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ADDITIONAL EVIDENCE CONSISTENT WITH SOLAR CYCLE VARIATIONS IN THE SOLAR WIND

DEVRIE S. INTRILIGATOR
Physics Department, University of Southern California
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ABSTRACT

Analyses of solar wind observations from mid-1964 through 1973 confirm the earlier results reported by Intriligator that there are statistically significant variations in the solar wind in 1968 and 1969, years of solar maximum. These variations are in phase with the solar cycle and are consistent with a solar cycle variation in the solar wind. High-speed stream parameters show that the number of high-speed streams in the solar wind in 1968 and 1969 and the total duration (in days) of high-speed streams in 1968 are considerably more than the predicted yearly average, and in 1965 and 1972 considerably less. Histograms of solar wind speed from 1964 through 1973 indicate that in 1968 there was the highest percentage of elevated solar wind speeds, and in 1965 and 1972 the lowest. Studies by others confirm these results, although their authors did not indicate this fact. The duration of the streams and the histograms for 1973 may imply a shifting in the primary stream source.

Subject heading: Sun: solar wind

I. INTRODUCTION

The activity of the solar wind varies in phase with sunspot activity from 1964 through 1972. The purpose of this paper is to confirm and extend the first report of this result in Intriligator (1974), to point out that other researchers' results confirm this observation (although the authors did not indicate this), and to suggest that the rise in stream activity in 1973 implies a shift in the primary source for streams near solar minimum. In this paper the original data set employed by Intriligator (1974) has been substantially augmented, as discussed in § II.

Intriligator (1974) emphasized the importance of high-speed streams in the solar wind and initiated the use of a number of parameters to characterize the high-speed streams and their duration. Previously, other investigators (Gosling, Hansen, and Bame 1971; Wolfe 1972; Diodato *et al.* 1974) had always computed averages of various solar wind parameters rather than focusing specifically on high-speed streams as indicators of solar wind activity. Intriligator (1974) initiated the use of three parameters as indicators of solar wind activity: the number of high-speed streams, the duration (in days) of these high-speed streams, and the product of the yearly average solar wind proton speed times the duration. A high-speed stream is defined as one having a rapidly rising increase in solar wind speed, V, and a peak speed greater than or equal to 450 km s^{-1}. The duration of a high-speed stream is defined from the start of the increase in solar wind speed through the peak ($V \geq 450$ km s^{-1}) to the time that the speed declines to 400 km s^{-1} (or to the start of the next high-speed stream if the speed at the beginning of the following stream exceeds 400 km s^{-1}). The value of the duration in days is rounded to the nearest whole day. The third parameter is the product of the yearly average solar wind speed (based on the available daily speeds for that year) times the duration in days. It should be emphasized that the same criteria for selecting high-speed streams have been employed in both the present paper and the original paper (Intriligator 1974).

II. DATA SET

In the present study we have substantially supplemented the original data in Intriligator (1974) with the additional data that have become available as summarized in Table 1. Many days for which there were only quick-look data (Intriligator 1974) have been replaced by three-hour averaged data, and some previous data gaps have been eliminated. In addition, the coverage of the data set has been extended so that it now includes solar wind data from mid-1964 through 1973. Column (2) in Table 1 shows the yearly totals of the number of days for which data (>0 points) are available. An indication of the quality of the data coverage is given in column (3), which shows the percentage of the days listed in column (2) for which four or more three-hour averages are available. Column (4) summarizes the numerous spacecraft data sets used. Data recorded near the Earth were used when available. Data gaps were sometimes filled in with data obtained elsewhere, corotated (Intriligator and Neugebauer 1975) to the Earth. However, if the general trend of the corotated data was not very similar to the available near-Earth data, then these data were not used to fill gaps. This has resulted in a few decreases in the total number of days of coverage in a year as compared with the coverage in Intriligator (1974), but the present data

TABLE 1

SUMMARY OF ALL AVAILABLE SOLAR WIND DATA AND RELEVANT PARAMETERS

Year (1)	Days (> 0 pts) (2)	≥4 pts/> 0 pts % (3)	Spacecraft (4)	Streams Observed (5)	% ≥ 450 (6)
1964...........	122	31	*a*	22	34
1965...........	284	52	*a, b, c*	33	23
1966...........	322	53	*b, c, d, e, f, a*	33	32
1967...........	353	81	*a, b, e, f, h, i*	47	33
1968...........	352	71	*a, d, e, f, i, j, k, l*	59	54
1969...........	336	75	*a, d, e, k, l, m*	57	34
1970...........	351	62	*a, d, l, m*	51	34
1971...........	344	62	*a, d, j, l, n*	44	39
1972...........	329	69	*a, j, n, o*	39	26
1973...........	329	90	*a, n, o, p*	47	53
'64–'73.........	3122	67	All	432	38

NOTES.—*a* = *Vela/IMP*; *b* = *Vela 3*; *c* = *Pioneer 6* (Ames); *d* = *Pioneer 6* (MIT); *e* = *Explorer 33*; *f* = *Pioneer 7* (MIT); *g* = *Pioneer 7* (Ames); *h* = *Explorer 34*; *i* = *Explorer 35*; *j* = *Pioneer 6* quick look; *k* = *Pioneer 9*; *l* = *OGO 5*; *m* = *HEOS*; *n* = *IMP*; *o* = *Pioneer 9* quick look; *p* = *Pioneer 8* quick look.

set has a high percentage of days with high-quality data coverage (as indicated in column [3] of Table 1), and represents the most complete, consistent coverage available near the Earth.

III. OBSERVATIONS

Using this new data set and the same criteria as those employed in Intriligator (1974), we compiled tables (Intriligator 1973, 1974) of high-speed streams in the solar wind. (The differences in the tabulated stream parameters, particularly the durations, reported below, compared with those in Intriligator 1974, are due to the replacing of quick-look data by more complete data coverage and the replacing of corotated deep-space data by data obtained in the vicinity of the Earth.) Figure 1 summarizes some of the results obtained with the aid of these tables. The shaded histograms show the total number of high-speed streams, with an increase of solar wind speed (ΔV) $\gtrsim$ 150 km s^{-1}, observed in each year from mid-1964 through 1973. If one were to assume that there were no solar cycle variation and that there was a constant rate of high-speed streams during this time, it can be approximated by

$$\sum_{\substack{(\text{mid})\\1964}}^{1973} (\text{number of streams}) \Big/ \sum_{\substack{(\text{mid})\\1964}}^{1973} [\text{days} \, (>0\,\text{points})] \approx 0.14 \text{ streams per day} .$$

This daily rate can then be multiplied by 365 days to obtain the (constant) yearly number of streams. The line at ~50.5 indicates this value. Using the daily rate for streams obtained above, we can predict the number of streams that should have been seen on the basis of the days of observations. These predicted values, adjusted for days of observations, are indicated by the stars and were obtained by multiplying the daily rate (from the equation) by the days (>0 points) for each year as listed in column (2) of Table 1. The dashed lines denote the yearly sunspot numbers. The dotted/dashed lines denote a rough estimate of the normalized (Vasyliunas 1975; Bame *et al.* 1976) yearly number of streams. This extrapolated value should more accurately be called the observed rate of occurrence of streams, since these values are obtained by simply assuming a constant rate of streams for that year based on the measured streams that year and the corresponding days of observations. (The poor data coverage for 1964 makes this [extrapolated] value very dubious.)

In 1968 and 1969 the observed number of high-speed streams exceed by ~1 standard deviation ($\sigma = \sqrt{N}$ for counting phenomena) the predicted (constant) yearly value. In addition, in 1965, 1966, and 1972 fewer high-speed streams were observed than predicted. Both of these features are additional evidence for a solar cycle variation in the solar wind.

The total duration (in days) of the high-speed streams, with $\Delta V \gtrsim$ 150 km s^{-1}, observed in each year from mid-1964 through 1973 are shown by the shaded histograms in Figure 2. If we estimate a daily rate by assuming that there is no solar cycle variation, then, using the same approach as in the equation above, we obtain ~0.40 duration per day. As in Figure 1, the line represents the (constant) yearly value; the stars, the predicted values adjusted for days of observation; the dashed lines, the yearly sunspot numbers; and the dotted/dashed lines, the extrapolated yearly normalizations of the observations.

In 1968 and 1973 the observed durations exceed the predicted (constant) yearly value. Also, in 1965, 1966, and 1972 the observed durations are less than the predicted values adjusted for the number of days of observations. The departures (above in 1968, and below in 1965, 1966, and 1972) from predicted values provide additional evidence for a solar cycle variation in the solar wind. The increased duration in 1973 may be consistent with a shifting at solar minimum of the

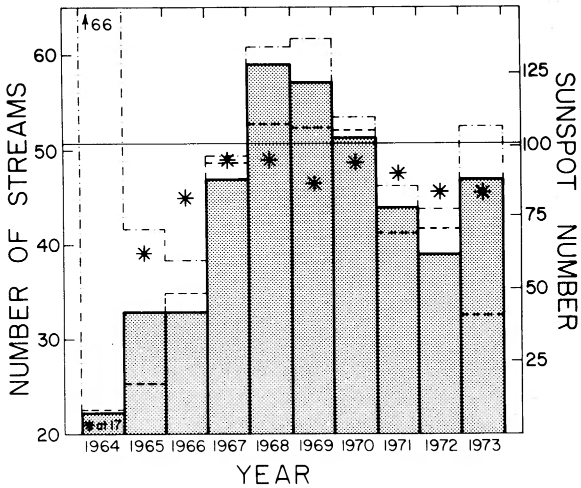

FIG. 1.—The shaded histograms show the number of high-speed streams (with $\Delta V \gtrsim 150$ km s^{-1}) in the solar wind that were observed based on the days of observations (Table 1, column [2]). The horizontal line at $\sim$50.5 indicates the (constant) yearly number of high-speed streams obtained by assuming that there is no solar cycle variation (see text). The stars indicate the predicted numbers of high-speed streams obtained by multiplying the daily rate (0.14) by the days (>0 pts) of observation listed in Table 1, column (2). The dashed line indicates the yearly sunspot number. The dotted/dashed line indicates the normalized (extrapolated) yearly values based on assuming a constant rate for each year (see text). In 1968 and 1969 the observed (*shaded histograms*) number of high-speed streams exceed by $\sim$1 standard deviation (σ) the predicted (constant) yearly value (*horizontal line*). In 1965, 1966, and 1972 the observed number of high-speed streams are less than the predicted values (the stars). These features are additional evidence for a solar cycle variation in the solar wind.

primary sources of streams observed in the ecliptic plane, as discussed below.

Similar results are obtained with the parameter the yearly average solar wind speed (in km s^{-1}) for each year multiplied by the corresponding observed total duration (in days) of high-speed streams (with $\Delta V \gtrsim$ 150 km s^{-1}) for that year. Again assuming that there is no solar cycle variation, we estimate a daily rate of $\sim$0.18 $\times$ 10^3 (km s^{-1} days) per day, thus yielding a (constant) yearly value of $\sim$6.6 $\times$ 10^4 km s^{-1} days. In 1968 and 1973 the observed quantities exceed the predicted (constant) yearly value, and in 1965, 1966, 1967, and 1972 the observed quantities are less than those predicted. These trends are similar to those discussed above for the duration of high-speed streams, as observed in the ecliptic plane, and provide additional evidence for a solar cycle variation in the solar wind and may imply a shift in 1973 of the primary stream source. It should be noted that in Vasyliunas (1975) there are also significant peaks in 1968 in both the "total duration" and "(speed) times (duration)."

In Bame *et al.* (1976), in the graph of the "average half-width (days)," if one considers the data from 1962 through 1971, there is a definite peak centered on 1968, a year of solar maximum. There are a number of other peaks in 1968 in the figures in Bame *et al.* (e.g., "average maximum speed," "streams with $V_{\rm MAX}$ > 700 km s^{-1}") that indicate an increased solar wind activity in 1968 as compared with the years 1965 through 1971. These authors, however, did not note these peaks and focused only on the high values obtained in years of solar minimum. The figure of the number of "all streams" in Bame *et al.* (1976) fails to show a peak in 1968, which at first glance is difficult to reconcile with the obvious increase in high-speed streams in 1968 found in all of our data. They, however, omitted from their data set the available (Intriligator and Neugebauer 1975) solar wind data in late 1968 and early 1969, at the time of highest mean monthly sunspot count (Dodson, Hedeman, and Mohler 1974). *If they had included these data in their study, then their figure "all streams" would have shown a definite peak in both 1968 and 1969.* One should also note that their normalization of their data for 1968 and 1969 drastically underestimates the total number of streams they would have observed if they had included the data from late 1968 and early 1969. For example, in 1968 they omitted more than

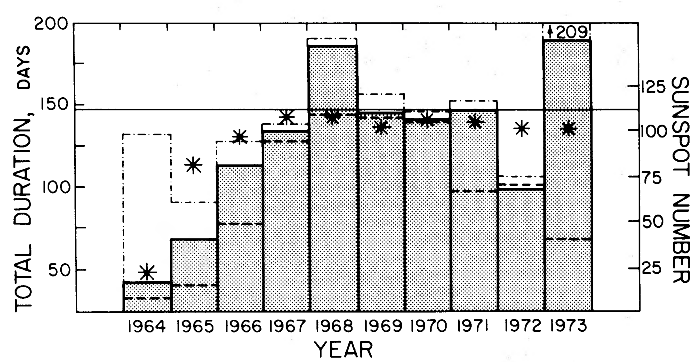

FIG. 2.—The shaded histograms show the total duration (in days) of high-speed streams (with $\Delta V \gtrsim 150$ km s^{-1}) in the solar wind that were observed based on the days of observation. The horizontal line is the (constant) yearly value obtained from assuming that there is no solar cycle variation (see text and Fig. 1 legend). As in Fig. 1, the stars indicate the predicted durations adjusted for days of observations. See text and Fig. 1 legend for explanation of other symbols.

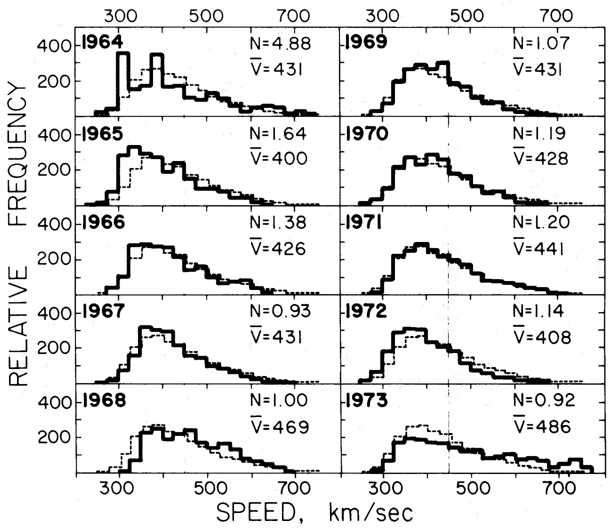

FIG. 3.—The dark lines indicate relative frequency of occurrence of the solar wind streaming speed in intervals of 25 km s^{-1} for each year from 1964 through 1973. The dashed line indicates the frequency histogram of the speed for the entire (parent) population composed of all the data from mid-1964 through 1973. The histograms have been normalized (there is the same area under each histogram), as indicated by the N's in the figure. The yearly average solar wind speeds are shown by the $\bar{V}$'s. The histograms indicate that there is an increased number of high solar wind speeds ($\gtrsim$450 km s^{-1}) in 1968. Table 1, column (6) shows that the highest percentage (54%) of elevated speeds is observed in 1968. This trend is present in the histograms of Gosling *et al.* (1971); however, neither they nor Bame *et al.* (1976) noted it.

30 days of data at the end of the year, and they omitted more than 60 days of data in early 1969 (they also omitted more than 30 days of data in 1967). If they had included these data, then, using *their* criteria, they would have observed 34 streams in 1967, 42 streams in 1968, and 45 streams in 1969, compared with their normalized values of 31, 29, and 30 streams, respectively. This argues against the reliance on the normalization techniques employed by Vasyliunas (1975) and Bame *et al.* (1976) and indicates the necessity of including all the available data and basing all substantive conclusions on the observations themselves, as emphasized in Intriligator (1974).

The dark lines in Figure 3 indicate the relative frequency of occurrence of the solar wind streaming speed in intervals of 25 km s^{-1} for each year in our data set from 1964 through 1973. The frequency histogram for the entire (parent) population composed of data from mid-1964 through 1973 is indicated by the dashed line. All the histograms have been normalized, indicated by the N's in the figure, so that there are equal areas under the histograms. The histogram for 1968 is skewed toward high speeds and the histograms for 1965 and 1972 are skewed toward low speeds. As listed in Table 1, column (6), the highest percentage (54%) of time during which the solar wind speed was greater than or equal to 450 km s^{-1} occurred in 1968 and the lowest percentages (23% and 26%) occurred in 1965 and 1972. This evidence for a solar cycle variation in the solar wind is also shown in the histograms for 1965 through 1970 in Gosling, Hansen, and Bame (1971), which indicate a definite increase in speed in 1968. These authors and Bame *et al.* (1976), however, did not note this trend in their data and erroneously concluded that there was no discernible upward shift in the bulk speed distributions with rising solar activity. The skewing of the 1973 histogram toward high speeds is consistent with the 1973 data in Figure 2, and may imply the shifting of the primary stream source in 1973, as discussed in § IV. The probability is at least 95% that in 1965, 1968, 1972, and 1973 the deviation of these yearly histograms from the parent is *not* merely a random fluctuation.

IV. SUMMARY

The observations above provide a great deal of additional evidence that confirms the earlier results reported by Intriligator (1974) that tabulations of high-speed streams yield many statistically significant variations in the solar wind that are in phase with the solar cycle. There is likewise an evident variation in the yearly histograms of the solar wind speed. In addition, these data may imply a shift in the primary source of high-speed streams in 1973.

The tabulations of the high-speed stream parameters for the solar wind data available from mid-1964 through 1973 indicate that during this period there is a statistically significant peak in 1968 for *each* of these parameters. These peaks in 1968, the year of solar maximum, provide additional evidence for a variation in the solar wind that is in phase with the solar cycle. This evidence for a peak in 1968 is also indicated in several figures in both Vasyliunas (1975) and Bame *et al.* (1976); however, these authors did not note these peaks in their data. Furthermore, if Bame *et al.* (1976) had included in their data set the available solar wind data for late 1968 and early 1969 (the time of highest mean sunspot count), then their figure "all streams" would also have shown a definite peak in *both* 1968 and 1969. Their normalization of these data drastically underestimates the total number of streams present, argues against the reliance (as in Vasyliunas 1975; Bame *et al.* 1976) on their normalization techniques, and indicates the necessity of including all available data and basing all substantive conclusions on the observations themselves, as emphasized in Intriligator (1974) and the present paper. Histograms of the solar wind speed are presented that indicate that the highest percentage (54%) of elevated speed ($V \geq 450$ km s^{-1}) is observed in 1968. This is also indicated in the histograms in Gosling (1971); however, these authors and Bame *et al.* (1976) did not note this trend. The data for 1973 in Figures 2 and 3 are consistent and may imply the shifting of the primary stream source in 1973.

In drawing their conclusions, Bame *et al.*, Gosling (1971), and Gosling *et al.* (1971) have not included the available data for 1967, 1968, and 1969, and they have emphasized the 1962 and 1964 normalized data which show high values. Since there are very few spacecraft data available for 1962 and 1964 (and none whatsoever for 1963), we have not emphasized these normalized data, since it is our view that the paucity of data in 1962 and 1964 invalidates the normalization process for these years. In addition, we point out that the 1973, 1974 data may represent a shift in solar behavior. This view is supported by Hansen, Hansen, and Sawyer (1976), who noted that "the global structure [of daily measurements of the intensity distribution of the white-light corona over the height range 1.1–2.7 R_S] became quite stable in late 1973 and throughout 1974." During this period, the *Skylab* observations of coronal holes also showed recurrent stream activity (Bohlin 1976) which was interrupted by the large flares in 1974 July (as also pointed out by Hansen *et al.*). Therefore, we emphasized the inclusion of all available spacecraft data in 1967, 1968, and 1969 and point out the lack of significant data on the left wing (1962 through 1964) of all of the solar wind histograms and the anomalously high values on the right wing (1973, 1974) of the histograms and conclude that the solar wind observations for the years 1964 through 1972 are in phase with the solar cycle and are consistent with a solar cycle variation in the solar wind.

Two possible sources of the increase in high-speed streams, observed in the ecliptic plane in the vicinity of the Earth, in 1968 and 1969 are (1) active regions or other solar near-equatorial phenomena, and/or (2) coronal holes or some other solar feature mainly at higher latitudes, but for which there is some focusing effect or latitude effect that results in this manifestation in the ecliptic plane. The peak in sunspot number in 1968 and 1969 of solar cycle 20 is not as high as that associated with the peaks in cycles 18 and 19. If at solar maximum many high-speed streams originate in sunspots or their associated active regions, there would have been more if the Sun had been more active; but if nonequatorial features caused these streams, a more active sunspot cycle might have masked this effect. The rises observed in 1968 *and* 1973 suggest that equatorial sources predominate at the peak of the cycle, while off-equatorial sources produce streams observed near the ecliptic plane at sunspot minimum (e.g., at solar minimum coronal holes may cover more latitude extending closer to the equator and the plasma and the field lines from coronal holes may extend farther toward the ecliptic plane without interacting with the particles and fields associated with sunspots and other near-equatorial sources).

One can further speculate on the possible relation between the sunspot count (which is reflected in the number of active regions) and high-speed streams near solar maximum by calculating the correlation coefficient between the high-speed stream parameters and the yearly sunspot number. For the years 1965 through 1972, extremely high correlation coefficients are found between *each* of the yearly normalized values of the high-speed stream parameters (i.e., the dotted/dashed lines in Figs. 1 and 2) and the yearly sunspot numbers. The correlation coefficients are, respectively, greater than 0.8 (more than 98% confidence), and ~0.8 (more than 98% confidence). The times of highest solar wind stream activity in late 1968 and early 1969 coincide with the time of highest monthly mean sunspot count (Dodson *et al.*). A similar calculation of the correlation between the high-speed stream parameters and the inverse (in percent) of the yearly average of the Deep River cosmic-ray neutron monitor data for 1965 through 1972 yields, respectively, correlation coefficients of greater than 0.8, and ~0.8 (with significances, respectively, above 99.5% and 98%). This may suggest a relationship between the high-speed streams and the modulation of cosmic rays (Jokipii 1971).

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DEVRIE S. INTRILIGATOR: 171 Stauffer Hall of Science, Physics Department, University of Southern California, University Park, Los Angeles, CA 90007