

# Solar-cycle variation of low density solar wind during more than three solar cycles

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**Abstract.** The May, 1999 low density ( $< 1 \text{ cm}^{-3}$ ) solar wind interval is one of a series of intervals of low density solar wind which have been detected since in-situ, near-Earth observations began. Examining the NSSDC OMNI database since 1965, covering solar Cycles 20-23, we show that such intervals, which are also periods of unusually low mass flux and low dynamic pressure, occur most frequently around sunspot maximum and are rarer at solar minimum. The occurrence rate of low-density plasma may be higher in weaker sunspot cycles (Cycle 20 and the current Cycle 23). Around two-thirds of periods with densities  $\leq 1 \text{ cm}^{-3}$  are associated with transient solar wind structures, in particular with ejecta and post-shock flows. The majority of other events are associated with corotating streams. The May 1999 event is unusual because it is not associated with an ejecta or stream. A similar period was observed in July-August 1979.

## Introduction

On May 10-12, 1999, the Earth was engulfed in a region of low density ( $< 1 \text{ cm}^{-3}$ ) solar wind. To place this region in the context of a wider range of data, we examine the occurrence of other intervals of low plasma density during solar Cycles 20-23 in the NSSDC OMNI near-Earth solar wind data base, and their relationship with solar wind structures. This database includes 1-hr averaged solar wind plasma parameters for 1965 - near present, compiled from near-Earth spacecraft after normalization to allow for different instrument responses [King, 1977].

## Observations

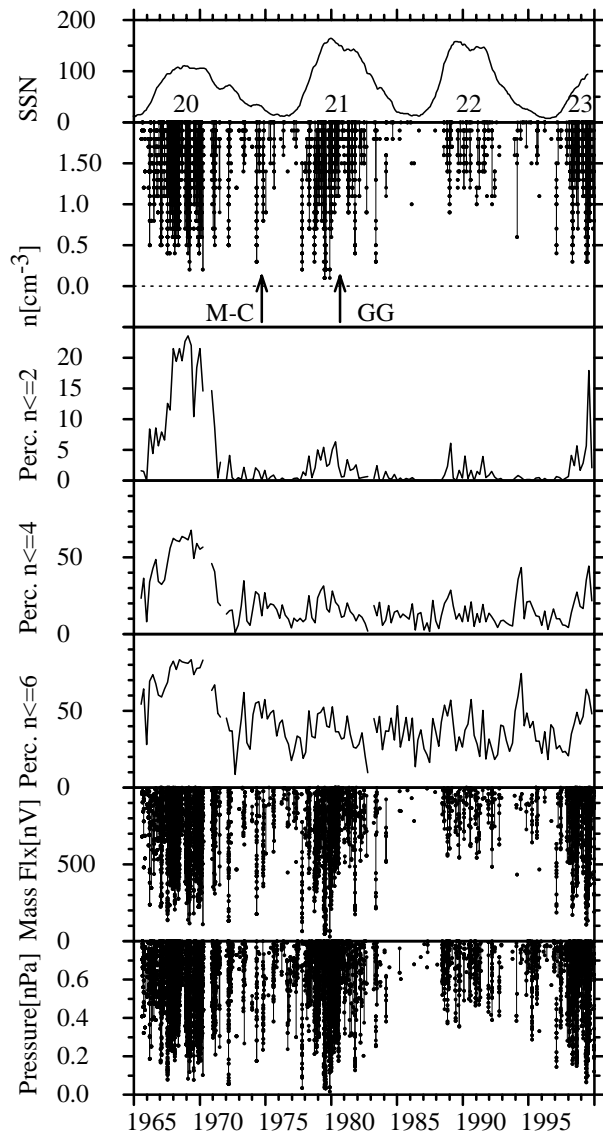
Figure 1 summarizes the occurrence of low density plasma in the OMNI data base during 1965-1999. The top panel shows the smoothed monthly sunspot number during

this period, which encompasses solar Cycles 20-23. The second panel shows 1-hr averaged solar wind density data in the range 0 - 2  $\text{cm}^{-3}$ . Lines join successive data points. Intervals of exceptionally low densities occur at all stages of the solar cycle but are evidently much rarer around solar minimum than at times of enhanced solar activity. To show this in another way, the third panel gives the occurrence rate (% of available observations) of densities  $\leq 2 \text{cm}^{-3}$  averaged over successive 3 solar-rotation periods. Interestingly, the occurrence rate is higher ( $\sim 20\%$ ) around the maximum of Cycle 20 than for the maxima of Cycles 21 and 22 ( $< \sim 5\%$ ). This difference may be related to the problem of accurately normalizing the OMNI plasma parameters across a data gap in 1971 [King, 1977]. A  $\sim 0.8 \text{ cm}^{-3}$  shift in the normalization would give similar occurrence rates during the maxima of each of these cycles. There is however, independent evidence suggesting that plasma conditions might have been unusual during Cycle 20. Figure 6 of Fairfield and Jones, [1996], for example, indicates that annual averages of the magnetic field strength in the lobes of the magnetosphere, which is largely determined by the solar wind dynamic pressure, proportional to  $nV_{sw}^2$ , were lower around the maximum of Cycle 20 than during the subsequent cycle. Thus, lower plasma densities in Cycle 20 may be consistent with the reduced lobe fields. We also note that the low density plasma occurrence rates in the current solar cycle have, at least temporarily, exceeded those in Cycles 21 and 22, suggesting that this cycle may be more like Cycle 20 from the point of view of the presence of low density plasmas. The maximum of Cycle 22 shows few densities below  $1 \text{ cm}^{-3}$  compared to the other cycles. This may be an artifact of the OMNI data from IMP 8 after 1984 [Ipavich et al., 1998]. However, the IMP 8 data for the current cycle do in fact show an increased occurrence of low density plasma relative to Cycle 22. Panels 4 and 5 of Figure 1 show that the solar cycle variation in densities  $\leq 2 \text{ cm}^{-3}$  is absent in the occurrence rates of  $\leq 4 \text{ cm}^{-3}$  and  $\leq 6 \text{ cm}^{-3}$  plasma. Therefore, it is only a feature of the lowest density plasmas.

The change in the occurrence of low density plasma during the ascending phase of Cycle 23 is illustrated by the scatter plots of the solar wind speed versus density for 1996 (solar minimum) 1997, 1998 and 1999 in Figure 2. The general anti-correlation between solar wind speed and density in 1996 becomes progressively more scattered in later years, and densities below  $1.5 \text{ cm}^{-3}$ , absent in 1996, ap-

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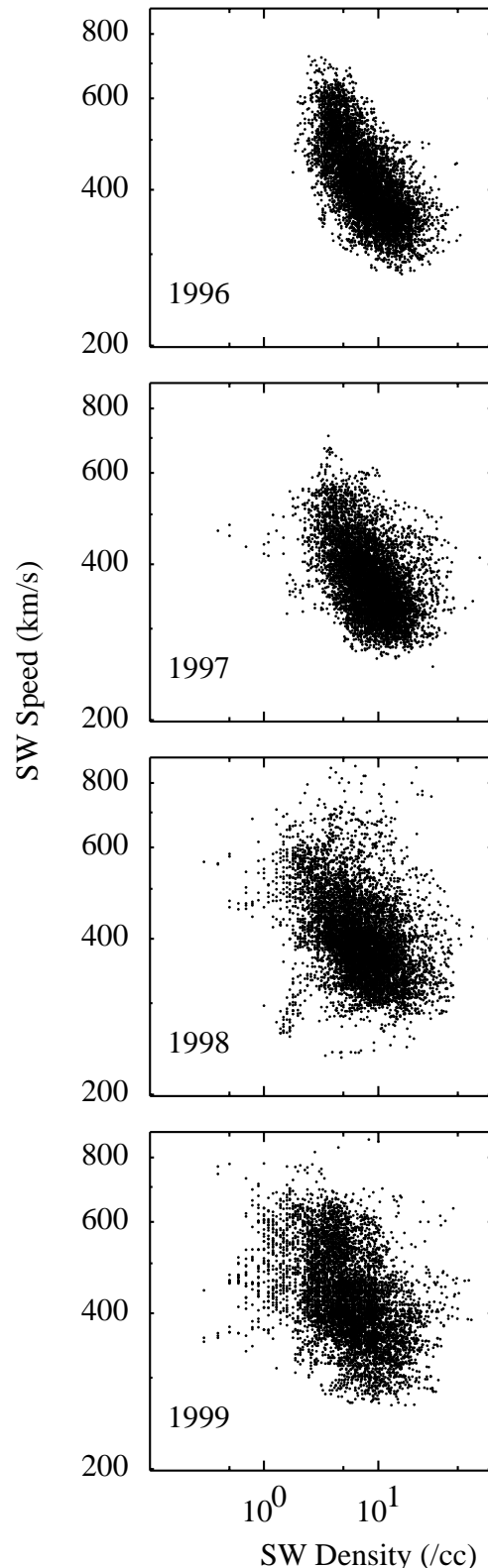
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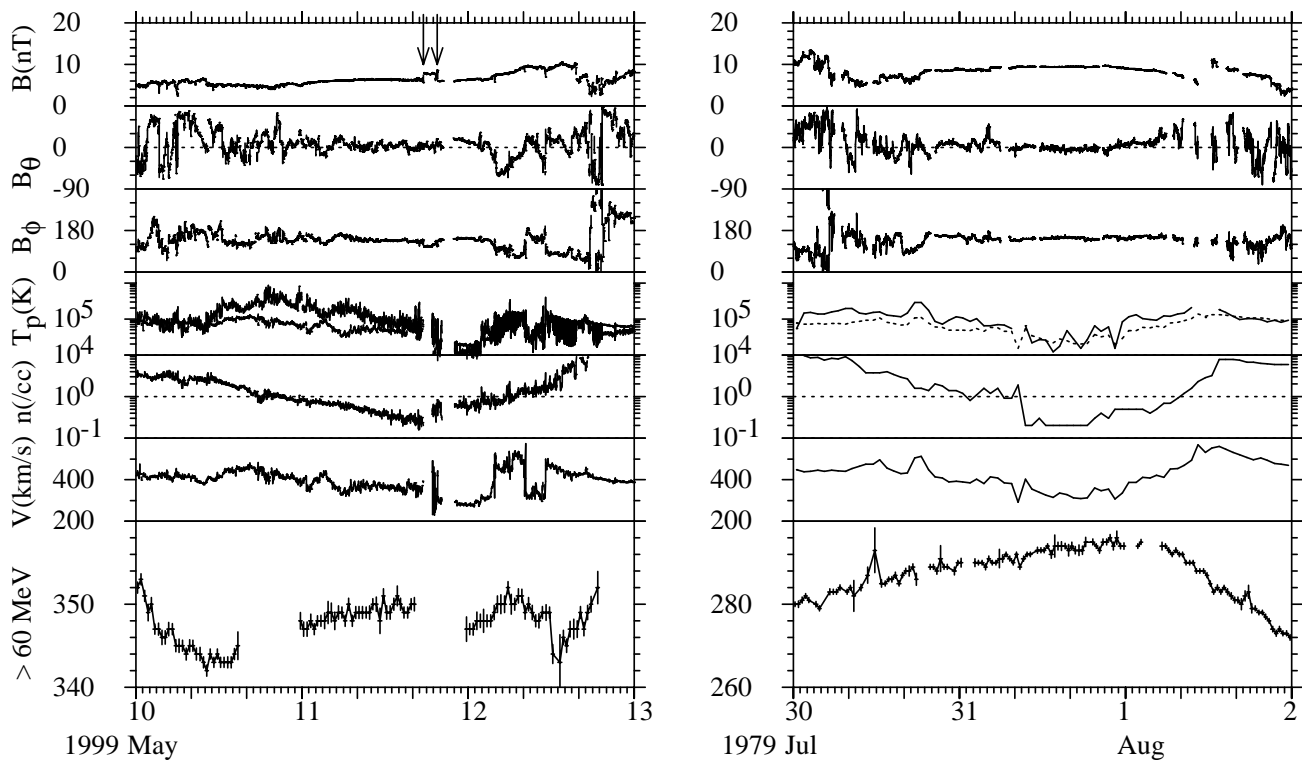
**Figure 1.** Summary of OMNI 1-hr averaged low density solar wind plasma from 1965 to 1999. The panels show the smoothed sunspot number; densities below  $2 \text{ cm}^{-3}$ ; occurrence rates (%) of densities below  $2 \text{ cm}^{-3}$ ,  $4 \text{ cm}^{-3}$ , and  $6 \text{ cm}^{-3}$ ; mass flux ( $\text{cm}^{-3} \times \text{km s}^{-1}$ ) and dynamic pressure. M-C=“mini-cycle”; GG=Gnevyshev Gap.

pear in increasing frequency. The low density plasmas are not simply associated with exceptionally high-speed flows. Thus, the mass flux (proportional to  $nV_{sw}$ ) may also be unusually low in these intervals. The sixth panel of Figure 1 shows that the lowest densities are indeed associated with the lowest mass fluxes, as well as with regions of unusually low dynamic pressure (bottom panel of Figure 1). We note that lower dynamic pressures around solar maximum have been previously reported in annual averages [Crooker and Gringauz, 1993; Fairfield and Jones, 1996]. The arrows in Figure 1 indicate two other interesting features: an increase in the occurrence of low plasma densities during what has been called a “mini-[solar] cycle” (M-C) in 1974 [Garcia-Muñoz et al., 1977], and a reduction in 1980 which may be a manifestation of the “Gnevyshev gap” (GG), a temporary

absence of energetic solar phenomena associated with solar magnetic field polarity reversal at solar maximum [Feminella and Storini, 1997, and references therein].



**Figure 2.** Scatter plots of OMNI solar wind speed vs. density for the years 1996 to 1999.



**Figure 3.** Magnetic field and solar wind data (from WIND) and the IMP 8  $> 60$  MeV cosmic ray counting rate during the May 11-12, 1999 low density period (left-hand panel; arrows indicate bow shock crossings), and for a similar period (field data from ISEE 3, plasma data from the OMNI database) in July-August 1979 (right hand panel).

## Structures Associated With Low Density Regions

We have examined the solar wind structures associated with densities  $\leq 1 \text{ cm}^{-3}$  during the period 1972 to 1984 which encompasses Cycle 21 and has reasonably complete solar wind observations. (We note that a similar analysis has been made by *Ipavich et al.*, [1998].) The structures are identified using a comprehensive set of plasma, magnetic field, and energetic particle observations, including signatures of possible ejecta such as magnetic clouds, bidirectional solar wind electron heat fluxes, bidirectional energetic ions, and helium abundance enhancements [*Gosling*, 1990; *Richardson and Cane*, 1995; *Richardson et al.*, 2000].

We identified 32 low density regions. The durations (1-35 hours; median 8 hours) indicate scale sizes of  $\sim 0.01$ -0.4 AU if convected at the solar wind speed. Thus, they may be substantial structures in the inner heliosphere. Of the 29 events where the associated solar wind structure can be identified, 13 (45%) occurred in ejecta, the interplanetary manifestations of coronal mass ejections (CMEs) at the Sun. An example is May 4, 1978. Four events (14%) followed ejecta (e.g., October 16, 1981), two (7%) closely followed shocks but were not associated with ejecta (e.g., May 25, 1983), two (7%) were located in declining speed gradients within corotating streams (e.g., July 4, 1979), five (17%) occurred in regions of high-speed streams with no declining speed gradients (e.g., April 23-24, 1981), and three (10%) occurred in slow solar wind (e.g., January 9-10, 1980). Thus, the strongest association of low density regions is with ejecta. If post-ejecta and post-shock intervals are included, then

around two thirds are closely associated with transient solar wind structures. Transient structures are most prominent around solar maximum, consistent with the variation in the occurrence rate of low-density plasma. The low in-situ densities in ejecta may arise from the three-dimensional expansion of the low density plasma observed behind the leading edge of CMEs in coronagraph images within a few solar radii from the Sun, or from low density source plasma extending from density-depleted prominence cavities. The plasma inside ejecta at 1 AU is not always low density however. Intrinsically higher density plasma, for example including prominence material, may be encountered, and plasma compression may also occur, for example at the leading edge where the ejecta interacts with the upstream solar wind. We note that, if high-speed ejecta with significant compressional effects were more frequent during the maxima of the stronger solar cycles in our study period (Cycles 21 and 22) than in Cycle 20 (and possibly in the current cycle), then this might help to explain why low density plasmas were less evident in Cycles 21 and 22.

The May 10, 1999 event (left-hand panel of Figure 3) is unusual because it does not show clear features of an ejecta or a corotating stream. The magnetic field and solar wind data are 1-minute averages and 15 second snapshots every 92 seconds, respectively, from the WIND spacecraft. Arrows indicate crossings of the Earth's bow shock, which had moved out to the spacecraft location ( $X_{GSE} \sim 50R_e$ ). Thirty-minute averaged counting rates from the anti-coincidence guard of the Goddard medium energy experiment on IMP 8 are also shown, which indicate the  $> 60$  MeV cosmic ray intensity. Another low-density period in the

OMNI data, on July 31-August 1, 1979 (also discussed by Gosling *et al.*, [1982]), is similar to the May 1999 event and is shown in the right-hand panel of Figure 3. The magnetic field data are 5-minute averages from ISEE-3. The guard rate is also shown. Similarities include the extended period of densities below  $\sim 1 \text{ cm}^{-3}$ , the proton thermal temperature depression, solar wind speed decrease, and a magnetic field below 10 nT with low fluctuation levels directed near the ecliptic approximately along the Parker spiral direction. The low temperature and smooth field might be indicative of ejecta material. However, the proton temperature in ejecta is typically significantly depressed below that expected for normally expanding solar wind,  $T_{ex}$  [Richardson and Cane, 1995].  $T_{ex}$  is shown by the second line in the  $T_p$  plot (dashed in the right-hand panel) which tracks the solar wind speed. Periods with  $T_p < 0.5 T_{ex}$ , shaded black in Figure 3, only occur on May 12, outside the low density region. The absence of cosmic ray depressions in these low density regions also suggests that they are not ejecta. In addition, we note that both regions occurred during the rising phase of the solar cycle.

## Summary

Reviewing the OMNI near-Earth solar wind density data for 1965-1999, we find that:

1) Low density periods occur throughout the OMNI data, and their occurrence rate follows solar activity levels. These intervals are accompanied by low mass fluxes and dynamic pressures.

2) Around two-thirds of regions with density  $< 1 \text{ cm}^{-3}$  are associated with transient solar wind structures, in particular ejecta where the low densities may arise for example from the expansion of the low density plasma in the dim core of CMEs observed by coronagraphs.

3) Around one quarter of low density regions occur in corotating high-speed streams. This association is not unexpected since in general faster solar wind speeds have lower densities.

4) The May 10, 1999 low density region is unusual in that it is not clearly associated with an ejecta or a corotating stream. A similar region passed Earth in July-August, 1979, also during the rising phase of the solar cycle.

5) Low density plasma was apparently observed more frequently around the maximum of solar Cycle 20 (and possibly also in the current cycle) than in Cycles 21 and 22. Thus, it may be a more prominent feature of weaker solar cycles.

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