HIGH CORONAL STRUCTURE OF HIGH VELOCITY SOLAR WIND STREAM SOURCES

J. T. NOLTE and A. S. KRIEGER
American Science and Engineering, Inc., Cambridge, Mass., U.S.A.

and

E. C. ROELOF and R. E. GOLD
Applied Physics Laboratory, Laurel, Md., U.S.A.

(Received 14 June; in revised form 29 September, 1976)

Abstract. When solar wind plasma in the trailing (eastern) edge of a high-speed stream is mapped back to its estimated source in the high corona using the constant radial velocity (EQRH) approximation, a large range of velocities appears to come from a restricted range in longitude, often only a few degrees. This actually constitutes a sharp eastern coronal boundary for the solar wind stream source, and demands that the boundary have a three-dimensional structure. Using interplanetary data, we infer a systematic variation in 'source altitude' (identified approximately with the Alfvén point), with faster solar wind attaining its interplanetary characteristics at lower altitudes. This also affects the accuracy of the source longitude estimates, so that we infer a width in the high corona of 4–6° for the source of the trailing edges of streams which appear to originate from a single longitude. We demonstrate that the possible systematic interplanetary effects (in at least some cases) are not large ($\lesssim 2°$ in heliocentric longitude). The relatively sharp boundaries imply that high-speed streams are well-defined structures all the way down to their low coronal sources, and that the magnetic field structure controls the propagation of the plasma through the corona out to the vicinity of the Alfvén point ($\gtrsim 20\ R_{\odot}$).

1. Introduction

While the existence of the solar wind can be understood in terms of current theoretical models, the details of its origin in observable regions of the solar atmosphere ($< 10\ R_{\odot}$ above the photosphere) and propagation beyond the observable corona out to spacecraft distances are not yet fully explained. It is therefore important to determine as much as possible about solar wind sources and propagation from spacecraft observations. Other useful information is contained in extrapolations and inferences from radio observations such as Type III bursts, e.g., Fainberg and Stone (1974) and references therein, and interplanetary scintillation close to the Sun, e.g., Coles *et al.* (1974).

Recently progress has been made on the identification of the low coronal sources of one type of high-speed stream, those associated with coronal holes (Krieger *et al.*, 1973; Neupert and Pizzo, 1974; Krieger *et al.*, 1974; Nolte *et al.*, 1976). The structure of these streams between a few solar radii and the closest spacecraft (usually near 1 AU) is not directly observable, however.

In this paper we use interplanetary measurements of solar wind plasma and magnetic fields to partially fill this gap by inferring some aspects of the structure of sources of stationary (slowly evolving) high-speed solar wind streams in the high corona. We deal only with the structure at the eastern edge of the stream source, i.e., in the falling portion of the velocity time profile, because the coronal information at the leading edge of the stream is obscured by the interplanetary stream-stream interaction.

By 'sources of solar wind streams' we mean the high coronal sources, at the altitude where the solar wind takes on its interplanetary character. This 'source altitude' is the boundary between the solar corona and the interplanetary medium.

In a simplified sense, one could consider coronal plasma to be completely channeled by magnetic structures which rotate rigidly with the Sun. Interplanetary solar wind, on the other hand, is flowing very nearly radially, and carries the magnetic field along. In these terms, the 'source' of the interplanetary solar wind, or the region in which the solar wind undergoes the transition from coronal to interplanetary conditions, is clearly an extended zone which Nolte and Roelof (1973) estimated to be in the vicinity of the Alfvén radius.

There are also two more direct physical arguments for associating the boundary between the corona and the interplanetary medium with the Alfvén point. First, the direct transfer of angular momentum from the Sun to the plasma through the magnetic field ends at the Alfvén point, since plasma beyond this point can exert no torque on the Sun. Second, at the Alfvén point the energy of bulk flow of the plasma becomes greater than the magnetic field energy, so that channeling of the flow by the magnetic field is much less effective.

We therefore assume that the high coronal source altitude of interplanetary solar wind is approximately the Alfvén radius.

As a first approach, we determine the approximate source longitude of the solar wind plasma using the Extrapolated Quasi-Radial Hypervelocity (EQRH) approximation discussed by Nolte and Roelof (1973). The EQRH terminology is used to emphasize that the estimated source longitudes are the *high* coronal sources. In this approximation, first utilized by Snyder and Neugebauer (1966), source longitudes are calculated as if the solar wind velocity were radial and constant all the way from the Sun to the point of observation. The errors introduced by ignoring corotation and interplanetary acceleration approximately cancel each other, resulting in a good estimate for the longitude of the high coronal source of the solar wind.

We further investigate the structure of the high coronal source of high velocity streams by examining the interplanetary data for indications of systematic variations of the actual solar wind sources from the EQRH estimates. We find that at the edges of high velocity solar wind streams there is a variation in both altitude and longitude of the sources of plasma of different velocities, with higher velocity plasma originating from lower altitudes.

2. EQRH-Approximation Solar Wind 'Dwells'

Near 1 AU, a high-speed solar wind stream is typified by a rapid increase in velocity, followed by a slow decrease. During the decrease in velocity, the EQRH-approximation source longitude of interplanetary plasma often remains nearly constant for a period of one to three days. These velocity structures, identified with sources of solar wind, have been called solar wind 'dwells' (Roelof and Krimigis, 1973; Gold *et al.*, 1974), since the approximate high coronal source location dwells at one longitude instead of moving across the solar surface at the normal solar rotation rate.

Solar wind streams, such as the example shown in Figure 1, often recur on several successive rotations, with only minimal differences in their amplitudes or structures. This implies that temporal variations in the source over a period of a few days are not significant. Additionally, due to the differences in transit time from the Sun to 1 AU, all the solar wind plasma observed during a dwell was emitted from the Sun at nearly the same time. Therefore, dwells in these streams are representative of the spatial structure

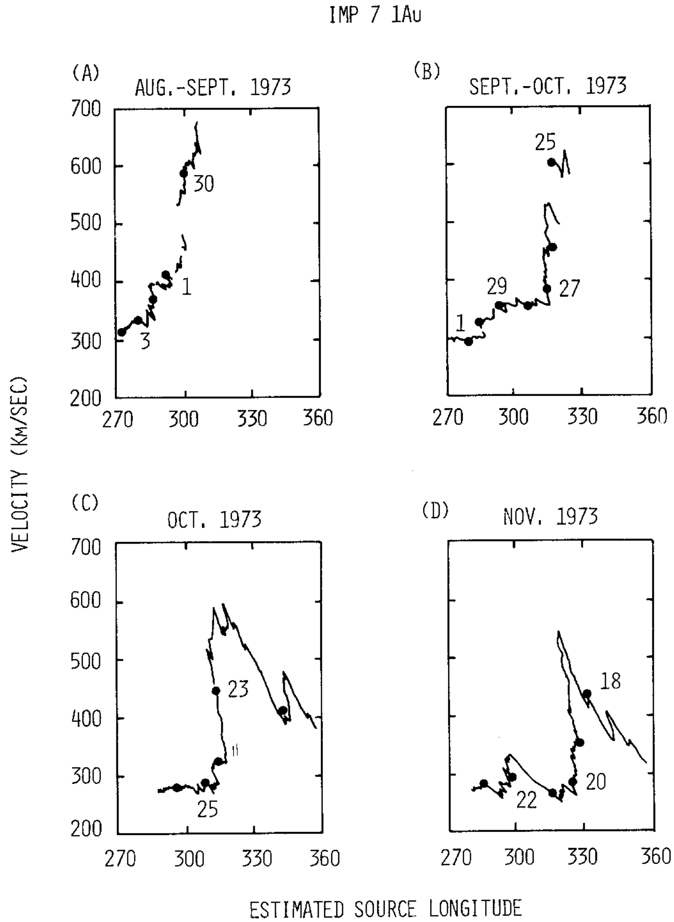

Fig. 1. Hourly averages of solar wind velocity plotted against estimated source longitude for a high-speed stream on four consecutive rotations. The first point of each day is indicated by a heavy dot, and alternate days are labeled. Note the near-vertical drop, or 'dwell' in source longitude, for two or three days at the eastern edge of each stream.

of the solar wind stream, rather than a temporal variation of the source. Here we shall use the interplanetary measurements of solar wind parameters to deduce some aspects of the longitudinal structure of the source of a stream of this type.

In Figure 1 we show four successive rotations of one of the high-speed streams seen by the MIT experiment on IMP 7 during the Skylab mission in 1973 (Nolte *et al.*, 1976). This recurrent high-speed stream was not associated with an equatorial coronal hole. However, it was selected as our principal example for this paper because this is the longest recurrence of a dwell which was well-observed on each rotation during that period. Hourly averages of the solar wind velocities measured by IMP 7 near Earth are plotted against the source longitudes estimated using the EQRH-approximation. In this figure, the first hourly average of each day is a heavy dot. Alternate days are identified by day of month. It is not clear whether IMP 7 observed the peak velocity in the stream in late August and September (Figures 1A and 1B), because the spacecraft was coming out of the magnetosphere. The basic structure of dwells is shown, however. There is some evolution in the shape of the dwell between late August and late September, with the estimated source longitude remaining more nearly constant in September. Also, during the four rotations, the estimated source location of the dwell drifts westward in Carrington longitude. On the last two rotations, when the peak velocity was definitely seen, the velocity decreases by a factor of 2, while the estimated source longitude remains constant, or even shifts slightly to the west during the dwell.

For comparison, in Figure 2 we show all four dwells in streams associated with equatorial coronal holes for which Nolte *et al.* (1976) had reasonably complete data. In their notation, Figures 2A and 2B are the stream from coronal hole 1 on the first two rotations of the Skylab mission, and Figures 2C and 2D are the stream from coronal hole 4 on two successive rotations near the end of the period. These dwells are similar, but less sharp than those of Figure 1, extending for $\sim 15°$ in heliocentric longitude. On the basis of this very limited sample, it appears that there may be a difference between the high coronal source profiles for the two kinds of recurrent high-speed streams.

These figures imply that either there are large longitudinal gradients in the high corona in the solar wind parameters which affect the velocity at 1 AU, or there are systematic, velocity-dependent effects in the EQRH estimates. Since such large gradients have significant implications for both interplanetary and coronal studies of solar wind propagation and origin, we investigate the possibility of systematic effects.

Processes such as magnetic channeling which occur primarily below the source altitude obviously affect the estimation of high coronal source locations from interplanetary solar wind data only to the extent to which the interplanetary flow is affected. Therefore the systematic effects could be either a variation in the angular momentum at the source, or variation in the amount of interplanetary acceleration or deflection of the solar wind. Since most of the channeling by the magnetic fields is likely to occur close to the Sun, at altitudes below $\sim 3\ R_{\odot}$ (Jackson, 1976), differences in angular momentum would be due to a variation in source altitude. We investigate the source latitude effect in the next section, but now show that interplanetary deflection is not likely to have a significant systematic effect on the estimates of source longitudes.

Interplanetary effects in the trailing edges of high-speed streams between 1 and 5 AU have been discussed by Lazarus (1975). He finds some streams with substantially non-radial flow in even the trailing edge. These streams apparently interact strongly with the surrounding solar wind. Such interactions can explain the apparent shift of the source longitude back to the west as seen in Figures 1C and 1D. He also finds some streams (the one we show in Figure 1A in particular) where there is little interplanetary effect between 1 and 4.6 AU. Therefore, in such streams any systematic effects (such as pressure gradients) which might affect the shape of the dwell must be most effective near the Sun, since they are not effective beyond 1 AU.

In order to demonstrate the magnitude of these possible effects, we approximate the effects of a pressure gradient as simply an increase in the azimuthal velocity of the slow

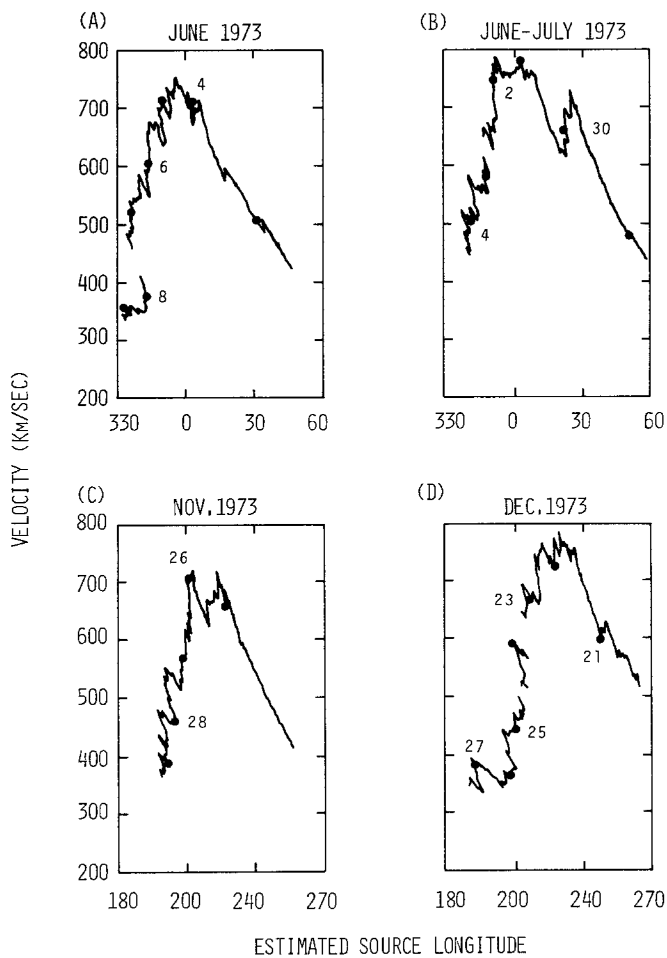

Fig. 2. Same as Figure 1, but for the solar wind streams associated with coronal holes.

solar wind at the source altitude, and assume that the plasma angular momentum (due to this increase) is conserved. As a numerical example, an increase of 10 km s^{-1} in azimuthal velocity at a source altitude of 0.1 AU ($\sim$20 $R_\odot$) results in a total extra interplanetary rotation of only 1.5° for 350 km s^{-1} solar wind. This is a fairly large perturbation, since 10 km s^{-1} is approximately one-quarter of the corotation velocity at that altitude, and is also almost three times larger than the largest azimuthal velocity which Weber and Davis (1967) calculated (occurring in their model at $\sim$13 $R_\odot$). For higher source altitudes, the effect is slightly reduced.

Based on this estimate, and on the results of Lazarus (1975), we tentatively conclude that systematic interplanetary effects during at least some dwells are less than 2°. Of course, the final test of this conclusion must come from a comparison of measurements of the same stream close to the Sun and at 1 AU.

3. Effect of Source Altitude Variation

Since interplanetary acceleration and deflection are apparently not substantial (in at least some dwells), there must be a source effect such that many velocities appear to originate from a single longitude. We demonstrate such an effect schematically in Figure 3. Figure 3A shows the EQRH-approximation streamlines for a hypothetical dwell following a high-speed stream. The streamlines are drawn on a plot of radius (r) vs longitude (ϕ) in rectangular coordinates. Therefore, the ideal spirals are straight lines. Because the source longitude does not change as the velocity changes, the dwell resembles a point source from which solar wind emanates at a variety of speeds. Figure 3B shows these EQRH streamlines together with a drawing of 'more realistic' streamlines which include corotation near the Sun, a smooth transition and interplanetary acceleration. Here we have assumed the same source altitude r_0 for all streamlines. Using the same interplanetary streamlines as in Figure 3B, we show the effect of reducing the source altitude with increasing velocity in Figure 3C. The effect shifts the 'actual' sources of faster solar wind to the west relative to slow solar wind sources. This appears to be a reasonable possibility, and we investigate the magnitude of the angular shift induced by a velocity-dependent source altitude in this section.

This investigation requires an estimate of the variation of the source altitude with velocity. As discussed above, we assume that the source altitude is near the Alfvénic critical point. We therefore estimate the variation of the Alfvén point implied by the variation of solar wind parameters measured at 1 AU during dwells.

We begin this analysis from the equations for conservation of magnetic flux and density. Since the interplanetary solar wind is divergent in dwells, we must use the forms of these equations appropriate for divergent flow:

$$B_r(r)r^s = B_0 r_0^s, \tag{1}$$

$$n(r)V(r)r^s = n_0 V_0 r_0^s, \tag{2}$$

where s is greater than 2; r_0 is a reference level (e.g., 1 AU); and B_0, n_0 and V_0 are the

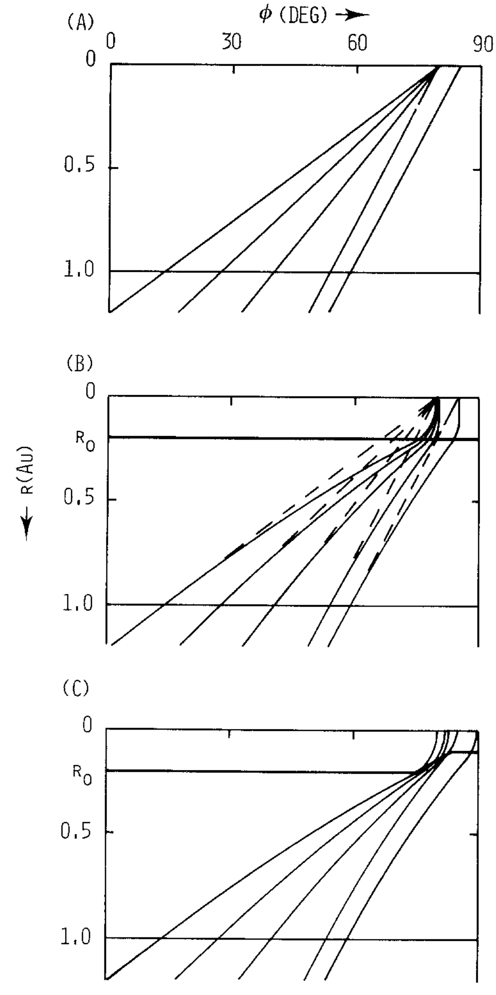

Fig. 3. The effect of variation of source altitude. (A) The EQRH-approximation streamlines on an r-ϕ plot (ideal spirals are straight lines). In the trailing (eastern) edge of the stream, all the plasma appears to be coming from a single longitude. (B) 'More realistic' streamlines (light solid lines) showing effects of corotation and interplanetary acceleration, assuming a constant source altitude. The EQRH-approximation streamlines from 3A are shown as the dashed lines. (C) 'More realistic' streamlines drawn with a varying source altitude. Sources of high velocity plasma are lower, and further west than the EQRH estimates.

values of B_r, n and V at r_0. The Alfvén critical point condition (equal Alfvén and flow speeds) may be rewritten as

$$B_r^2(r_A) = 4\pi mn(r_A)V^2(r_A), \tag{3}$$

where r_A is the Alfvénic critical radius. Using (1) and (2) to express this in terms of the reference level parameters results in

$$\left(\frac{r_A}{r_0}\right)^s = \frac{B_0^2}{4\pi mn_0 V_0 V(r_A)}. \tag{4}$$

In this form the Alfvén points could be evaluated if the velocity of the solar wind as a function of radius were available. However, since the velocity model cannot be verified experimentally, and since the Alfvén point need not be exactly the source altitude, it is more appropriate to calculate the ratio of the Alfvén radii. This ratio is not strongly dependent on the velocity model, and is also a reasonable estimate for the variation of the source. We shall assume $V(r) \sim r^q$, where Burlaga (1967) used $q = \frac{1}{4}$ as a fit to Parker's (1963) curves. Then the ratio of the Alfvén altitudes for two different parts of the dwell may be expressed as:

$$\left(\frac{r'_A}{r_A}\right)^{s+q} = \frac{B_0'^2 n_0 V_0^2}{B_0^2 n'_0 V_0'^2}. \tag{5}$$

To estimate the variation in density n, we use some of the results of Diodato *et al.* (1974) and Formisano *et al.* (1974), who studied average properties of the solar wind. Although these results are long-term averages, at speeds above the ambient solar wind speed they are heavily weighted in favor of the dwells, due to the form of solar wind streams (fast rise, long dwell). The various results shown in these two papers can be expressed as $n \sim V^{-j}$, with $1 < j < 1.5$. This provides a reasonable range to use in Equation (5).

We use the interplanetary magnetic field strength measured by Heos 1 and 2 during the four dwells shown in Figure 1 to estimate the effect due to variation of the magnetic field (kindly supplied by the National Space Science Data Center at GSFC). The field strength plotted against time during these dwells is shown in Figure 4. We have plotted the magnitude of the field as positive if the garden hose component of the field was directed away from the Sun, and negative if toward.

This figure demonstrates that a reasonable estimate is that field strength is constant during dwells. There is no significant general trend evident in these plots. Another interesting point is evident in Figure 4C. There is a change in interplanetary magnetic polarity (i.e., a sector boundary) during this dwell, which implies that the dwell must have some measurable extent in longitude.

In order to estimate the divergences we consider the cross-sectional area ΔA of a small flux tube as a function of radius. In the ecliptic plane ($\theta \cong 90°$), at r_A,

$$\Delta A(r_A) = K r_A^s = \Delta\theta_A \Delta\phi_A r_A^2, \tag{6}$$

where $\Delta\theta_A$ and $\Delta\phi_A$ are the heliocentric angles subtended by the area ΔA at r_A. Similarly, at r_0,

$$\Delta A(r_0) = K r_0^s = \Delta\theta_0 \Delta\phi_0 r_0^2. \tag{7}$$

Since the divergence at a rate greater than r^{-2} (due to velocity differences) is in ϕ, we write $\Delta\theta_0 = \Delta\theta_A$, and $\Delta\phi_0 = C\Delta\phi_A$, where C is a constant giving the aximuthal divergence from r_A to r_0. Then

$$K r_0^s = C\Delta\theta_A \Delta\phi_A r_0^2 = CK r_A^{s-2} r_0^2, \tag{8}$$

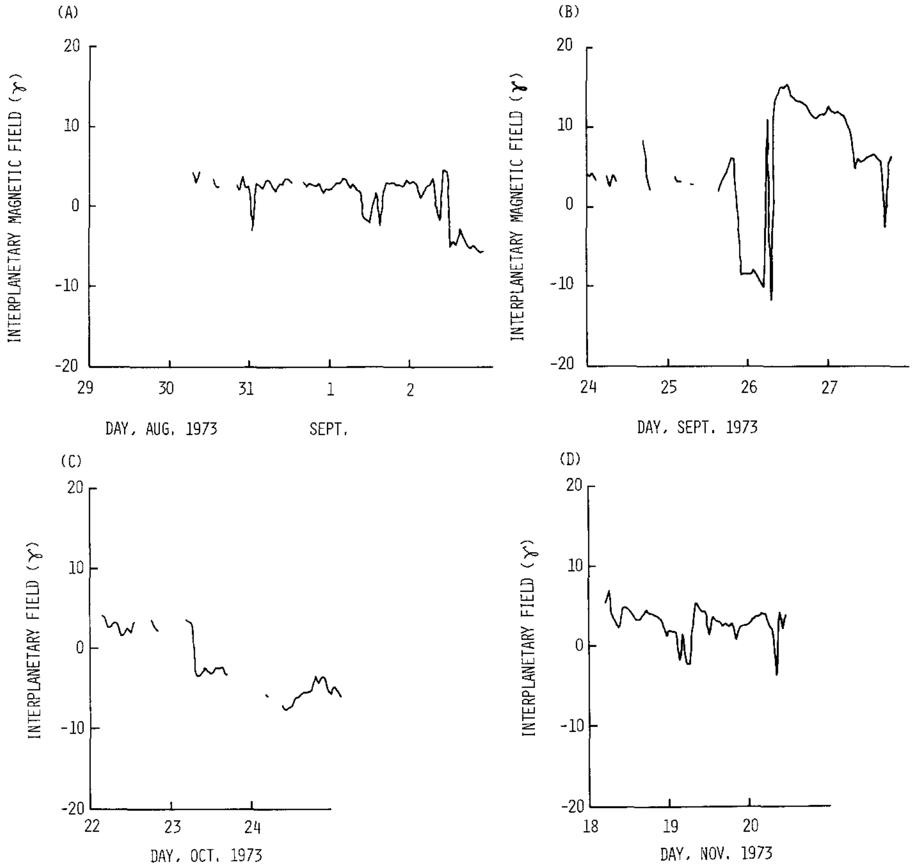

Fig. 4. Interplanetary magnetic field strength in the four dwells of Figure 1. There is no consistent systematic variation. Note the change in polarity on 23 October in Figure 4C.

so that

$$s = 2 + \frac{\ln C}{\ln\left(\dfrac{r_0}{r_A}\right)}. \tag{9}$$

We estimate s using the following assumptions, noting also that s is not strongly dependent on the values of the parameters. The reference level r_0 is at 1 AU, and we use the Weber and Davis (1967) estimates for the critical radii of 15–50 $R_\odot$. We also note that the interplanetary magnetic field strength in dwells is not drastically lower than normal. Thus the actual longitudinal extent at r_A is at least a few degrees, while the extent at 1 AU is $\sim 30°$. Thus C should be within the range 5–15. These constraints imply that $2.5 < s < 4$.

Putting these results into Equation (5), we find

$$\frac{r'_A}{r_A} = \left(\frac{V_0}{V'_0}\right)^k \tag{10}$$

with $0.1 < k < 0.4$. If $V_0 \cong 2V'_0$, as in the dwells in Figure 1,

$$1.07 < \frac{r'_A}{r_A} < 1.32. \tag{11}$$

Therefore, we conclude that the altitude of the Alfvén point, and also of the source altitude, increases by 7–32% as the velocity falls in the trailing edge of a solar wind stream. This implies that the high speed plasma carries less angular momentum away from the Sun than the slower plasma does, assuming that total angular momentum is determined by the Alfvén altitude.

4. High Coronal Structure of Solar Wind Stream Sources

The final step in our derivation of the shape in radius and longitude of the high coronal structure of stationary high-speed solar wind stream sources is the determination of the longitudinal extent of the dwell sources. For a dwell with no change in longitude in the EQRH-approximation, this is the variation in the estimated source locations due to the variation in altitude of r_A, and also includes the interplanetary effects ($\lesssim 2°$) discussed in Section 2.

We start from Equation (5) from Nolte and Roelof (1973), which gives the longitude ϕ of the source location relative to the observer at 1 AU, rewritten in the notation of the present paper as

$$\phi = \left[1 - \left(\frac{r_A}{r_0}\right)^{3/4}\right] \frac{4 r_0 \Omega}{3 V_0}, \tag{12}$$

where Ω is the sidereal rotation rate of the Sun. The variation $\Delta\phi$ due to corotation effects (assuming the same interplanetary acceleration model) introduced by using the same source altitude $\tilde{r}_A$ for the entire dwell instead of the correct r_A for a particular point is

$$\Delta\phi = \phi - \tilde{\phi} = \left[\left(\frac{\tilde{r}_A}{r_0}\right)^{3/4} - \left(\frac{r_A}{r_0}\right)^{3/4}\right] \frac{4 r_0 \Omega}{3 V_0} =$$
$$= (1 - \alpha^{3/4}) \left(\frac{\tilde{r}_A}{r_0}\right)^{3/4} \frac{4 r_0 \Omega}{3 V_0}, \tag{13}$$

where $\alpha = r_A/\tilde{r}_A$. Putting in $V_0 = 600$ km s^{-1}, if $\tilde{r}_A = 0.1$ AU, the shift of the source of the slowest solar wind relative to that of the fastest is $\Delta\phi_{max} = 1.9°$: if $\tilde{r}_A = 0.25$ AU, $\Delta\phi_{max} = 3.7°$.

The principal result is quite clear: the eastern edge of a high-speed stream can be very narrow in the high corona, often only a few heliocentric degrees. The approximate total systematic effect is less than 6°, ~2° due to interplanetary effects, $\lesssim 4°$ due to source altitude variation.

It is interesting to compare the radial and azimuthal variations of the source altitude.

For a slow stream source altitude of 0.1 AU, the maximum longitudinal variation of 1.9° is $\sim 5 \times 10^5$ km, for a change in altitude of 3.6×10^6 km. If the source altitude is 0.25 AU, the longitudinal variation of 3.7° corresponds to 2.3×10^6 km, and implies a decrease of 9.1×10^6 km in altitude of the high-speed source. The variation in altitude is $\sim$4–7 times the variation in longitude.

These variations actually provide us with the approximate shape of the source region of vertical dwells. As we noted above, it is possible that these dwells are more typical of recurrent streams not associated with an equatorial coronal hole. A schematic drawing of the source of a stream of this kind is shown in Figure 5A. The 'source altitude' is marked by a heavy line, with schematic solar wind streamlines as light lines. The western edge of the stream is drawn with the same shape as the eastern edge, and the high-speed stream is drawn arbitrarily as 20° wide.

On the basis of a limited data sample, dwells in streams not associated with equatorial coronal holes appear to be sharper than those in streams from equatorial holes. This must be considered when sources of these recurrent high-speed streams are suggested. For example, these streams may originate from extensions of the polar holes toward the equator (Nolte *et al.*, 1976). Then a detailed model of solar wind streams from coronal holes must explain why there is a sharper boundary of the stream observed when the spacecraft measuring the solar wind does not pass directly over the hole.

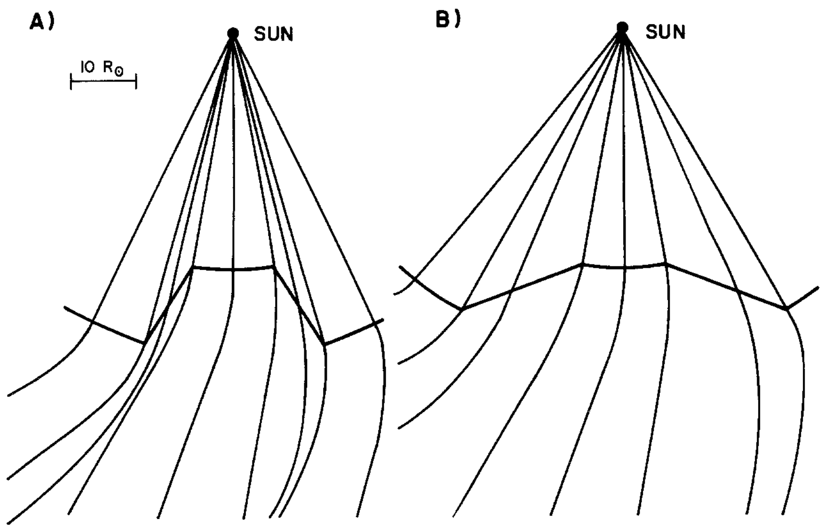

Fig. 5. A schematic drawing of the magnetic field near the source altitude. The varying source altitude is indicated as a heavy line, with nearly radial fields inside, and the beginning of the spiral field pattern outside for (A) a fairly sharp longitudinal gradient, and (B) a somewhat more gradual change. Note that the Sun is drawn approximately to scale. See text for estimates of size of the structures. It seems possible that (B) is appropriate for high-speed streams which come from equatorial coronal holes, while (A) shows the structure of other high-speed streams.

If this apparent difference is real, then the source of a stream from an equatorial coronal hole would appear as shown schematically in Figure 5B. The only difference between this and Figure 5A is a smaller gradient in longitude: the boundary of the stream is not as steep. The gradient is still quite large, however. There is an observed velocity difference of $\sim 350 \text{ km s}^{-1}$ for a source longitude variation of $\sim 20°$. This gradient suggests an obvious explanation for at least part of the large latitudinal gradients such as have been inferred by Hundhausen *et al.* (1971) and Smith and Rhodes (1975), and observed by Coles *et al.* (1974). Whenever coronal holes extend from the poles to near, but not across, the solar equator, the ecliptic plane would be in the region of large gradients at the edge of the hole.

5. Conclusions

With this brief analysis we have demonstrated that the transition from a high-speed stream source to the ambient coronal conditions is quite rapid in longitude in the high corona. This sharp edge of the sources of quasi-stationary high-velocity solar wind streams is strongly suggested by the solar wind 'dwells' which appear in plots of solar wind velocity vs EQRH-approximation source longitudes.

We have investigated the possibility of a systematic velocity-dependent effect in the EQRH-approximation which would cause this boundary to appear sharper than it actually is. There are two possible sources of such a systematic effect. There could be a velocity-dependent interplanetary propagation effect, or the 'source altitude' could depend on velocity.

We have found that, for at least some dwells, it is not likely that there are significant interplanetary effects.

We have calculated the variation of the Alfvénic critical radius in solar wind dwells and found that the high velocity stream originates from a significantly lower altitude than the ambient solar wind. This variation was used to estimate the shape of the high coronal source of the solar wind stream. We note that this source of solar wind is the *physical* source; that is, the boundary between the high corona and the interplanetary medium.

The magnitude of the longitudinal effect due to source altitude variation is only $\sim 4°$ in heliocentric longitude. We therefore conclude that there is a sharp longitudinal transition in the high corona between the high-speed stream source and the 'ambient' solar wind source at the eastern edge of the high-speed stream. Since there is no reason to believe that the western, unobservable edge is significantly different in the corona (i.e., the stream is symmetric), this implies that quasi-stationary high-speed streams are well-defined structures, with relatively sharp boundaries in the high corona.

It seems quite likely that the sharp eastern edge of the high-speed stream sources is caused by magnetic channeling in the corona. If this is so, high-speed streams must be well-defined structures all the way down to their ultimate sources in the very low corona.

Acknowledgements

It is a pleasure to acknowledge Mr William Valente and the staff of the National Space Science Data Center for their prompt and courteous handling of our request for interplanetary magnetic field data. In carrying out this research, the authors have benefited from their participation in the Skylab Solar Workshop Series on Coronal Holes. The Workshops are sponsored by NASA and NSF and managed by the High Altitude Observatory. This work was supported at AS&E by NASA under contract NAS8-27 758 and at JHU/APL by NASA and by Air Force Geophysics Laboratory under Task I of Navy contract N00017-72-C-4401.

References

Burlaga, L. F.: 1967, *J. Geophys. Res.* **72**, 4449.
Coles, W. A., Rickett, B. J., and Rumsey, V. H.: 1974, in C. T. Russell (ed.), *Solar Wind Three*, p. 351.
Diodato, L., Moreno, G., Signorini, C., and Ogilvie, K. W.: 1974, *J. Geophys. Res.* **79**, 5095.
Fainberg, J. and Stone, R. G.: 1974, *Space Sci. Rev.* **16**, 145.
Formisano, V., Moreno, G., and Amata, E.: 1974, *J. Geophys. Res.* **79**, 5109.
Gold, R. E., Nolte, J. T., Roelof, E. C., and Reinhard, R.: 1974, *Space Research* **XIV**, 477.
Hundhausen, A. J., Bame, S. J., and Montgomery, M. D.: 1971, *J. Geophys. Res.* **76**, 5145.
Jackson, B. V.: 1976, *Bull. Am. Astron. Soc.* **8**, 325.
Krieger, A. S., Timothy, A. F., and Roelof, E. C.: 1973, *Solar Phys.* **29**, 505.
Krieger, A. S., Timothy, A. F., Vaiana, G. S., Lazarus, A. J., and Sullivan, J. D.: 1974, in C. T. Russell (ed.), *Solar Wind Three*, p. 132.
Lazarus, A. J.: 1975, invited review, *EOS* **56**, 438.
Neupert, W. M. and Pizzo, V.: 1974, *J. Geophys. Res.* **79**, 3701.
Nolte, J. T. and Roelof, E. C.: 1973, *Solar Phys.* **33**, 241.
Nolte, J. T., Krieger, A. S., Timothy, A. F., Gold, R. E., Roelof, E. C., Vaiana, G., Lazarus, A. J., Sullivan, J. D., and McIntosh, P. S.: 1976, *Solar Phys.* **46**, 303.
Parker, E. N.: 1963, *Interplanetary Dynamical Processes*, Interscience, New York.
Roelof, E. C. and Krimigis, S. M.: 1973, *J. Geophys. Res.* **78**, 5375.
Smith, E. J. and Rhodes, E. J.: 1975, *J. Geophys. Res.* **80**, 917.
Snyder, C. W. and Neugebauer, M.: 1966, in R. J. Mackin and M. Neugebauer (eds.), *The Solar Wind*, Pergamon Press, N.Y., p. 25.
Weber, E. J. and Davis, L., Jr.: 1967, *Astrophys. J.* **148**, 217.