

SPATIAL VARIATION OF THE SOLAR WIND SPEED IN 1976 AND 1977

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Abstract: Spatial variations of the solar wind speed with respect to angular distance from the heliospheric current sheet (HCS) reported by ZHAO and HUNDHAUSEN (J. Geophys. Res., **88**, 451, 1983) and by HAKAMADA and MUNAKATA (J. Geophys. Res., **89**, 357, 1984) are re-examined. During the period considered here, the solar wind reaches higher speeds in magnetic northern higher latitudes than in magnetic southern higher latitudes, as shown by ZHAO and HUNDHAUSEN, although the solar wind speed in magnetic southern middle latitudes has a steeper gradient than in magnetic northern middle latitudes. Further, the solar wind speed is minimum on the HCS.

This situation of the solar wind speed can be approximated by a simple functional form of

$$V(\text{km/s}) = V_a \tanh^2 (C(\lambda - \lambda_m)) + V_m,$$

where λ is an angular distance of the earth from the HCS, which is measured perpendicular to the HCS. V_a , C , V_m and λ_m are constants determined by the least squares method. V_a and C are 225 km/s and 0.032 for $\lambda > 0$, and 134 km/s and 0.061 for $\lambda < 0$, respectively. V_m and λ_m are equal to 390 km/s and 0 degree, respectively.

1. Introduction

Heliographic latitude dependence of the solar wind speed has been discussed in conjunction with semi-annual variations of geomagnetic activity (see the review paper by WILCOX (1968) and the book by AKASOFU and CHAPMAN (1972) for detailed references on this subject). HUNDHAUSEN *et al.* (1971) first pointed out the presence of the semi-annual variations of the solar wind speed using *in situ* observations. RHODES and SMITH (1976a, b) showed direct evidence of heliographic latitude variations of the solar wind speed by space probe observations. Further, COLES and RICKETT (1976) showed these heliographic latitude variations of the solar wind speed in a wide range of latitude with their interplanetary scintillation (IPS) measurements.

HAKAMADA and AKASOFU (1981) attempted to interpret temporal variations of the solar wind speed assuming that the solar wind speed increases toward higher solar-magnetic latitude on a so-called "source surface" of $2.5 R_s$ and an apparent magnetic dipole wobbling around the solar rotational axis. ZHAO and HUNDHAUSEN (1981) obtained an empirical formula which represents the solar wind speed as a function of angular displacement, λ , from an assumed sinusoidal HCS. Most recently, ZHAO

and HUNDHAUSEN (1983) have demonstrated that the solar wind speeds estimated by the IPS (COLES *et al.*, 1980) depend on the angular displacement from the HCS on a sphere of 1.5 solar radii (R_s) estimated by the maximum brightness curve (MBC) on a map of white light corona (BURLAGA *et al.*, 1981). HAKAMADA and MUNAKATA (1984) have pointed out that a significant part of the temporal variations of the solar wind speed observed by satellites is caused by the spatial variations of the solar wind speed on the source surface. They have emphasized that the solar wind speed depends on the angular distance from the HCS but not on the heliographic latitude, by using HCS computed by HOEKSEMA *et al.* (1982) from photospheric magnetic fields with a potential field model. This solar wind speed variation depending on the angular distance, λ , from the HCS is called λ -dependence hereafter in this paper.

In this paper, we re-examine the data reported by ZHAO and HUNDHAUSEN (1983) and HAKAMADA and MUNAKATA (1984) to show that the λ -dependence may be represented for the wide range of λ by a simple functional form of

$$V \text{ (km/s)} = V_a \tanh^2(C(\lambda - \lambda_m)) + V_m,$$

where V_a , C , V_m , and λ_m are constants determined by the least squares method.

2. Data Analysis and Results

We use the solar wind speed, V , and the angular distance from the HCS, λ , shown in Fig. 4 of ZHAO and HUNDHAUSEN (1983) and in Fig. 3a of HAKAMADA and

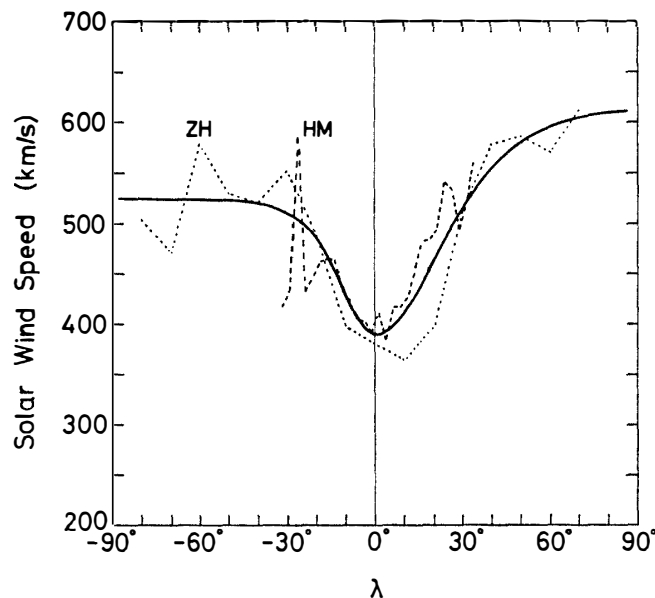


Fig. 1. λ -dependence of the solar wind speed. λ is an angular distance from the heliospheric current sheet measured perpendicular to it. A dashed curve is the result of HAKAMADA and MUNAKATA (1984) and a dotted curve is the result reported by ZHAO and HUNDHAUSEN (1983). A heavy solid curve is computed by the empirical formula of $V(\text{km/s}) = V_a \tanh^2(C(\lambda - \lambda_m)) + V_m$, obtained from this analysis, where V_a and C are 225 km/s and 0.032 for $\lambda > 0$, and 134 km/s and 0.061 for $\lambda < 0$, respectively. V_m and λ_m are 390 km/s and 0 degree, respectively.

MUNAKATA (1984). These data are shown in Fig. 1 of this paper with dotted and dashed curves marked by ZH and HM, respectively. The two curves show essentially the same tendency, although ZH is slightly smaller than HM for $\lambda > 0$.

Since the warping of the HCS is confined to $\pm 40^\circ$ in heliographic latitude during the particular time period considered here, the angular distance of the satellite from the HCS is also confined in almost the same angle in solar-magnetic latitude. This is the reason that the curve HM is confined to $\pm 40^\circ$ in latitude.

We use the simple functional form of $V = \tanh^2(C(\lambda - \lambda_m)) + V_m$, where V_a , C , V_m , and λ_m are determined by the least squares method on the assumptions that V_a and C have different values for $\lambda > \lambda_m$ and for $\lambda < \lambda_m$ and that the curve has the minimum value of V_m and continues smoothly at $\lambda = \lambda_m$ with a flat tangent on the $\lambda - V$ diagram as shown by the heavy solid line in Fig. 1. The following value is computed for the least squares method:

$$S = \sum_{i=1}^{27} n_i (v_i - \hat{V}_i)^2 + \sum_{j=1}^{16} (v_j - \hat{V}_j)^2,$$

where v_i and v_j are solar wind speeds reported by HAKAMADA and MUNAKATA (1984) and ZHAO and HUNDHAUSEN (1983), \hat{V}_i and \hat{V}_j are solar wind speeds calculated by the empirical formula at the same angular distance corresponding to the observations.

Table 1. Parameters for the empirical formula.

	Magnetic southern hemisphere	Magnetic northern hemisphere
	$\lambda < 0$	$\lambda > 0$
V_a	134 km/s	225 km/s
C	0.061	0.032
V_m	390 km/s	
λ_m	0 degree	

Solar wind speed, V , has the minimum value of 390 km/s on the heliospheric current sheet.

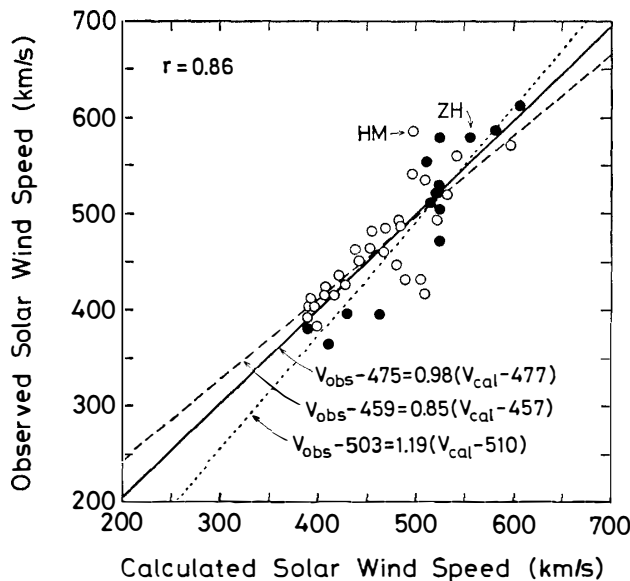


Fig. 2. Diagram of correlation between calculated and observed solar wind speeds. Open circles are the data from HAKAMADA and MUNAKATA (1984), filled circles are the data from ZHAO and HUNDHAUSEN (1983). Best fitted lines to the data points are shown by a dashed line for open circles and a dotted line for filled circles. A heavy solid line is best fitted to all data points. Regression equations of three lines are also shown in the figure.

For the first term, each value of $(v_i - \hat{V}_i)$ is weighted by the number of data points in the i -th bin. For the second term, each value of $(v_j - \hat{V}_j)$ is equally weighted by unity. Consequently, the data around $\lambda=0$ is significantly weighted because of the large number of data points. The parameters of V_a , C , V_m , and λ_m are determined so that the value of S has the minimum value. The parameters thus determined are summarized in Table 1.

A correlation diagram between the solar wind speed reported by HAKAMADA and MUNAKATA (1984) and ZHAO and HUNDHAUSEN (1983) and the solar wind speed calculated by this empirical formula is shown in Fig. 2. Open circles and filled circles show the data from HAKAMADA and MUNAKATA (1984) and ZHAO and HUNDHAUSEN (1983), respectively. A solid straight line is the best fit line to all data points in this correlation diagram. A dashed line and a dotted line are the best fit lines to the open circles and the filled circles, respectively. Equations of these lines are also shown in Fig. 2, demonstrating good correlations between them.

3. Conclusion and Discussion

Figure 3 shows six curves drawn by various line style and labeled by the initials of the authors who reported empirical formulae used in computing these six curves.

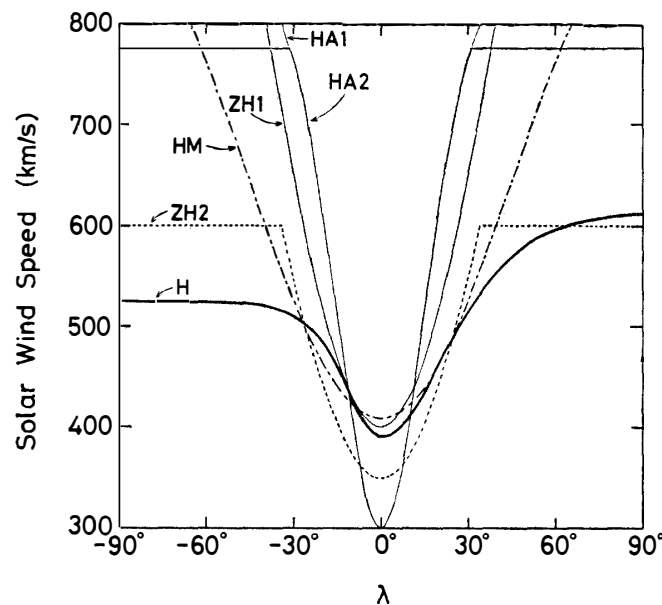


Fig. 3. Curves computed by six different empirical formulae are shown by different line styles. Each curve is labeled by the initials of the authors who reported the empirical formula. A heavy solid line is the result of this analysis.

The curves labeled by HA1 and HA2, and ZH1 are drawn by empirical formulae reported by HAKAMADA and AKASOFU (1981, 1982) and ZHAO and HUNDHAUSEN (1981), for which they used data taken from time intervals different from those of the other curves.

By using the IPS observations, COLES *et al.* (1980) pointed out that the solar wind

does respond dramatically to the solar activity cycle. However, as clearly shown by HAKAMADA and MUNAKATA (1984), the solar wind speed depends upon the angular distance from the HCS, not upon the heliographic latitude. Therefore, there is a possibility that the solar cycle dependence of the solar wind speed reported by COLES *et al.* (1980) is indeed the solar cycle variation of the λ -dependence of the solar wind speed. Thus, λ -dependence may change its functional form in the course of solar activity cycle. This may be one reason why HA1, HA2, and ZH1 are very different from the other curves: HM and H used the same time interval and ZH2 used the subset of the time intervals of HM and H.

The relations between the solar wind speeds, V , observed by the interplanetary scintillation and the satellites, and the angular distance from the HCS, λ , estimated by the MBC of the white light corona and by the photospheric magnetic fields with the potential field model have been re-examined. It has been shown that the solar wind speed can be approximated by the simple empirical formula as

$$V \text{ (km/s)} = V_a \tanh^2 (C(\lambda - \lambda_m)) + V_m ,$$

where V_a and C are 225 km/s and 0.032 for $\lambda > 0$ and 134 km/s and 0.061 for $\lambda < 0$, respectively. V_m and λ_m are equal to 390 km/s and 0 degree, respectively, as summarized in Table 1. During the time interval considered here, the solar wind speed has a minimum value on the HCS ($\lambda_m = 0$). The solar wind emanating from the magnetic northern hemisphere reaches a higher speed in the higher latitudes than in the magnetic southern higher latitudes, although the speed shows a steeper gradient in the magnetic southern middle latitudes than in the magnetic northern middle latitudes.

References

- AKASOFU, S.-I. and CHAPMAN, S. (1972): Solar-Terrestrial Physics. Oxford, Clarendon Press, 901 p.
- BURLAGA, L. F., HUNDHAUSEN, A. J. and ZHAO, X.-P. (1981): The coronal and interplanetary current sheet in early 1976. *J. Geophys. Res.*, **86**, 8893–8898.
- COLES, W. A. and RICKETT, B. J. (1976): IPS observations of the solar wind speed out of the ecliptic. *J. Geophys. Res.*, **81**, 4797–4799.
- COLES, W. A., RICKETT, B. J., RUMSEY, V. H., KAUFMAN, J. J., TURLEY, D. G., ANANHAKRISHNAN, S., ARMSTRONG, J. W., HARMONS, J., SCOTT, S. L. and SIME, D. G. (1980): Solar cycle changes in the polar solar wind. *Nature*, **286**, 239–241.
- HAKAMADA, K. and AKASOFU, S.-I. (1981): A cause of solar wind speed variations observed at 1 A.U. *J. Geophys. Res.*, **86**, 1290–1298.
- HAKAMADA, K. and AKASOFU, S.-I. (1982): Simulation of three-dimensional solar wind disturbances and resulting geomagnetic storms. *Space Sci. Rev.*, **31**, 3–70.
- HAKAMADA, K. and MUNAKATA, Y. (1984): A cause of the solar wind speed variations; An update. *J. Geophys. Res.*, **89**, 357–361.
- HOEKSEMA, J. T., WILCOX, J. M. and SCHERRER, P. H. (1982): Structure of the heliospheric current sheet in the early portion of sunspot cycle 21. *J. Geophys. Res.*, **87**, 10331–10338.
- HUNDHAUSEN, A. J., BAME, S. J. and MONTGOMERY, M. D. (1971): Variations of solar wind properties; Vela observations of a possible heliographic latitude-dependence. *J. Geophys. Res.*, **76**, 5145–5154.
- RHODES, E. J., Jr. and SMITH, E. J. (1976a): Evidence of a large-scale gradient in the solar wind velocity. *J. Geophys. Res.*, **81**, 2123–2134.
- RHODES, E. J., Jr. and SMITH, E. J. (1976b): Further evidence of a latitudinal gradient in the solar wind velocity. *J. Geophys. Res.*, **81**, 5833–5840.

- WILCOX, J. M. (1968): The interplanetary magnetic field; Solar origin and terrestrial effects. *Space Sci. Rev.*, **8**, 258–328.
- ZHAO, X.-P. and HUNDHAUSEN, A. J. (1981): Organization of solar wind plasma properties in a tilted heliomagnetic coordinate system. *J. Geophys. Res.*, **86**, 5423–5430.
- ZHAO, X.-P. and HUNDHAUSEN, A. J. (1983): Spatial structure of solar wind in 1976. *J. Geophys. Res.*, **88**, 451–454.

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