THE SOLAR WIND: FROM SOLAR MINIMUM TO SOLAR MAXIMUM

John D. Richardson, Chi Wang, and Karolen I. Paularena

Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

ABSTRACT

We describe the evolution of the heliosphere from solar minimum to solar maximum from a solar wind perspective. With the current fleet of spacecraft progress can be made in separating radial distance, heliolatitude, and solar cycle effects. The solar wind speed decreases with distance, but the changes from solar minimum to solar maximum produce a larger effect. The latitudinal gradients of density and speed reverse over the solar cycle; at solar maximum speeds are higher near the solar equator whereas at solar minimum speeds are least near the equator. Variations in speed and density result in dynamic pressure changes of a factor of two over the solar cycle at all solar latitudes. The MIR (merged interaction region) frequency increases during the ascending phase of the solar cycle and affects the cosmic ray intensities. Shock strength and particle injection at shocks both decrease with distance from the Sun.

INTRODUCTION

The transition from solar minimum to solar maximum is a restructuring of the entire heliosphere. At solar minimum, the average solar wind magnetic field strength is low, the solar surface field is nearly dipolar, and the tilt of the dipole relative to the spin axis is small. Polar coronal holes extend to low latitudes, so that fast solar wind is observed above 20-30° heliolatitude and slow solar wind at lower latitudes (Phillips et al., 1995). Transient events such as coronal mass ejections (CMEs) are few. The cosmic ray intensities in the heliosphere increase since there is little magnetic structure to limit their inward diffusion.

With the approach of solar maximum, the solar wind magnetic field strengthens while the surface field structure becomes more disorganized. The polar coronal holes retreat and may even disappear. The width of the slow speed region increases. CMEs become much more frequent (Gosling, 1997). Merged interaction regions (MIRs) develop with high magnetic fields which cause decreases in and eventually a general lowering of the cosmic ray intensities (Burlaga and Ness, 1998).

This paper concentrates on changes in the solar wind from solar minimum to solar maximum (see review by Gazis, 1996, and references therein for prior work on this subject). Emphasis is placed on the 1996-2000 transition, although other transitions will be shown for comparison and to fit the recent data into the overall pattern of solar cycle changes. We will discuss changes in the plasma speed, density, pressure and general solar wind structure.

SOLAR WIND TIME EVOLUTION

We currently (in 2000) have a fleet of spacecraft located throughout the heliosphere. The trajectories of Voyager 2, Ulysses, and IMP 8 are shown in Figure 1. The Voyager 1 and 2 spacecraft are at 75 and 60 AU and 34° N and 22° S latitude, respectively. Ulysses is moving southward, starting its second polar orbit, this time near solar maximum (see McComas et al., 2000, for a review of the first polar orbit of Ulysses). WIND, IMP 8, ACE, and other spacecraft monitor the solar wind near Earth. Combining data from these spacecraft helps to differentiate between solar wind changes due to solar cycle variation, latitude, and radial distance.
Fig. 1. Radial distances and heliolatitudes of IMP 8, Voyager 2 and Ulysses.

The solar wind speed varies with radial distance, heliomagnetic latitude, and solar cycle. Figure 2 compares the differences between speeds observed by Voyager 2 and IMP 8 and the differences in latitudes between these spacecraft. The speed difference shown in the top panel is calculated by time-shifting the Voyager 2 data back to 1 AU using a 50-day running average of the observed speed, interpolating data to fill in gaps, and then subtracting the 100-day-running average of speed observed by Voyager 2 from that observed by IMP 8. The latitude differences are calculated in a similar manner, except that 1-year averages are used so that Earth's excursions in heliolatitude are not apparent. The times of solar minimum are shown by the hatched regions.

Fig. 2. Speed and heliolatitude differences between IMP 8 and Voyager 2.

The average speed differences are usually relatively small (< 50 km/s) and not predominantly positive or negative, except during the solar minimum periods and after the 1996 solar minimum. At solar minimum, latitudinal gradients of speed are large (Miaye et al., 1988; Gazis, 1993; Richardson and Paularena, 1997), so the spacecraft at higher latitude observed higher speeds. In 1986, Voyager 2 was near the helioequator and saw lower speeds than IMP 8. In 1996, Voyager 2 was at higher latitudes and saw significantly higher speeds.
than those observed at IMP 8. Note that these latitude effects are only important near solar minimum; at other times the latitudinal speed gradient is not an important contributor to the speeds observed by Voyager 2 and IMP 8.

Beginning in 1998, the speed observed by Voyager is less than that observed by IMP 8. This speed decrease has two causes, the speed decreases with distance, due to the effect of pickup ions, and with latitude, due to a decrease of speed with increasing latitude before solar maximum. We discuss each of these effects in more detail below.

Radial Speed Dependence

The neutral component of the local interstellar medium (LISM) is not affected by the solar magnetic field and thus can penetrate into the heliosphere. Eventually almost all of these neutrals are ionized by either photoionization or charge exchange. Once ionized, they are subjected to the influence of the IMF and are accelerated by the Lorenz force up to the local solar wind speed and have an initial thermal energy equal to the solar wind dynamic energy. The energy for this acceleration and heating (about 2 keV/ionized H) comes from the bulk motion of the solar wind. Thus if one can determine the rate of slowing of the solar wind one can estimate the density of the LISM.

Several studies use observations to quantify this slowdown (Richardson et al., 1995; Wang et al., 2000a,b). The most recent and convincing study is that by Wang et al. (2000b), who compared Ulysses and Voyager 2 speeds from 1999 when these spacecraft were at similar latitudes. They use the Ulysses data as input to a 1-D MHD model which propagates the solar wind to the location of Voyager 2, at 55 AU. The density of the LISM II at the termination shock is varied to best match the speeds observed at Voyager 2. Figure 3 shows histograms of the speeds observed at Voyager 2, the speeds predicted by the model in the absence of the LISM, and speeds predicted by the model if the LISM density at the termination shock were 0.05 cm$^{-3}$. The observed speeds at Voyager 2 are about 40 km/s less than those at Ulysses. Using the expression $n_{\text{pu}}/n_{\text{sw}} = 7/6(\Delta v/v_{\text{sw}})$ (Lee, 1995; Richardson et al., 1995) appropriate if the ratio of specific heats is 5/3 (where $n_{\text{pu}}$ is the density of pickup ions, $n_{\text{sw}}$ is the density of the thermal solar wind plasma, $\Delta v$ is the change in speed due to the pickup ions, and $v_{\text{sw}}$ is the solar wind speed), the pickup ion density comprises 11% of the solar wind density at 55 AU.

![Histograms of the solar wind speed: observations and model results with and without pickup ions.](image_url)

The 0.05 cm$^{-3}$ value for the LISM density agrees with other values in the literature based on the solar wind speed decrease (Richardson et al., 1995; Wang et al., 2000a). However, values for the density in the LISM based on in situ observations of pickup ions and ultraviolet H emissions are near 0.22 cm$^{-3}$. About 50% of these neutrals are lost before they reach the termination shock (Gloeckler et al., 1997), so the value derived based on the slowdown is about 50% less than those based on other data. We note that the in situ results are derived from a selected set of solar wind conditions, whereas the slowing of the wind is an integral process occurring over 60 AU, which could explain the apparent discrepancy.

Latitudinal Speed and Density Dependence

At solar minimum, the latitudinal speed and density gradients are large. A narrow, 10-20° half-width band of slow (400 km/s), dense (8 cm$^{-3}$) solar wind is centered about the current sheet near the helioequator (Miyake et al., 1988: Gazis, 1993; Richardson and Paularena, 1997). At higher latitudes the solar wind...
speeds are high (700 km/s) and densities are low (3 cm\(^{-3}\)). This general pattern has been observed at solar minimum in several solar cycles and was very clearly seen in the Ulysses fast latitude scan (Phillips et al., 1995). Figure 4 shows the density and speed observed by IMP 8, Ulysses, and Voyager 2 from the beginning of solar minimum in 1995 until mid-2000. The Voyager and Ulysses data are time-shifted to 1 AU using 50-day averages of the observed solar wind speeds. Densities are normalized to 1 AU assuming a \(R^{-2}\) dependence. IMP 8 densities are systematically higher than those measured by the other two spacecraft; to make the densities consistent we multiply IMP 8 densities by 0.8.

![Figure 4. Solar wind speeds and normalized densities time-shifted to 1 AU.](image)

Figure 4 shows the evolution of the solar wind configuration from solar minimum to solar maximum. Since the radial change in solar wind parameters is relatively small, the changes in Figure 4 result from the different spacecraft latitudes and the evolution in time due to solar cycle effects. From 1995-1997 strong latitudinal gradients in speed and density are observed. At high latitudes, Ulysses observes speeds over 700 km/s and densities just above 2 cm\(^{-3}\). Near Earth, IMP 8 observes speeds near 400 km/s and adjusted densities near 8 cm\(^{-3}\). Voyager 2 at intermediate latitudes observes intermediate speeds and densities. In late 1997 and early 1998 when Ulysses has returned to low latitudes, it observes solar wind parameters very similar to those observed by IMP 8. As solar maximum approaches and Ulysses moves to southerly latitudes in 1999 and 2000, a reversal of the solar minimum pattern is seen. Ulysses speeds become lower than those observed by IMP 8 and densities are higher (McComas, 2000). The coronal holes have retreated to very near the poles and no high speed solar wind is observed. Voyager 2 speeds are lower than those observed by the other spacecraft, probably due to the pickup ion slowing discussed above. The Voyager 2 density structure is dominated by MIRs which have formed as the solar wind moves outward and thus direct comparison with data from the inner heliosphere is difficult. The decrease of speed and increase of density with latitude near solar maximum were not expected; however, comparison of IMP 8, Voyager 2, and Pioneer 11 data before the 1989-1990 solar maximum shows a similar effect (Richardson, 2001). One possible explanation is that CMEs, which are more frequent near solar maximum and also at low-latitudes (Gosling, 1997), could produce these latitudinal differences.

**Solar Cycle Dynamic Pressure Variations**

The solar wind dynamic pressure \(p v_{sw}^2\), where \(p\) is the mass density and \(v_{sw}\) is the solar wind speed, varies by a factor of two over the solar cycle (Lazarus et al., 1990). Figure 5 shows the dynamic pressure
profile over the last solar cycle observed by Ulysses, IMP 8, and Voyager 2. Similar profiles are observed for previous solar cycles; the pressure rises by a factor of 2 over 1-2 years beginning near solar maximum, then slowly decreases until the next solar maximum. This figure clearly demonstrates that a similar change in dynamic pressure occurs at all solar latitudes. Even during time periods when the three spacecraft observe very different solar wind conditions (see Figure 4), the pressure profiles remain very similar (Richardson and Wang, 1999). The implication of this result is that the heliospheric boundaries experience a factor of two change in internal pressure at all latitudes. Thus the models based on this assumption which predict termination shocks motions of 13-15 AU over the solar cycle (Karmesin et al., 1995; Wang and Belcher, 1999) are justified.

Fig. 5. Dynamic pressure for Ulysses (bold), Voyager 2 (gray) and IMP 8 (thin).

SOLAR WIND STRUCTURE

In addition to changes in the values of solar wind parameters, the solar wind structure also changes over the solar cycle. Stream interaction effects are less important at solar minimum when the tilt of the heliospheric current sheet (HCS) is small. Transient events such as CMEs also occur less often near solar minimum (Gosling, 1997). In the rising and declining portions of the solar cycle, corotating interaction regions (CIRs) are important, since the HCS tilt becomes large and regions of high speed coronal hole flow are present. At solar maximum, the smaller latitudinal speed gradients result in CIR effects being less important, but CME activity is near its maximum and probably plays the dominant role in determining the solar wind structure.

Figure 6 shows a comparison of Voyager 2 one-hour average speed profiles near solar minimum and as solar maximum approaches. As discussed above, the speeds observed by Voyager 2 are higher near solar minimum. The nature of the profile also shows significant changes; the stream structure is more pronounced during the ascent to solar maximum. Very few shocks are observed in 1996 compared to 1999-2000. The regular nature of the shock remnants in 1999-2000 suggests they are due to stream interactions resulting from the tilted HCS.

Figure 7 shows profiles of density (line) and greater than 70 MeV/nuc cosmic ray ions (dots) observed by the Voyager 2 CRS (Cosmic Ray Subsystem). The density profile has several large enhancements which occur with increasing frequency during the ascent of the solar cycle. The increase in 1998 has been identified as a MIR based on the Voyager magnetic field data (Burlaga and Ness, 2000). The enhanced field in the MIR causes a decrease in the CRS counts. The other three density enhancements, in 1997, 1999, and 2000, are probably also MIRs, although magnetic field data from these time periods is not yet available. Each of these MIRs causes a drop in the CRS counts and the MIR in 2000 probably signals the start of the large decrease in the cosmic ray intensity observed in past solar cycles as solar maximum approached (McDonald, 1998). The Voyager 1 CRS profiles look nearly identical to those at Voyager 2 even though these spacecraft
are separated by 50° of latitude and 45° of longitude. This result verifies that the MIRs cover a very large region of the heliosphere.

The triggers for the generation of these large MIRs are probably not the corotating interaction regions, since these are omnipresent, but large CMEs or groups of CMEs. A test of this hypothesis is to associate the MIR drivers with plasma having CME characteristics. At 1 AU, these characteristics include low temperatures, smooth field rotations (magnetic clouds), counter streaming electrons, and enhanced helium abundances (Gosling, 1997). Given the large amount of evolution which occurs in the solar wind, the signature most likely to remain in the outer heliosphere is the increased helium abundance. A recent study of helium abundance enhancements, defined as times when the helium abundance is over 10%, has identified remnant CMEs along Voyager 2's trajectory (Wang and Richardson, 2001c). One drawback to this approach is that while this large a helium abundance is probably sufficient to identify a CME, many CMEs do not have helium abundances which are 10% or higher. But even with this overly exclusive criteria, one of the MIRs in Figure 7 does show evidence of being driven by a CME. The vertical gray bar on the trailing side of the 1999 CME shows a 5-day period where helium abundances are over 10%, providing good evidence that this MIR is driven by CME ejecta. More thorough analysis which relaxes the 10% helium threshold is needed to see if this is the case for the other MIRs as well.

Large MIRs are also hypothesized to be the triggers for the 2-3 kHz heliospheric radio emission observed
in 1983 and 1992 (McNutt, 1988; Gurnett et al., 1993). The largest CME of this solar cycle to date occurred on July 14, 2000. The speed observed near the Sun was 1300-1800 km/s; at Earth solar wind speeds were well above 1000 km/s. The Forbush decrease observed by the Moscow Neutron Monitor for this event was 22% (http://helios.izmiran.rssi.ru/cosray/main.htm), comparable to those in 1982 and 1991 (21% and 29%, respectively) which are hypothesized to trigger the previous radio emission events (Gurnett et al., 1993). Thus it seems reasonable to hypothesize that this event could trigger a radio emission episode when it reaches the appropriate distance. Wang et al. (2001b) use a 1-D MHD model including the effect of pickup ions to propagate the data observed by IMP 8 and WIND at 1 AU to the outer heliosphere. The model predicts that a strong forward shock will arrive at Voyager 2 in early January, 2001, with a speed jump of ~70 km s⁻¹ and a compression ratio of ~2.0. The strong forward shock will continue to travel in the supersonic solar wind and collide with the termination shock in April of 2001. The shock resulting from the interaction of the interplanetary shock with the termination shock will still be relatively strong and will impinge on the heliopause in December of 2001. The interaction of the shock with the heliopause could trigger the next 2-3 kHz radio emission event; if so, the start time of the emission combined with these model results could help pinpoint the source region.

SHOCKS

In the inner heliosphere shocks and/or the turbulent regions behind them accelerate energetic particles, which may become the seed population for the anomalous cosmic rays. Recent work suggests that injection of energetic ions may be less important in the outer heliosphere as shock strengths weaken. Paularena et al. (1999) recently surveyed shocks observed by Voyager 2 from 1977-1999. Figure 8 shows a plot of shock strengths for forward shocks or shock remnants observed by Voyager 2. Forward shock events were defined as having increasing speed, density, and temperature across the discontinuity. As Voyager 2 moves farther from the Sun, the “shocks” broaden in extent but are still included in the survey. The plot shows that the shock frequency lessens with distance as shocks dissipate and interact. The strengths of the shocks also weaken on average with increasing distance.

Lazarus et al. (1999) first showed that in the outer heliosphere energetic particle peaks tend to follow the shocks, sometimes arriving several days later. Rice et al. (2000) attributed this disconnection between the shocks and the energetic particles which were presumably accelerated by the shocks to a turnoff of the acceleration process as the shocks weaken. The shocks would then continue to propagate through the solar wind plasma, while the particles energized before the acceleration process halted would remain entrained in the solar wind and fall behind. Decker et al. (2001) tested this hypothesis by looking at the lags between shocks and energetic ion peaks in 1983-1984 and 1993-1994. Figure 9 shows a comparison of the lags from
these two time periods. In 1983-1984 most of the lags are near 0 and all are less than 2.5 days. In 1994-1995, all the lags are greater than 1 day and they average 3-4 days. The increase of lags with distance is consistent with the idea that injection of these particles ceases in the outer heliosphere.

\[ \text{Fig. 9. Time lags between shocks and energetic particle peaks} \]

**SUMMARY**

We investigated changes in the solar wind with distance, heliolatitude, and solar cycle. The speed and density gradients in latitude reverse over the solar cycle, with minimum speed at the equator at solar minimum and vice versa. We show that the slowdown of the solar wind between Ulysses and Voyager 2 is consistent with a LISM density at the termination shock of 0.05 cm\(^{-3}\). The MIR frequency increases towards solar maximum, decreasing the cosmic ray intensities. These MIRs are probably driven by CMEs; we show one case where we have clear evidence of a MIR driven by CMEs. Both the strength and importance of shocks weaken with distance, with little particle injection from shocks observed at 35 AU.

**ACKNOWLEDGMENTS**

We thank D. McComas for the Ulysses data used in this paper and E. Stone for the Voyager CRS data. This work was supported under NASA contract 959203 from the Jet Propulsion Laboratory to the Massachusetts Institute of Technology and by NASA Heliospheric GI grant NAGW-6473.

**REFERENCES**


Gosling, J. T., Coronal mass ejections: An overview, in *Coronal Mass Ejections*, edited by N. Crooker, J.


McComas, D. J., Ulysses observations of the three-dimensional solar wind over the solar cycle and their implications for the outer heliosphere, EOS, 81, F983, 2000.


