TEMPORAL EVOLUTION OF VELOCITY STRUCTURES IN THE SOLAR WIND

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ABSTRACT Generally poor correlations have been obtained of solar wind flow speed measurements at one point in the ecliptic plane with measurements at the same point 28 days (one solar rotation) earlier or with measurements at other points in the ecliptic plane separated by 50° or more in solar longitude. This is evidence that either the flow speed is a very sensitive function of solar latitude or that temporal processes *typically* alter the speed of the wind emanating from particular solar regions on a time scale of about 4 days. From a measure of the persistence of the flow speed at the orbit of the earth, it appears that the temporal explanation is more likely to be the correct one.

The daily variation of the solar wind speed at the orbit of the earth is one of the wind's most interesting observational features. For some time now we have been endeavoring to determine the relative importance of solar rotation and true temporal evolution in producing these variations. The present paper reports on the current status of these investigations.

Recently an extensive autocorrelation analysis of the Vela 2 and 3 solar wind speed data for July 1964 through December 1967 was completed [*Gosling and Bame,* 1972]. One result of that study is shown in figure 1. The upper autocorrelation curve was obtained using daily averages of the data, while the lower curve was obtained from 3-hr averages. The 95 percent confidence limits are derived from the number of *independent* data points used in the calculation of the correlation. For an uncorrelated set of data, 95 percent of the calculated correlation values would fall within $\pm 1.96\,n^{-1/2}$ of zero, n being the number of independent data points available [*Brooks and Carruthers,* 1953]. Despite the differences in the averaging intervals, the two autocorrelation curves are remarkably similar. Both curves exhibit a statistically significant peak near a lag of 28 days, while the daily-average curve exhibits a second small, but significant, peak near the 55-day lag. Although statistically significant, the correlations near 28- and 55-day lags are small, about 0.30 and 0.15, respectively. If we associate these correlations with the solar rotation, we see that there is only a slight tendency for particular speeds measured during one solar rotation to recur 28 days (one solar rotation) later.

The degree of correlation at 28 days is, perhaps, better appreciated by a study of figure 2, which is a scatter plot of $V(t_0 + L)$ versus $V(t_0)$ with L equal to 28 days. Were the solar wind speed pattern stationary in time and the same for latitudes ±7° from the solar equator, then all points in figure 2 would lie along the 45° line drawn. The best fit line V_c (in the least-squares sense) amply demonstrates that the recurrence tendency is slight. Indeed, the slope of V_c is a direct measure of the correlation involved.

We should qualify the above comments in two respects. First, there is no *a priori* reason to expect that the solar wind observed near the earth emanates from any particular point on the sun, such as the center of the visible solar disk. If all solar latitudes are allowed, then differential rotation of the sun ensures that a variety of periods from about 27 to 31 days will be present in the data, perhaps at the same time. In fact, when one breaks

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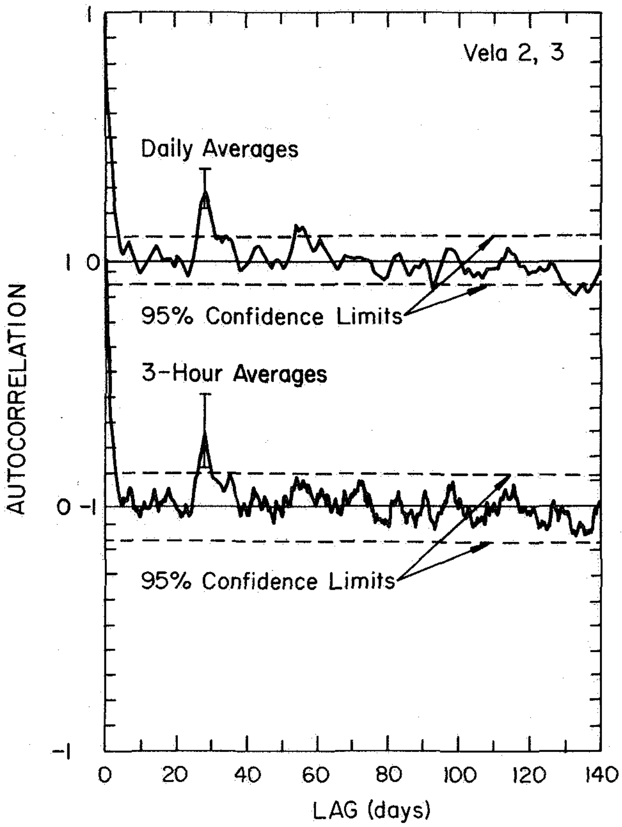

Figure 1. *Autocorrelation of the solar wind flow speed for the interval July 1964-December 1967 using daily averages (upper curve) and 3-hr averages (lower curve) [from Gosling and Bame, 1972].*

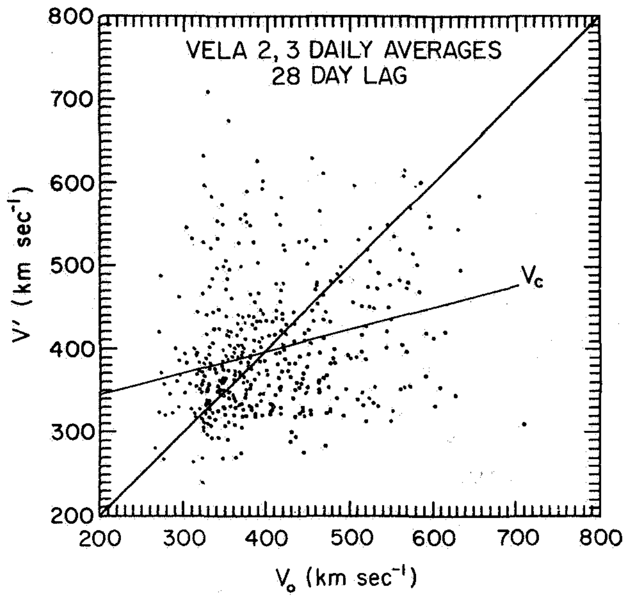

Figure 2. *Scatter plot of 3½ years of daily average solar wind speeds measured 28 days apart [from Gosling and Bame, 1972].*

the 3½ years of Vela 2 and 3 data into smaller time series, one notes that a variety of recurrence periods seem to be present [*Gosling and Bame,* 1972]. Such an effect serves to diminish the amplitude of the correlation at any particular lag. Second, analysis of the data taken 6 months at a time reveals that the recurrence tendency waxes and wanes. For some 6-month intervals the peak correlation near 28 days exceeds 0.5; for others, the peak correlation near 28 days is less than 0.1. The average peak correlation near 28 days for the 6-month analysis is 0.37; this value slightly exceeds the 0.30 value derived from treating all the data at once (fig. 1) because the peak correlations occur at a variety of lags near 28 days. Despite the above qualifications, it is nevertheless true for the Vela 2 and 3 data that most speed structures observed on one solar rotation do not reappear on subsequent rotations.

One possible interpretation of this result is that solar wind speed structures are highly constricted in solar latitude, with different latitude structures being sampled as the earth in its orbit oscillates ±7° from the solar equator. A more likely interpretation is that most speed structures evolve on a time scale that is short compared to 28 days.

To examine this question further, it is necessary to analyze data taken over an extended period of time by observers stationed at different points along the earth's orbit. The Pioneer 6 and 7 satellites, which were launched into nearly circular orbits about the sun, and the Vela 3, 4, and 5 satellites, which were launched into large, nearly circular orbits about the earth, provide an opportunity for such a study. Figure 3 shows the position of the Pioneer satellites relative to the sun and earth in 1969-1970, the period we shall consider. Sample measurements of the solar wind speed by these satellites were reported routinely in the *Solar Geophysical Reports,* the quantity varying from day to day and from spacecraft to spacecraft. This body of data was combined into a set of daily averages for each spacecraft as described in *Gosling,* [1971*a*]. Although the speed values quoted in the *Solar Geophysical Reports* are usually mere "snapshots" of the solar wind speed, they are usually representative for a given day as has been discussed by Wolfe and Intriligator (p. 198). This is a consequence both of the speed values quoted being selectively chosen and the very high persistence of the solar wind throughout a day [*Gosling and Bame,* 1972]. Figure 4 shows histograms displaying the frequency with

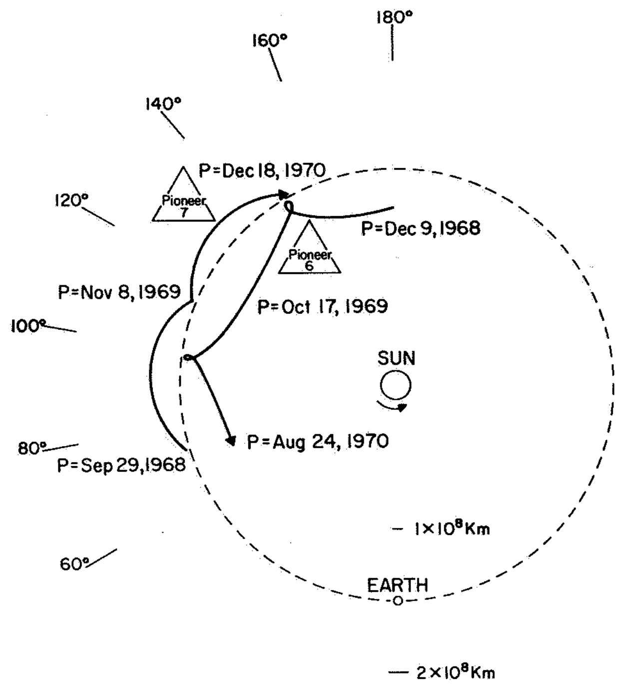

Figure 3. *Relative positions of Pioneer 6 and 7 to the earth and sun in the ecliptic plane [from Gosling, 1971a].*

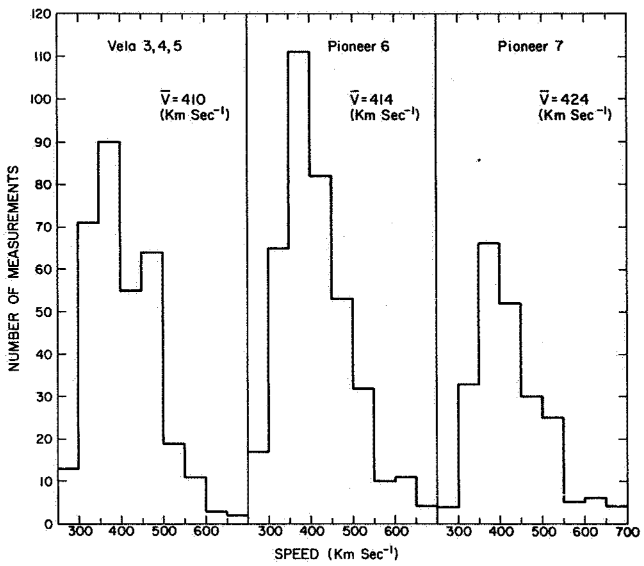

Figure 4. *Histograms of the daily average solar wind speeds measured by Pioneer 6 and 7 and Vela 3, 4, 5 during 1969-1970. Note the similarities of the histograms including the near equivalence of average ($\bar{V}$) and most probable speeds [from Gosling, 1971a].*

which different solar wind speeds were measured by the different satellites under consideration. Note that the distributions are quite similar despite wide separations of the satellites along the earth's orbit. From this we can conclude that differences in the calibration of the various instruments aboard the different satellites are small and any lack of correlation between satellites is real rather than instrumental.

If one can assume that the solar wind is emitted uniformly at all pertinent latitudes, that the emission is steady in time, and that the solar plasma moves radially with a constant convective speed near 1 AU, then it should be possible to predict the arrival of solar wind speeds at one satellite on the basis of earlier measurements at another. Comparison of the data will provide a test of the validity of the assumptions. Figures 5 and 6 are scatter plots of the Pioneer 6 and 7 daily measurements against the Vela daily measurements. In constructing these plots the Pioneer data were shifted in time for the expected earth-arrival based on a synodic rotation rate of 27 days; in that sense, the measurements are "simultaneous." Shifts of from 6 to 12 days are involved in these plots. Were there good agreement between the Pioneer predictions and the Vela measurements near the earth, then the points in these plots would cluster close to the 45° line drawn. This does not appear to be the case. In fact, when one calculates the correlation

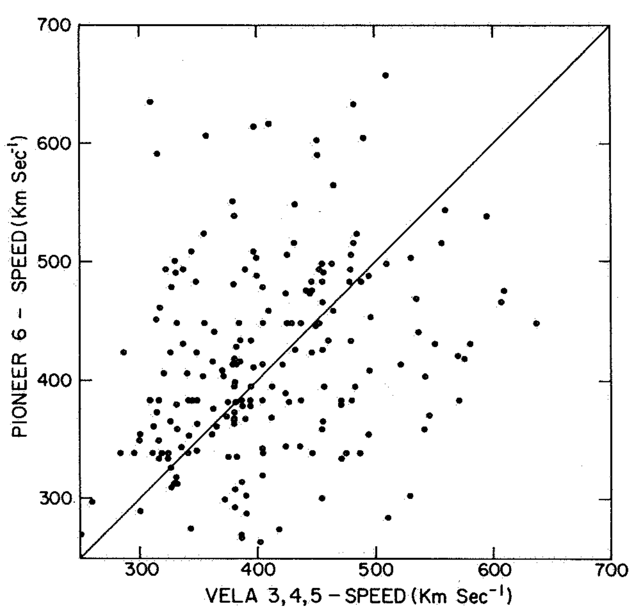

Figure 5. *Scatter plot of Pioneer 6 and Vela 3, 4, 5 solar wind speed data. The data from the two satellites are simultaneous in the sense discussed in the text. Temporal shifts of 6 to 13 days are involved [from Gosling, 1971a].*

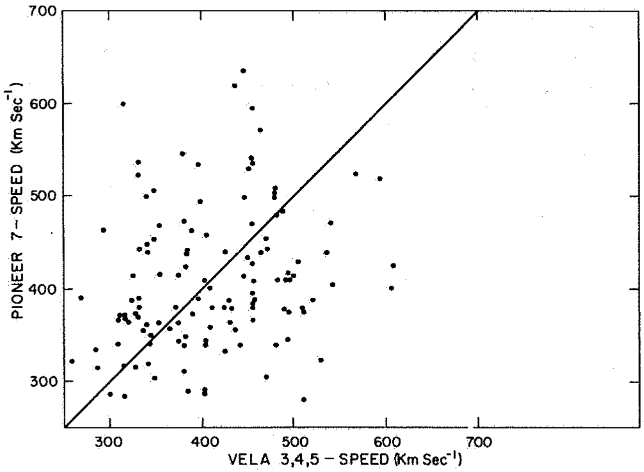

Figure 6. *Scatter plot of Pioneer 7 and Vela 3, 4, 5 solar wind speed data. The data from the two satellites are simultaneous in the sense discussed in the text. Temporal shifts of 6 to 13 days are involved [from Gosling, 1971a].*

coefficients for these plots one finds correlations of 0.37 and 0.29, respectively, for the Pioneer 6 and 7 plots, indicating that this is not a very good way to make predictions of the solar wind speed at the orbit of the earth [*Gosling,* 1971*b*].

Using the Pioneer satellites it is possible to show that the degree of correlation between satellites depends on the separation of the satellites. We note that the Pioneer satellites were moving in opposite directions relative to the earth and passed one another in December, 1969. Figure 7 is a scatter plot of the Pioneer 7 data against the Pioneer 6 data for spatial separations of 2 days or less (in the corotation sense). As before, the data have

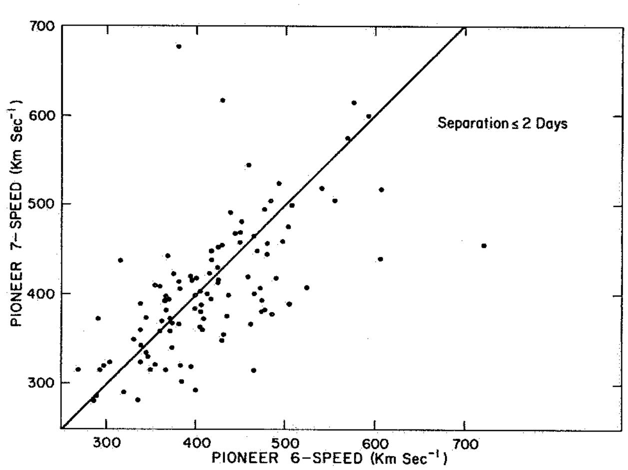

Figure 7. *Scatter plot of Pioneer 6 and 7 solar wind speed data for satellite separations of less than 2 days in the corotation sense [from Gosling, 1971a].*

been shifted in time and are "simultaneous" in the corotation sense. It is evident that here the two sets of data are more closely, although imperfectly, correlated (the correlation coefficient is 0.66). Figure 8 is a corresponding plot of the Pioneer 6 and 7 data for spatial separations greater than 4 days. We see that this plot resembles the Pioneer-Vela plots, although the available number of data points is considerably reduced. The calculated correlation coefficient is 0.28.

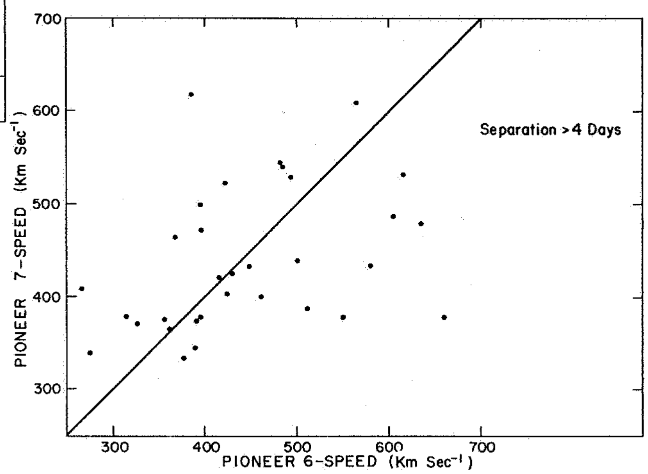

Figure 8. *Scatter plot of Pioneer 6 and 7 solar wind speed data for satellite separations of 4 days or greater in the corotation sense [from Gosling, 1971a].*

We can summarize the above results as follows: the assumption of a steady state, constant velocity solar wind, emitted uniformly over several degrees of solar latitude, flowing nearly radially near 1 AU and corotating with the sun is seldom sufficient for correlation of measurements between observers separated by more than 4 days in the corotation sense; for lesser separations, the correlation improves under these assumptions although remaining imperfect even for separations of 2 days or less. The weakest parts of our assumptions are those of steady state and uniformity with solar latitude. Thus, we can conclude that either temporal evolution processes typically alter the speed of the wind emanating from particular solar regions on a time scale of approximately 4 days and/or the solar wind expansion is a very sensitive function of solar latitude [*Gosling,* 1971*a*].

We have already noted that the solar wind speed is quite persistent at the orbit of the earth. Stated another way, closely spaced measurements (in time) are seldom independent of one another. An autocorrelation analysis at short lag times provides a method of establishing the typical time interval over which measurements of the speed demonstrate persistence. Figure 9 displays the autocorrelation of the Vela 2 and 3 speed data near zero

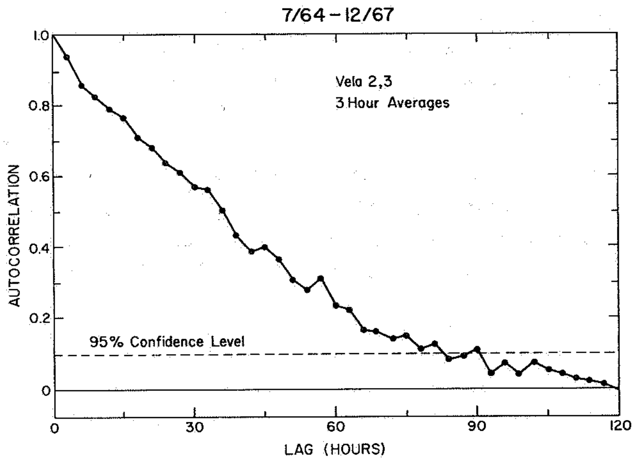

Figure 9. *Autocorrelation of Vela 2 and 3 3-hr average solar wind speed data near zero lag. Significant correlations extend out to a lag of about 75 hr [from Gosling and Bame, 1972].*

lag using 3-hr averages. A statistically significant persistence is observed out to a lag of 75 hr. Thus, on the average, measurements separated by 3 days or more are independent of one another, while those separated by less than 3 days are not. Either temporal evolution of the outer solar atmosphere or solar rotation and a finite spatial scale size of speed structures can be dominant in limiting persistence at the earth. If persistence is limited by solar rotation effects, then emission from the sun must typically be coherent over about 40° (13.3°/day×3 days) in longitude. (The actual scale size back at the sun may be smaller or larger than this depending upon the degree and manner in which the flow departs from the radial.) It seems reasonable to assume that the emission should be coherent over a similar extent in latitude; if so, solar latitiude effects are insufficient to explain the results of the Pioneer-Vela study. It is well to note, however, that latitude and longitude effects in the solar wind are fundamentally different owing to solar rotation and the attendant interaction of high and low speed longitudinal structures [*Siscoe et al.*, 1969; *Hundhausen*, 1971]. If we can neglect such effects, we can conclude that it appears that true temporal processes generally dominate the solar wind speed variations on a time scale of 4 days or greater, with rotational effects becoming increasingly more important at shorter intervals. Stated another way, for an observer rotating with the sun the solar wind speed *typically* would be "steady" for approximately 2 or 3 days; after about 4 days an entirely new velocity regime would be established. We emphasize that the above represents only a typical situation; as noted earlier, certain velocity structures do endure at the earth for longer than 28 days.

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DISCUSSION *E. C. Roelof* In the proceedings of the Budapest conference on Cosmic Rays in 1969, Balasubrahmanyan, Bukata, Palmeira, and I presented a paper covering one of the periods here, namely the end of 1966. We did an autocorrelation and cross-correlation analysis of the quiet time cosmic ray flux near the earth, and at Pioneer 6, some 50° west of the earth. We detected corotating regions, quasi-rigid regions of cosmic ray variations that seem to be related to your solar wind streams. Just eyeballing your figure, I would say our autocorrelation and cross-correlation curves look very similar to your solar wind auto- and cross-correlation curves. So, maybe even the GEV particles are telling us something about the solar wind.

J. H. Wolfe The Pioneer 6 and 7 comparisons you're talking about here are around 1969, 1970, aren't they?

J. Gosling The Vela autocorrelation data are 1964 through 1967; the Vela and Pioneer correlation study was 1969, 1970. So we're actually comparing data from two different times.

J. H. Wolfe We are specifically comparing 6 and 7. What dates were those?

J. Gosling That's 1969-70.

J. H. Wolfe I think that if you go back to the Mariner 2 and IMP-1 solar wind data, you will find several rotations in which the speed structure was repeated almost identically. In that case an observer rotating with the sun would not see things evolve in 4 days but perhaps could see steady-state conditions throughout the solar rotation.

J. Gosling I don't mean to imply that all velocity structures evolve on a time scale of 4 days. I do say that this time scale is typical of the 1964-1967 data and the 1969-1970 data. Even here, however, there are some stationary structures that endure for several solar rotations.

J. H. Wolfe These data were taken during an interval of changing sectors rather than during relatively quiet intervals.

J. Gosling That's certainly true. Even in these data there are certain periods when the solar wind is more stationary than at other times. From one solar rotation to the next you sometimes see the same feature. Typically, that's not the case, however.