Solar Wind Four

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AVERAGE CHARACTERISTICS OF THE SOLAR WIND AND ITS VARIATION DURING THE SOLAR CYCLE

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1. INTRODUCTION

The most recent reviews on different manifestations of the solar cycle were presented by Akasofu, Howard, Bridge, and Hultqvist (1976) at the International Symposium on Solar Terrestrial Physics in Boulder (Colorado) in June 1976. Bridge's report dealt with the solar wind variations during the solar cycle, which is also a topic of this review.

It is well known that the first detected manifestation of the solar cycle is the periodic variation of the number of sunspots. From the above mentioned reviews it can be seen that the cause of this solar cycle manifestation, as well as the causes of many other interplanetary and geomagnetic events, is still obscure or, at least, not completely clear.

Bridge (1976) noted, after he had analyzed the data on the 20th cycle, which were available in 1976: "... one firm conclusion can be drawn: in contradiction to many predictions and general expectations, no large changes in the yearly averages of plasma flux density, velocity or number density occurred during this period. On the other hand, the yearly average velocities are almost certainly higher by about 30 % near the minimum of the solar cycle than near the maximum. It is possible that the number density increased near solar minimum but no firm conclusion can be drawn until the results from 1972 through 1975 are analyzed."

This was the situation two years ago. Even though during the last two years only few papers appeared containing experimental data on the solar wind near the Earth's orbit, some progress has been made which was connected with the following:

(1) The solar wind results obtained for the period from 1971 to 1976 by means of th IMP 6, 7, 8 satellites (Feldman et al., 1978) have been published.

(2) It has been found that the 20th solar cycle is abnormal as compared with the te previous cycles from the viewpoint of the relation between the solar activity i dex (number of sunspots) and the geomagnetic indices (Svalgaard, 1977; Gosling al., 1977b).

(3) A positive correlation between the solar wind velocity averaged over time intervals of the order of a year and average indices of geomagnetic activity for the same intervals (Crooker et al., 1977; Svalgaard, 1977) has been established.

Thus, it will be suggested herein that variations of the average annual velocity of the solar wind during the last century might be obtained with some degree of confidence (the first suggestion on the possibility of deducing solar wind velocity from geomagnetic indices was made by Russell (1975).

Publications which appeared before 1976 and are identical in subject are listed in the previous reviews (e.g. Diodato et al., 1974; Neugebauer, 1975; Bridge, 1976). In this brief review the main attention is given to the results published from the second part of 1976 on and to their relation with the earlier results.

2. PECULIARITIES OF THE GEOMAGNETIC ACTIVITY IN THE 20th SOLAR CYCLE

Svalgaard (1977) and Gosling et al. (1977b) noted that in the 20th solar cycle the average annual indices of geomagnetic activity relate differently to the annual sunspot numbers as compared to other cycles during the last century. Fig. 1 (Gosling et al., 1977b) gives average annual numbers of sunspots and geomagnetic aa-indices for the last ten solar cycles.

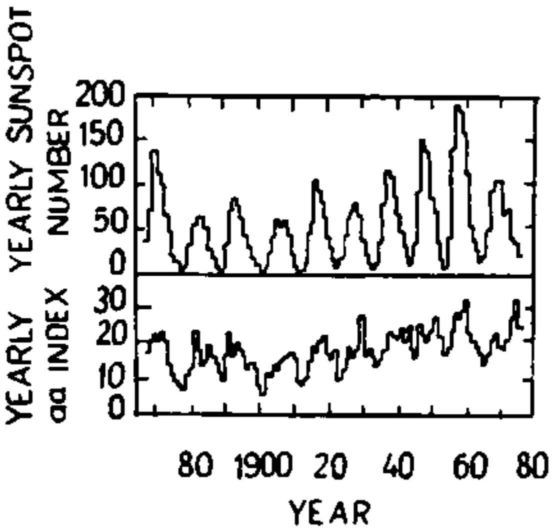

Fig. 1 Average annual sunspot numbers and aa-indices (Gosling et al., 1977b)

It can be seen that, as a rule, the decrease of the average annual aa-indices occurs somewhat later (2 to 3 years) than that of the sunspot number. However, geomagnetic activity increases in the 20th cycle within the major part of the descending leg of the sunspot number curve.

Fig. 2 plotted using the data of Gosling et al. (1977b) clearly illustrates the peculiarity of the 20th cycle. There, the x-axis gives the average annual sunspot number and the y-axis represents the average annual aa-indices. The arrows on the plots indicate the time direction and the numbers denote the years after sunspot maximum. The plot in the lower left side of Fig. 2 refers to the data averaged over the 11th to 19th cycles; the plot in the lower right side refers to the data averaged over the even cycles. The upper plots in Fig. 2 refer to the 19th and 20th cycles. Fig. 2 shows that on average the maximum of geomagnetic activity is two years later than the maximum of the sunspot number; in the previous (19th) cycle the delay was three years. The geomagnetic activity, as a rule, is higher when the sunspot number decreases rather than when it increases. Considering the high geomagnetic activity at small sunspot numbers and the displacement of the geomagnetic activity maximum relative to the maximum of sunspot number the 20th solar cycle is unique in the last century.

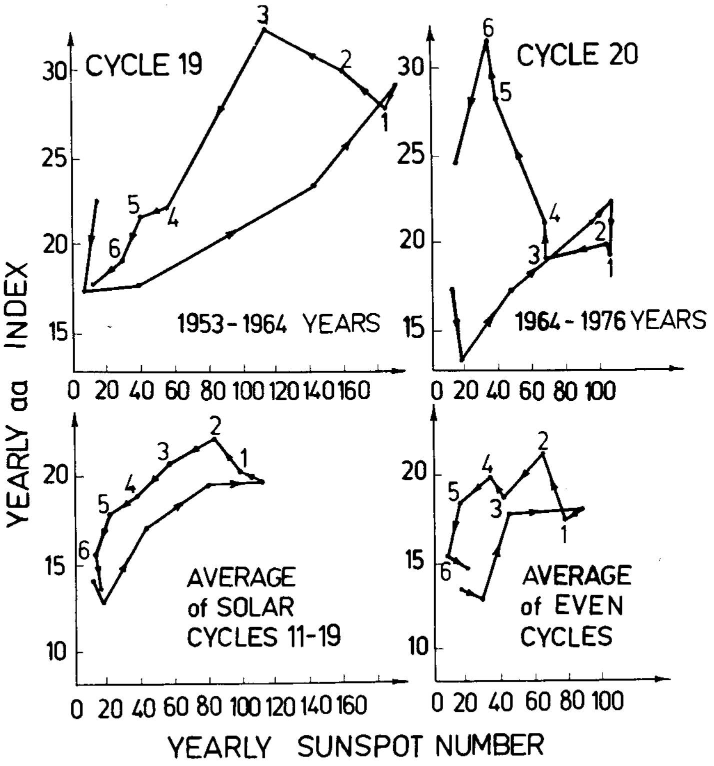

Fig. 2

The peculiarity of 20th solar cycle (see text)

3. AVERAGE ANNUAL BULK VELOCITIES OF THE SOLAR WIND AND THEIR CORRELATION WITH AVERAGE ANNUAL GEOMAGNETIC INDICES IN THE 20th SOLAR CYCLE. AVERAGE ANNUAL VELOCITIES OF THE SOLAR WIND IN THE LAST CENTURY.

Bridge (1976) discussed the variations of average annual bulk velocity V up to 1974 as shown in Fig. 3. Two series of data are given up to and including 1972: the first series with the marked confidence intervals (Diodato et al., 1974) was obtained using the data from five spacecraft involving four scientific groups namely LASL - Los Alamos Scientific Laboratory, MIT - Massachusetts Institute of Technology, GSFC - Goddard Space Flight Center in the USA and the Space Plasma Laboratory in Italy; the second series, denoted by circles, show the results from the LASL group only.

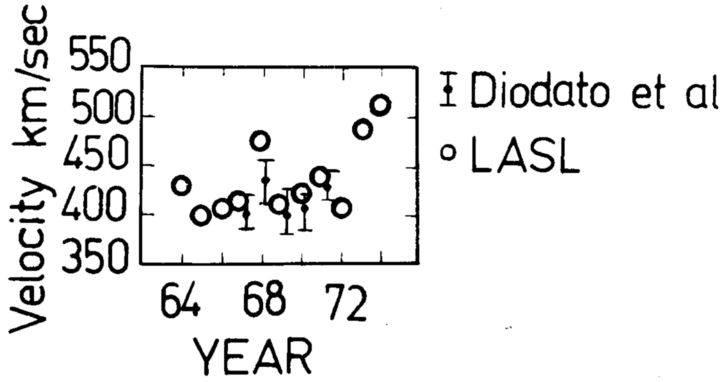

Fig. 3 Velocity variations up to 1974 (Bridge, 1976)

These two series are very different in some years (e.g. in 1968). The disagreement is apparently caused by the lack of intercalibration of the instruments and by different methods used for processing the experimental data. (Note, however, that the velocity data obtained by various laboratories are more similar than the data of other solar wind parameters, e.g. density and temperature of protons.) Hence, if the long-term variations of the solar wind parameters are to be studied, it is very important that the data should, in principle, be obtained with identical instruments and be processed by the same method. At present, the LASL data are undoubtedly the most uniform series obtained during the 20th solar cycle at a distance of 1 AU in the Earth's vicinity. This became especially clear after the publication of results from IMP 6, 7 and 8 during the period from 1971 to 1977 (Feldman et al., 1978).

Average annual V-values for the period from 1969 to 1973 have also been published by Intriligator (1978). In addition to the above mentioned data, Intriligator used data obtained by Ames Research Center (ARC) and Jet Propulsion Laboratory (JPL) in the USA, i.e. data from more than ten space vehicles.

Let us briefly return to the subject of geomagnetic activity. According to some existing concepts, geomagnetic activity (more precisely, the magnetospheric substorm) is intimately connected with the efficiency of the "dynamo" (current generator) produced by the solar wind-magnetosphere system. Therefore, geomagnetic activity depends to some extent on the solar wind velocity. However, the "dynamo" efficiency is modulated by the southward component of the interplanetary magnetic field B_z (Akasofu, 1976; Svalgaard, 1977). It seems that since the B_z-value fluctuates on a comparatively short time scale, B_z fluctuations do not have a significant effect on geomagnetic indices when averaged over long-time periods. Geomagnetic indices correlate well with the respectively averaged values of V^2 (Crooker et al., 1977; Svalgaard, 1977).

Crooker et al. (1977) found that there is a good correlation of half-year averages of solar wind bulk velocity V taken from Gosling et al. (1976) and of monthly means of the geomagnetic activity index Ap (for the period up to 1975). The correlation coefficient between $< Ap >$ and that of $< V^2 >$ is 0.9.

The same correlation between the geomagnetic activity index am and the value of V^2 averaged over long periods can be seen in Fig. 4 (Svalgaard, 1977). Fig. 4 is plotted using the data of more than 2000 three-hour intervals from 1965 to 1973. The area of each black circle is proportional to the number of three-hour intervals used.

Since the question of the solar wind interaction with the Earth's magnetosphere is not included in this conference program we will not discuss possible mechanisms of such a correlation. This correlation is of interest here in so far as there are rather reliable data available

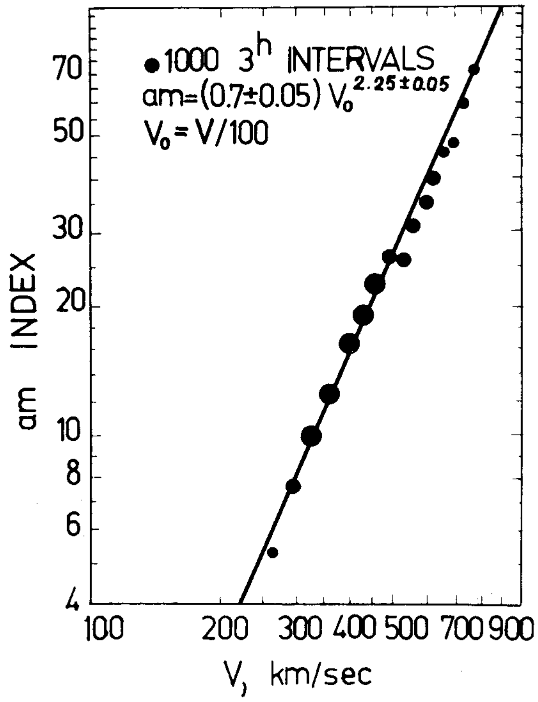

Fig. 4
Correlation between averaged am indices and V^2 (Svalgaard, 1977)

about the aa-indices of the geomagnetic activity obtained during the century starting in 1868. Data about the solar wind velocity, however, were obtained for only one solar cycle. If their correlation were good enough, it would be worth-while to try to restore the variations of the average annual values of V during the last century.

Let us check the existence of this correlation using the data published in 1977-1978. In Fig. 5 the solid thin curve shows the average annual variation of V from the LASL data as obtained by means of the IMP 6, 7 and 8 satellites (Feldman et al., 1978). The dotted line shows the above mentioned average annual values of V from the data of more than ten satellites (Intriligator, 1978). These curves are somewhat different for 1966-1967, 1969-1970 years but almost coincide for the other years. The thick curve gives the variations of average annual aa-indices (Gosling, 1977) as shown by the scale on the right side of Fig. 5. Good correlation is evident in this case. This is expected since Crooker et al. (1977) used similar data for V from the LASL group and the Ap-indices; the averaged aa-indices differ from Ap-indices only in the number of contributing geomagnetic observatories.

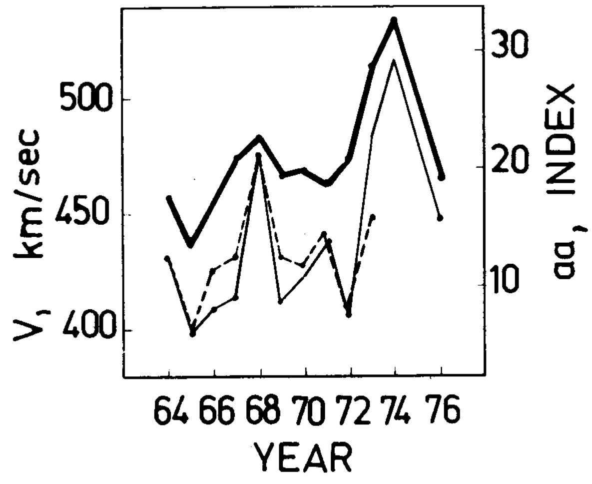

Fig. 5 Variations of yearly averaged aa-indices and velocity values (see text)

The variations of the geomagnetic activity during the 20th solar cycle show an atypical behavior relative to the previous solar cycles (cf. Fig. 2). Nevertheless, they correlate well with the data for the average annual solar wind velocity in the 20th cycle as shown in Fig. 5. Therefore it seems likely that the restoration of the variations of the average annual bulk velocity of the solar wind during the last century can be made with a reasonable degree of confidence.

Crooker et al. (1977) compared the correlation of Ap-data averaged over a long period with the product of $<|B_z|> \cdot <V^2>$ and with $<V^2>$ alone. They found that the available data set is not large and not accurate enough to determine which correlation is better. Therefore, we can assume that the aa-index, averaged over one year, does correlate with $<V^2>$ alone.

We then use the values of aa-indices, averaged over one year (Gosling et al., 1977b), and the average annual values of V from the LASL results (including data for 1971 - 1976, Feldman et al., 1978). The relationship between the average annual values of aa-indices and V can be approximated as

$$aa = 1.6 \times 10^{-4} \left(V \frac{\text{km}}{\text{sec}}\right)^2 - 10 \qquad (1)$$

Fig. 6 illustrates the relationship between the average annual values of V determined using both aa-indices and equation (1) and the V values obtained from the LASL data. There, the solid curve shows the calculated V and the circles, the measured V.

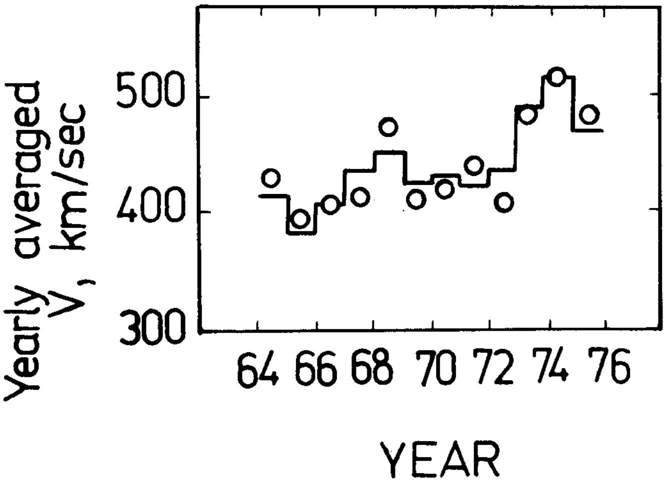

Fig. 6 Yearly averaged velocity values obtained by use of aa-indices (solid line) and from LASL data (circles)

Fig. 7 shows the changes of the average annual number of sunspots and the average annual value of V determined from equation (1) for the last ten solar cycles. The plot of Fig. 7 allows the value of δ to be estimated.

$$\delta = \frac{V_{max} - V_{min}}{V_{max} + V_{min}}$$

where V_{max} and V_{min} are the maximum and minimum average annual velocities of the solar wind for various solar cycles. According to Fig. 7 δ = 15 % for the 20th cycle; the maximum δ occurred in the 13th cycle (δ = 20 %) and δ = 25 % for the last century. The smallest average annual value: V = 314 km/sec (13th cycle); the largest average annual velocity in the last century occurred during the 20th cycle ($\simeq$ 516 km/sec).

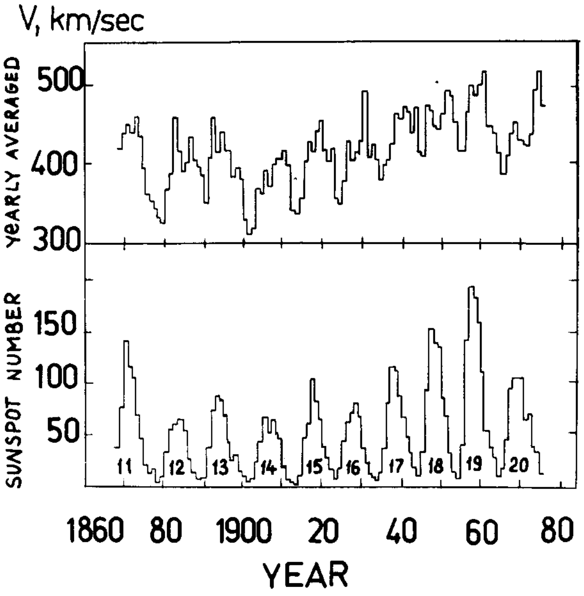

Fig. 7 Yearly averaged velocity values obtained by use of aa-indices according to Eq. (1)

The regression equation (1) is based on a very low number of yearly averaged V-values, defined with some errors, and all inside a rather narrow interval (400-600 km sec^{-1}). The use of equation (1) for determination of a large series of V-values and for a larger interval of bulk speeds naturally can lead to substantial errors. In the author's opinion the graph (Fig. 7) can be regarded only as showing a trend in V-variations during the past solar cycles but not as giving accurate V-values. According to our evaluations, in the speed interval 450-600 km sec^{-1} errors can be as great as ±50 km sec^{-1}, in the 350-450 km sec^{-1} interval ±35 km sec^{-1}, but at low bulk speeds the errors reach ±75 km sec^{-1}.

In the future, direct measurements of averaged V-values and aa-indices will continue. The amount of data will increase and the accuracy of the determination of V for past solar cycles will surely be improved.

5. LONG-PERIOD VARIATIONS OF PLASMA DENSITY, PARTICLE FLUXES AND ENERGY IN THE SOLAR WIND

Fig. 8 shows data on the average annual values of the density n from 1964 to 1976. The values of n until 1971 are given in the form presented by Bridge (1976) who used the data of Diodato et al. (1974), which were based on the results obtained from several spacecraft. The vertical bars correspond to the formal "errors" relative to Vela-3 data and not to the absolute errors of measurements. The proper errors of the Vela-3 measurements are estimated as 25 % (Bridge, 1976). The values of n from 1972 to 1976 are determined using the data of the LASL group from IMP 6, 7, 8 (Feldman et al., 1978). During 1971, only the average monthly value for the first half year were published using the data from IMP 6, 7, 8. The average semi-annual value of n is shown by the triangular symbol. It differs considerably from the average annual value of n during the same year according to the data given by Diodato et al. (1974).

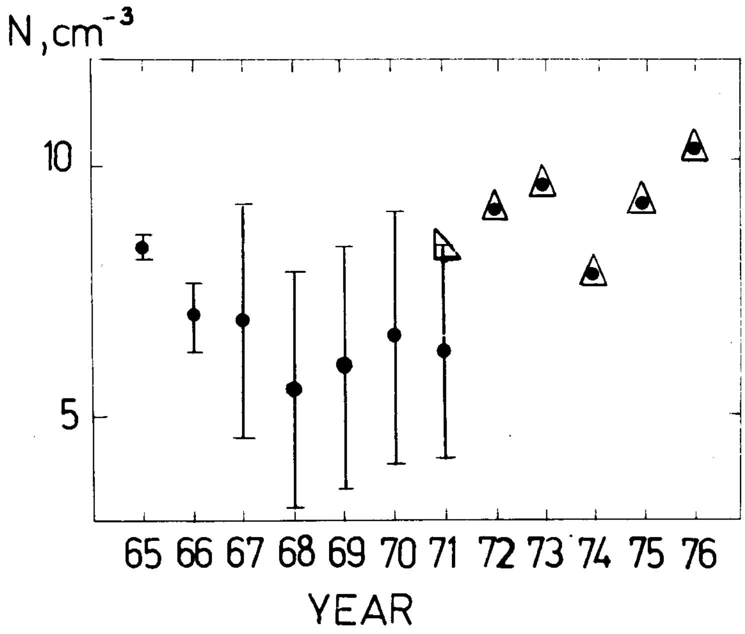

Fig. 8 Yearly averaged density data (see text)

Fig. 8 shows minima of n in 1968 and 1974. They coincide with the maxima of V discussed above (Fig. 5). However, as a whole, our knowledge of the density variation during the solar cycle seems to be insufficient because of substantial discrepencies in determination of n from various spacecraft. Measurements of the particle density n in the solar wind are less accurate than measurements of the velocity V. Variations in the gain coefficient or degradation of the channeltron or electrometer in the instrument in fact do not influence the determination of V but can strongly affect the measurement of n. Feldman et al. (1977) note the difference of density values obtained from Vela-3 and the IMP satellites and some possible causes associated with the instrument errors. In some cases the results of the density determination depend on the calculation methods. Therefore, a comparison of data for n obtained from various spacecraft involves considerable difficulties. We have solar wind measurements from the satellites of the Prognoz series obtained from 1972 to 1976. Although the V values determined from these data are very close to those obtained from other Earth satellites, we do not use Prognoz results in this paper since the problem of normalizing our density results to the data of other scientific groups has not been solved yet.

The uncertainty of the density data, which have been obtained during the 20th cycle, leads to a corresponding uncertainty of the particle and energy flow values. The IMP 6, 7, 8 (Feldman et al., 1978) data were obtained by the LASL group during almost the whole second half of the 20th cycle with the help of nearly identical instruments and were processed with the same technique. The fact that they were mutually calibrated is of great importance, since they obviously correctly reflect relative variations of the density.

Fig. 9a gives V, T_p and n values averaged over 27 days from IMP 6, 7, 8 data from 1971 to 1976. The proton temperature varies almost in phase with V (as followed from earlier solar wind measurements). Fig. 9b gives similar data on V, kinetic energy flow (in erg $cm^{-2}sec^{-1}$) and particle flow (in units of $10^{-8}cm^{-2}sec^{-1}$). The horizontal straight lines correspond to the mean values averaged over the total measurements until 28 August 1972 and after October 1972.

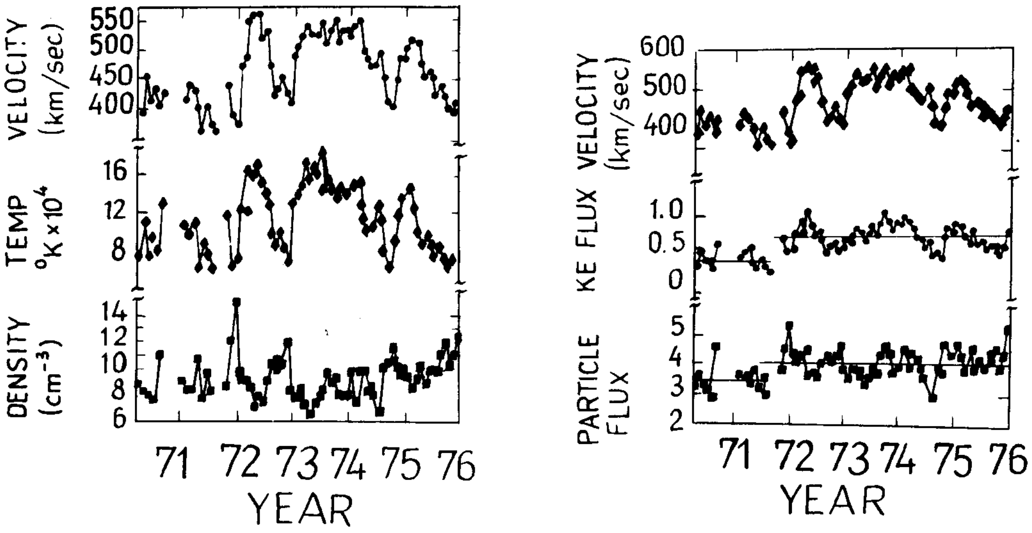

Fig. 9a, b Data from IMP 6, 7 and 8 averaged over 27 days (Feldman et al., 1978)

The graphs of Fig. 9b show that during the last 4 years of the 20th solar cycle the mean flow of particles per solar rotation is about $4x10^8cm^{-2}sec^{-1}$ with a maximum deviation of $\pm1.5x10^8cm^{-2}sec^{-1}$ and the flow of kinetic energy is $\sim$0.75 erg $cm^{-2}sec^{-1}$ with a maximum deviation of $\pm$0.3 erg $cm^{-2}sec^{-1}$. A noticeable systematic variation of these flows was not observed during the years of declining solar activity.

Gosling et al. (1977a) presented and systematized the data on the cases when a considerable solar wind plasma density and a more or less stable or even decreasing bulk velocity V was observed. Examples of such events (hatched regions) can be seen in Fig. 10 where the average three-hour values of n and V for late 1973 are given. The authors called them "non-compressive density enhancements" (NCDE) to distinguish them from the compression regions in front of high speed streams. The event was called NCDE if $n \geq 15\ cm^{-3}$ and the gradient of the velocity, determined from the given and the two preceding three-hour intervals was ≤ 0.

The sources of NCDE in the corona are not exactly determined. A proposal was made that some of these events are related to nonstationary coronal phenomena; since such phenomena generally occur near solar activity centers, it might be expected that the frequency of appearance of NCDE and their peculiarities can have long-period variations in the solar cycle. Some results of a search for such variations from 1972 to 1976 are given by Feldman et al. (1978). The number of events did not decrease with the decrease of the number of sunspots. Long-period variations related to the solar cycle were not detected in the NCDE events.

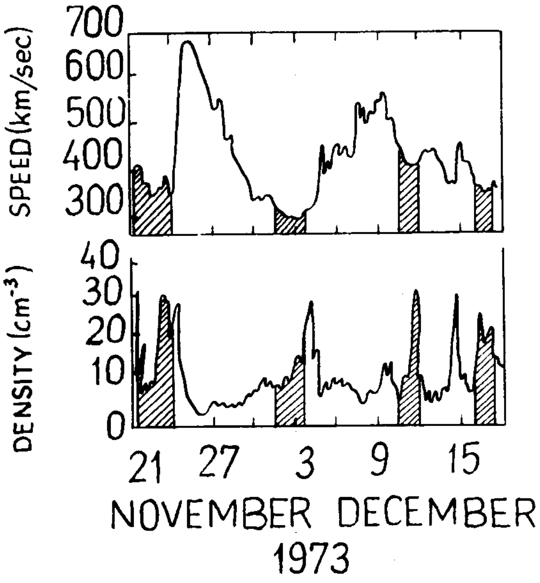

Fig. 10 Examples of non-compressive density enhancements (NCDE) (Gosling et al., 1977a).

6. VARIATIONS OF RELATIVE CONTENT OF HELIUM

The state of the problem on the variations of relative content of α-particles in the solar wind during the 20th solar cycle up to 1972 is described by Ogilvie and Hirshberg (1974); this paper contains a detailed list of literature concerning this problem. Since then the only new experimental data are the results from IMP 6, 7 and 8 (Feldman et al., 1978). These data suggest the possibility that in the 20th cycle the value of the average annual n_α/n_p ratio varies from about 3 to 5 in phase with the number of sunspots. There seems to be some phase shift, however, as in 1972 the number of sunspots decreases while n_α/n_p remains close to the maximum value.

7. VARIATIONS OF THE INTERPLANETARY MAGNETIC FIELD

Since the symposium in Boulder (1976), the review of Siscoe et al. (1978) was the only publication dealing with variations of the interplanetary magnetic field during the solar cycle. Bridge, however, was obviously acquainted with its contents and partially reflected it in his review (Bridge, 1976). Nevertheless, to update the facts more completely, we present briefly some conclusions about the magnetic field variations during the 20th solar cycle:

(1) During the period from 1969 to 1976 there were no significant variations in the value of the magnetic field depending on the phase of the solar cycle (mean value ~ 6.2 γ) (King, 1976).

(2) During the time from 1963 to 1973 the total energy of the magnetic field component B perpendicular to the spiral direction had minima in 1963 and 1973 and a double maximum in 1967 and 1970.

The total amplitude of variations (between extremal values) was about 67 % (Hedgecock, 1975).

(3) The average annual values of the component $|B_z|$ normal to the ecliptic plane approximately coincides with the average annual number of sunspots. During the years of the solar activity maximum the probability of large values of B_z was higher than during the years of the solar activity minimum (Siscoe et al., 1978).

8. CONCLUSIONS

The 20th cycle turned out to be anomalous from the viewpoint of variations in the geomagnetic perturbations which increased as the solar activity decreased. A good correlation was found between the Ap indices of the geomagnetic perturbations averaged over long-time periods and the square of the bulk velocity V of the solar wind ions. Assuming that the same correlation occurs in the other solar cycles, variations in the average annual values of V during the last century were derived. The average annual values of V did not vary more than 15 % in the 20th cycle and not more than 25 % during the century.

Based on the published results of plasma density measurements, variations in the average annual values from ~ 5.5 cm^{-3} to ~ 10 cm^{-3} were observed in the 20th solar cycle which obviously are not associated with solar activity as determined by the number of sunspots. It seems that they were anticorrelated with variations in the mean velocity of V. However, during the entire 20th cycle our judgement on density variations (and hence on variations in the mass and kinetic energy flows) is made with less certainty than on velocity variations because of measurement errors associated with the instrumentation and the techniques of data processing from different spacecraft. Of course, if the measurements are made with identical instruments and the results are processed with the same technique these diffculties will not arise. Therefore, the measurements carried out by LASL are of particular importance. It cannot be excluded that in the 21st cycle the data of direct measurements of the solar wind characteristics, carried out in different countries and even by different scientific groups in one country will again be conflicting. I guess that it would be expedient to make recommendations to unify the measurement techniques, the procedure of laboratory and flight calibration of the instruments and the techniques of data processing. The available results of measurements of the proton temperature T_p indicate that T_p varies in the solar cycle approximately in phase with variations of V (note that the data of T_p measurements from various satellites are conflicting (Formisano et al., 1974)). Unfortunately, there are no published data which allow to judge on long-period variations of anisotropy of the proton temperature $T_{p_\parallel}/T_{p_\perp}$ and the electron temperature T_e at 1 AU. Most of the solar wind average characteristics are not simply related to solar activity as characterized by the number of sunspots.

In the 20th solar cycle only few solar wind characteristics, averaged over long periods, varied in approximate agreement with the averaged number of sunspots (relative content of helium, magnetic field component B_z, probability of appearance of large values of B_z). The physical cause for this agreement is unknown.

Studies of the solar corona and interplanetary medium carried out during the 20th solar cycle made it possible to reveal coronal holes as the sources of high-speed streams. We hope that the studies during the 21st cycle will allow us to pass from the hypotheses on the origin of slow flows (Axford and Keller, 1977) to its comprehensive knowledge.

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