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EVIDENCE OF SOLAR-CYCLE VARIATIONS IN THE SOLAR WIND

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ABSTRACT

Solar-wind observations are presented from 1965 July through 1971 June that show the first evidence for long-term variations in the solar wind associated with changes in the solar cycle. The observations indicate that the frequency of high-speed streams in the solar wind and their duration vary over the solar cycle. There are more days associated with high-speed streams during solar maximum than during solar minimum. The yearly average of the solar-wind speed varies over the solar cycle and is highest at solar maximum. These measurements also provide the first direct observational evidence for changes in the solar wind which can account for the solar-cycle modulation of the cosmic-ray intensity.

Subject headings: cosmic rays — solar activity — solar wind

I. INTRODUCTION

Many investigators have tried to associate changes in the interplanetary medium with changes on the Sun. Interplanetary shocks and high-speed streams have been associated with individual events on the Sun such as large solar flares and some longer-lived corotating active regions. Nevertheless, although it has been searched for, there has been no evidence of any longer-term variations in the interplanetary medium (Hedgecock 1973; Gosling, Hansen, and Bame 1971). Many years of observation (Forbush 1966; Jokipii 1971) have established that there is a solar modulation of cosmic-rays in antiphase with the 11-year solar cycle. It is currently believed that this modulation depends on the velocity of the solar wind, fluctuations in the Sun's magnetic field, and the extent of turbulence in the solar wind; but specific quantities which correlate with the 11-year cosmic-ray variation have not yet been found (see, e.g., Hedgecock 1973; Mathews, Quenby, and Sear 1971). This paper presents the first evidence of long-term variations in the solar wind as a result of changes in the high-speed stream structure. These changes provide the first observations of a specific quantity which may be partially responsible for the 11-year modulation of cosmic rays.

II. OBSERVATIONS

Figure 1 shows the streaming speed, V, of solar-wind protons during solar rotations 1812 and 1813 (1965 December 24 through 1966 February 15). These data were obtained by the Ames Research Center solar-wind plasma spectrometer (Wolfe and McKibbin 1968; Intriligator and Wolfe 1970) on the *Pioneer 6* spacecraft (which is in heliocentric orbit). This figure shows the familiar feature of high-speed streams in the solar wind. There are three high-speed streams in solar rotation 1812. The first high-speed stream begins on 1965 December 25 and lasts through 1965 December 30. The highest solar-wind speed measured is 600 km s^{-1}

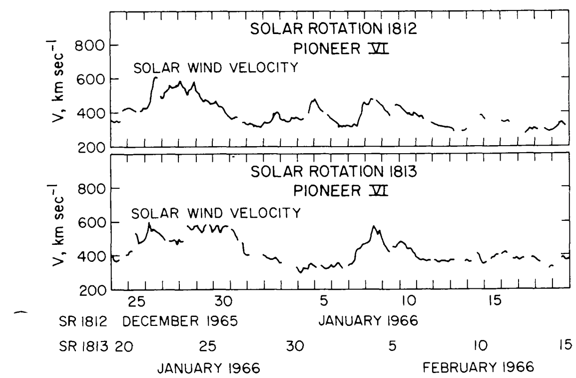
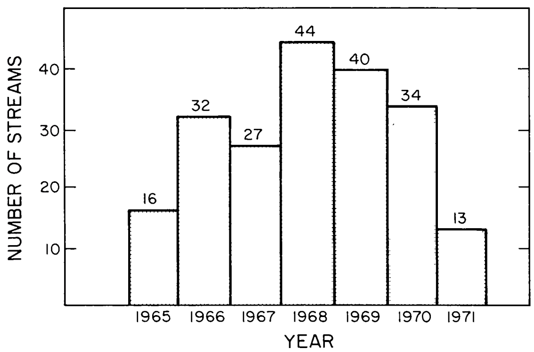


FIG. 1.—The solar wind speed during solar rotations 1812 and 1813 as measured by the Ames Research Center solar-wind plasma spectrometer on *Pioneer 6*.

on 1965 December 26. The second high-speed stream begins on 1966 January 4. Its duration is 1.3 days, and the highest measured streaming speed of solar-wind protons is 497 km s^{-1}. To more quantitatively analyze the stream structure of solar wind protons, some indices were developed by Intriligator (1973). Table 1 summarizes the indices and their values for solar rotations 1812 and 1813. Columns (1) and (2) list, respectively, the year, month, day, and approximate hour (if known) in UT of the beginning of the high-speed stream. Column (3) indicates the approximate duration of the high-speed stream in days. Column (4) indicates the increase in the solar-wind speed during the high-speed stream in increments of 50 km s^{-1}. For example, if before the beginning of the stream the solar-wind speed was 300 km s^{-1} and if later the peak speed in the stream was 700 km s^{-1}, then there was a base-to-peak increase in solar-wind speed of 400 km s^{-1}· i.e., there are "eight" 50 km s^{-1} increases. Columns (5), (6), and (7) list, respectively, the approximate peak speed of the stream, and the approximate day and hour (in UT) of the peak.

Tables similar to table 1 have been compiled (Intriligator 1973*a*) based on solar-wind observations from 1965 July through 1971 June. Figure 2*a* summarizes some of the results obtained with the aid of these tables. The lines in figure 2*a* show the total number of high-speed streams observed in each year from 1965 through 1971. Figure 2*a* shows that the total number of high-speed streams observed were: 16 in 1965 (based only on data from 1965 June–December); 32 in 1966; 27 in 1967; 44 in 1968; 40 in 1969; 34 in 1970; and 13 in 1971 (based only on data from 1971 January–June).



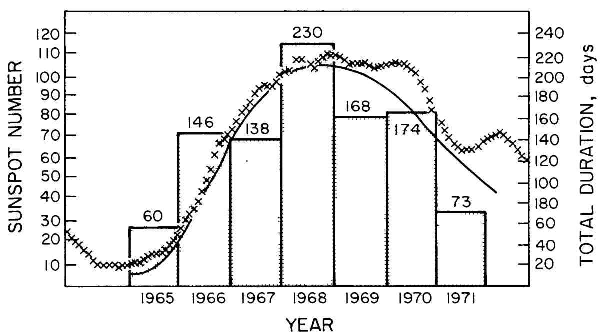


FIG. 2*a*.—The number of high-speed streams per year in the solar wind. The data for 1965 and 1971, respectively, are based on only 136 and 270 days of data (see table 2).

FIG. 2*b*.—The total duration of days per year of high-speed streams in the solar wind is shown by the histogram-type graph. This indicates that the number of days per year in which the solar wind is "gusty" rather than "quiet" varies over the solar-cycle. The smoothed sinusoidal curve and the curve with the crosses, respectively, indicate the smoothed sunspot numbers and the measured sunspot numbers for this solar cycle.

Data gaps affect the accurate determination of the total number of high-speed streams. There are two sources of these gaps: (1) before 1965 June and after 1971 June there are currently no available spacecraft data, and (2) between 1965 June and 1971 June there are some intervals when the *Pioneer* and *Vela* spacecraft were not being tracked by ground stations or when the *Vela* spacecraft were in the magnetosphere and not in the interplanetary medium.

Figure 1 and table 1 clearly indicate that the duration of high-speed streams varies even within one solar rotation. To more fully evaluate the long-term variation of high-speed streams we tabulated the duration of each stream (e.g., table 1, col. [3]). Figure 2*b* shows the total duration (in days) per year of high-speed streams from 1965 June through 1971 June. This total for each year was obtained by adding the duration of each of the individual streams that were observed in that year. The histogram-type graph in figure 2*b* indicates that in 1965 (based on one-half year of data only) there were a total of 60 days associated with high-speed streams; in 1966 there were 146 days; in 1967 there were 138 days; in 1968 there were *230 days;* in 1969 there were 168 days; in 1970 there were 174 days; and in 1971 (based on 270 days of data only) there were 73 days.

The smoothed sinusoidal curve and the curve with the crosses in figure 2*b* indicate, respectively, for this solar cycle the smoothed sunspot numbers and the measured sunspot numbers.

Figure 2*b* clearly indicates that there were more days in 1968 on which there were high-speed streams in the solar wind than there were in any other year from 1965 to 1971. The fact that 230 days (out of 366 days) in 1968 were associated with high-speed streams in the solar wind is quite striking. In other words, on the

TABLE 1

HIGH-SPEED STREAMS IN THE SOLAR WIND*

Date (1)	Time (2)	Duration (Days) (3)	Number of 50 km s^{-1} Increases (4)	Peak Speed (5)	Day of Peak (6)	Time of Peak (7)
1965 Dec. 25.....	20	5.2	4	600	26	12
1966 Jan. 4......	12	1.3	2	497	5	0
1966 Jan. 7......	12	4	3	506	8	6
1966 Jan. 20.....	14	7.7	4	626	24	9
1966 Feb. 3......	8	3.9	3	586	4	9

* Solar rotation 1812 (1965 December 24–1966 January 19). Solar rotation 1813 (1966 January 20–1966 February 15). *Pioneer 6* spacecraft.

average, almost two out of every three days in 1968 were associated with a high-speed stream.

Table 2 lists the yearly averages of the solar-wind speed for 1965 through 1971 and also indicates the total number of daily averages of solar-wind speed that were available for this study. To maximize the number of daily points, quick-look data (see *Solar-Geophysical Data*) were included as "averages" if no other data were available. The replacing of this quick-look data by real daily averages and the filling in of other data gaps to bring the total number of daily averages for each year closer to 365 days would be of significant interest if the data ever becomes available. Table 2 clearly indicates that the solar-wind speed was highest (461 km s^{-1}) in 1968 during solar maximum.

Figure 3 is a graph of the yearly solar-wind speed for each year multiplied by the corresponding total duration of high-speed streams for that year. The graph indicates that this composite parameter does vary over the solar cycle showing an enhanced peak in 1968 at solar maximum. The curved line in figure 3 shows the best fit sinusoidal-type curve to this data using the seven yearly averages and assuming a duration of 10 years 6 months for this part of the solar cycle.

The parameter in figure 3 reflects two long-term changes in the solar wind: the change in the yearly average of the solar-wind speed and the change in the total yearly duration of high-speed streams. Both of these long-term changes in the solar wind indicate that there are changes in the interplanetary medium associated with changes in the Sun. Furthermore, they both provide the first observational explanation for the solar modulation of cosmic rays. This modulation is in antiphase with the solar cycle. Figures 2 and 3 indicate that at solar maximum the probability is highest (230 days)/(366 days) that cosmic rays entering the solar system will encounter high-speed streams. Table 2 and figure 3 indicate that at solar maximum the average solar-wind speed is highest; therefore, cosmic rays entering the solar system at solar maximum are more likely to encounter higher solar-wind speeds than they would if they entered the solar system at other times. As a result, there is more modulation of cosmic rays at solar maximum than at other times. Furthermore, the general variation in the yearly average solar-wind speed from 1965 to 1971 shown in table 2 might be sufficient to account for the solar modulation of cosmic rays during this entire period since the cosmic-ray modulation by the solar wind is a highly nonlinear function of the wind velocity and diffusion coefficient.

TABLE 2

YEARLY AVERAGES OF SOLAR-WIND SPEED

Year	Total Number of Daily Averages	Yearly Average of Solar-Wind Speed (km s^{-1})
1965...........	136	397
1966...........	331	425
1967...........	331	407
1968...........	358	461
1969...........	323	426
1970...........	349	412
1971...........	270	435

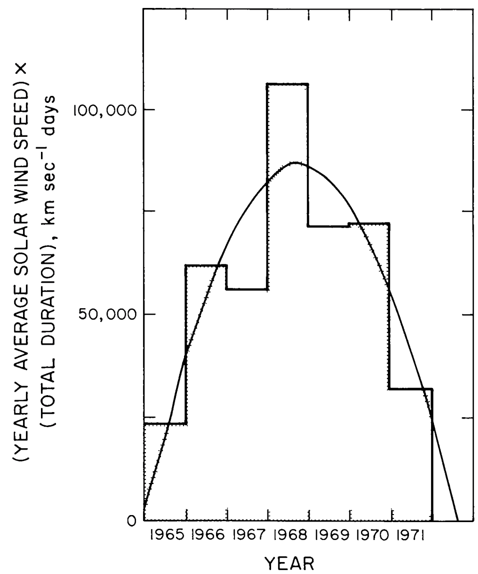


FIG. 3.—The yearly average solar-wind speed per year multiplied by the total duration in days of high-speed streams for that year is shown by the histogram-type graph. The curved line indicates the best-fit sinusoidal-type curve to this data (see text).

III. SUMMARY

The observations presented above provide the first evidence of long-term variations in the solar wind. This evidence is of considerable astrophysical significance. It provides the first evidence that long-term changes on the Sun (e.g., the phase of the solar cycle and the number of sunspots) give rise to changes in the solar wind. In addition, these changes in the solar wind provide the first direct observational evidence of a specific quantity which can account for the solar-cycle modulation of cosmic rays.

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