LONG-TERM VARIATIONS OF THE SOLAR WIND DENSITY-VELOCITY RELATION

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ABSTRACT. The relation between density and velocity of the solar wind is determined for the individual phases of solar activity cycles 20 and 21, using daily averaged values of the solar wind parameters (November 1963 - May 1980, Bartels rotations Nos 1783-2006). It was found that the particle concentration decreases in all analysed phases of the two solar cycles with increasing solar wind velocity. In most phases of cycles 20 and 21 (with the exception of the ascending branch of cycle 20), the density decreases as $n \sim V^{-1.5}$. As regards the quiescent solar wind with no marked velocity gradients, it was found that $n \sim V^{-(1.6-1.7)}$. During the ascending phase, it appears that $n \sim V^{-1.1}$ is realistic. In both cycles, 20 and 21, it was found that the particle density of the solar wind is higher on the average (about 1.5 times) in the solar activity minimum than in its maximum.

ДОЛГОВРЕМЕННЫЕ ВАРИАЦИИ СООТНОШЕНИЯ ПЛОТНОСТЬ-СКОРОСТЬ СОЛНЕЧНОГО ВЕТРА. В работе на основе средних суточных величин параметров солнечного ветра выведены соотношения между плотностью и скоростью солнечного ветра для отдельных фаз 20-ого и 21-ого циклов солнечной активности (ноябрь 1963 - май 1980, обороты Бартельса № 1783-2006). Найдено, что для всех анализируемых фаз обеих солнечных циклов плотность частиц убывает с повышением скорости солнечного ветра. Для большинства фаз 20-ого и 21-ого циклов (кроме восходящей ветви 20-ого цикла) плотность убывает согласно соотношению $n \sim V^{-1.5}$. Для спокойного солнечного ветра без присутствия крупных скоростных градиентов была найдена зависимость в виде $n \sim V^{-(1.6-1.7)}$. Для восходящей ветви можно, по-видимому, зависимость записать в виде $n \sim V^{-1.1}$. Для обеих циклов № 20 и 21 было подтвердено, что в миниме солнечной активности в основном плотность частиц солнечного ветра выше (коэффициент умножения около 1.5) чем в максимуме.

DLHODOBÉ VARIÁCIE VZŤAHU HUSTOTA-RÝCHLOSŤ SLNEČNÉHO VETRA. V práci je na základe priemerných denných hodnôt parametrov slnečného vetra určovaný vzťah medzi hustotou a rýchlosťou slnečného vetra pre jednotlivé fázy 20. a 21.cyklu slnečnej aktivity (november 1963 - máj 1980, Bartelsove rotácie č. 1783 - 2006). Bolo zistené, že pre všetky analyzované fázy oboch slnečných cyklov koncentrácia častíc klesá so vzrastaním rýchlosti slnečného vetra. Pre väčšinu fáz 20. a 21. cyklu (okrem vzostupnej vetvy 20. cyklu) klesá hustota podľa vzťahu $n \sim V^{-1.5}$. Pre kľudný slnečný vietor bez prítomnosti výrazných rýchlostných gradientov bola nájdená závislosť v tvare $n \sim V^{-(1.6-1.7)}$. Pre vzostupnú vetvu sa zdá byť reálnou závislosť v tvare $n \sim V^{-1.1}$. Pre oba cykly č. 20 a 21 sa potvrdilo, že v minime slnečnej aktivity je v priemere vyššia (asi 1.5-krát) hustota častíc slnečného vetra ako v maxime.

1. INTRODUCTION

Regardless of the fact that direct observations of the solar wind by man-made satellites have only been available since the beginning of the 1960´s, there is still no solar wind theory which would take into account all the inhomogeneities solar wind observations provide. There is still no adequate theory of its origin, propagaion through interplanetary space and its effect on the Earth and its magnetosphere.

The interrelations between the various solar wind parameters (e.g. density-velocity, particle flow-velocity, temperature-velocity, etc.) are some of the properties which should be included in the solar wind theory. As regards the theoretical modelling of expansion and propagation of the solar wind (hereinafter abbreviated to SW) in interplanetary space, it is also important to know the properties of the quiescent SW with no effects due to the interaction of SW streams with the quiescent background. Consequently, every model of generation and propagation of the SW should take into account the differences in the relations between the SW parameters, for various velocity regimes, as well as various solar activity phases.

Considerable attention has already been devoted in the literature to the relations between the basic SW parameters such as particle density of protons (n), proton temperature (T), particle flux (J) and others in dependence on the solar wind velocity (V) in papers of a number of authors. The relation between temperature and SW velocity was studied, e.g. by Burlaga and Ogilvie (1970a), Burlaga and Ogilvie (1973), Geranios (1982), Lopez and Freeman (1985). A large number of papers deals with the relation between the particle flux (usually only protons) and the SW velocity (e.g., Burlaga and Ogilvie, 1970b; 1973).

The relation between particle density and SW velocity has been studied in the papers by Burlaga and Ogilvie (1970b), Hundhausen et al. (1970), Diodato et al. (1974), Steinitz and Eyni (1980), etc. The individual studies differ in the method used, amount and nature of data processed, or in the data used for the different time intervals. For example, Hundhausen et al. (1970) report results concerning the relation between particle density and SW velocity determined on the basis of observations of SW parameters made on board the Vela-3 satellite and covering the interval from July 1965 to November 1967; in this particular case, the particle density data were averaged over 25 km/s velocity intervals. Burlaga and Ogilvie (1970b) report the results and the relation n(V), determined from Explorer-34 data for the period June-December 1967. Wolfe (1972) gives the results of an analysis of the n(V)-relation based on data from the Pioneer-6 probe for the interval December 1965 to March 1966; he analysed the n(V)- relation using daily averaged values of proton density and SW velocity. Diodato et al. (1974) compared the dependence of proton density on SW velocity for the invervals December 1963 - February 1964 (IMP-1 data), July-December 1965 (Vela-3), June-December 1967 (Explorer-34) and December 1968 - March 1970 (HEOS-1), using the 3-hour averaged values of these parameters as the initial data, which enabled them to study the density-velocity relation for intervals with different degrees of solar activity. Steinitz and Eyni (1980) give the relation between n and V based on data from IMP-6, 7 and 8, whose data they averaged of a whole solar rotation.

Some authors, besides the relation n(V), also studied the relations mentioned above taking into account the distance d from the Sun as a further parameter, n(V,d), or time t, n(V,d,t), e.g. Diodato et al. (1974), Eyni and Steinitz (1980), Steinitz (1983) and Gazis (1984).

The purpose of this paper is to study the relation between the particle density of the SW and the SW velocity, as well as their long-term changes in dependence on the 11-year solar activity cycle.

2. DATA USED AND THE METHOD OF PROCESSING

For the purpose of determining the relations between the particle density and SW velocity in the various phases of the solar cycle, we used the SW data published by King (1977, 1979, 1983) for the interval November 1963 to May 1980 (Bartels rotations Nos 1783-2006), which we obtained on magnetic tape via the NSSDC/WDC-A, Goddard Space Flight Center, Greenbelt, Maryland, USA. Since we studied the above relations on a large time scale, we used daily averaged values of the SW velocity and density as the initial data for further processing. We investigated the relation n(V) only for the constant distance of 1 AU from the Sun, due to the nature of the data we used (King, 1977, 1979, 1983). The range of the data, which cover nearly two whole solar cycles, Nos 20 and 21 (with the exception of the minimum of cycle 21), made it possible to study the changes of the density-velocity relation in dependence on the individual phases of the 11-year solar activity cycle. The studied interval of Bartels rotations Nos 1783-2006 was divided into separate phases as is given in Tab. 1. Division of the whole analysed time interval into the separate pha-

Table 1

Serial number of solar cycle	Solar cycle phase	Time interval (month, year)	Time interval (Bartels rot.)
20	minimum	November 1963 - - December 1965	1783 - 1811
	ascending branch	December 1965 - - October 1967	1812 - 1835
	maximum	October 1967 - - November 1970	1836 - 1877
	descending branch	November 1970 - - October 1974	1878 - 1930
21	minimum	October 1974 - - August 1977	1931 - 1969
	ascending branch	August 1977 - - December 1978	1970 - 1987
	maximum	December 1978 - - May 1980	1988 - 2006

ses of the solar cycles Nos 20 and 21 was done on the basis of visual inspection of the course of monthly smoothed relative sunspot numbers. The division introduced by Hoeksema (1984) that was based mainly on physical consideration (large-scale solar and heliospheric magnetic field configuration) was also taken into account for the 21^{st} solar cycle.

The data were analysed with regard to determining the n(V)-relation in each phase of the solar activity cycles separately for:

a) all days, i.e. also on days on which high-speed streams occurred;

b) the days when no high-speed streams occurred.

The days on which high-speed SW streams occurred, and which were not included to the processing per b), were taken from the catalogue of high-speed SW streams (Kulčár et al., 1984).

The density-velocity relation was approximated for each phase of the solar cycle using the method of least squares as

$$\log n = a + b \log V, \qquad (1)$$

where a and b are constants for a particular solar cycle phase. Besides this, we determined the correlation coefficient r of the values log n and log V, which represented a supplementary parameter providing information about the closeness of n(V)-relation.

Since the n(V,t)-relations were studied from the point of view of large-scale time structures, we then divided the whole velocity interval, in which the daily averaged values of the SW density and velocity occurred, into narrower velocity intervals separately for all solar cycle phases. The velocity intervals were taken to be $\Delta V = 50$ km/s as follows: $200 \leq V < 250$ km/s, $250 \leq V < 300$ km/s, $300 \leq V < 350$ km/s, etc., up to the maximum velocity which occurred in the particular cycle phase. We determined the average particle density for each of these velocity intervals using the data relevant to each velocity interval.

3. RESULTS AND DISCUSSION

Using the methods described above, we determined the values of constants a and b and of the correlation coefficient r, characterizing the relation between the particle (proton) density and SW velocity, as well as the average values of the densities n for the given velocity intervals in the various phases of the 11-year solar activity cycles Nos 20 and 21. The values of parameters a and b, and of the correlation coefficient r for these phases are given in Tabs 2 and 3.

Table 2

Solar cycle phase		r	a	b	N
Minimum	of cycle 20	-0.51	4.8	-1.5	203
Ascending branch	of cycle 20	-0.36	3.6	-1.1	512
Maximum	of cycle 20	-0.46	4.7	-1.6	647
Descending branch	of cycle 20	-0.54	4.3	-1.3	1016
Minimum	of cycle 21	-0.68	5.2	-1.6	950
Ascending branch	of cycle 21	-0.52	4.9	-1.5	475
Maximum	of cycle 21	-0.48	4.8	-1.5	474

Table 3

Solar cycle phase		r	a	b	N
Minimum	of cycle 20	-0.48	5.1	-1.6	170
Ascending branch	of cycle 20	-0.29	3.7	-1.1	422
Maximum	of cycle 20	-0.36	4.6	-1.5	525
Descending branch	of cycle 20	-0.40	4.7	-1.5	710
Minimum	of cycle 21	-0.47	5.3	-1.7	656
Ascending branch	of cycle 21	-0.46	5.6	-1.8	379
Maximum	of cycle 21	-0.43	5.1	-1.6	392

Table 2 gives the results for all days, including those on which high-speed streams occurred, Tab. 3 gives the values for the days on which these streams were absent. The last column of each table gives the number of days (N) used to determine parameters a, b and r. As regards the values in Tabs 2 and 3 (mainly the parameter a), it should be pointed out that they were obtained for particle densities expressed as the number of particles per cu.cm. This manner of expressing the n-values was chosen in this case in order to make the results compatible with the data published in the literature, where particle concentration is usually expressed in units of cu.cm.

Besides the results given in Tabs 2 and 3, we also give the results of calculating constants a and b and of the coefficient of correlation r for the case in which the input data were the average values of n and V for the individual Bartels rotations covering the whole period of November 1963 to May 1980. We obtained the following values:

$a = 2.8, \quad b = -0.7, \quad r = -0.26,$

the number of input pairs being $N = 191$.

To estimate the accuracy of the results of the regression analysis, whose results are given in Tabs 2 and 3, the following should be mentioned: As regards the relation n(V), which in this case was obtained by fitting a regression line to pairs of values log n and log V using the least-squares method, this case was more complicated than simple linear regression, because the density values n as well as the velocities V were subject to observation errors. Therefore, the accuracy in determining the parameters of the regression line a and b, obtained by the least-squares method, was tested in two ways:

- by interchanging the independent and dependent variable (in this particular case log V and log n),
- by testing the significance of the correlation coefficient according to the t-distribution (Student´s test) at two levels of significance, $p = 0.05$ and $p = 0.01$. The results of both these testing methods indicate sufficient statistical significance of the relation between the density and SW velocity, the results for the ascending phase of cycle 20 being the least accurate and the results for the minimum of cycle 21 being the most accurate.

Figures 1a-g, 2 and 3 show the results of the statistical processing of the density n in dependence on the SW velocity V using the method of division into velocity intervals. Figures 1a-g show n(V) for the separate phases of cycles 20 and 21 together with the standard deviations of the average density values. Figures 2 and 3 represent a superposition of Figures 1a-d and 1e-g, respectively, and provide an illustrative overview of the changes of n(V) with time. The relations n(V) and n(V,t) in Figs 1a-g, and 2 and 3, respectively, refer to all days including those on which high-speed SW streams occurred. The abscissae give the velocity intervals in such a way that, e.g., the value 200 km/s, marked on the graph, corresponds to the velocity interval $200 \leq V < 250$ km/s, etc.

Based on the results given in Tabs 2 and 3 and in Figs 1a-g, 2 and 3, the following conclusions can be drawn:

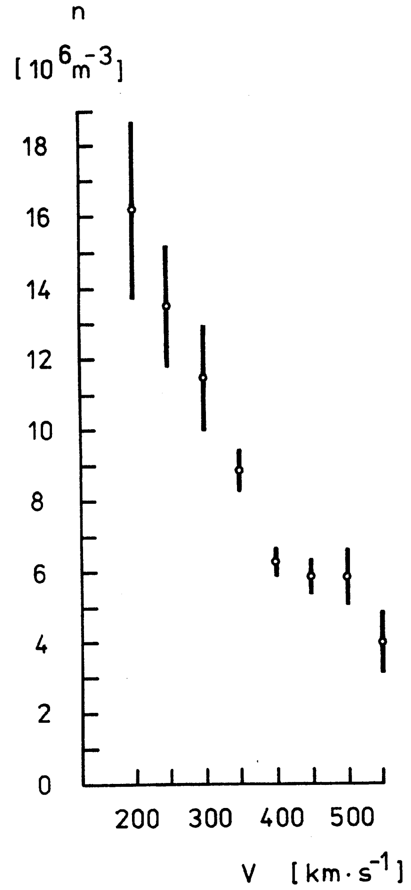

Fig. 1a. Graph of the solar wind density-velocity relation for the minimum of solar activity cycle 20.

It has been proved that the concentration (density) of particles (protons) decreases with increasing SW velocity. The same conclusion was drawn by Hundhausen et al. (1970), Burlaga and Ogilvie (1970b), Wolfe (1972), Diodato et al. (1974), Neugebauer (1976) and others.

The particle concentration displays a decrease with increasing SW velocity in all phases of solar activity cycles 20 and 21. This conclusion agrees with that of Diodato et al. (1974) who claim that the average values of the proton concentration are subject to long-term variations with the cycle under quiescent as well as disturbed SW velocity regimes.

In the majority of the phases of cycles 20 and 21 (with the exception of the ascending phase of cycle 20), the dependence of the particle concentrati-

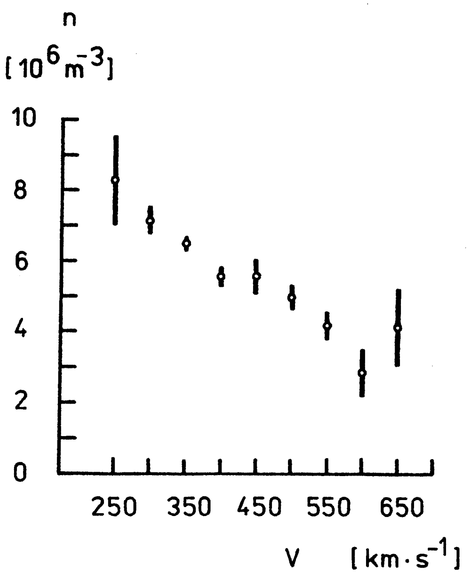

Fig. 1b. Graph of the solar wind density-velocity relation for the ascending phase of solar activity cycle 20.

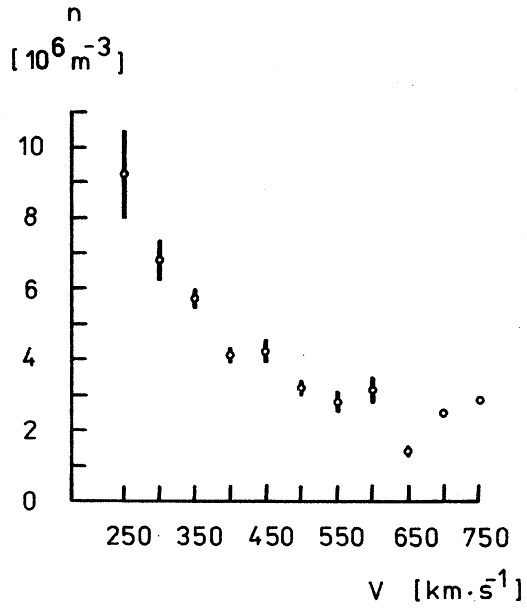

Fig. 1c. Graph of the solar wind density-velocity relation for the maximum of solar activity cycle 20.

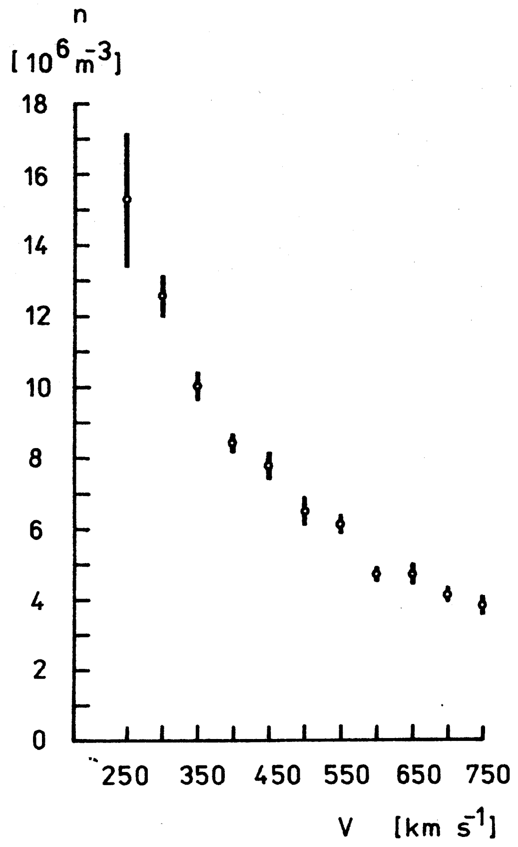

Fig. 1d. Graph of the solar wind density-velocity relation for the descending phase of solar activity cycle 20.

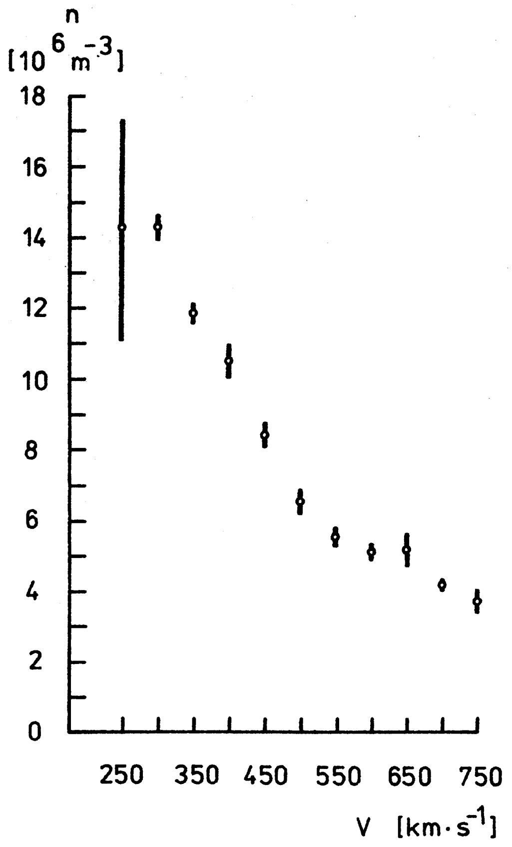

Fig. 1e. Graph of the solar wind density-velocity relation for the minimum of solar activity cycle 21.

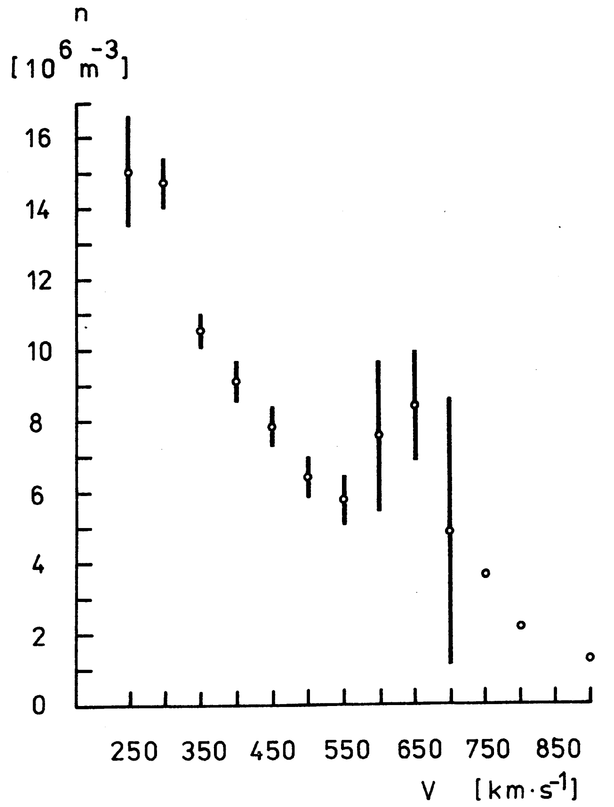

Fig. 1f. Graph of the solar wind density-velocity relation for the ascending phase of solar activity cycle 21.

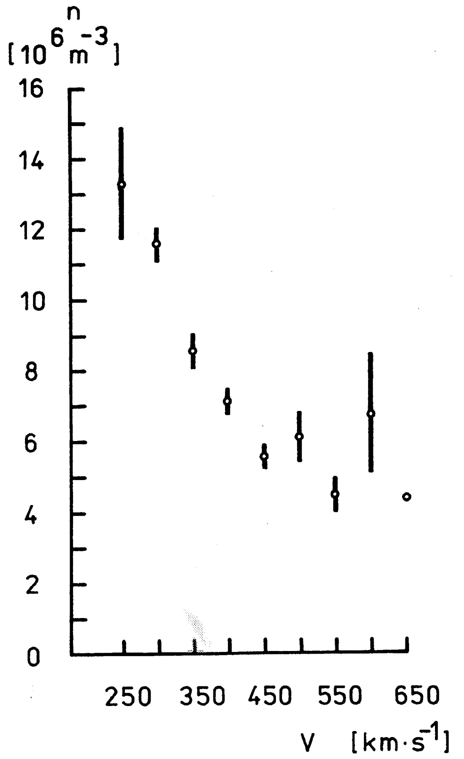

Fig. 1g. Graph of the solar wind density-velocity relation for the maximum of solar activity cycle 21.

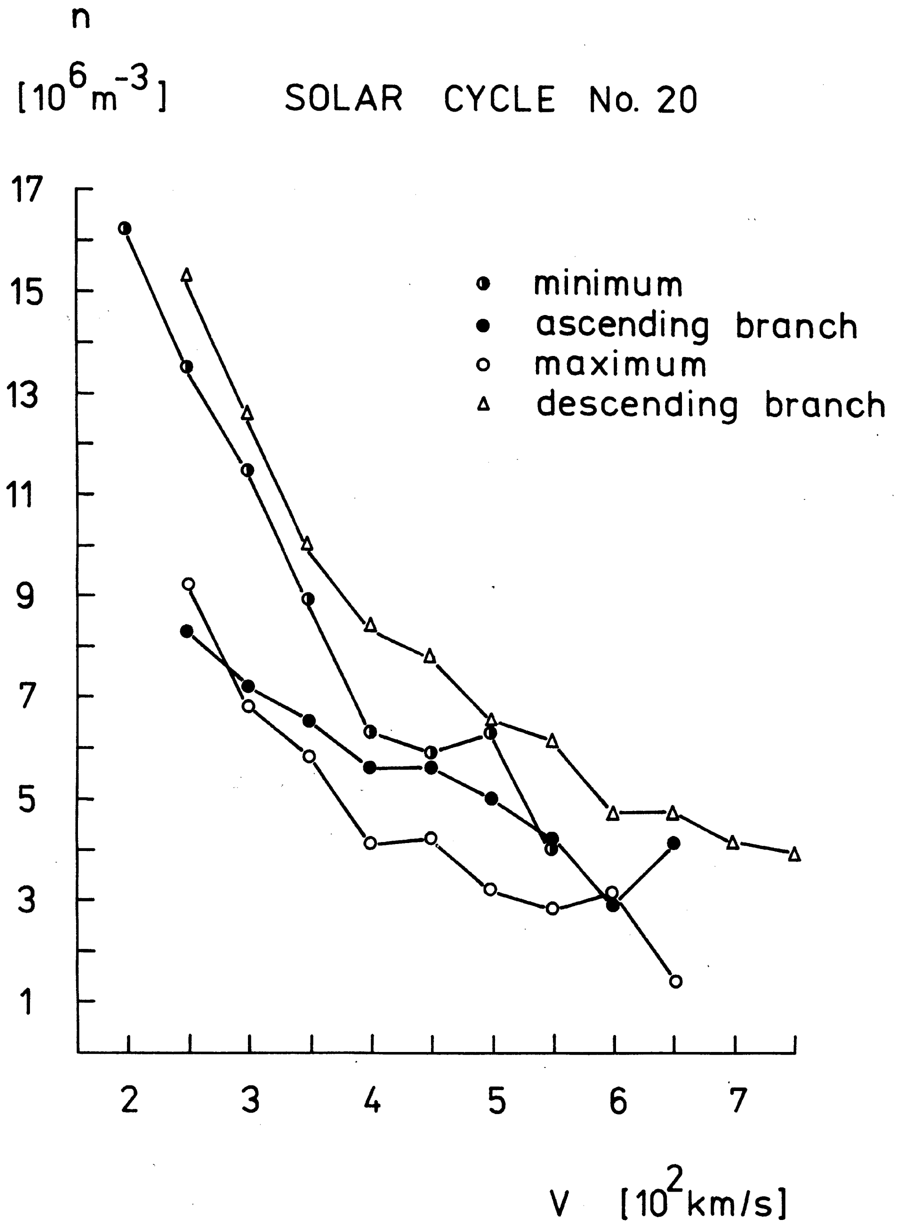

Fig. 2. The solar wind density-velocity relation for solar activity cycle 20.

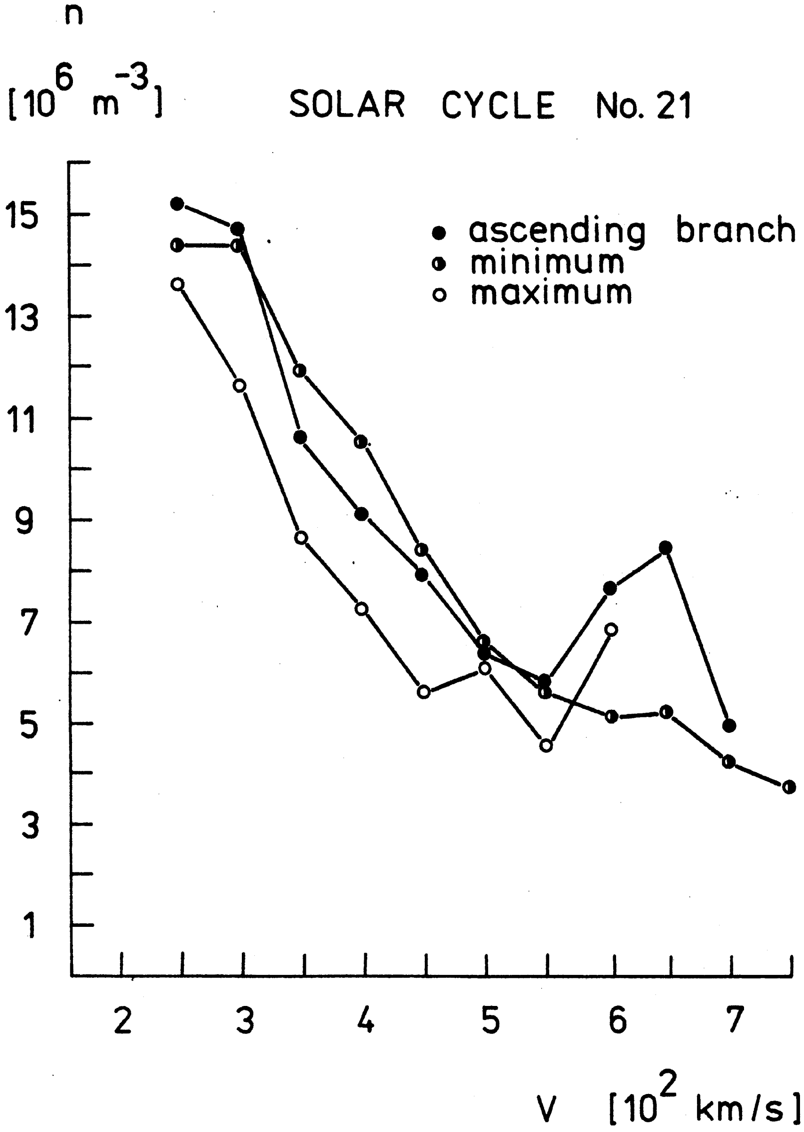

Fig. 3. The solar wind density-velocity relation for solar activity cycle 21.

on on velocity can be expressed approximately by the functional dependence $n \sim V^{-1.5}$. In the ascending branch of cycle 20 this dependence can be expressed in the form $n \sim V^{-1.1}$. The results we have obtained agree well with the results reported by other authors in the literature. For example, Wolfe (1972) used Burlaga's and Ogilvie's data (1970b) and after supplementing them with data obtained by other satellites and probes (IMP-1, HEOS-1, Pioneers 6 and 7, etc.) he reported this dependence as $n \sim V^{-1.5}$. Hundhausen et al. (1970) present this dependence as $n \sim V^{-1}$ for velocities lower than 500 km/s and the interval of July 1965 to November 1967 (which covers partly the minimum period and mainly the ascending phase of cycle 20), and this is good agreement with the value of the exponent, -1.1, we obtained for the ascending phase of cycle 20. The value is the lowest value (in absolute value) of the exponent b in Eq. (1) of all the values given in Tabs 2 and 3. These low values of the exponent are caused by low values of the particle density being recorded at low SW velocities, as compared to the other phases of cycles 20 and 21, during the ascending phase of cycle 20, whereas the densities for high velocities were not lowered markedly. It is interesting to note that no anomaly of this kind was registered during the ascending branch of cycle 21. The physical explanation of this effect is not clear.

The values of constants a and b and of the correlation coefficient r do not display any characteristic trend with time. A certain trend may possibly be seen in the data in Tab. 2, in which there is some indication of a decrease of all three parameters, a, b and r (decrease in their absolute values) between the minimum and maximum of cycle 21. We can see from these changes that the correlation between the quantities n and V is decreasing (change in the correlation coefficient from -0.68 to -0.48).

As regards the descending phase of cycle 20, Tabs 2 and 3 indicate that the value of exponent b in this period is lower (in absolute value) as compared to its values in the other phases of the solar cycle (with the exception of the value -1.1 for the ascending phase of cycle 20, which has already been discussed above). The low values of exponent b during the descending phase are probably due to the presence of a larger number of high-speed streams.

Tables 2 and 3 show that the value of exponent b, under a relatively quiescent SW structure (see Tab. 3 - data without high-speed streams), is higher for most of the phases of cycles 20 and 21. Exceptions are the phases of the maximum of cycle 20, when this relation is inverted, and the ascending phase of cycle 20, when the values of the exponent are the same. It follows that, in the quiescent SW velocity structure, the slope of the line representing the relation between log n and log V is steeper, whereas under higher velocities the slope is more gradual. This is caused by the presence of high-speed streams in the SW velocity field in all phases of cycles 20 and 21, evidence of which are the different values of N in the last columns of Tabs 2 and 3.

The higher values of correlation coefficients in Tab. 2 against the same values in Tab. 3 give evidence about the fact that the inverse correlation of the n(V)-relation is closer for the cases when high-speed solar wind streams are also taken into consideration in processing than for the quiet SW only. In the result that is expressed via the values of r in Tabs 2 and 3 is reflected the fact that high-speed SW streams are in general in their nature the regions with lower particle density than their surroundings. The exceptions are high density compressions at the leading edge of the streams. The influence of these compressions is very restricted in this case because of their short duration in domparison with the whole duration of the stream.

Steinitz and Eyni (1980) give the following values for the n(V)-relation, determined on the basis of the average values of n and V for solar rotations (56 values from IMPs 6, 7 and 8 covering the period 1971-1974): a = 3.95, b = -1.12. The values we obtained, i.e. a = 2.8 and b = -0.7, differ from Steinitz´s and Eyni´s values which may be due to the different initial values of n and V covering different time intervals.

Figures 2 and 3 display a tendency in the changes of the n(V)-relation in dependence on the phases of solar activity cycles. Comparing the n(V)-relations in individual phases of solar cycles 20 and 21, the average values of the particle density decrease for the given velocity ranges in the following order: descending phase, minimum, ascending phase and maximum. It follows that SW particle concentration is higher on the average in the minimum than in the maximum of solar activity. According to our data, the factor of SW particle contentration increase in cycles 20 and 21 between the maximum and minimum is about 1.5, which agrees well with the result of Diodato et al. (1974) who give the values as 1.5 - 2.0. This factor of increase is too large to enable these changes in concentration to be ascribed to observation errors, instrumental errors, or to the difference in the methods of processing the data used. Moreover, this increase in concentration between maximum and minimum is observed in all velocity ranges. We may thus conclude that the increase is a real phenomenon.

The comparison of the SW particle density and the electron density in the corona in dependence on the 11-year cycle of solar activity indicates that the variations in the particle concentration in the corona and solar wind display a phase shift: whereas the maximum of the particle concentration in the corona is observed at the time of maximum solar activity, the maximum of the SW particle concentration is displaced to the descending phase of the 11-year cycle. This phase shift is very probably caused by the solar magnetic field and its actual configuration which, in the maximum of solar activity, prevents the escape of a large amount of plasma from the Sun, whereas at the time of lower solar activity, when the number of active regions on the Sun gradually decreases, their mutual relations, mediated by magnetic fields simplifies, thus creating conditions for easier escape of the solar plasma in the form of solar wind into interplanetary space.

Diodato et al. (1974) claim that, under velocities of less than 300 km/s, the average values of the SW particle concentration observed at the time of the solar maximum (1968) were roughly the same as the values observed during the minimum (1965) of cycle 20. Our results do not support the conclusion of Diodato et al. (1974) for cycle 20. According to our data, the values of the average particle densities for velocities below 300 km/s during the solar minimum differ considerably from the values for the maximum. The values we obtained for the minimum of cycle 20 were in the range (12.0 - 18.5)x10^6 m^{-3}, whereas for the maximum of cycle 20 (6.0 - 10.5)x10^6 m^{-3}. For the same velocity ranges and phases of cycle 20, Diodato et al. (1974) reported the values (9.5 - 14.0)x10^6 m^{-3} and 13.5x10^6 m^{-3}, respectively. The difference is not negligibly small and cannot be ascribed to inaccuracies. For low velocity ranges, this difference is quite distinct not only in the ascending and descending phases of cycle 20, but also in the maximum and minimum. On the other hand, however, for cycle 21 we obtained results which agree with the conclusions of Diodato et al. (1974). Figures 1e, 1g and 3 show that, in this case, the differences are minimal, (11.0 - 17.5)x10^6 m^{-3} and (11.5 - 15.0)x10^6 m^{-3}, and can be ascribed to the errors and inaccuracies in the data. Similarly, in the ascending phase of cycle 21 the particle density is around 15.0x10^6 m^{-3} under low SW velocities.

Figures 1a-g, 2 and 3 show that the dependence n(V) is not "smooth" for all phases of the solar cycles, but that the particle concentration displays an increase at certain velocities of the SW. In some cases this increase is also observed at two different velocities.

In solar cycle 20, the density values increase at velocities between 450 and 500 km/s, except in the minimum when the increase is observed at SW velocities between 500 and 550 km/s. The second local maximum of the increased n-values occurs at velocities of 600 to 700 km/s. In cycle 21, the double local maximum of increased n-values occurs only during the cycle maximum, the first at velocities of 500 to 550 km/s and the second at 600 to 650 km/s. As regards the other phases of cycle 21, only one maximum can be observed, which is more pronounced as compared to those in cycle 20, at velocities of 600 to 700 km/s. The comparison of the occurrence of the local maxima of the n-values in cycles 20 and 21 indicates that the first increase in cycle 20 as compared to the first increase in cycle 21, is displaced towards lower SW velocities, whereas the second increases fall within the same velocity interval in both the cycles.

Similar increases in the n-values can also be seen in the data reported by Diodato et al. (1974) who, apart from two local increases at high velocities, also reported another increase at low velocities of around 350 km/s, which we did not observe.

The increases in the SW particle density mentioned above can be explained by the presence of density compressions observed at the leading edge of the high-speed streams which are generated by the interaction of fast SW streams with the slow background SW velocity field during its propagation through the interplanetary medium (see, e.g., Kane, 1974; Montgomery et al., 1972).

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