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Spatial Structure of Solar Wind in 1976

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Interplanetary scintillation measurements of the solar wind speed from 1976 show the expected trends toward high speed at either high heliographic latitudes or at large angular displacements from an interplanetary neutral sheet deduced from coronal observations. However, detailed examinations of the speed measurements when the neutral sheet is displaced from the solar equator reveals a lack of equatorial symmetry and suggests a minimum speed near the neutral sheet. For this epoch, the average solar wind speed u varies with angular displacement λ from the neutral sheet as $u = 350 \text{ km s}^{-1} + 800 \sin^2 \lambda \text{ km s}^{-1}$ for $|\lambda| \leq 35°$ and is approximately constant at 600 km s^{-1} for $|\lambda| > 35°$.

INTRODUCTION

Recent studies of the three-dimensional structure of interplanetary space [see *Neugebauer*, 1975; *Dobrowolny and Moreno*, 1976] have been focused on the solar wind speed and its relationship to the polarity of the interplanetary magnetic field. The view that solar wind speed increases with displacement from an interplanetary neutral surface that separates hemispheres of opposite magnetic polarity has gained considerable acceptance (see the reviews by *Svalgaard and Wilcox* [1978] and *Hundhausen* [1979] and recent work by *Hakamada and Akasofu* [1981], *Borrini et al.* [1981], *Feldman et al.* [1981], *and Gosling et al.* [1981]). *Zhao and Hundhausen* [1981] have attempted to quantify this relationship for the 1974 epoch when the solar corona and solar wind displayed unusually simple spatial structure. They interpreted the two-stream, two-sector pattern of recurrent solar wind variations observed in the ecliptic plane in terms of a planar neutral sheet tilted at 30° to the ecliptic, with the solar wind speed u varying with angular displacement λ from this sheet according to the expression

$$u = 400 \text{ km s}^{-1} + 1000 \sin^2 \lambda \text{ km s}^{-1} \qquad |\lambda| \leq 40°$$

We describe here an extension of this work to the 1976 epoch, near the minimum of solar activity when the solar wind might be expected to be least perturbed by time-dependent phenomena. *Burlaga et al.* [1981] have used coronal and interplanetary observations from early 1976 to examine the suggestion [*Newkirk*, 1972; *Hansen et al.*, 1974; *Howard and Koomen*, 1974; *Hundhausen*, 1978, 1979] that the band of bright corona encircling the sun near its equator and culminating in a 'belt' of streamers in the outer corona corresponds to a magnetic neutral sheet. They found that a curve drawn through the brightest portion of the corona on synoptic maps based on Mauna Loa Observatory observations usually agreed with Helios spacecraft observations of sector boundaries (or neutral sheet) crossings to within ±10° of solar longitude. In this paper we use interplanetary scintillation observations of the solar wind speed provided by W. A. Coles and colleagues of the University of California at San Diego to search for an organization of speed with respect to the nonplanar neutral sheet suggested by *Burlaga et al.* [1981].

THE DATA

Daily Mauna Loa observations of the coronal polarization brightness as a function of heliographic latitude and height above the solar limb can be used to construct synoptic maps [*Hansen et al.*, 1974; *Hundhausen et al.*, 1981] that reflect the large-scale density structure of the corona if that structure does not change greatly on the 27-day time scale over which all of the data on such a map is accumulated. Maximum brightness curves (MBC's), continuous lines drawn through the brightest regions of the corona as described in *Burlaga et al.* [1981], are shown in Figure 1. This set of MBC's is based on observations made at half a solar radius above the solar limb during Carrington solar rotations 1636–1643 (December 1975 to July 1976). The same curves for rotations 1637–1640 were used by Burlaga et al.; the Helios interplanetary magnetic polarity from the same set of Carrington rotations is indicated by the plus and minus signs on Figure 1. During the eight rotations of the sun, the position of the MBC's (in heliographic latitude and Carrington longitude) changed slowly. Early in the epoch the MBC's implied a neutral line with a mixture of dipole (two-sector) and quadrapole (four-sector) displacements from the solar equator. Late in the epoch the quadrapole pattern became dominant. The changes between successive Carrington rotations were sufficiently small to justify our use of the synoptic maps as approximations to the prevailing spatial structure.

Interplanetary scintillation (IPS) measurements of the solar wind speed during the same epoch were made for the locations shown on Figure 1 by dots. These locations are known to ≈10° in both latitude or longitude (D. Sime, personal communication, 1981); the speed is measured with an accuracy of ±50 km s^{-1} [*Coles et al.*, 1980]. The IPS observations extend as far as 60° from the solar equator; although their coverage in latitude is not continuous, the ±60° span of the measurements is obviously a great advantage in any study of large-scale spatial variations.

ANALYSIS

Let us now consider the spatial variations in solar wind speed implied by the IPS observations made at the locations summarized in Figure 1. Figure 2 displays the average solar wind speeds in 10° bands of heliographic latitude based on all of the measurements during Carrington rotations 1636–1643

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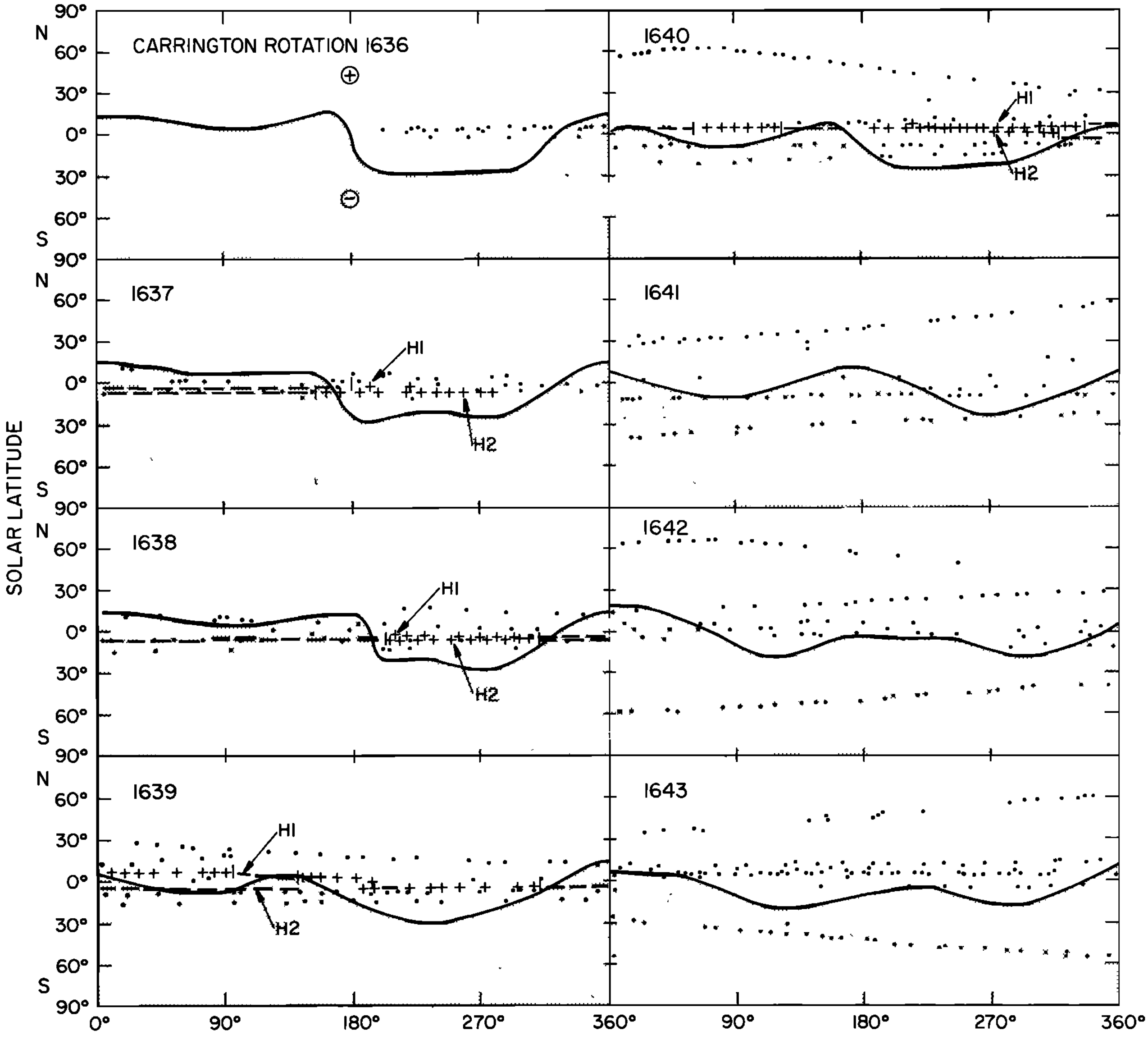

Fig. 1. The maximum brightness curves at 1.5 R_S (solid curve) deduced from the HAO K—coronameter observations and the positions (points) of the UCSD IPS observations as functions of of solar latitude and longitude for Carrington rotations 1636–1643. Also shown are the projected IMF polarities (plus indicating a field pointing away from the sun, minus indicating a field pointing toward the sun) observed by Helios during Carrington rotations 1637–1640.

and for a subset of rotations, 1637–1640, to be discussed below. The bar centered on each average value denotes the confidence interval of the unbiased sample mean (i.e., the average speed) of the observations at the 95% confidence level (as in *Zhao and Hundhausen* [1981]). The tendency for high average solar wind speeds at large heliographic latitudes, reported for this same data set at several phases of the past sunspot cycle by *Coles et al.* [1980], is clearly present during the epoch under discussion here.

A close examination of the IPS observations reveals a spatial variation more complex than the average structure shown in Figure 2. Early in 1976, the interplanetary neutral line indicated by the MBC's of Figure 1 was located just above the solar equator (at about 10° ± 5° north latitude) for Carrington longitudes between 0° and 180° and well south of the solar equator (at about 30° south latitude) for Carrington longitudes between ≈190° and 320°. The average solar wind speed variation with heliographic latitude for Carrington rotations 1637–1640 is shown in Figure 2 and is little different from that for the entire epoch. Figure 3 shows the heliographic latitude variations of the solar wind speed averaged in these two separate longitude intervals for the subset of Carrington rotations 1637–1640. In the 0° to 180° longitude interval, the average solar wind speed has a minimum value of ≈350 km s^{-1} at or just north of the solar equator, or at the same latitude as the MBC. The average solar wind speed rises to 500 km s^{-1} or more at ≈30° latitude on either side of this minimum. In contrast, the average solar wind speed in the 190° to 320° longitude interval decreases monotonically from ≈500 km s^{-1} at 10° north latitude, through ≈425 km s^{-1} at the solar equator, to approach 350 km s^{-1} at 20° south latitude. This is consistent with a minimum value near the MBC location, 30° south latitude, although the absence of any observations at latitudes below 20° south precludes the definitive demonstration of such a minimum value. Even though the general trend toward high solar wind speeds at high heliographic latitudes holds for this subset of Carrington rotations, it is evident from Figure 3 that the true spatial distribution of solar wind in early 1976 is not symmetric about the solar equator (or the solar rotation axis). It would again appear to be more nearly symmetric about the position of the interplanetary neutral sheet deduced from the MBC's.

Finally, Figure 4 displays the average solar wind speed as a function of angular displacement from the MBC's, or inferred neutral surfaces, shown on Figure 1. Averages have again been computed in 10° intervals, and the bars indicate confidence limits. The bottom frame of the figure is based on all eight Carrington rotations under discussion, the top frame is based on the subset of rotations 1637–1640 when the MBC's and solar wind speeds were not symmetric about the solar equator. Both plots are consistent with the hypothesis that solar wind speed increases with displacement from an interplanetary neutral sheet, as advocated by *Zhao and Hundhausen* [1981] for the 1974 epoch. Here, however, the IPS measurements from high heliographic latitudes provide information about angular displacements from the neutral sheet greater than the magnitude of the warping of that sheet away from the equator. These measurements indicate that the rapid rise in solar wind speed with angular displacement applies only with ≈35° of the neutral sheet; the solar wind speed appears to be nearly constant at ≈600 km s^{-1} for larger displacements. The curve

$$u = 350 \text{ km s}^{-1} + 800 \sin^2 \lambda \text{ km s}^{-1} \qquad |\lambda| \leq 35°$$

is shown on the bottom frame of Figure 4 and gives a good representation of the variation of average solar wind speed in the ±35° interval. This relationship is remarkably close to that deduced for 1974. Given the use of IPS observations in this work and of in situ observations in the earlier paper, the differences between the two results may reflect nothing more than experimental errors.

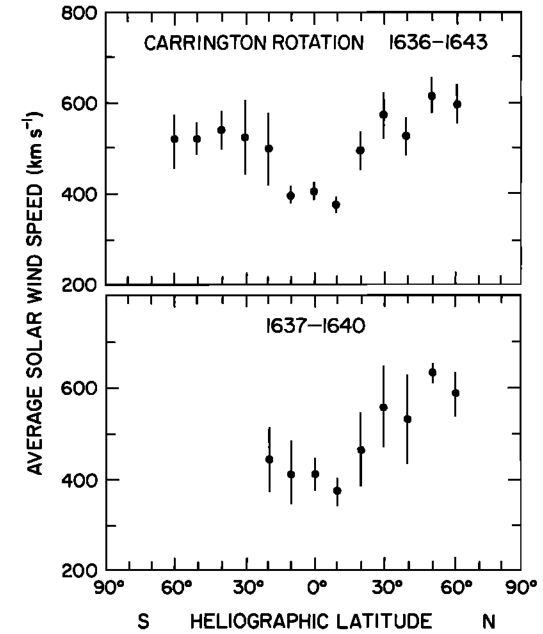

Fig. 2. The heliographic latitude variation of the average solar wind speed over Carrington rotations 1636–1643 (top) and 1637–1640 (bottom). Also shown are the 95% confidence intervals.

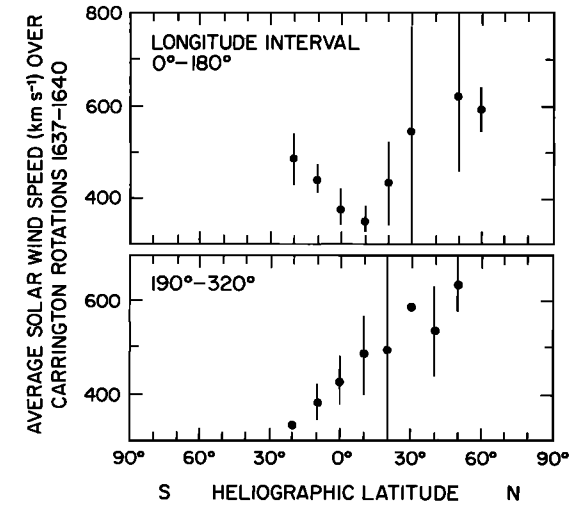

Fig. 3. The heliographic latitude variations of the average speed over 10° latitude intervals and longitude intervals 0° to 180° (top) and 190° to 320° (bottom) in Carrington rotations 1637–1640. Also shown are the 95% confidence intervals (bars).

Summary and Discussion

The IPS observations of solar wind speed from the epoch December 1975 to July 1976 reveal an increase in averaged (over longitude) speed with heliographic latitude within ≈35° of the solar equator and a nearly constant, high speed at higher latitudes (Figure 2). During most of this epoch, the maximum brightness curves derived from synoptic maps of coronal polarization brightness are close to the solar equator, implying an interplanetary neutral surface that is close to the solar equatorial plane. Thus the variation of solar wind speed with angular displacement from this inferred neutral surface (Figure 4) is very little different from its variation with heliographic latitude. Nonetheless, significant local displacements of the neutral sheet from the equatorial plane, as indicated by the maximum brightness curves in early 1976, are associated with large local deviations from equatorial symmetry in the spatial variation of the solar wind speed (Figure 3). We thus have another piece of evidence for a close relationship between the spatial structure of the solar wind speed and the global polarity structure of the magnetic field that dominates any simple variation of a wind speed with heliographic latitude. It should, of course, be understood that our emphasis on a single neutral sheet encircling the sun is a conscious oversimplification. Other magnetic neutral surfaces may well extend from the corona into interplanetary space [e.g., *Hundhausen*, 1979; *Gosling et al.*, 1981; *Niedner*, 1982] and produce more complex spatial structure than considered here.

The particular relationship between solar wind speed u and angular displacement λ from the neutral surface, derived for the 1976 epoch, is

$$u = 350 \text{ km s}^{-1} + 800 \sin^2 \lambda \text{ km s}^{-1} \qquad |\lambda| \leq 35°$$

$$u(\lambda) = 600 \text{ km s}^{-1} \qquad |\lambda| > 35°$$

This variation within the neutral sheet centered 'belt' is virtually the same as inferred by *Zhao and Hundhausen* [1981] from 1974 in situ solar wind observations; the constant high-speed 'cap' at large displacements from the neutral sheet was also suggested in the interpretation of 1974 IPS and in situ observations [e.g., *Hundhausen*, 1978].

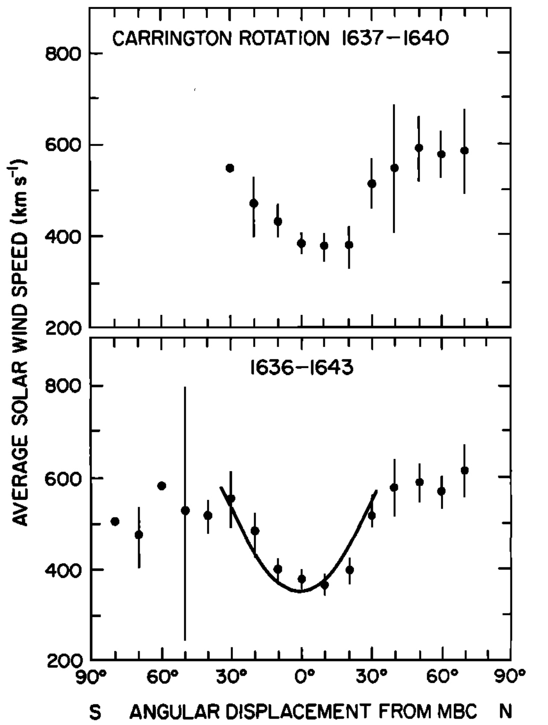

Fig. 4. The heliomagnetic latitude variation of the average speed over Carrington rotations 1637–1640 (top) and 1636–1643 (bottom). The bar on each point is the 95% confidence interval. The curve shown in the bottom frame approximated the average speed variation.

This relationship again suggests that the primary spatial modulation of the coronal expansion is produced by some simple, perhaps geometric property of the coronal magnetic field. Such an effect is predicted by some coronal expansion models that incorporate either the interaction of the coronal plasma and magnetic field [e.g., *Pneuman and Kopp*, 1971] or the flow of plasma in a prescribed magnetic geometry. The close resemblance of the 'heliomagnetic latitude' variations in solar wind speed for 1974 and 1976 raises the interesting question of the applicability of this relationship to other phases of the sunspot cycle. Were such a relationship to apply, for example, at other times when the 'heliomagnetic equator' is the basic organizer of the interplanetary magnetic field, the notion of a simple geometric influence of the coronal magnetic field on the speed of the solar wind would gain considerable credence.

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