SOLAR WIND SPEED AND CORONAL FLUX-TUBE EXPANSION

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ABSTRACT

The hypothesis that the solar wind speed at 1 AU and the rate of magnetic flux-tube expansion in the corona are inversely correlated is shown to be consistent with observations extending over the last 22 years. This empirical relationship allows the daily wind speeds at Earth to be predicted from a current-free extrapolation of the observed photospheric field into the corona. We attribute the narrow boundaries of high-speed wind streams to steep gradients in the flux-tube expansion rates at the edges of coronal holes. When a heliospheric current sheet is included in the model, we find that the flux tubes near the hole axis, although diverging more slowly than those near the hole boundary in the corona, have undergone the greatest net expansion at 1 AU, an effect consistent with the low densities within high-speed streams.

Subject headings: Sun: corona — Sun: solar wind

I. INTRODUCTION

During the Skylab era, it was discovered that high-speed solar wind streams originated from large coronal holes, which in turn were characterized by open and rapidly diverging magnetic field geometry (see Zirker 1977). These findings continue to motivate theoretical studies of the relationship between wind acceleration and nonradial expansion near the Sun (see Withbroe 1988, and references therein). However, because coronal holes vary in size, shape, and latitudinal location during the sunspot cycle (see, for example, Broussard et al. 1978), the question arises as to whether the Skylab-based inferences about the source regions of the solar wind are generally valid. Using observations extending over the last 22 years, we present here an empirical study of the long-term relationship between wind speed and the magnetic properties of the source regions.

II. LONG-TERM CORRELATION BETWEEN WIND SPEED AND TOTAL CORONAL HOLE AREA

Figure 1a shows 3 month running averages of the solar wind bulk speed (v_w) at 1 AU during 1967–1988. The data were recorded by the Los Alamos and MIT plasma experiments on board the Vela, IMP, and ISEE 3/ICE spacecraft series. It is apparent that the average wind speeds were considerably lower near the 1969 and 1980 sunspot maxima than during the 3-4 years preceding the 1976 and 1986 sunspot minima. The well-defined series of peaks seen during 1973–1976 corresponds to the long-lived coronal hole patterns observed during the Skylab era (see Zirker 1977).

For comparison, Figure 1b shows 3 month running averages of the unsigned radial component (B_r) of the interplanetary magnetic field (IMF) near Earth during 1969–1985, as derived from magnetometer measurements on board IMP 8 and ISEE 3/ICE (see Couzens and King 1986). Whereas B_r and the total IMF strength B (not shown here) remained relatively constant during sunspot cycle 20, they increased during cycle 21, reaching a peak in 1982 (see King 1979; Slavin, Jungman, and Smith 1986; Wang and Sheeley 1988). While Figure 1b suggests some tendency for fluctuations in B_r and v_w to occur in phase, the long-term variations of these quantities differ considerably. In particular, the high wind speeds observed during 1973–1976 were not accompanied by correspondingly large increases in B_r. The absence of a long-term correlation between v_w and B_r appears to be inconsistent with some theoretical models that invoke Alfvén waves to accelerate the wind: for a given coronal temperature, such models predict a monotonic increase in the wind speed with increasing radial IMF strength (see Leer, Holzer, and Flä 1982).

The thick line in Figure 1c shows the total fraction (A_T) of the Sun's surface area occupied by open magnetic flux during 1967–1988. Here 3 month running averages of A_T were calculated by using the potential field approximation to extrapolate the observed photospheric field to a "source surface" r = R_S, where the field lines are required to be radial (see Schatten, Wilcox, and Ness 1969). Following Hoeksema (1984), we take R_S = 2.5 R_S, where R_S is the solar radius; we also assume that the large-scale field is predominantly radial at the photosphere, as inferred observationally by Howard and LaBonte (1981).

The coronal hole patterns were in the form of Carrington synoptic maps (resolution 91 pixels in longitude by 34 pixels in sine latitude) from Mount Wilson Observatory (MWO).

It is apparent that the quantity A_T shows a better long-term correlation with the observed wind speed (Fig. 1a) than does the radial IMF strength. If we identify open field regions with coronal holes, Figure 1c indicates that high wind speeds tend to be observed when coronal holes cover a relatively large fraction of the Sun's surface. The polar regions provide a substantial contribution to A_T near sunspot minimum, when the large-scale photospheric field becomes concentrated toward the poles (Wang, Nash, and Sheeley 1989). The polar coronal holes that form within these unipolar regions are observed to extend down to a latitude of ~60° around sunspot minimum, covering over 13% of the solar surface. Figure 1c also shows the fraction A_L (dotted curve) of the solar surface occupied by open field regions located below latitude 45°. Here it may be noted that although A_L decreased to very small values during 1985–1987, the average wind speeds remained high.

Figure 1d shows that the average (unsigned) field strength B_H in open field regions is strongly anticorrelated with the solar wind speed at 1 AU, with B_H (evaluated at the photosphere) peaking sharply in 1979 near sunspot maximum (see Harvey, Sheeley, and Harvey 1982). As in Figure 1c, open
field regions were identified by applying the source surface method with $R_s = 2.5 \, R_\odot$ to the MWO photospheric fields, which were multiplied by 1.8 to correct for the saturation of the Fe I 5250 Å line profile (see Svalgaard, Duvall, and Scherrer 1978).

We conclude that the long-term variation of $v_w$ shows a better correlation with the total area $A_T$ occupied by coronal holes than with either the area $A_L$ of low-latitude holes, the photospheric field strength $B_H$ within holes, or the radial field strength $B_x$ near Earth.

III. EMPIRICAL MODEL FOR THE SOLAR WIND SPEED

Nolte et al. (1976) demonstrated that the areas of large, near-equatorial coronal holes during the Skylab period were highly correlated with the maximum speeds of the associated wind streams. Levine, Altschuler, and Harvey (1977) interpreted this result in terms of the expansion of magnetic flux tubes: high-speed winds originate from large coronal holes and from the centers of coronal holes because these regions are characterized by the least flux-tube expansion. We now show that this Ansatz can be used to simulate the observed daily wind speeds over the interval 1967–1989.

Following Levine, Altschuler, and Harvey (1977), we use the potential-field source-surface method to determine the coronal field configuration from the observed photospheric field and to evaluate the factor by which flux tubes expand in solid angle between the photosphere and the source surface. Again taking $R_s = 2.5 \, R_\odot$ and employing MWO Carrington maps of the photospheric field, we calculate daily values of the quantity $f_s = (R_\odot/R_s)^3[B^2(R_\odot)/B^2(R_s)]$, where $B^2(R_s)$ denotes the field strength at the Earth's projected position $P$ on the source surface, and $B^2(R_\odot)$ denotes the field strength at the photospheric footpoint of the flux tube traversing $P$. In determining $P$, we include the effect of the Sun's 7°25 axial tilt and allow for a 5 day Sun-Earth transit time for the radially propagating solar wind. The parameter $f_s$ measures the rate at which the Earth-directed flux tube expands in cross section between the photosphere and the source surface, as compared with a purely radial expansion.
Our empirical model associates a range of daily wind speeds at Earth with a corresponding range of the parameter $f_w$ as shown in Table 1. This particular set of rules was chosen for simplicity and is meant to be illustrative; similar results were obtained when the ranges of $f_w$ were varied by as much as 25%. The first column of Figure 2 (Plate 25) displays the model wind speeds calculated for the 22 yr interval 1967–1989. Here the daily wind speeds are represented by color-coded pixels arranged in 27 day rows (Bartels format). For comparison, the second column of Figure 2 shows the observed wind speeds in the same 27 day format.

From these plots, we conclude that the model reproduces reasonably well the coherent patterns of high-speed wind observed during 1973–1976 and during 1982–1986, suggesting that these high-speed streams were indeed associated with low areal divergence rates near the Sun. (The agreement is better during the 1982–1986 interval for reasons that we discuss below.) The corresponding flux tubes often have their footpoints located along the equatorward extensions of the large polar holes that form during the declining phase of the sunspot cycle. The high-speed streams may also originate along the warped high-latitude boundaries of the polar holes themselves, or within small, detached coronal holes at low latitudes. In contrast, around sunspot maximum (near 1970 and 1980), both the simulated and observed Bartels maps show a “lull” in the wind speeds. During this period, the solar wind in the ecliptic emanates from a collection of small, often elongated holes located at low or mid latitudes. Because the total photospheric area covered by these holes is small, the magnetic flux must generally expand rapidly in solid angle between the photosphere and the source surface, resulting in high values of $f_w$ and low wind speeds. Remarkably, the presence of large polar holes or nearby holes of the same polarity can turn such regions into sources of high-speed wind by restricting the volume that their flux can occupy, and thus lowering the associated values of $f_w$.

It is interesting to compare the simulated and observed wind-speed patterns with the corresponding magnetic polarity patterns. The polarity of the source surface field at the sub-Earth position $P$ is shown in Bartels format in the third column of Figure 2, while the observed daily IMF polarities near Earth (from Vela, IMP, and ISEE 3/ICE spacecraft measurements) are displayed in the fourth column of Figure 2. It is apparent that both the simulated and observed patterns of high-speed wind tend to follow the shape of the magnetic polarity structure. In particular, high velocities tend to occur inside the polarity sectors, and lower velocities tend to occur near their boundaries. (The 5 day Sun-Earth transit time used in determining $P$ characterizes the slow wind near the sector boundaries.) We note also that while the extrapolated and observed polarity patterns show good agreement from about 1979 onward, the patterns inferred from the MWO photospheric fields are very noisy during earlier years. This noise, which is caused by instrumental problems and by data gaps in the MWO synoptic maps, may explain some of the discrepancies between the simulated and the observed wind-speed patterns. For example, during 1973–1976 and 1974–1977, extrapolation of the MWO fields yields positive polarity sectors that are more extensive than observed, and the corresponding model wind-speed patterns are therefore too broad and diffuse. The rebuilding of the MWO magnetograph in 1981 (Howard et al. 1983) contributed to the later reduction of the noise level, allowing the complex wind-speed patterns observed during 1982–1985 to be reproduced.

Near the 1986 sunspot minimum, the IMF polarity patterns show a horizontal orientation (predominantly one-sector structure) as the heliospheric neutral sheet is flattened toward the equatorial plane by the Sun’s strong polar fields. The sector polarity at Earth then undergoes a seasonal variation because of the Sun’s $7^\circ25$ axial tilt. The continued observation of high-speed streams during this period (see Fig. 2) implies that large latitudinal gradients in the wind speed are present around the heliospheric current sheet near sunspot minimum (see Bruno et al. 1986). The model yields high-speed wind in the ecliptic because active regions occasionally erupt even at sunspot minimum; thus small equatorward spurs whose field lines are characterized by low divergence rates continue to form along the polar-hole boundaries. As shown in § IV, steep gradients in the expansion factor $f_w$ would be present even at the boundary of an axisymmetric polar hole. However, such a hole would not produce high-speed streams in the ecliptic unless its size were considerably greater than that typically observed near sunspot minimum.

In Figure 3, we have plotted 3 month running averages of the simulated wind speeds. For this purpose, we first converted the flux-tube expansion factors into daily wind speeds according to the scheme shown in Table 2, which replaces the ranges of $v_w$ given in Table 1 by characteristic discrete values. From Figure 3, it is apparent that the resulting 3 month averages of $v_w$ (thick line) show good overall agreement with the corresponding observed values (dotted line) during the interval 1967–1988. The correlation coefficient between the (281 monthly pairs of) simulated and observed wind-speed averages has a value of 0.57.

### TABLE 2

<table>
<thead>
<tr>
<th>$f_w$</th>
<th>$v_w$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;$3.5</td>
<td>700</td>
</tr>
<tr>
<td>3.5–9</td>
<td>600</td>
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<td>9–18</td>
<td>500</td>
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<tr>
<td>18–54</td>
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<td>$&gt;$54</td>
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</table>

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Fig. 2.—Simulated and observed solar wind speeds (columns 1 and 2), and simulated and observed IMF polarity patterns (columns 3 and 4). Daily wind speeds and IMF polarities near Earth during 1967–1989 are represented by colored pixels arranged in 27 day rows. Color-coding for the simulated and observed wind speeds: red ($v_w > 650$ km s$^{-1}$); yellow ($550$ km s$^{-1} < v_w \leq 650$ km s$^{-1}$); green ($450 \leq v_w \leq 550$ km s$^{-1}$); blue ($v_w \leq 450$ km s$^{-1}$); black (no data). Color-coding for the simulated and observed IMF polarities: yellow (positive polarity); blue (negative polarity); green (mixed polarity); black (no data). The model polarity patterns were obtained by a current-free extrapolation of the MWO photospheric field to a source surface at 2.5 $R_\odot$; the model wind speeds were inferred from the flux-tube expansion factors at 2.5 $R_\odot$ according to Table 1.
FIG. 2.—Simulated and observed solar wind speeds (columns 1 and 2), and simulated and observed IMF polarity patterns (columns 3 and 4). Daily wind speeds and IMF polarities near Earth during 1967–1989 are represented by colored pixels arranged in 27 day rows. Color-coding for the simulated and observed wind speeds: red ($v_w > 650$ km s$^{-1}$); yellow ($550$ km s$^{-1} < v_w \leq 650$ km s$^{-1}$); green ($450$ km s$^{-1} < v_w \leq 550$ km s$^{-1}$); blue ($v_w \leq 450$ km s$^{-1}$); black (no data). Color-coding for the simulated and observed IMF polarities: yellow (positive polarity); blue (negative polarity); green (mixed polarity); black (no data). The model polarity patterns were obtained by a current-free extrapolation of the MWO photospheric field to a source surface at 2.5 $R_\odot$; the model wind speeds were inferred from the flux-tube expansion factors at 2.3 $R_\odot$ according to Table 1.

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We note that if the angular distance \( \delta_p \) of the sub-Earth point \( P \) relative to the source-surface neutral line were used as the relevant parameter (in place of the expansion factor \( f_e \)), the resulting model would be unable to reproduce the long-term variation of the wind speeds. Because the neutral line intersects the ecliptic at relatively large angles near sunspot maximum (when the polar fields are weak), the average value of \( \delta_p \) will be correspondingly large during that time. Thus, if \( v_w \) were assumed to be an increasing function of \( \delta_p \), the highest wind speeds would be obtained near sunspot maximum, contrary to observations. The expansion factor \( f_c \) successfully describes both the long- and short-term variations of the wind speed because its value depends not only on the distance from the neutral line, but also on the configuration and total areal extent of the underlying coronal holes.

From an analysis of data spanning three consecutive Carrington rotations in 1979, Suess et al. (1984) have suggested that the source-surface field strength at the sub-Earth point may be correlated with the observed wind speeds. However, the long-term variation of \( B^r(R_o) \) is quite different from that of \( v_w \). In contrast to the latter quantity, the field strength at \( P \) attains its largest values during the years around sunspot maximum and becomes very small near sunspot minimum, when the neutral line lies close to the ecliptic (see Fig. 1 in Wang and Sheeley 1988).

IV. FLUX-TUBE EXPANSION IN AXISYMMETRIC POLAR HOLES

The empirical wind-speed model shown in Figure 2 depends on the values of the flux-tube expansion factor \( f_c \), which were calculated from the observed photospheric field using the potential-field source-surface method. However, this extrapolation technique is not expected to be reliable for \( r > R_w \), where the presence of a current sheet is required to explain the long-term behavior of the IMF strength (Wang and Sheeley 1988). In order to determine the sensitivity of \( f_c \) to the coronal model, we compare the rates of flux-tube expansion calculated using the source surface (SS) method with those obtained using a current sheet (CS) model originally formulated by Wolfson (1985). The actual heliospheric field configuration can be simulated by combining features of the SS and CS models (see Wang and Sheeley 1988).

For the illustrative calculations of this section, we assume that the radial component of the photospheric field has the form \( B_r(R_o, \theta) = \cos^n \theta \), where \( \theta \) is colatitude and \( n \) is an odd integer. In the CS model, the magnetic field is taken to be potential everywhere except in an equatorial current sheet, where \( B_r \) changes sign discontinuously and \( B_p \) vanishes. The inner boundary of the current sheet is located at a radius which we shall again denote by \( R_c \) and set equal to 2.5 \( R_o \). The coefficients in the solution of Laplace's equation, determined by matching the photospheric flux distribution and requiring both \( B_r \) and \( B_p \) to be continuous across \( r = R_w \), can be evaluated numerically using the expressions given in Sheeley, Wang, and Harvey (1989). In the limit \( r \to \infty \), the model implies a purely radial field, which is independent of \( \theta \) in each hemisphere and reverses its direction at the current sheet.

Using the CS method, we have computed the magnetic field configuration for values of the flux concentration index \( n \) ranging from 1 to 11 and investigated the behavior of the expansion factor along different field lines. Table 3 lists the angular half-width \( \theta_o \) of the polar coronal hole corresponding to each \( n \), the total expansion factor of the hole \( f_c \) (as \( r \to \infty \)), and the expansion factors \( f(r, \theta) \) evaluated at \( r = R_w \) and \( r = \infty \) along flux tubes having footpoint colatitudes \( \theta_0 = 0^\circ \) and \( \theta_0 = \theta_o \). By definition, \( f(r, \theta) = (R_o/r)^n B_r(r, \theta)/(B(r, \theta_0)) \), where the colatitudinal position \( \theta \) along the flux tube is a function of \( r \) and \( \theta_0 \). Also listed (in parentheses) in the table are the corresponding values of these quantities obtained using the SS method.

<table>
<thead>
<tr>
<th>( n )</th>
<th>( \theta_o )</th>
<th>( f_c )</th>
<th>( f(R_w, 0^\circ) )</th>
<th>( f(R_w, \theta_o) )</th>
<th>( f(\infty, 0^\circ) )</th>
<th>( f(\infty, \theta_o) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45.4(49.7)</td>
<td>3.4(2.8)</td>
<td>2.2(1.7)</td>
<td>3.91.7)</td>
<td>3.8(1.7)</td>
<td>2.8(1.7)</td>
</tr>
<tr>
<td>3</td>
<td>36.7(41.0)</td>
<td>5.0(4.1)</td>
<td>3.4(2.5)</td>
<td>6.8(2.5)</td>
<td>3.5(2.5)</td>
<td>4.4(2.5)</td>
</tr>
<tr>
<td>5</td>
<td>31.5(35.6)</td>
<td>6.8(5.4)</td>
<td>4.5(3.3)</td>
<td>9.7(3.3)</td>
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<td>6.2(3.3)</td>
</tr>
<tr>
<td>7</td>
<td>28.0(31.9)</td>
<td>8.5(6.6)</td>
<td>5.6(4.1)</td>
<td>12.7(4.1)</td>
<td>5.3(4.1)</td>
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<tr>
<td>9</td>
<td>25.3(29.1)</td>
<td>10.3(7.9)</td>
<td>7.4(5.8)</td>
<td>15.6(5.8)</td>
<td>6.2(5.8)</td>
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</tr>
<tr>
<td>11</td>
<td>23.5(27.0)</td>
<td>12.1(9.2)</td>
<td>7.8(5.6)</td>
<td>18.6(5.6)</td>
<td>7.1(5.6)</td>
<td>9.4(5.6)</td>
</tr>
</tbody>
</table>

* Numbers in parentheses refer to the source surface model. The quantity \( f_c = (1 - \cos \theta_o)^{-1} \) represents the total expansion factor (as \( r \to \infty \)) of a coronal hole having angular half-width \( \theta_o \). The position-dependent, flux-tube expansion factor is defined as \( f(r, \theta_o) = (R_o/r)^n B_r(R_o, \theta_o)/B(r, \theta_0) \), where \( \theta_0 \) denotes the footpoint colatitude of a flux tube passing through \([r, d_r, d_0]\).
larger divergence rates near the axis. At \( r = R_s \), the expansion factors calculated with both models increase away from the axis and diverge as \( \theta \to 90^\circ \) (\( \theta_s \to \theta_0 \)), where a cusp in the field-line topology occurs. As \( r \to \infty \), however, the expansion factors obtained with the CS method end up decreasing away from the axis, whereas in the SS model the latitudinal distribution remains the same as at \( r = R_s \). The asymptotic behavior of the expansion factors in the CS model follows from the fact that the magnetic flux eventually becomes uniformly spread in latitude, whereas it is strongly concentrated toward the pole near the Sun.

Figure 4a illustrates, for the case \( n = 7 \), the magnetic field-line geometry computed using both the CS method (solid lines) and the SS method (dotted lines). For these same configurations, Figure 4b shows the radial dependence of the expansion factor \( f(r, \theta_0) \) along flux tubes originating at \( \theta_0 = 0^\circ, 20^\circ, 27^\circ, \) and \( 31^\circ \). In the CS model, the expansion factor changes nonmonotonically along flux tubes near the edge of the hole, reaching a maximum at some radius beyond \( R_s \). The subsequent decline in the expansion factor implies that \( B_r \) falls off less rapidly than \( r^{-2} \) in this region.

In the near region \( r \leq R_s \), both the CS and SS methods yield steep latitudinal gradients in the expansion factor near the edge of the hole. Figure 5 shows explicitly how the function \( f(R_s, \theta_0) \) evaluated at \( R_s = 2.5 R_Q \) varies with footpoint colatitude \( \theta_0 \) for both models. Here, in addition to the case \( n = 7 \), we display the results for a less concentrated polar field with \( n = 1 \), corresponding to a larger coronal hole (see Table 3). In general, we see that the expansion factors change relatively slowly with \( \theta_0 \) until within a few degrees of the edge of the hole \( \theta_0 = \theta_s \), where they increase sharply. Moreover, the "boundary layer" within which the function \( f(R_s, \theta_0) \) attains very large values becomes narrower as the hole widens.

As pointed out by Sheeley, Wang, and Harvey (1989), a flux concentration index \( n \sim 7 \) is similar to that observed for the polar fields near sunspot minimum; the value of \( \theta \), calcu-
lated with both the CS and SS models is close to 30°, and agrees with the observed size of polar coronal holes. As Table 3 shows, the corresponding coronal hole expansion factors are also consistent with the value \( f_c \approx 7 \) determined observationally by Munro and Jackson (1977).

In summary, the CS and SS methods yield qualitatively similar behavior for the field configuration near the Sun: for the distributions of surface flux considered in this section, the field lines diverge rapidly above small holes and at hole boundaries (the largest expansion rates in fact occur along closed field lines). Since more realistic extrapolation models yield results intermediate between the CS and SS approximations (see Wolfson 1985; Wang and Sheeley 1988), this justifies our use of the SS method to estimate the parameter \( f_s \) used in the wind speed model of § III. On the other hand, it is apparent that the actual values of \( f_s \) corresponding to a given range of wind speeds may differ quantitatively from those adopted in Tables 1 and 2.

V. IMPLICATIONS FOR WIND ACCELERATION MODELS AND EMPIRICAL FORECASTING

In this study, we have shown that solar wind and photospheric field observations over the last 22 years are consistent with the hypothesis that the wind speed at 1 AU and the divergence rate of the coronal magnetic field are inversely correlated. This result agrees with the earlier findings of Levine, Altschuler, and Harvey (1977) based on individual Skylab coronal holes.

It may be difficult to explain this empirical relationship with present wind acceleration models. As reviewed by Leer, Holzer, and Flã (1982), thermally driven wind models predict only a weak dependence of \( v_w \) on the expansion factor, and in any case cannot produce the observed high speeds; while models that include Alfvén-wave acceleration in the supersonic regime yield final wind speeds which are sensitive to the magnetic field strength and to the coronal base temperature. According to a recent two-fluid, Alfvén-wave model (Esser et al. 1986), rapid areal divergence should lead to higher rather than lower wind speeds.

In most calculations of this kind, the coronal base parameters are assigned arbitrarily. However, Withbroe (1988) has shown that the coronal density and temperature may be functions of the magnetic geometry, as also implied by the two-dimensional MHD simulations of Steinolfson, Suess, and Wu (1982). If the mechanical energy input is assumed to be approximately invariant at the coronal base (see Withbroe 1988), greater acceleration might be expected along flux tubes that expand slowly, provided the densities remain also relatively low. Another possibility consistent with the empirical relation found here was suggested by Rosner and Vaiana (1977): the Alfvén waves which would otherwise accelerate the wind to high speeds outside the sonic point may be dissipated lower in the corona if the flux tubes diverge rapidly there.

In studying how a current sheet affects the expansion factors in an axisymmetric coronal hole (§ IV), we found that the flux tubes that initially diverge the most slowly (those near the hole axis) end up with the largest cross sections far from the Sun. This effect may explain why the high-speed wind near the axis of a large hole ends up with a low density at 1 AU (see Zirker 1977), even though it undergoes the least lateral expansion in the corona. Similarly, the slow wind near the hole boundary may be characterized by relatively high densities at 1 AU because the rapidly diverging coronal flux tubes are subsequently "refocused." (Variations in the coronal base density within the hole may also contribute to the observed behavior.) Our analysis thus suggests that nonmonotonic expansion factors should be included in theoretical models that attempt to account for the differences between high- and low-speed flows. Above all, there is a need for MHD models which incorporate the balance of stresses between adjacent flow tubes, allowing a self-consistent determination of the expansion factors (see Withbroe 1989).

The analysis of § IV also indicates that steep latitudinal gradients in the coronal flux-tube expansion factors occur at the boundaries of large polar holes. Such gradients may account for the steep rise in the wind speed observed on each side of the heliospheric current sheet near sunspot minimum (see Bruno et al. 1986, and references therein). Indeed, for a photospheric flux distribution of the form \( \cos^7 \theta \), the model of § III would yield polar holes extending down to latitude 60° and wind speeds exceeding 550 km s\(^{-1}\) at an angular distance of only \( \sim 17° \) from the source-surface neutral sheet, consistent with observations. The flattening of the latitudinal wind-speed gradients toward sunspot maximum noted by Bruno et al. (1986) may be attributed to the rapid shrinking of hole areas during the rising phase of the cycle and the accompanying increase in the divergence rates at the hole centers.

Our results suggest that both fast and slow winds originate from coronal holes and that their speed is related to the rate at which the open field lines diverge close to the Sun. We emphasize that the source regions of high-speed winds are by no means confined to the centers of large holes. Indeed, field-line tracing shows that the lowest divergence rates are associated with regions of relatively weak field located between concentrations of like-polarity flux, where the unipolar flux distribution has a local minimum. Such configurations, which include the polar hole extensions, are of particular relevance to the high-speed streams observed in the ecliptic, and they will be analyzed in detail in a subsequent paper. We note here that the flux-tube expansion factors generally show abrupt changes at hole boundaries and that these sharp transitions may be reflected in the "mesa-like" profiles of high-speed streams recorded near the Sun (Schwenn et al. 1978).

Finally, we point out that the empirical relation between wind speed and coronal flux-tube expansion may have practical applications to the forecasting of high-speed wind streams and associated geomagnetic activity. By use of the flux transport code developed by DeVore, Sheeley, and Boris (1984), a synoptic map of the present photospheric field can be evolved forward in time under the influence of differential rotation, supergranular diffusion, and meridional flow. The algorithm of § III can then be applied to the simulated photospheric field to predict the wind speed at Earth. Since large coronal holes and their extensions are generally formed within slowly evolving unipolar regions, this procedure may allow high-speed streams to be forecast several months in advance during periods of low solar activity.

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