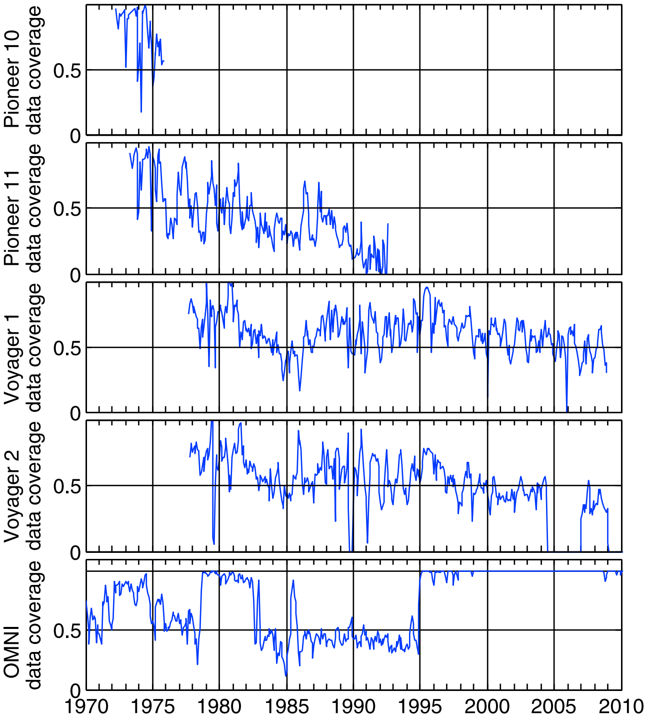

Figure 2. Data coverages in consecutive 27-day segments for Pioneer 10 and 11, Voyager 1 and 2 and OMNI data set.

field may start disturbing the measurement of the HMF. In this study we determine the HMF sectors from Voyager and Pioneer magnetometer data by using the tangential component of the magnetic field. The HMF polarity measurement has been found to be reliable at least until the HMF intensity of about 0.03 nT [*Burlaga et al.*, 2002]. We calculated the HMF sector occurrences and tangential field components for field intensities above this limit only, but found little difference to results obtained by using all HMF values. This is in a good agreement with *Burlaga et al.* [2002]. Therefore, we use here all measured HMF data. Note also that, in difference to the sector definition in the four probes, we use here the quadrant division in the GSE coordinate system ($B_x > 0$ and $B_y < 0$ for T-sector; $B_x < 0$ and $B_y > 0$ for A-sector) to determine the HMF polarity in OMNI data because the average spiral angle at 1 AU is about 45°.

[10] Using these sector definitions we determined for each hour whether HMF is pointed either away (A-sector) or toward (T-sector) the Sun. We summed up these sector occurrences of the two polarities during a 27-day (solar rotation) period and then calculated the corresponding 27-day T/(T + A) ratio. This procedure is then repeated every 27 days. We also calculated the similar sums of sector occurrences for 13 solar rotations (roughly one year) from hourly data and calculated the same ratio. This procedure is stepped every 27 days, leading to a 13-rotation running mean T/(T + A) ratios. Note also that there are timing differences between the probes (and the Earth) due to their different radial distances. While the solar wind travel time from the Sun to the Earth is roughly four days, it takes about one year to reach the termination shock. This is the maximum time lag in the present study and must be remembered especially when comparing Voyager results with OMNI data.

3. HMF Polarities at the Four Probes

[11] Figure 3 presents the 27-day T/(T + A) ratios and the corresponding 13-rotation running means. We have noted in Figure 3 with blue (red, respectively) color whenever the probe is above (below) the equator.

3.1. Observations in the 1970s

[12] Soon after the launch in March 1972 Pioneer 10 observed a weak A-sector dominance while around the equator. In 1974, when the probe was already at northern latitudes, the T-sector dominated in Pioneer 10 observations. Thereafter in 1975, still in the north, Pioneer 10 observed an A-sector dominance until the magnetometer broke down. As seen in Figure 3, these fluctuations in the sector occurrence ratio were very similar in Pioneer 11 and OMNI data. This indicates a very coherent HCS evolution in the inner heliosphere at this time at radial distances of about 1–7 AU. These observations also give evidence for shifts of the average HCS location by a few degrees toward the south in 1973, to the north in 1974 and to the south again in 1975. (Note that the latitude of Pioneer 10 did not change much from 1974 to 1975). E.g., the change of the T-sector dominance to A-sector dominance at Pioneer 10 in early 1975 was due to the increase of the extent of the A-sector and the related southward shift of the HCS.

[13] Pioneer 11 was launched in April 1973, heading first northward and crossing the equator in July 1973. In the mid-1970s Pioneer 11 briefly attained somewhat more northern latitudes than Pioneer 10, reaching its locally maximum latitude of about 16° in 1976 (see Figure 1). Corresponding to the prevailing solar magnetic polarity, Pioneer 11 detected a very strong A-sector dominance at this time, reaching a maximum A/(T + A)-ratio of about 0.84 (minimum T/(T + A)-ratio of 0.16) in the 13-rotation mean in 1976. The strong A-sector dominance lasted until 1978 when Pioneer 11 moved to southern latitudes for a while. Note, however, that the strength of the A-sector dominance at Pioneer 11 in mid-1970s is not only due to the probe's northern latitude but also due to the expansion of the A-sector beyond the equator. This global evolution is evidenced by the simultaneous A-sector dominance in OMNI data. Note also that both in Pioneer 11 and OMNI the A-sector dominance lasted for about 3 years in 1975–1977. (Unfortunately there was no probe at southern latitudes at this time to further verify this development).

[14] Voyagers were launched in August-September 1977, when Pioneer 11 was already located at about 5–6 AU. In the late 1970s and early 1980s both Voyagers as well as Pioneer 11 were at southern latitudes. All probes first observed a relative increase of the T-sector occurrence leading to a weak T-sector dominance in 1978–1979 in the two Voyagers, corresponding to the polarity of the previous minimum. All probes also detected a subsequent relative increase of A-sector occurrence with a maximum in 1979–1980, close to the polarity reversal time. A similar evolution is also seen in the OMNI data.

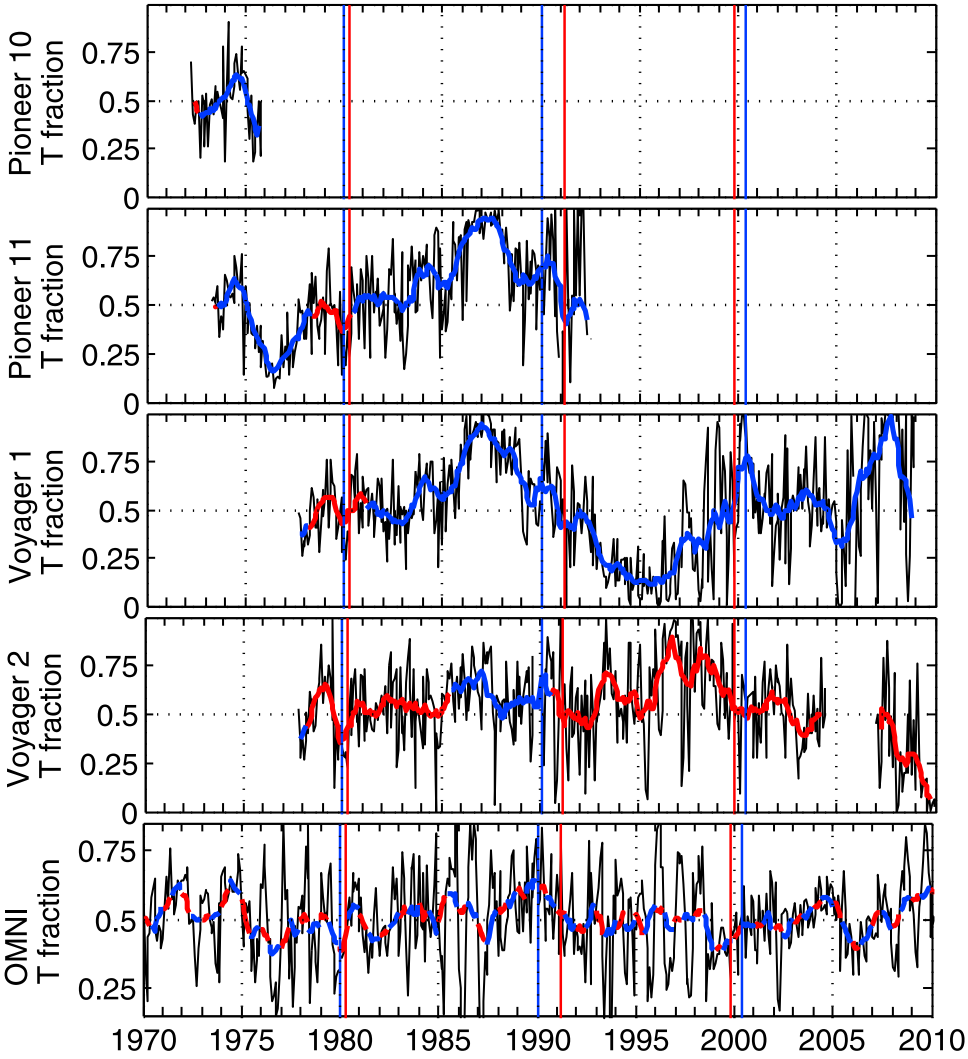

Figure 3. T-sector occurrence ratios T/(T + A) for Pioneer 10 and 11, Voyager 1 and 2 and OMNI data. Thin line: 27-day averages; thick colored line: 13-rotation running means stepped every 27 days. Blue (red) color indicates that the probe was above (below) equator. Vertical blue (red) lines mark the northern (southern) polar field reversal times according to Wilcox Solar Observatory.

3.2. Observations in the 1980s

[15] In 1981 the latitude of Voyager 2 separates from that of Pioneer 11 and Voyager 1, which head more rapidly northward (see Figure 1). This is seen in Figure 3 as a corresponding difference in sector occurrences since 1983 when Pioneer 11 and Voyager 1 detect a rapid increase of T-sector occurrence when already at rather high northern latitudes of about 15 and 20 degrees, resp. Note, however, that the T-sector increase in 1983 occurs almost simultaneously at Pioneer 11 and Voyager 1 despite their latitudinal difference at that time, suggesting that the increase is due to the temporal evolution of the HMF rather than due to the increasing latitude of the two probes. The increase of T-sector occurrence since 1983 is due to the expansion of polar coronal holes in the northern hemisphere, which increases the occurrence of the new dominant polarity field of the northern pole at midlatitudes (at least down to 15°).

[16] This expansion proceeds in two phases, the first in 1983–1984 and the second in 1985–1987, leading to the T-sector occurrence maximum of about 0.94 (0.93, respectively) in Pioneer 11 (Voyager 1) in 1986–1987. Note that these developments are also seen in OMNI and Voyager 2 data. Even the first expansion (see later), but especially the latter, stronger expansion proceeds below the heliographic equator, since both Voyager 2 and OMNI see a clear T-sector dominance starting in 1985. Voyager 2 was below the equator at the start of the T-sector dominance and reached only the latitude of 2° until the T-sector maximum in 1986–1987 (see Figure 1). Thereafter, the T-sector dominance starts reducing, first in OMNI data in mid-1986 then, with a small lag corresponding to the radial separation, in the heliospheric probes in late 1986 to early 1987. The two phases of expansion were separated by a short period in 1984 when Voyager 2 momentarily observed A-sector dominance in a few 27-day averages (too short to lead to A-sector dominance in the 13-rotation curve). These developments suggest that the sector structure even slightly below the equator in Voyager 2 data was dominated by the northern

hemisphere. The expansion of coronal holes in the north was clearly stronger than in the south over most of the solar minimum until 1986, when a brief encounter of A-sector dominance is seen at 1 AU, indicating an activation of the southern coronal holes. This suggests that the HMF sector asymmetry around the equator and the over-expansion of the northern field across the heliographic equator (bashful ballerina) are related to the difference in the temporal evolution and spatial extent between the northern and southern coronal holes.

3.3. Observations in the 1990s

[17] Pioneer 11 and Voyager 1 observed a very similar sector structure evolution during the rest of Pioneer 11 lifetime, in spite of the increasing separation in latitude and radial distance, by about 10° and 10 AU at the end of Pioneer data interval in 1992. Both probes observed the long period of consecutive T-sector dominance until 1989 and the last activation of the T-sector dominance in 1989–1990, i.e., just prior to the polar field reversal. Note that the lower latitude Pioneer 11 as well as Voyager 2 and OMNI observed a stronger T-sector than Voyager 1 at high latitudes during the last activation. This indicates that most of T-sector field originated from low to midlatitude coronal holes, not from the polar coronal hole, in agreement with the appearance of low-latitude coronal holes during solar maximum times.

[18] Since the early 1990s Voyager 1 is flying at slightly increasing latitudes above 30° north, while Voyager 2 is moving toward higher southern latitudes (see Figure 1). Both Voyagers observed an increase of the A sector in 1992, which changed to a T sector dominance at Voyager 2 in 1993. This indicates that the northern coronal hole activated slightly earlier than the southern coronal hole. Voyager 1 observed a fairly smoothly increasing A-sector dominance, which culminated at the maximum of about 0.89 in A/(T + A) ratio in 1995. Interestingly, the increase of the T-sector occurrence in Voyager 2 was halted later in 1993, reducing to a minimum of 0.48 in 1995, the year of maximum A-sector occurrence in the north. This different development of coronal holes in 1993–1995 is also reflected in HCS evolution. After the expansion of polar coronal holes in the southern hemisphere was halted in 1993, the continuing expansion of the northern coronal holes pushed the HCS region southward. This is seen as a reduction of the T-ratio below 0.5 in OMNI data (see Figure 3) in 1993–1995. The southward shift of the HCS exactly in these years was also seen in WSO PFSS predictions [*Zhao et al.*, 2005] and during the Ulysses first fast latitude scan [*Crooker et al.*, 1997; *Virtanen and Mursula*, 2010].

[19] Later in 1995, the southern coronal holes recovered rapidly, leading to a T-sector maximum of about 0.90 in Voyager 2 already in 1996. At this time both the northern and southern coronal holes had a large extension, leading to a narrow latitudinal extent of the HCS region and large latitudinal gradients in sector occurrence around the equator. This situation is seen particularly clearly at 1 AU where the 27-day sector occurrence ratio depicts an annual variation with a large amplitude (see Figure 3), following the annual variation of the Earth's heliographic latitude. A similar annual variation was also seen in OMNI data during the other solar minima included in this study (1976–1977, 1986–1987 and 2008–2009). This annual variation had its largest amplitude around the minimum in 1980s, in agreement with the finding that the HCS was thinnest around this minimum [*Richardson and Paularena*, 1997]. Note also that the amplitude of the annual variation reflects the strength of solar polar fields and, as verified by Figure 3, this strength has been declining since 1980s [*Smith and Balogh*, 2008].

[20] The northern coronal hole started slowly contracting already slightly before the southern hole reached its maximum. Both coronal holes experienced a rapid decline in 1996–1997, which was halted by a second expansion in 1997–1998, leading to a two-top structure of T-sector dominance at Voyager 2 during this minimum. (The expansion was less pronounced at Voyager 1, but is seen in a few 27-day values). Both hemispheres recovered the sector balance roughly simultaneously in 1999, slightly before polarity reversal. In 2000 Voyager 1 observed a brief T-sector dominance of about 0.77, which is different from Voyager 2 or OMNI data where sectors were roughly equally divided, and may be due to a short-lived coronal hole in the north appearing at the time of reversal. Note also that in 1999, when the two Voyager probes detected almost equal sector amounts, OMNI observed a period of A-sector dominance due to low-latitude coronal holes. Such differences are typical for solar maximum times.

3.4. Observations in the 2000s

[21] In 2001–2004 Voyagers observed a fairly symmetric evolution, with the T-sector fraction alternating slightly around its mean in anti-phase between the two probes. The delayed appearance of a clear sector dominance (i.e., polar coronal holes) in either hemisphere is a specific phenomenon of SC 23 and related to the appearance of persistent low to midlatitude coronal holes still fairly late in the declining phase of this cycle [*Gibson et al.*, 2009]. The similarity of sector evolution at the two probes in 2001–2004 also suggests that the proximity of termination shock (crossed by Voyager 1 in 2004 and Voyager 2 in 2007) had no significant effect on the relative distribution of sectors in the outer heliosphere. In fact, it is even likely that the temporal evolution of sector occurrence ratios just outside the termination shock is quite similar as inside it. Thus, Voyager 1 observations show that the development of the northern polar coronal hole only started in 2006 and culminated in the overwhelming T-sector dominance (0.95) in 2007. Although there is an unfortunate data gap in Voyager 2 data in and around 2005, we can see that the coronal hole development in the two hemispheres is quite different. The sector ratio in Voyager 2 is close to 0.5 still at the turn of 2006–2007, and starts to develop an A-sector dominance (leading to a maximum of 0.77 in 2008) almost at the same as the northern coronal hole starts to contract. Although comparing results across the termination shock may be slightly questionable, we would still like to note that the temporal delay in the evolution of southern coronal holes suggested by Voyager 1 and 2 observations at this time is very similar as in the same phase of the previous solar cycles.

3.5. Modeling the T Sector Fraction of Voyager 2

[22] We have modeled the T sector fractions observed by the Voyager 2 probe using hemispherically symmetric models in order to see if such models can explain the observed fractions or not. We have used the HCS tilt angles

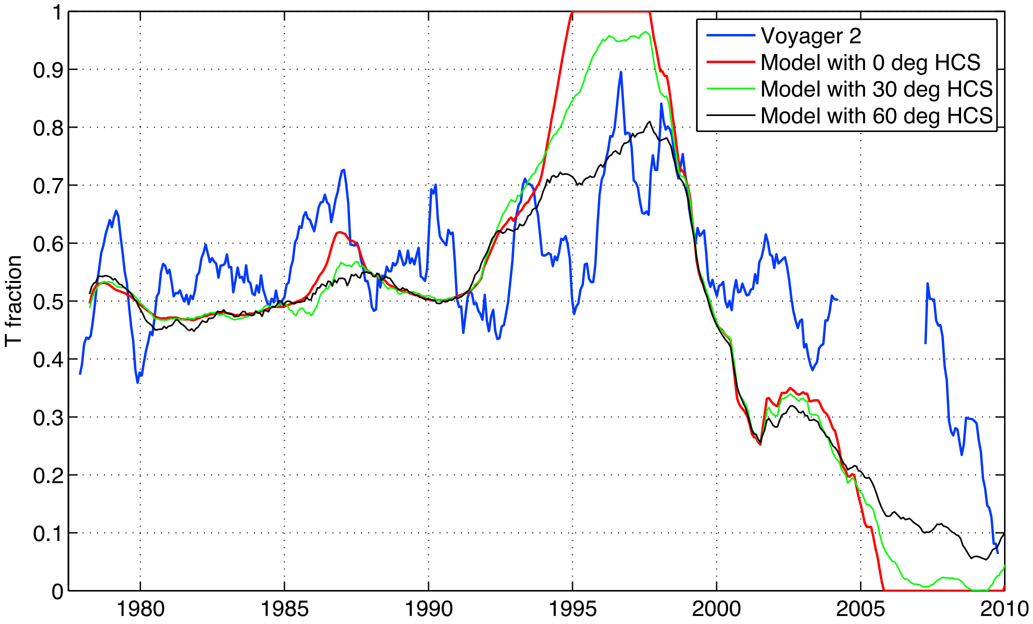

Figure 4. 13-rotation running means of the observed (blue) and the three modeled T sector fractions at Voyager 2: zero-width HCS model (red), 30° HCS model (green) and 60° HCS model (black).

determined by the Wilcox Solar Observatory for each solar rotation, and continued the momentary HCS latitude to the outer heliosphere using the (rotationally averaged) solar wind speed observed at the probe. We have used three values for the effective width of the HCS region: vanishingly narrow HCS (zero-width HCS), 30° and 60° wide HCS. (Note that there is no direct information about the momentary HCS width in the outer heliosphere. Therefore, we have used two quite different values in order to obtain robust estimates.) In the case of zero-width HCS, the probe is located either above or below the HCS, observing the sector structure of the respective solar hemisphere at that time. For a finite HCS width, the HCS latitude is varied randomly around the tilt angle by the value given by the respective HCS width model angle (±15° or ±30°).

[23] Figure 4 depicts the observed and modeled T sector fractions of Voyager 2. The zero-width model gives a very simple temporal variation of the modeled T sector fraction, being around the mean of 0.5 until the probe leaves the equatorial region in early 1990s. (There is a small positive deflection already in 1986–1987, when the probe is slightly above the equator during the solar minimum). The T sector attains the theoretical maximum in 1995–1997 when the HCS tilt remains below the probe latitude. Correspondingly, the T sector vanishes in 2005–2010 when the tilt is sufficiently reduced during the next solar minimum. The two models with a finite HCS width follow the zero-width HCS model at all other times, except for the two solar minima when Voyager 2 was at rather large southerly latitudes, when the finite HCS models yield T sector fractions that are considerably closer to the mean than the zero-width model.

[24] Note that the observed T sector fractions deviate systematically from the modeled values during the above discussed times when the HCS was found to be shifted southwards. For the first time this is the case from 1982 until 1984 when Voyager 2 is slightly below the equator and is expected to see a T sector fraction below 0.5, as given by the zero-width HCS model (see Figure 4). However, the observed value is slightly above 0.5, due to the earlier and more vigorous expansion of the northern coronal hole, as discussed above. Later in 1985–1986, Voyager 2 detects a larger dominance of the T sector than it is expected to see at the respective low northern latitudes if the HCS was symmetric. Note also that the more realistic finite-width HCS models give a slightly larger difference with the observed T sector fractions than the zero-width model, emphasizing the relevance of the observed difference.

[25] Similar differences between the observed and modeled T sector fractions are seen also during the declining phase of the next solar cycle. The models predict that Voyager 2 should see a considerable dominance of the T sector in 1991–1992, when heading toward increasingly high southerly latitudes. However, as discussed above, the starting expansion of northern coronal holes at this time leads to a roughly equal occurrence of T and A sectors at Voyager 2 at this time. The southern coronal hole expansion starts in 1993, leading momentarily to a close agreement between the observed and modeled T sector fractions. However, as noted earlier, this expansion is halted by the more vigorous expansion of northern coronal holes, leading to a sudden dropout of the T sector fraction considerably below the expected value. This continues until 1996, when the southern coronal holes start expanding more systematically, and the observed T sector fraction increases close to the values predicted by the finite-width HCS models. Accordingly, there is clear, quantitative evidence that the T sector fractions observed at Voyager 2 during the declining phase of cycles 21 and 22 are in a serious disagreement with HCS models that are hemispherically symmetric. (As discussed above, the situation is more complicated during cycle 23

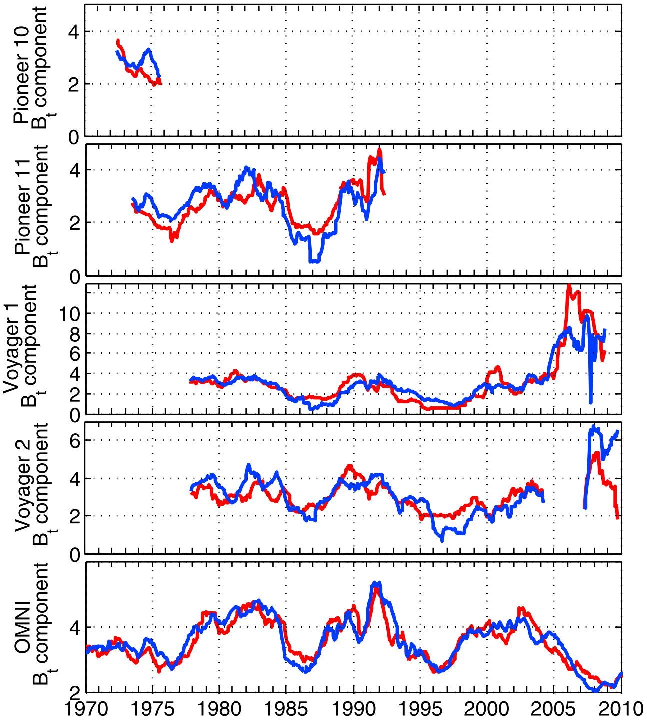

Figure 5. 13-rotation running means of the B_t component, stepped every 27 days, for Pioneer 10 and 11, Voyager 1 and 2 and OMNI data. Separate curves for A-sector (blue line) and T-sector (red line).

because of the exceptional evolution of coronal holes and the location of the probe around the termination shock).

3.6. Variability Around Minima

[26] Note that the level of variability in the 27-day sector ratios (around the 13-rotation mean) shows interesting differences between the four solar minima included in this study. There is quite little variability in the 27-day values during the solar minima in 1975–1976 and 1986–1987, as evidenced by Pioneer 11 and Voyager 1 sector ratios (see Figure 3). There is more of such variability in 1995–1996 in Voyager 1 even if it was then at higher latitudes than either Pioneer 11 or Voyager 1 during two previous minima. Variability in Voyager 2 in 1997 is also fairly large. However, this is the only measure in the southern hemisphere, which can not be straightforwardly compared with earlier minima since the evolution in the south may be different from the north (see previous discussion). Variability around the Voyager 1 minimum in 2007 or at Voyager 2 around 2008–2009 can hardly be compared with observations around other minima due to the different conditions outside the termination shock.

[27] We have shown earlier [*Virtanen and Mursula*, 2010] using Ulysses fast latitude scans in 1994–1995 and 2007 that the latitudinal extent of the HCS region was considerably wider during cycle 23 minimum than cycle 22 minimum. The increase of the 27-day variability of the sector occurrence since 1980s and the related increase of the HCS latitudinal extent reflect the decline of polar field strength during this time [*Smith and Balogh*, 2008]. As noted above, the HCS width was exceptionally narrow [*Richardson and Paularena*, 1997] and the annual variability of the sector occurrence at 1 AU had its largest amplitude in 1986–1987, declining during subsequent solar minima due to the reducing latitudinal gradients around the ecliptic (solar equator).

4. HMF Tangential Component in Two Sectors

[28] Figure 5 presents the tangential components B_t of the HMF observed by the four heliospheric probes. We first scaled the data to 1 AU assuming that the tangential field behaves like $B_t \propto 1/r$. Then the hourly B_t components were divided into T and A-sectors (positive and negative RTN coordinate values) and the absolute values of their 13-rotation running means were calculated separately, stepping every 27 days. (Very similar results are obtained if one first calculates 27-day averages and then their 13-rotation means). Figure 5 also includes the corresponding GSE B_y components at 1 AU (using the quadrant sector division as discussed earlier).

[29] One obvious feature in Figure 5 is the solar cycle variation of B_t intensity. This naturally follows the solar cycle variation of HMF total intensity [*Luhmann et al.*, 2002], since B_t forms the dominant HMF component at the radial distances where the probes travel. The minima of B_t agree quite well with sunspot minima. This is true for B_t minima in 1976 and in 1986–1987 in Pioneer 11, in 1985–1986 and in 1995–1997 in Voyager 1 and in 1986–1987 and in 1995–1996 in Voyager 2. Note that the minima for the two sectors may differ by up to 2 years during one minimum even in one satellite. Also, the same minimum observed by different satellites may differ by up to 2 years, even for the same polarity. Solar cycle maxima of HMF intensity are known to occur slightly after sunspot maxima, around the time of solar dipole reversal [*Luhmann et al.*, 2002]. The same phasing is roughly seen in cycle maxima of the B_t component during all three solar cycles and in all heliospheric probes. However, as for cycle minima, the maxima for the two sectors observed by one satellite, or for same sector observed by two satellites may differ by up to 2 years.

[30] The solar cycle variation of B_t observed by the probes in the middle and outer heliosphere agrees quite well with the similar variation at 1 AU, as depicted by the OMNI data (see Figure 5). However, there are some differences, e.g., in the relative heights of some peaks between the heliospheric observations and at 1 AU. This is particularly true for SC 22 where OMNI data depicts in 1991 its highest peak in B_y for the 35 years included in Figure 5. A similar all-time peak is not found in other heliospheric probe data except for perhaps in Pioneer 11 where very large B_t values were observed at the end of observations. Despite some differences, there are also convincing agreements between observations in far heliosphere and at 1 AU. E.g., the SC 23 maximum of OMNI B_y in 2002 (and prior evolution) is closely reproduced in 2003 by Voyager 2 observations, although the probe was at about 70 AU distance and the relative noise level was already quite high. (Voyager 1 did not see a clear maximum at this time due to the proximity of the termination shock).

[31] Note that the amplitude of solar cycle variation of B_t is somewhat larger in the heliospheric probes than at 1 AU both in absolute value and relative to the overall level. Moreover, the cycle amplitude of the heliospheric probes seems to slightly grow as the probes move further out to

higher heliospheric latitudes. This development is caused by the decrease of the cycle minimum levels of B_t, while no similar decrease is seen in maximum levels of B_t. This decrease of B_t minima is seen, e.g., in Pioneer 11 where the T-sector minimum in mid-1980s is lower than the A-sector minimum in mid-1970s. (For the selection of sectors in this comparison, see later). A similar decrease is seen in Voyager 1 from the T-sector minimum in mid-1980s to the A-sector minimum in mid-1990s. (Although Voyager 2 also depicts decreased minima from mid-1980s to mid-1990s, a similar sector comparison is not straightforward since the probe was located in opposite hemispheres during the two solar minima). The systematic reduction of cycle minima of B_t is due to the fact that, as the probes move to higher latitudes, they meet with more and more of high speed winds around solar minimum times. High speed streams carry magnetic field which is less spiraled than in the slow solar wind, leading to the observed decrease of B_t intensities as probes move away.

[32] Note also that there are systematic differences between the B_t intensities of the two HMF sectors. Pioneer 11 indicates that the A-sector has a more intense B_t component in mid-1970s than the T-sector (see Figure 5). (Pioneer 10 supports this difference for the last years of its lifetime). On the other hand, Pioneer 11 shows that there is a similar but oppositely signed difference in B_t intensity in mid-1980s so that the T-sector now has a more intense B_t than A-sector in 1984–1988. The larger intensity of the T-sector B_t in the northern hemisphere in mid-1980s is supported by Voyager 1 observations (see Figure 5). Voyager 1 also sees very consistently a stronger A-sector B_t in 1993–1999. Voyager 2, while briefly below the equator in early 1980s, sees a stronger A-sector B_t intensity and in late-1990s, when permanently in the southern hemisphere, a stronger T-sector B_t. Note that the time of a stronger T-sector B_t in Voyager 2 occurs only in 1996–1999, coinciding with the delayed expansion of southern coronal holes, and several years later than the corresponding A-sector B_t dominance in Voyager 1. Note also that the two Voyagers depict very similar differences between sector B_t values even in 2000s despite the fact that they are already beyond the termination shock and that the absolute intensities are much larger. The sector differences in B_t values appear both at Voyager 1 and Voyager 2 only when the corresponding coronal holes start developing (see Figure 3). Moreover, the development of the difference is delayed in Voyager 2 compared to Voyager 1 exactly in the same way as during the previous solar minimum when both probes were still well inside the heliosphere.

[33] In all the above mentioned cases the sector that is dominating in the respective hemisphere has the larger B_t intensity. This sector typically comes from large polar coronal holes, while the opposite (sub-dominant) sector, which has a weaker B_t intensity, typically comes from closer to the current sheet. We note that the difference in solar wind speed between the dominant and subdominant sectors is rather small and cannot explain the difference in B_t intensity.

[34] Note also that the above mentioned differences in B_t intensity between the two HMF sectors are generally much larger in all the heliospheric probes than in OMNI data. This is because the 13-rotation OMNI curves include data roughly equally from both northern and southern hemispheres, but the probes stay longer times or permanently either below or above the solar equator. However, even in OMNI data, the A-sector is seen to have a systematically stronger B_t intensity in the mid-1970s and early 1990s, while the T-sector has a stronger B_t intensity in mid-1980s. These differences coincide with the times when the HCS is shifted southward. When the HCS is shifted southward (even if only by a couple of degrees), the HMF sector of the northern hemisphere comes, on an average, from regions that are slightly further away from the HCS than the opposite (sub-dominant) sector, leading to larger B_t values in the dominant sector.

5. Discussion

[35] We have studied in this paper the relative occurrence of the two HMF sectors and the strength of the dominant tangential component of the HMF using observations at the four heliospheric probes (Pioneer 10 and 11, and Voyager 1 and 2) and in the OMNI database. The results concerning the overall HMF structure are in a good agreement with earlier studies [see, e.g., *Burlaga et al.*, 2002; *Burlaga and Ness*, 1994]. We have shown that the measurements at very widely separated locations in the heliosphere up to the termination shock (and even partly beyond) depict a very consistent pattern and yield very similar results. This underlines the overall coherence of the observed development of the heliospheric magnetic field and the heliospheric current sheet over a wide range of radial distances. It also emphasizes the astounding performance of the related instruments [*Smith*, 1973; *Smith et al.*, 1974; *Behannon et al.*, 1977] over extensive periods of time, which we wish to explicitly credit.

[36] The region of the heliosphere covered by the four probes was limited to rather low latitudes until mid-1980s and mainly to the northern hemisphere until mid-1990s. This restricts the availability of simultaneous information about the HMF in the two hemispheres until 1990s. However, even data from this limited region can be used to study the development of coronal holes and the heliospheric current sheet, especially when compared with the continuous measurements at 1 AU included in the OMNI database. For example, Pioneer 11, while flying at northern latitudes, observed the great dominance of the northern HMF sector in 1975–1977 around the minimum of SC 20. Both Pioneer 10 and 11 observed a stronger HMF B_t component in the “dominant” A-sector at this time. This period marks the largest extension of the (northern) coronal holes during this minimum. Simultaneously at 1 AU, OMNI data depicts a systematic dominance of the A-sector, indicating the expansion of the northern field over the heliographic equator [*Mursula and Hiltula*, 2003].

[37] The configuration of probes was more complete in 1980s when Voyager 2 was in the southern hemisphere at the same time as Pioneer 11 and Voyager 1 traversed at northerly latitudes. Note first that the largest sector dominance maximum was obtained during this minimum, although the probes continued to fly to even higher latitudes. This verifies the earlier observation that the latitudinal width of the HCS was smallest (and coronal hole extent largest) during this minimum [*Richardson and Paularena*, 1997]. The same fact is also supported by the annual variation of the sector occurrence at 1 AU (see Figure 3), which has its largest amplitude during this minimum.

[38] The expansion of the northern coronal hole started in 1982, was temporarily halted in 1984, and reactivated again in 1985. Interestingly, no corresponding activation of the southern coronal hole was seen by Voyager 2 at slightly lower southern latitudes. Rather, the reactivation led to a T-sector dominance also at Voyager 2, which started even when the probe was still in the southern hemisphere. This implies that the dominant HMF sector of the northern hemisphere expanded over the equator to the southern hemisphere. This development is further evidenced by OMNI data, where a surplus of T-sector is observed in 1983–1986, except for a short halt in 1984. Also, modeling shows that the T sector fractions observed by Voyager 2 are in a disagreement with corresponding results expected from a hemispherically symmetric HCS. Accordingly, the observations of the heliospheric probes confirm the occurrence of the southward shifted HCS at this time until the radial distance of at about 15–20 AU of Voyager 2. This similarity and coherence of the HCS evolution over such a large radial distance contradicts with some preliminary modeling results [*Usmanov and Goldstein*, 2004] where coronal hemispheric asymmetries were found to vanish well before 1 AU.

[39] An even better possibility for comparing the development of coronal holes and the HMF in the two hemispheres took place in 1990s when the two Voyagers were located at considerable northern and southern latitudes. Despite some difference in absolute latitude, the growth of polar coronal holes was seen to start in both hemispheres almost at the same time in 1992–1993. However, while the CH growth was very systematic in the north, it was halted in the south for several years, and continued only in 1996. Despite this delay, the maximum fractions of the dominant sector were almost the same at the two probes (0.89 in Voyager 1 and 0.90 in Voyager 2), indicating that, eventually, both coronal holes did obtain roughly equal maximum extents. However, even for this declining phase, detailed models of the T sector fractions based on a symmetric HCS are in a clear disagreement with observations, and support the southward HCS shift. Note also that this temporal difference is seen not only in the sector fractions but also in the relative strength of the B_t component in the two hemispheres. While Voyager 1 sees a very long period of systematically stronger A-sector B_t component in 1993–1999, Voyager 2 sees a stronger T-sector B_t only after the southern coronal hole expansion in 1996. Finally, we note that OMNI data depicts a southward shifted HCS and a stronger B_t component in the A-sector in 1991–1995. This suggests that the periods of southward shifted HCS (the bashful ballerina times), are due to a systematic difference in the evolution of coronal holes, in particular, due to a faster and more persistent increase of CH in the northern hemisphere and a delayed growth in the south.

[40] During the next solar cycle 23, the two Voyagers did not observe the start of growth of either polar coronal hole until rather late in the declining phase of the cycle, thus verifying the exceptional evolution of coronal holes during this cycle [*Gibson et al.*, 2009]. By that time both probes were already outside the heliosphere (termination shock crossings in 2004 and 2007). However, we noted that the evolution of the sector fractions and the relative strengths of the B_t component in the two sectors observed by the two probes beyond the termination shock are very similar as those observed during the earlier cycles inside the heliosphere. E.g., Voyager 1 verifies a systematic development of northern coronal holes since 2005–2006, and Voyager 2 a delayed evolution of southern holes since 2007–2008. Also, in both probes the B_t component is clearly stronger in the corresponding dominant sector. This suggests that the sector fractions and relative B_t strengths remain largely unaffected by the TS crossing, and yield additional evidence for the suggested connection between polar CH evolution and HCS asymmetry.

[41] Finally, we also note of a recent model, according to which hemispherically asymmetric flux generation may lead to HCS asymmetry [*Wang and Robbrecht*, 2011]. There, the dominant HMF polarity at the heliographic equator is determined by the north-south asymmetry of sunspots, and the HCS may be shifted southward or northward, depending on the leading sunspot polarity of the more active hemisphere. The connection presented here between the different evolution of coronal holes in the two hemispheres (more persistent in the north) and the HCS asymmetry is in principle independent of the flux generation asymmetry model [*Wang and Robbrecht*, 2011], although the two may be interrelated.

6. Conclusions

[42] HMF observations by the four heliospheric probes and at 1 AU show a very consistent picture of the large scale structure of the heliospheric magnetic field and current sheet, in particular of HMF sector occurrence ratios and B_t component strengths in the entire heliosphere, and even beyond the termination shock. The minimum time B_t values systematic decrease as the probes move to higher latitudes, since they meet with more of high speed winds, which carry less spiraled magnetic field than the slower wind of maximum times. This modifies the radial dependence of the B_t component and leads to a larger solar cycle variation in time.

[43] HMF observations of the four probes verify the southward shift of the HCS during the declining phase of solar cycle, which is observed earlier at 1–2 AU by the Ulysses probe [*Virtanen and Mursula*, 2010] and by the Earth-orbiting satellites [*Mursula and Hiltula*, 2003]. The present observations show that the HCS was southward shifted at these times over a wide range of radial distances until the termination shock and, most likely, even beyond. We have verified by explicit modeling of the T sector fractions at Voyager 2 that the observations are in a clear disagreement with a hemispherically symmetric HCS.

[44] Pioneer 11 and Voyager 1 probes also show that the development of northern polar coronal holes was very systematic and active during all the four solar minima in 1970s, 1980s, 1990s and 2000s. On the other hand, Voyager 2 observations show a less systematic and delayed development of southern coronal holes in 1980s, 1990s and 2000s. This delay in the evolution of southern coronal holes with respect to the rapid and systematic evolution of northern coronal holes leads to a larger extent of northern coronal holes and a southward shift of the heliospheric current sheet (the bashful ballerina phenomenon) for a few years in the late declining phase of each solar cycle. Although the evidence for the connection between the temporal difference in the evolution of polar coronal holes and the bashful ballerina times is based only on three solar cycles, this may be a common pattern for solar coronal hole evolution since the

southward shift of the HCS has occurred at least since solar cycle 16.

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