THREE-DIMENSIONAL EVOLUTION OF SOLAR WIND DURING SOLAR CYCLES 22–24

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ABSTRACT

This paper presents an analysis of three-dimensional evolution of solar wind density turbulence and speed at various levels of solar activity between solar cycles 22 and 24. The solar wind data used in this study have been obtained from the interplanetary scintillation (IPS) measurements made at the Ooty Radio Telescope, operating at 327 MHz. Results show that (1) on average, there was a downward trend in density turbulence from the maximum of cycle 22 to the deep minimum phase of cycle 23; (2) the scattering diameter of the corona around the Sun shrunk steadily toward the Sun, starting from 2003 to the smallest size at the deepest minimum, and it corresponded to a reduction of ∼50% in the density turbulence between the maximum and minimum phases of cycle 23; (3) the latitudinal distribution of the solar wind speed was significantly different between the minima of cycles 22 and 23. At the minimum phase of solar cycle 22, when the underlying solar magnetic field was simple and nearly dipole in nature, the high-speed streams were observed from the poles to ∼30° latitudes in both hemispheres. In contrast, in the long-decay phase of cycle 23, the sources of the high-speed wind at both poles, in accordance with the weak polar fields, occupied narrow latitude belts from poles to ∼60° latitudes. Moreover, in agreement with the large amplitude of the heliospheric current sheet, the low-speed wind prevailed in the low- and mid-latitude regions of the heliosphere. (4) At the transition phase between cycles 23 and 24, the high levels of density and density turbulence were observed close to the heliospheric equator and the low-speed solar wind extended from the equatorial-to-mid-latitude regions. The above results in comparison with Ulysses and other in situ measurements suggest that the source of the solar wind has changed globally, with the important implication that the supply of mass and energy from the Sun to the interplanetary space has been significantly reduced in the prolonged period of low solar activity. The IPS results are consistent with the onset and growth of the current solar cycle 24, starting from the middle of 2009. However, the width of the high-speed wind at the northern high latitudes has almost disappeared and indicates that the ascending phase of the current cycle has almost reached the maximum phase in the northern hemisphere of the Sun. However, in the southern part of the hemisphere, the solar activity has yet to develop and/or increase.

Key words: scattering – solar wind – Sun: activity – Sun: heliosphere – Sun: magnetic topology – turbulence

Online-only material: color figures

1. INTRODUCTION

The behavior of the Sun before the transition between solar cycles 23 and 24 exhibited very long and deep periods of minimum activity. At the long-decay phase, the magnetic configuration of the Sun went through remarkable changes that were different from those observed at the corresponding previous minimum phase. For example, the number of days without a sunspot was large (more than 800 days at the deep minimum phase, compared to ∼300 days at the minimum of cycle 22) and the fluxes of extreme ultraviolet, soft X-ray, and radio intensity at 10.7 cm reached their lowest levels. Moreover, unusually long-lasting high-speed streams from the low-latitude coronal holes of open magnetic field lines and their interaction with low-speed flows from closed-field corona resulted in a complex heliosphere of low speed and density. The reasons for the long duration as well as the depth of the peculiar minimum have been much studied in terms of solar interior characteristics, manifestation of the sunspot, polar field strength, transmission of solar wind, shaping of the heliosphere, geo-effectiveness, solar irradiance, etc. (see, e.g., Basu et al. 2010; Feynman & Ruzmaikin 2011; Jian et al. 2011; Lallement et al. 2010; Lee et al. 2009; Lo et al. 2010; Manoharan 2010b; McComas et al. 2008; Smith & Balogh 2008; Tapping & Valdés 2011; Tokumaru et al. 2010). An international campaign on the “Whole Heliosphere Interval” was also organized to study the three-dimensional aspects of the “solar–heliospheric–planetary connected system.” The period of the campaign covered a part of the deep minimum phase (i.e., Carrington Rotation 2068, 2008 March 20–April 16) and included studies from the low solar photosphere, through interplanetary space, and down to Earth’s mesosphere (e.g., Thompson et al. 2011).

The extended decay of cycle 23 and the later-than-expected onset of cycle 24 provided an opportunity to examine the link between the solar activity and the three-dimensional heliosphere. In principle, the three-dimensional view of the solar wind can be inferred by the radio remote sensing interplanetary scintillation (IPS) technique, which can provide estimates of solar wind speed and density turbulence. Several authors employed the IPS technique and studied the changes to the solar wind as functions of the helio latitude and distance, as well as over the solar cycle and compared them with three-dimensional coronal density and magnetic field structures on the Sun (e.g., Rickett & Coles 1991; Kojima & Kakinuma 1990; Manoharan 1993, 1995, 1997; Manoharan et al. 1994). Recently, based on IPS observations from STELab, a distinct decrease in the solar wind speed at the high-latitude regions of the heliosphere was revealed for solar cycle 23 (Tokumaru et al. 2010).

In the present study, the large IPS database collected from the Ooty Radio Telescope (ORT), operated by the Radio Astronomy Centre, Tata Institute of Fundamental Research, India, at 327 MHz (Swarup et al. 1971), has been employed to analyze...
the three-dimensional distributions of the solar wind density turbulence and speed at different levels of solar activity during 1985–2011. It is the detailed study of the preliminary results presented at a proceeding conference (Manoharan 2010b) and covers more than two solar cycles. A careful examination of the consequences of various levels of Sun’s activity embedded in the solar wind gives insight into the fundamental physical processes involved in shaping the heliosphere. This paper is structured as follows. A brief description of the IPS observation is given in Section 2. The next section covers the results on the distribution of the density turbulence at different phases of solar cycles 22–24. The latitudinal changes of the solar wind speed from the IPS and the Ulysses spacecraft are discussed in Section 4. In Section 5, measurements obtained from near-Earth spacecraft are discussed. Section 6 summaries the results and discussion.

2. INTERPLANETARY SCINTILLATION

The IPS technique exploits the scattering of radio waves from a distant compact source of angular size $\Theta \leq 500$ mas (e.g., a radio galaxy or quasar) by the density turbulence in the solar wind (e.g., Hewish et al. 1964; Coles 1978; Manoharan & Ananthakrishnan 1990; Kojima et al. 2004). The measurable quantity in an IPS observation is the time series of intensity fluctuations resulting from the radio-wave scattering caused by the plasma density irregularities convected at the speed of the solar wind, and it includes an irregularity structure of spatial scales from about the size of the Fresnel scale and below. For example, the IPS used in this study, at 327 MHz, can probe turbulence scales below 400 km. A suitable calibration of the temporal spectrum of intensity fluctuations can provide the solar wind speed (e.g., Manoharan & Ananthakrishnan 1990; Manoharan et al. 2000; Tokumaru et al. 1994, 2011; Yamauchi et al. 1996, 1998; Liu et al. 2010) and the scintillation index, $m$ (e.g., Coles 1978; Manoharan 1993; Asai et al. 1998). The scintillation index, $m$, is a measure of the electron-density turbulence in the solar wind ($m^2 \sim \int \delta N_e^2(z)dz$) along the line of sight ($z$) to the radio source (e.g., Manoharan 1993; Manoharan et al. 2000).

An IPS measurement therefore represents the integration along the line of sight to the radio source. However, since most of the scattering power is concentrated at the point of the closest approach of the line of sight to the Sun, as given by the typical steep radial fall of the density turbulence, $\delta N_e^2(R) \sim R^{-4}$, the IPS basically probes properties of the solar wind at the region of the closest solar offset on the source–Earth path (Coles 1978; Manoharan 1993). In fact, the line-of-sight integration can pose a problem when a short-lived solar wind transient of enhanced density turbulence and speed with respect to the ambient solar wind is studied based on a single IPS observation, which may lead to positional uncertainty along the integration path. However in the present study, the high level of scintillation associated with solar wind transients, e.g., coronal mass ejections (CMEs), have been removed. In the case of a slowly varying large-scale ambient solar wind, an IPS observation can only systematically underestimate the solar wind by $\sim 5\%–10\%$ (Manoharan et al. 1994, 2000; Yamauchi et al. 1996). Moreover, when a day-to-day monitoring of the IPS is made on a large number of scintillators having different lines of sight, cutting across different parts of the heliosphere, it can probe the substantial portion of the inner heliosphere. Such data sets are extremely useful to study the evolution of the large-scale features of the solar wind over an extended period of time (Manoharan 2006, 2010a, 2010b). Since the primary aim of the present study is to understand the three-dimensional changes of the large-scale structure of the solar wind over a long period of time (e.g., at timescales of a fraction of a year to a solar cycle), no attempt has been made to remove the systematic line-of-sight integration effect included in the IPS observation.

In this study, a large amount of the IPS data, collected during 1985–2011 from ORT operating at 327 MHz (Swarup et al. 1971), has been employed. This set of the IPS data from Ooty probed the solar wind in the heliocentric distance range of $\sim 10–250$ solar radii ($R_\odot$, $1 R_\odot = 6.96 \times 10^9$ km, $1 AU \approx 215 R_\odot$) and at all heliographic latitudes. It allowed the study of the three-dimensional evolution of the heliosphere over solar cycles 22–24. It may be noted that before the upgrade of the feed system of the ORT around the middle of 1992, everyday IPS measurements were limited to a small number of radio sources (≈ 40–50 radio sources). The increased sensitivity of the upgraded system, however, enabled the observations of $\sim 300$ sources per day, and this source count steadily increased to the present monitoring of a grid of more than 1000 sources per day. Currently, the ORT is being upgraded and the number of the IPS sources observed per day is expected to increase by $\sim 4–5$ fold by the end of this year (Prasad & Subrahmanya 2011). The regular monitoring of the IPS so far at Ooty covers an extended period of more than two solar cycles and it has led to the detection of more than 3500 scintillating sources at 327 MHz, over the entire right ascension range. Results on the compact component structure of these sources are in preparation (P. K. Manoharan 2012, in preparation).

3. SOLAR CYCLE CHANGES OF SOLAR WIND DENSITY

3.1. Scintillation Index and Large-scale Density Turbulence

The degree of IPS is given by the scintillation index, $m = \text{rms of intensity fluctuations/mean intensity of the source}$, which is a measure of density turbulence in the solar wind, $(m^2(R) \sim \int \delta N_e^2(R) dR)$. Figure 1 shows the scintillation index measurements made with ORT at 327 MHz in the heliocentric...
distance range of 10–250 R⊙ on a compact radio quasar 1148-001, for selected years between 1985 and 2011. The above radio quasar has a compact component size of ~15 mas (Manoharan et al. 1995). As indicated by the peak value of the scintillation index close to unity, the compact component of the above source contains more than 90% of its total flux density. It is to be noted that for a given radio source, the entire scintillation index profile, m(R), is attenuated by the brightness-distribution function associated with the size of the scintillating component. Therefore, the peak value of the scintillation can vary between unity and null, respectively, for an ideal point source and a non-scintillator (Coles 1978; Manoharan et al. 1994; Manoharan 2006). Since in the above plots the enhanced scintillations caused by intense solar wind transient events (e.g., CMEs, refer to Manoharan et al. 2000) have been excluded, these plots represent the average condition of the ambient density turbulence of the heliosphere at different phases of solar cycles 22–24. Moreover, the radio quasar 1148-001 is an ecliptic source and its IPS measurements are confined to the equatorial region of the heliosphere. Therefore, Figure 1 represents the solar wind changes that occurred in the equatorial belt of the heliosphere.

In Figure 1, the best fit to the data points is shown by a continuous curve. As shown in the figure, the level of scintillation as the Sun is approached increases to a peak value near a distance of R ≈ 40 R⊙ and then decreases for more closer solar offsets, where the scattering becomes strong and saturated (e.g., Manoharan 1993). The turnover point of the scintillation index moves close to the Sun as the observing frequency is decreased. However, for a given observing frequency, it depends only on the level of turbulence. In the above log–log “m–R” plots shown in Figure 1, the peak value of the scintillation index increases or decreases, respectively, in tune with the maximum or minimum of solar activity. However, in order to infer the global characteristics of density turbulence in the heliosphere, the area under the best-fit m²(R) profile has been computed for several scintillators as given by

\[ A = \int_{R=40 R_{\odot}}^{R=200 R_{\odot}} m^2(R) dR. \]  

For each source, the area has been computed in the weak-scattering regime (R in the range ~40–200 R⊙). Since most of the scattering power is contained within ~200 R⊙, the above summation provides an average quantitative estimate of the large-scale density fluctuations in the inner heliosphere with a radius of ~0.2–1 AU over a period of about six months. Figure 2 shows the area of the m²(R) curve plotted against the year for 12 compact scintillating sources. These sources have been selected on the criteria: (1) a strong scintillator having the compact component size of Θ ≤ 100 mas, (2) more than 50% of the total flux density of the source lies in the compact component (or the peak of the scintillation index curve is 〈δN₂(0) = Φ₂(R)c R = 1 km at ∼200 R⊙), (3) the observations of these sources fall in the ecliptic plane (i.e., in the equatorial region of the heliosphere). For each source, the computed area has been normalized by its average density turbulence, \( A \approx \int_{R=40 R_{\odot}}^{R=200 R_{\odot}} m^2(R) dR. \)

\[ \Phi(q, R) = C_2^q(R) \Phi_0^{(q) -3.3} \]

and it gets attenuated at the high-wavenumber portion by the dissipative-scale (or inner-scale) size increasing linearly with the heliocentric distance, \( S_i \approx (R/R_{\odot})^{-1.0 \pm 0.1} \) km at \( R \leq 100 R_{\odot} \) (Manoharan et al. 1988, 1994; Coles & Harmon 1989; Yamauchi et al. 1998). However, at larger distances from the Sun, ~100–200 R⊙, the inner scale tends to stay at a constant value of \( S_i \approx 100 \) km (Manoharan et al. 1988, 1994). The inner-scale cutoff is attributed to occur near the ion (proton) inertial scale, which is determined by the local Alfvén speed and ion cyclotron frequency (e.g., Coles & Harmon 1989; Coles et al. 1991; Manoharan et al. 1994). Therefore, the contributions to the overall turbulence spectrum include magnetic fluctuations (associated density structures) and density fluctuations and their radial changes as a function of the scale size.

For example, using log–log plots shown in Figure 1, the radial dependence of scintillation can be obtained from the linear slope of the m – R curve at distances >40 R⊙. Thus, the radial dependence of scintillation, \( m = m_0 R^{-\alpha} \) (m₀ is the scintillation index at the unit distance from the Sun), corresponds to changes in the density turbulence with the heliocentric distance. The m – R curves of the compact sources used in Figure 2 have been employed to estimate the radial fall of the density turbulence. For each year, the weak-scattering portion of the m – R curve (at distances ≥50 R⊙) has been fitted with a least-squares straight-line fit. The magnitude of slopes (α) obtained from all the sources vary between 1.7 and 2.1, with an average of ~1.8. In the period considered between 1985 and 2011, the slopes do not show significant changes in correlation with the solar cycle. However, marginal changes are observed in the radial
Figure 2. Area under the $m^2(R)$ profile (Equation (1)) plotted as a function of the year. The area has been computed in the weak-scattering region in the distance range of 40–200 $R_\odot$, as indicated by the shaded area shown in Figure 1 (refer to the 1988 plot). Different symbols correspond to different scintillating sources. These are strongly scintillating sources, having an equivalent diameter $\leq 100$ mas and their compact components contain more than 50% of the source total flux density. The continuous line is the segment-wise best fit to the data points. It is clear from the plot that the deepest minimum of the solar cycle 23 is revealed by the lowest level of the density turbulence around the middle of 2008.

(A color version of this figure is available in the online journal.)

dependence of the density turbulence between periods before 2003 and later. In the prolonged minimum phase, after the year 2003, the radial fall shows an average indolent (or slow) slope of $\alpha \approx 1.7$ and a steeper slope (i.e., $\alpha \approx 1.9$) is observed for years before 2003, i.e., over the period of cycle 22 and until about the maximum of cycle 23.

As it was stated in Section 3.1, the integration along the line of sight would reduce the radial power by one unit (Readhead et al. 1978; Manoharan 1993). Therefore, the “distance–density turbulence” relationship, $\delta N_2^2(R) \sim R^{-\beta}$, is related to the slope of the scintillation index curve by $2\alpha + 1 = \beta$. The steep slope observed, $\alpha \approx 2.1$, indicates that the density turbulence falls off rapidly with distance, which is about $\delta N_2(R) \sim R^{-2.6}$. Whereas the value of the shallow slope, $\alpha \approx 1.7$, suggests a typical $R^{-2.2}$ dependence, which is close to the symmetrically expanding solar wind. These results are in agreement with the earlier findings obtained for the solar cycle 21 (Manoharan 1993; Coles et al. 1995; Coles 1996). The marginally less rapid slope observed in the long-deep minimum phase, $R^{-2.2}$, in comparison to the average steep slope of $R^{-2.3}$, indicates that the slow fall of the solar wind is likely linked to the energy and mass fluxes associated with the solar wind originating at the base of the corona and its interaction with the background flow in the inner heliosphere. Thus, the excessive turbulence is possibly due to the interacting flows at $R > 100 R_\odot$, largely due to mid- and low-latitude coronal holes, which in fact persisted in the long-decay phase.

However, the mechanism of observed rapid fall in the range, $\delta N_2^2(R) \sim R^{-(\beta\approx 4-5)}$, and its possible influence beyond 1 AU are required to be addressed. For example, a study of radial dependence of density turbulence by Bellamy et al. (2005), based on Voyager 2 spacecraft data, has shown much lesser fall in the outer heliosphere. Below 30 AU, small slopes of $\beta = 2.3 \pm 0.9$ and $\beta = 3.3 \pm 0.9$ are reported, respectively, for 96 s and
192 s sampling intervals, which correspond to spatial scales of about one to two orders of magnitude larger than scales probed by the IPS observation. The above study also reveals that the level of $C_2^N(R)$ drastically changes with the employed sampling rate (i.e., the probed scale size of turbulence). Thus, at distances beyond 1 AU, the radial dependence of the turbulence spectrum, $\Phi(q, R)$ (also $C_2^N(R)$), shows flattening, enhancement, and dissipation as a function of spatial scales and tends to be independent of the regular expansion of the background solar wind (Bellamy et al. 2005; Hunana et al. 2008; Zank et al. 1996).

### 3.3. Scattering Diameter of the Corona

The routine monitoring of the IPS at Ooty, on a large number of compact radio sources during the period 1985–2011, has been used to estimate constant density turbulence contours at different phases of solar cycles 22–24 (Manoharan 2006, 2010b). At an observing frequency, the peak of the scintillation curve, $m-R$ (refer to Figure 1), depends on the fixed level of the density turbulence, and the heliographic coordinates of several peaks distributed around the Sun are useful to find the contour of the constant (or same) level of density turbulence ($\delta N_e(R)$ in the heliosphere (e.g., Manoharan 1993; Coles 1978). At 327 MHz, the turnover of scintillation occurs around $\sim 40 R_\odot$. In Figure 1, although these are log–log plots, a careful examination reveals that the peak point of the scintillation curve (i.e., the constant value of $\delta N_e(R)$) moves close or away from the Sun, respectively, at the minimum or maximum phase of the solar cycle. Therefore at 327 MHz, the estimation of $m-R$ curves of several elliptic and out-of-elliptic sources in a year and their corresponding peaks located at different latitudes (as well as heliocentric distances) can provide the trace of a constant level of density turbulence around the Sun in the distance range of 30–50 $R_\odot$.

In a year for each source, the average peak of the scintillation and its heliographic coordinates are obtained and plotted around the Sun on a north-east-south-west-north radial diagram. As shown in Figure 3, the latitude-bin average of peaks at different latitudes and the line joining them can provide the constant density turbulence contour around the Sun (e.g., Manoharan 1993). Although this figure includes average constant $\delta N_e(R)$ contours for selected years between 1985 and 2011, the data coverage was sparse during the solar cycle 22. It was due to the fact that in the early days’ observations at Ooty, less concentration was given to the IPS below 50 $R_\odot$ and measurements were mostly limited to the weak-scattering regime, $> 50 R_\odot$. However, starting from the second half of cycle 22, IPS measurements were carried out over the full distance range of 10–250 $R_\odot$ and they enabled the determination of the transition of scintillation for sources favorably positioned with respect to the Sun. In Figure 3, the mean traces of the constant level of density turbulence indicate that in general at the polar regions, the constant level of turbulence is observed closer to the Sun than at the equatorial region. It is in agreement that at the descending phase of the activity, the low-density (i.e., high-speed) streams from the coronal holes fill the polar regions, leading to the low level of density turbulence, and the constant $\delta N_e(R)$ contour moves close to the Sun to compensate for the fall in scattering power at the high-latitude region of the corona. However, as the Sun approaches to the minimum of activity, the size of the coronal hole increases and extends to mid latitudes (Manoharan 1993; Coles et al. 1995; Coles 1996). In such a phase, the density turbulence contour takes a shape close to an ellipse, in which the contour at the mid-latitude part also moves close to the Sun (Figure 3, refer to 1994–96 plots). In the ascending phase, the ratio between the poleward and equatorial diameters, however, gradually decreases from the minimum to maximum phase of the cycle (e.g., Manoharan 1993; Coles et al. 1995), and the ratio of diameters tends to be unity at the maximum of the cycle. The solar wind flow thus attains a spherically symmetrical flow, as revealed by the almost circularly symmetrical distribution of streamers at the maximum phase of the corona observed during the total solar eclipse (e.g., Koutchmy et al. 1992).

The interesting result of this study is that after about the year 2003, the overall scattering diameter of the corona has gradually decreased with respect to the center of the Sun and a given level of turbulence has steadily moved close to the Sun at all latitudes. The diameter of contours during the years 2007–2009 appears symmetrical, but much smaller than the contours observed in the cycle 22. The typical radial dependence of turbulence, $C_2^N(R) \sim R^{-4}$ to $R^{-4.4}$, suggests that the scattering has remained nearly the same at the low-latitude regions between 1995 and 2003, but steadily decreased to $\sim 60\%$ level around the middle of 2009, where the deepest minimum of cycle 23 was observed. The shrinking of the scattering diameter of the corona is in agreement with the measured level of scintillation displayed in Figure 2, which also shows the overall gradual reduction in scattering power between the years 1986 and 2010. The equatorial diameter starts to increase between 2010 and 2011, indicating the onset and progress of the solar cycle 24. The steady and significant long-term trend of the shrinking of the scattering power of the heliosphere means a natural reduction in supply of mass and energy at the low corona.

### 3.4. Latitudinal Distribution of Density Turbulence

At Ooty, the IPS on a source is measured at different solar offsets. For each source, the scintillation index plot ($m(R)$) in a year, as plotted in Figure 1, can be least-squares fitted with an average curve. The ratio between the observed and expected (or fitted) indexes at a given heliocentric distance, $g = \text{observed scintillation/average expected scintillation}$, can be used to assess the level of density turbulence of the slowly varying solar wind structures in comparison with the ambient (or background) solar wind plasma (Manoharan 2006). The above normalized scintillation index, $g$, is independent of the systematic fall of $m$ with solar offset and source-size attenuation. For example, a value of the normalized index close to unity ($g \approx 1$) represents the undisturbed (or background) condition of the solar wind, $g > 1$ corresponds to the enhanced level of density turbulence, and $g < 1$ indicates the reduction of turbulence in the solar wind. An IPS measurement is therefore sensitive to detect even a small fractional change in the density turbulence, and the routine monitoring of the IPS on a grid of sources can easily detect the large-scale structures over a given period of time (Manoharan 2006).

For each source, the best fit to the $m-R$ curve of a given year is estimated and it is used to eliminate the intense transients caused by the CMEs. The data sets of a given source with the transients removed, available for the period between 1985 and 2011, are then combined and the overall least-squares fit is computed. Thus, the value of $g$ obtained from the fitted curve and each observed scintillation index allows an easy comparison of levels of turbulence measured on a number of IPS sources at different time periods and it enables the detection of slowly varying large-scale density structures in the solar wind. Figure 4 displays the “latitude–year” plot constructed from the normalized scintillation index estimates obtained from
Figure 3. Constant $\delta N_e(R)$ contours plotted on a “north-east-south-west-north” polar diagram for selected years between 1985 and 2011. The last plot includes data up to 2011 November. In each plot, reference circles are drawn, respectively, at radii 45 and 60 $R_\odot$ and 30° latitude sectors are shown by the dotted lines. During 2008–2009, the scattering diameter of the corona has shrunken to the smallest size and the solar activity has touched the deepest minimum of solar cycle 23. The increase in the diameter of the contour in the year 2011 evidently reveals the progression of cycle 24.

(A color version of this figure is available in the online journal.)
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Figure 4. Helio latitudinal distribution of solar wind density turbulence as a function of the year. This image has been made by allowing data in the heliocentric distance range of 75–125 \( R_\odot \) and it shows the condition of the heliosphere at the midway point between the Sun and Earth. The distribution of the density turbulence shows remarkable change between minima of solar cycles 22 and 23. (A color version of this figure is available in the online journal.)

on the source surface of the Sun divides regions of opposite polarities. It is swept radially outward by the solar wind and forms the heliospheric current sheet (HCS). At the time of polarity reversal, the amplitude of HCS extends to high latitudes suggesting a complex closed magnetic field topology resulting between the coronal holes and active regions. For example, in Figure 4, the disappearance of the solar wind (Lazarus 2000), shown by the vertical low-density structure around the middle of 1999, is consistent with the complex as well as a rather closed-field corona to confine the plasma, as the Sun approaches toward the peak of the cycle 23 (Figure 7).

The other interesting feature in Figure 4 is the CIRs-dominated heliosphere resulting from the persistent large coronal holes in the latitude range of \( \pm 45^\circ \), as shown by the vertical intense density structure caused by moderate compression during 2003–2004 (Zhang et al. 2008; Abramenko et al. 2010). In this period, each solar rotation possessed more than one HCS, running almost parallel to the latitude axis, increased the possibility of interaction between the low- and high-speed streams. These interactions caused weak-to-moderate storms on the Earth during 2003, as indicated by the geomagnetic disturbance index, Ap (refer to Figure 9).

The density distribution in the maximum phases of solar cycles 22 and 23, respectively, centered around the years 1991 and 2001, shows rather remarkable differences. The low- and mid-latitude regions of the heliosphere near the maximum of cycle 22 were associated with the high-density structures. Whereas the large portion of the heliosphere, even at the maximum of cycle 23, was occupied by a relatively low-density plasma, as was indicated by the density turbulence contours (refer to Figures 2 and 3). It is also interesting to note large differences in the low-density plasma turbulence at the polar regions near the minima of cycles 22 and 23. During the years 1996–1997, the low level of turbulence was confined to latitudes above \( 45^\circ \) in the northern and southern hemispheres. In the prolonged minimum period, during the years 2006–2009, the density was much lower than that of the previous minimum as well since it occupied a broader latitude range extending from high to low latitudes. The low-density plasma prevailed in the large portion of the inner heliosphere around the unusual deep minimum phase and is in agreement with the corresponding shrinking of the scattering diameter of the corona (Figure 3). The density distribution observed after about the year 2010 indicates that the heliosphere is gradually climbing toward the maximum phase of the solar cycle 24. The rate of the increase of density to a high latitude in the north pole seems to be faster than that observed at the south pole, suggesting that the solar cycle 24 tends to approach a near-maximum phase in the northern hemisphere.

3.5. Density Distribution in the Near-Sun Corona

Ooty density turbulence results are consistent with the brightness measured from the Thomson-scattered white light in the near-Sun region. Figure 5 shows the “latitude–year” image of the white light, which is associated with the density of free electrons, measured at 2.5 \( R_\odot \) above the east limb of the Sun for the period starting from the launch of LASCO coronagraph to nearly the middle of the year 2011 (refer to Brueckner et al. 1995 for details on the LASCO coronagraph). As shown by the IPS data, the heliosphere was prevailed by the low density during the prolonged minimum of the solar cycle 23. The latitudinal extents of the large-scale low-density structures in the mid- and high-latitude regions are also in agreement with the IPS density turbulence distributions. The intense density structure observed on the IPS image, associated with CIRs generated by the mid- and low-latitude coronal holes around 2003, is represented on the LASCO image by a less-brightness stripe, which provides evidence for the low-density wind originating above the coronal hole and in particular, not-yet-developed...
interaction as well as compression at the closer solar offset. In the minimum phase of cycle 23, the long-lived coronal holes observed during 2003 might have a more direct involvement in shaping the magnetic state of corona at the deep minimum phase (Abramenko et al. 2010). The three-dimensional distribution of Ly$\alpha$ brightness, which reflects the ionization of the neutral gas by the solar wind, is also in agreement and showed a latitudinal distribution similar to the above shown density turbulence and density images, respectively, displayed in Figures 4 and 5 (Lallement et al. 2010). The onset of the solar cycle 24 in the year 2009 and the gradual increase in the latitudinal extent of the high-density wind to higher latitude between 2010 and 2011 (particularly at the north pole side) are evident in Figure 5. However, as indicated by the density turbulence (Figure 4), the southern hemisphere seems to progress slower than the northern part.

4. SOLAR CYCLE CHANGES OF SOLAR WIND SPEED

For an IPS observation in the weak-scattering regime, a suitable calibration of the temporal power spectrum of intensity fluctuations, having sufficient signal-to-noise ratio (i.e., $\geq 15$ dB), can provide the speed of the solar wind (Manoharan & Ananthakrishnan 1990; Manoharan et al. 2000; Tokumaru et al. 1994, 2011; Yamauchi et al. 1996, 1998; Liu et al. 2010). Figure 6 shows the “latitude–year” distribution of solar wind speed estimates obtained from the IPS data collected from the ORT, as it was displayed in the plots of density and density turbulence (Figures 4 and 5). During the minimum of solar cycle 22, polar regions were dominated by the high-speed streams in the range of $\sim 700–800$ km s$^{-1}$ from open-field coronal holes, and low and variable flow speeds, $\leq 450$ km s$^{-1}$, were observed at the low- and mid-latitude regions of the complex/closed-field corona (Phillips et al. 1995; McComas et al. 2008; Smith & Balogh 2008). The striking features in this image are (1) the confined period of the minimum for cycle 22, centered around the year 1996 and the high-speed wind (or the extension of coronal holes) observed from poles to the mid-latitude region of $\sim \pm 30^{\circ}$ and (2) in contrast, the effects of the minimum of cycle 23 were stretched over a long period of time, and the width of the high-speed belt was limited to latitudes higher than 60$^{\circ}$ in the north and south poles; a deep minimum-like condition was observed between the years 2008 and 2009, during which the extent of the high-speed belts at the north and south poles were limited between the poles and $\sim 60^{\circ}$ latitudes. Furthermore, the speed originating above them has been considerably reduced. The low-speed solar wind distribution along the equatorial belt seems to be highly variable in the range of 300–500 km s$^{-1}$, and the “disappearance of solar wind” (i.e., extremely low density and speed) that occurred in the early part of the year 1999 as well as the coronal-hole dominance in the mid-latitude region of the heliosphere during 2003 are evidently revealed.

Figure 7 shows the smoothed plots of the tilt angle of the magnetic HCS and the strength of the polar magnetic field. For reference, the sunspot number and radio flux density at 10.7 cm are also included in this figure. The magnetic field data sets have been obtained from the Wilcox Solar Observatory$^1$ and the solar activity indexes are from the Solar Geophysical Data Center.$^2$ These plots cover a period from 1985 to the later part of 2011, i.e., solar cycles 22–24. The large-scale magnetic field, shown by the amplitude of the current sheet during the years 2004–2008, resembles a corona of complex field, but with reduced activity. The remarkable increase in the latitudinal width of the low-speed flow during the extended minimum of cycle 23 is directly linked and in good agreement with the observed polar field strength and warping of the current sheet, which is caused by the extension of the global field from the Sun into the interplanetary medium. The solar wind speed distributions observed for solar cycles 22 and 23 correlate, respectively, with the polar field strength of $\sim 100$ to 50 $\mu$T. Thus, the magnetic field has been weaker by

$^1$ http://wso.stanford.edu

$^2$ http://www.ngdc.noaa.gov/stp
Figure 6. Helio latitudinal distributions of the solar wind speed obtained from Ooty IPS data plotted for the years 1989–2011. This image has been made by tracing backward/forward from the measurement location onto a sphere with a radius of ∼125 solar radii. At the minimum of solar cycle 22, the effects of the high-speed wind were observed from poles up to about ∼30° latitudes. However, in the prolonged minimum, the high-speed streams were located close to the poles.

(A color version of this figure is available in the online journal.)

∼40%–50% in the minimum phase of cycle 23 than that of cycle 22 (Figure 7). The magnetic pressure associated with the polar coronal holes consequently seems to play a significant role in the acceleration of the high-speed wind. The weak field may be due to the fact that the polar field has not fully developed after the field reversal between 2000 and 2002 (Figure 7).

It was reported that the Sun went through a period of a large number of “sunspot-free” days3 (more than 800 days between 2006 and 2009, in comparison with ∼300 days of “spotless” days in the minimum of cycle 22). Moreover, at the extreme minimum phase of cycle 23, the solar wind distribution around the equatorial belt as well as the tilt angle (refer to Figure 7) suggest that the magnetic field of the Sun did not approach the expected dipole geometry, as it did for the minimum phase of cycle 22 (Riley et al. 2003; Tokumaru et al. 2009). The weakening of the large-scale coronal field has also been revealed by the weak emission of the Fe xiv green line at 5303 Å (Rybanský et al. 2005). Additionally, Ulysses and near-Earth observations (Figures 8 and 9) made over the solar cycles 22 and 23 are in good agreement with speed and density distributions presented in the previous sections (McComas et al. 2008; Smith & Balogh 2008; Lee et al. 2009). Figure 8 shows the daily averages of the magnitude of the interplanetary magnetic field and solar wind speed, as measured by the Ulysses spacecraft around the minima of solar cycles 22 and 23. Ulysses measurements evidently show an overall reduction in field strength, density, and speed, as well as the increased width of the equatorial flow and poleward shrinking of the high-speed wind for the similar latitudinal and heliodistance passes of cycles 22 and 23. The lack of sunspot activity governing the radiative energy from Sun, in combination with the weakening of the interplanetary field and turbulence, allowed the penetration of cosmic rays at the minimum phase of cycle 23 by more than ∼20% compared with the 1997–1998 period (Mewaldt et al. 2010).

As observed in density and density turbulence plots (refer to Figures 4 and 5), the speed distribution plot (Figure 6) also shows that after the onset (i.e., in the ascending phase) of

3 http://sidc.oma.be/sunspot-data/
Figure 8. Daily averages of the magnitude of the interplanetary magnetic field and solar wind speed at the orbit of Ulysses as a function of the year, around the minimum phases of solar cycles 22 and 23. Close tracking of the location of Ulysses on the heliosphere, for these two passes, clearly shows (1) a significant reduction in equatorial flow widths, (2) a rapid decline in the speed and a weaker field at minimum of cycle 23 than that of the corresponding previous minimum of cycle 22. (A color version of this figure is available in the online journal.)

The changes observed in the distribution of the high-speed solar wind at the north and south polar regions are different. In particular, in the later part of 2011, the high-speed belt at the northern region has moved almost close to its pole. However, in the southern part, it has remained nearly unchanged. It suggests that the area of the northern coronal hole associated with the high-speed wind has reduced and shrunk close to the north pole. In other words, the increase in the solar activity (i.e., the vanishing of the source of the high-speed wind) is significant at the northern hemisphere and indicates nearly (or close to) the maximum phase of cycle 24. It is consistent with the yearly average values of the flare index\(^4\) observed at the northern and southern hemispheres over the year 2010, respectively, 0.26 and 0.12. The northern hemisphere of the Sun was two times more active than the southern hemisphere.

5. SOLAR CYCLE CHANGES AT NEAR-EARTH SPACE

Figure 9 shows the 27 day average of 1 AU measurements of the solar wind proton speed and its flow directions (i.e., latitude and longitude), number density, temperature, dynamical flow pressure, magnitude of interplanetary magnetic field, and the ratio of alpha particle to proton densities, observed between the years 1985 and 2011. A plot of the geomagnetic index, Ap, is also included in the figure. These data sets have been extracted from the NASA/GSFC’s OMNI database.\(^5\) It is evident that in the near-Earth region, the solar wind dynamical pressure started to decrease after the maximum phase of cycle 22 (after about year 1992) to a deep minimum during the years 2008–2009. Although there was a moderate enhancement in the solar wind pressure at the maximum of cycle 23, it was, however, nearly 40% lower than the corresponding increase observed at the previous activity maximum. In the long-decay phase of cycle 23, the intercomparison of results from previous sections with 1–AU measurements of solar wind speed, proton and alpha particle densities, temperature, pressure, and interplanetary magnetic field suggests that the reduction in density and magnetic energy of the solar wind streams has organized the heliosphere. Thus, the energy of the solar wind started to decrease after the maximum of the cycle 22 and continued up to the transition between cycles 23 and 24.

In Figure 9, there are two interesting periods, 1993–1994 and 2003–2004, in which the presence of equatorial coronal

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\(^4\) ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA

\(^5\) http://omniweb.gsfc.nasa.gov/
holes dominated the solar wind flow. They are prominently seen as an enhancement in speed and temperature and a depletion in density. The period 2003–2004 is shaded on plots of speed, density, temperature, and the ratio of alpha particle to proton densities, as a function of the year. The geomagnetic index, Ap, is shown in the bottom plot. The yellow shades show the CIR-dominated period during the minimum of cycle 23. The vertical dotted lines indicate the deep minimum phase of cycle 23.

(A color version of this figure is available in the online journal.)

Figure 9. Plots of a 27 day average of the solar wind proton speed and flow directions (i.e., latitude and longitude in degree), number density, temperature, dynamical flow pressure, magnitude of the interplanetary magnetic field, and the ratio of alpha particle to proton densities, as a function of the year. The geomagnetic index, Ap, is shown in the bottom plot. The yellow shades show the CIR-dominated period during the minimum of cycle 23. The vertical dotted lines indicate the deep minimum phase of cycle 23.

6. DISCUSSION AND SUMMARY

This paper presents the analysis of the three-dimensional evolution of the large-scale structures of solar wind density turbulence and speed at different levels of solar activity between 1985 and 2011, which includes solar cycles 22–24. The long-term IPS observations obtained from the ORT at 327 MHz, supplemented with other ground- and space-based measurements, show that the solar cycle changes in the solar wind are significantly different between cycles 22 and 24. The main results of this study are the following.

1. The value of the density turbulence in the inner-heliospheric region was the highest at the maximum of solar cycle 22 (around the year 1991) and decreased to a level of \( \sim 70\% \) in the subsequent minimum phase (around the 1996). A similar reduced trend was also observed at the transition phase between cycles 21 and 22 (around the year 1986).

2. However, at the deepest minimum of the cycle 23 in 2009, the density turbulence decreased to a level of \( \sim 30\% \) in comparison with the highest level observed at the maximum of the cycle 22 in 1991. This indicates that during the long-decay phase of cycle 23, the source region of the solar wind on the Sun has experienced severe deficiency in energy as well as density.

3. The important result of this study is that the scattering diameter of the corona (i.e., the density turbulence contours displayed in Figure 3) has steadily decreased after about 2003 and attained the smallest size during the middle of 2009. For a typical radial fall of scattering power, \( R^{-4} \) to \( R^{-1.4} \), it suggests a reduction of more than 60%. The amplitude \( \sim 2^\circ–4^\circ \) observed in the solar wind flow latitude were likely caused by the latitudinal warping of the HCS. In contrast, the regular variations in flow latitude and longitude (\( \sim 3^\circ–4^\circ \)) between 1999 and 2003 show that the flow direction exhibits cyclic changes in the west-north-east-south direction. The mean period of oscillation is \( \sim 6 \) months, which indicates a cyclic behavior linked to the slow changes (\( \sim 27 \) day period) of large-scale structures of the source of the solar wind. However, the above cyclic pattern of the solar wind flow direction disappears between 2003 and the middle of 2004, in coincidence with the duration of the high-speed wind caused by the large mid-latitude coronal hole. But, it appears back in a later subsequent time, and the solar wind flow geometry changes to a reversed opposite cyclic behavior of an east-north-west-south pattern.

In the ascending phase of solar cycle 23, after the year 1994, the dominance of the equatorial coronal holes disappeared, and the solar wind flow direction switched from largely north pointing to an equatorial flow. This implies that the large-scale magnetic field averaged over a solar rotation, with respect to the heliospheric equator, has gone through a systematic reversal during the ascending phase of the solar cycle. In the case of solar cycle 23, the persistence of the cyclic pattern from 2004 to 2011 indicates the continued presence of the large-scale magnetic configuration of a complex field, which may be caused by the group of long-lived small coronal holes of opposite polarities in the low-latitude region of the Sun. Thus, the net effect of the formation and decay of coronal holes, as a result of the magnetic reconnection between global and active region fields (Fox et al. 1998), essentially has determined the magnetic field configuration of the corona and heliosphere as well as the rate of occurrence of CIRs and associated transients (Zhang et al. 2008; Yashiro 2005).
gradual decrease in the scattering power of the corona is consistent with the global downward changes observed in the strength of the solar magnetic field, leading to a reduction in the supply of mass and energy at the base of the corona and into the heliosphere.

4. The three-dimensional results of the solar wind speed also show remarkable changes in the latitudinal distributions of high- and low-speed flows between solar cycles 22 and 23. For example, the source region of the high-speed wind (i.e., \( \sim 700-800 \text{ km s}^{-1} \)) at the minimum of cycle 22 was wide in latitude and extended from poles to mid latitudes of \( \sim 30^\circ \). However, during 2006–2009, the high-speed regions were narrow in latitude and confined close to the poles. Thus, in the long decay phase of cycle 23, the heliosphere encountered a net decrease in the solar wind speed at most of the latitudes.

5. Both speed and density turbulence distributions obtained from the IPS are consistent not only with the reduction of the solar activity but also with the relatively complex corona for most of the minimum phases of the cycle 23. Results on the latitudinal spread suggest that the solar corona did not reach the simple “dipole” shape often observed during the solar minima, while low-latitude coronal holes and their associated corotating high-speed solar wind streams persisted until the deepest minimum and caused large-amplitude HCS, which heavily modulated the solar wind and opposed the formation of dipole-shaped corona.

6. The results from the IPS and LASCO confirm the onset and growth of the solar cycle 24, starting from about the middle of 2009. It is interesting that the high-speed wind (also the high-density plasma) at the northern side has almost moved close to the pole, indicating a reduced area of the coronal hole at a phase similar to nearly approaching maximum phase of the cycle, but, in the southern hemisphere, the activity has yet to develop. The question then is how far the maximum of the current cycle will rise.

In the decay phase of cycle 23, the reasons for the reduction in global field strength, density, and flow speed are possibly due to changes in the movement of large-scale fields, as the reversal of polarity progresses. It corresponds to the rate of poleward and equatorward meridional flows, which acts as the conveyor belt in transporting the magnetic flux (i.e., because of the high electrical conductivity of the plasma, the magnetic field is “frozen-in” to the plasma) at the solar interior. In the deep minimum phase, the weak fields observed at the poles are likely to be associated with the transport of unbalanced flux by the meridional flow, and a faster flow rate (relative to diffusion) will result in a less unbalanced flux in each hemisphere as well as cause weaker fields at the poles (e.g., Sheeley 2010).

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Due to an error at the publisher, Figures 1 and 2 appeared in the wrong order and with their captions interchanged in the published article. The correct order of the figures and their respective captions are displayed below. IOP Publishing sincerely regrets this error.

**Figure 1.** Scintillation index as a function of the distance from the Sun for the radio quasar 1148-001 measured from the Ooty Radio Telescope, operating at 327 MHz, over the years 1985–2011. The peak of the \( m-R \) curve, close to unity, shows that the radio quasar 1148-001 is compact, which in fact has an equivalent diameter of \( \sim 15 \) mas. In each plot, the best fit to the data points is shown by a continuous curve. The shaded portion shown on the plot of year 1988 indicates the radial distance range over which the area has been computed as given in Equation (1).

(A color version of this figure is available in the online journal.)
Figure 2. Area under the $m^2(R)$ profile (Equation (1)) plotted as a function of the year. The area has been computed in the weak-scattering region in the distance range of 40–200 $R_\odot$, as indicated by the shaded area shown in Figure 1 (refer to the 1988 plot). Different symbols correspond to different scintillating sources. These are strongly scintillating sources, having an equivalent diameter $\leq 100$ mas and their compact components contain more than 50% of the source total flux density. The continuous line is the segment-wise best fit to the data points. It is clear from the plot that the deepest minimum of the solar cycle 23 is revealed by the lowest level of the density turbulence around the middle of 2008.

(A color version of this figure is available in the online journal.)