LARGE-SCALE CHANGES IN THE INTENSITY OF THE GREEN CORONA AND THEIR REFLECTION IN THE SOLAR WIND PARTICLE FLUX
PART 1: THE EQUATORIAL PROBLEM

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Received 17 September 1986

ABSTRACT. The way marked changes of the intensity of the green emission corona from the region of the solar equator are reflected in the solar wind particle flux is studied. The analysis is large-scale in terms of space and medium-scale in terms of time, and covers the period from November 1963 to October 1976. The analysis, based on a quantitative as well as qualitative approach, indicates that an increase or decrease in the solar wind particle flux is observed with equal probability after an increase in the intensity of the green corona. However, a marked decrease in the intensity of the green corona is accompanied by an increase in the solar wind particle flux with a probability exceeding 70 %. A possible interpretation of the statistical results is also given.

ИЗМЕНЕНИЯ ИНТЕНСИВНОСТИ КРУПНОМАСШТАБНЫХ СТРУКТУР ЗЕЛЁНОЙ КОРОНЫ И ИХ СВЯЗЬ С ПОТОКОМ ЧАСТИЦ СОЛНЕЧНОГО ВЕТРА. ЧАСТЬ I: ЭКВАТОРИАЛЬНЫЙ СЛУЧАЙ. В работе исследована связь значительных изменений интенсивности зелёной эмиссионной короны из области солнечного экватора с потоком частиц солнечного ветра. Анализ сделан для пространственно крупномасштабных и временно среднемасштабных структур солнечной короны для временного интервала с ноября 1963г. до октября 1976 г. Из анализа, основанного на количественном и качественном подходах, вытекает, что повышение интенсивности зелёной короны приводит почти с одинаковой вероятностью к повышению или к понижению потока частиц солнечного ветра. С другой стороны, большому понижению интенсивности зелёной короны соответствует с вероятностью больше чем 70 % повышение потока частиц солнечного ветра. Приводится также возможная интерпретация статистических результатов.

VEĽKOŠKÁLOVÉ ZMENY V INTENZITE ZELENEJ KORÓNY A ICH ODRAZ V TOKU ČASTÍC SLNEČNÉHO VETRA. ČASŤ 1: ROVNÍKOVÝ PROBLÉM. V práci je študované, ako sa výrazné zmeny intenzity zelenej emisnej koróny z oblasti slnečného rovníka odrážajú v toku častíc slnečného vetra. Analýza je robená z hľadiska priestorovo veľkoškálového a časovo strednedobého pre obdobie od novembra 1963 do októbra 1976. Z analýzy založenej tak na kvantitatívnom ako aj na kvalitatívnom prístupe vyplýva, že po zvýšení intenzity zelenej koróny sa pozoruje približne s rovnakou pravdepodobnosťou zvýšenie alebo zníženie toku častíc slnečného vetra. Avšak, na druhej strane, výrazný pokles intenzity zelenej koróny je sprevádzaný vzrastom toku častíc slnečného vetra s pravdepodobnosťou väčšou ako 70 %. Je uvedená tiež možná interpretácia štatistických výsledkov.

1. INTRODUCTION

The problems of research into the properties of the solar corona in relation to the condition of interplanetary medium are quite extensive and complicated. The study of the mutual relations between the solar corona, solar wind and interplanetary medium as a whole became important namely when it was found that the latter was a link via which the Sun influences and affects the Earth. This medium has the capability to change, in a certain way and to a certain extent, the properties and impact the parameters characterizing the original agent generated on the Sun, modulate it in time, space and intensity. This is the reason why the relation between the solar corona and the properties of interplanetary medium is complicated, why it depends on many factors whose role and extent of influence are still not sufficiently known.

The relation of the solar corona in general, as well as that of one of its components, the green emission corona (Fe XIV, $\lambda = 530.3$ nm), to various parameters of the solar wind has been studied in a large number of papers. For example, Pathak (1971) found a positive correlation between the intensity of the green corona and the solar wind velocity. Kovalenko and Malyshkin (1976) proved that, in general, the positive correlation between the intensity of the green corona and the solar wind velocity was not beyond doubt, but that, on the contrary, it was negative during some intervals of time. A similar conclusion was also drawn by Gulbrandsen (1974), Roelof et al. (1975) and others.

In most of the studies devoted to these problems, only the relations between the values of the green corona intensity and the values of the solar wind velocity were investigated. The purpose of the present paper is to determine whether there is a connection between the time variations of the green corona intensity and the variations of the solar wind particle flux. The study of this problem was prompted by the fact that the white as well as the green solar corona can be considered, to a certain extent, as an indicator of the content of free particles (in the broader sense of plasma) in the solar corona. Although the brightness of the green corona is also a function of the plasma temperature (see, e.g., Shklovskij, 1962), it has been found that the temperature contributes to the variations of the green corona intensity only secondarily (Korzhov, 1985; Newkirk: in Wolfe, 1972; Nikol´skaya, 1985). In formulating the present problem, we drew on the observation which indicated that, in the process of dynamic changes taking place from time to time in the configuration of the magnetic fields on the Sun and in its atmosphere, a certain amount of plasma escapes into interplanetary space, usually carrying with it the non-radial components of the magnetic field B_ϑ and B_φ , and usually with a particle density different to that of the immediate neighbourhood. A similar process may also take place if, for some reason, the complicated and hitherto compact structure of the magnetic fields is upset completely, thus rendering the magnetic lines of force within a limited volume divergent (open) and enabling a continuous escape of particles from the corona into interplanetary space. In the opposite case, when the lines of force close above a particular place, we should observe, for a certain period, a deficit in the plasma flowing from the region of the solar corona involved.

2. MATERIAL USED AND THE WAY IT WAS PROCESSED

For the purpose of studying the reflection of the variations of the green corona intensity in the solar wind particle flux, we have used the following two types of data:

- Three-point smoothed homogenized series of diurnal intensities of the green emission corona from November 1963 to October 1976, which were arranged into synoptic tables by Bartels rotations (Bartels rotations Nos. 1783-1957). A detailed description of the data, the manner in which they were obtained, their homogenization and smoothing can be found in the papers of Sýkora (1971a, 1971b, 1971c, 1975, 1982) and of Letfus and Sýkora (1982).
- Average diurnal values of velocities and concentrations of solar wind particles for the same period. The solar wind data were obtained with a time resolution of one hour by probes close to the Earth and were made available by the NSSDC/WDC-A, Greenbelt, USA (King, 1977; 1979; 1983).

We considered the solar wind particle flux J, defined as

$$J = nV \qquad (1)$$

where n is the particle density and V the solar wind velocity, as the most convenient and physically justified parameter of the solar wind, in the variations of which we studied the reflection of the changes of coronal intensities.

Because of the nature of the coronal data which were available, we studied the relations between the corona and solar wind, mentioned above, on a spatially large-scale basis. As regards the time resolution, we studied the changes in intervals of a medium length, i.e. with a time resolution of one Bartels rotation, in other words, changes of the parameters involved from one Bartels rotation to the next. In terms of space, we restricted ourselves to the latitudinal zone centered at the solar equator, 40° wide in heliographic latitude, ranging from -20° to $+20^{\circ}$. The reflection of the variations of coronal intensity related to higher heliographic latitudes in the solar wind particle flux will be studied in Part 2 of this paper.

Since the above relations are being studied from a large-scale point of view, we adopted the following procedure in processing the data: Each of the latitude zones, centred around the solar equator, was divided in each Bartels rotation into 9 smaller areas (boxes), each of which amounted to 40° (or 3 days) in heliographic longitude. Since the spatial resolution of the original coronal data in heliographic latitude was 5°, each of these boxes contained 27 coronal intensity data. Their average represents the value characterizing the mean intensity of the corona $I_{i,j}$ of the j-th box during the i-th Bartels rotation. We then determined the relative changes of intensity between one (i-th) and the next (i+1st) Bartels rotation for the particular j-th box using the relation

$$\Delta I_{i,j}^{rel} = \frac{I_{i,j} - I_{i-1,j}}{I_{i,j} + I_{i-1,j}} \qquad (2)$$

where i is the ordinal number of the Bartels rotations (i = 1784,1785,..., 1956,1957), and j is the ordinal number of the box within a particular Bartels rotation (j = 1, 2, ..., 8, 9); the index "rel" indicates that a relative change is involved.

The nature of the available coronal data only enabled us to study large-scale changes in the corona, so that we restricted ourselves just to the pairs of rotations for which the relative changes of the coronal intensities satisfied the condition

$$\left|\Delta I_{i,j}^{rel}\right| \geq 0.2 \quad . \qquad (3)$$

It is evident that the relative changes of coronal intensities in themselves are not a sufficient characteristic of the coronal changes from rotation to rotation. Consequently, to condition (3) we added another condition which reflects a certain limitation imposed on the changes of coronal intensities expressed in absolute units:

$$\left|\Delta I_{i,j}^{abs}\right| \equiv \left|I_{i,j} - I_{i-1,j}\right| \geq M \qquad (4)$$

where the indices i and j have the same meaning as in (2) and M is a parameter. The value of parameter M was taken to be variable and dependent on the average level of solar activity, which in fact eliminated the 11-year solar activity cycle. The values of parameter M as a function of $I_{i,j}$ are given in Tab. 1.

Table 1

$I_{i,j}$ (absolute coronal units)	M (absolute coronal units)
0 - 10	5
11 - 50	10
51 - 100	20
101 - 150	30
151 and over	40

Figure 1 shows two synoptic maps of the green corona, borrowed from the Atlas of the Green Corona (Letfus and Sýkora, 1982) as an example; they show a conspicuous decrease of the average coronal intensity in the region of the solar equator and boxes 6 and 7 between rotation 1952 and 1953.

Figure 2 depicts all the cases which were indicated in the studied period by the program to satisfy conditions (3) and (4), as well as Eq. (2) and Tab. 1 for selecting cases with large relative and absolute changes of the corona. In Fig. 2 the Bartels rotations are arranged in groups of five, each rotation being divided into 9 boxes 3 days in longitude. The white circles in the appropriate boxes indicate the occurrence of large changes in coronal intensity with a positive character of the change, the oblique line segments indicate the occurrence of negative changes (according to Eq. (2)).

We shall now describe the method used to evaluate the reflection ot the changes in the green corona in the particle flux J of the solar wind. We determined the average diurnal values of the densities and velocities, as well as the average diurnal values of the solar wind particle flux using Eq. (1), for every day on which at least 12 hourly values of density and solar wind velocity were available. Since the coronal data we used were, on the one hand, three-point smoothed with decreasing heliographic longitude and, on the other, averaged in the 9 boxes of each Bartels rotation, we converted the values of the solar wind particle flux to dimensionless indices J, ranging from 0 to 20, using the key given in Tab. 2.

The time required for the solar wind particles to cover the distance between the Sun and the Earth was taken to be 4 days in all cases, which corresponds to a uniform velocity of solar wind propagation of about 430 km/s.

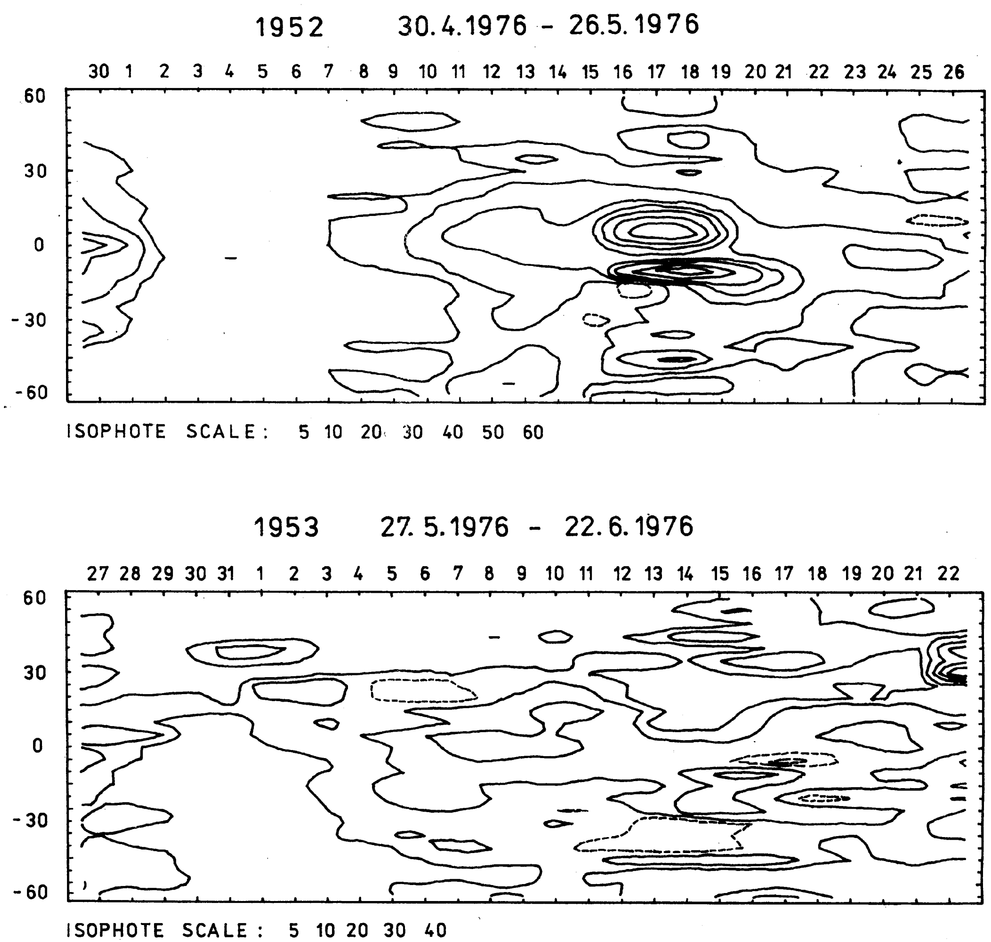

Fig. 1. Two synoptic maps of the green corona borrowed from the Atlas (Letfus and Sýkora, 1982) which show marked decrease of coronal intensity in the region of the solar equator between rotation no. 1952 and 1953.

The absolute changes in the solar wind particle flux $\Delta J^{abs}_{i,j}$, which characterized the absolute changes in the particle flux from the (i-1)st to the i-th rotation for a particular j-th 3-day interval were determined using the relation

$$\Delta J^{abs}_{i,j} = \sum_{k=1}^{3} J^{k}_{i,j} - \sum_{k=1}^{3} J^{k}_{i-1,j} \qquad (5)$$

where i and j have the same meaning as in Eq. (2) and k is the ordinal index of the day in the 3-day interval.

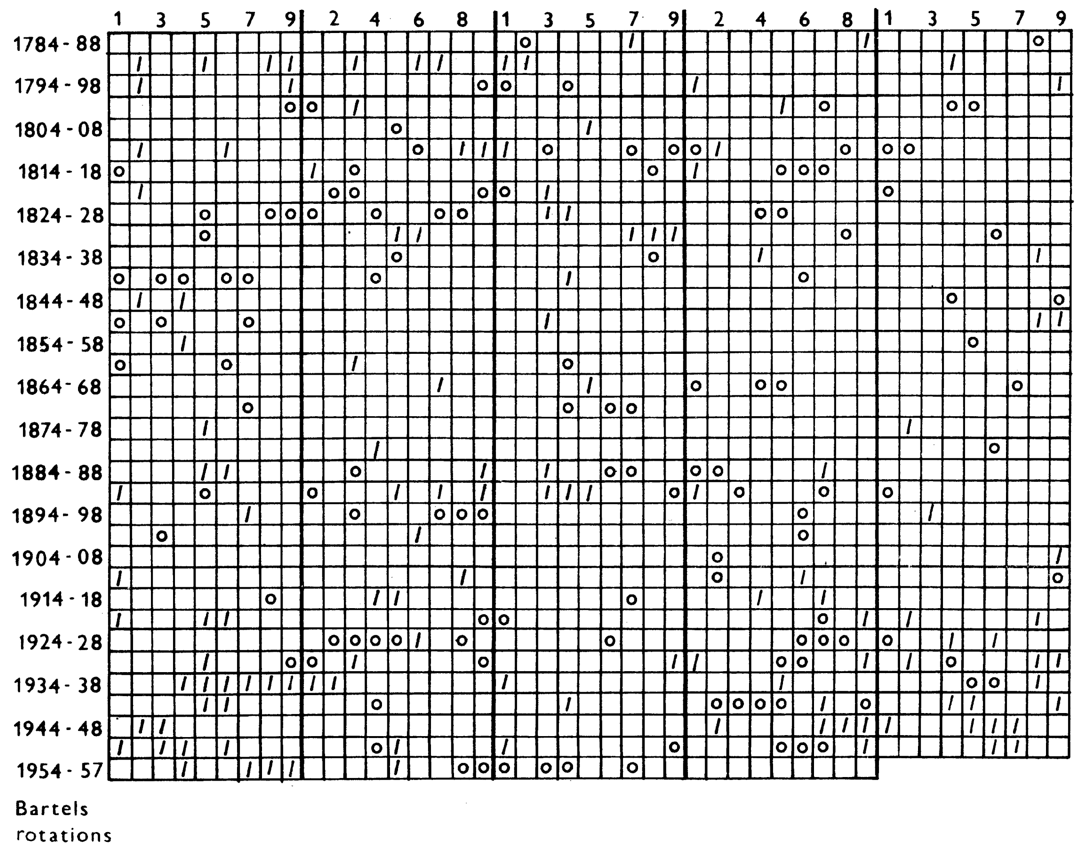

Fig. 2. Illustration of the occurrence of marked changes in the intensity of the green corona in Bartels rotations Nos 1784-1957.

Table 2

J (10^{12} m^{-2} s^{-1})	J
0.00 - 0.99	0
1.00 - 1.49	1
1.50 - 1.99	2
2.00 - 2.49	3
.	.
.	.
.	.
9.50 - 9.99	18
10.00 - 10.49	19
10.50 and over	20

In Eq. (5) the summation is over all three days of the 3-day interval, the days on which the particle flux data, J, were lacking because no data on particle density and solar wind velocity were available, were disregarded in the summation.

Besides the absolute value of the change in the solar wind particle flux J, we also determined two types of relative changes, i.e.

$$\Delta J_{i,j}^{rel1} = \frac{\sum_{k=1}^{3} J_{i,j}^{k} - \sum_{k=1}^{3} J_{i-1,j}^{k}}{N_k} \qquad (6)$$

and

$$\Delta J_{i,j}^{rel2} = \frac{\sum_{k=1}^{3} J_{i,j}^{k} - \sum_{k=1}^{3} J_{i-1,j}^{k}}{\sum_{k=1}^{3} J_{i,j}^{k} + \sum_{k=1}^{3} J_{i-1,j}^{k}} \qquad (7)$$

where N_k in (6) is the number of days in the 3-day interval for which data on the solar wind particle flux were available. Equation (6) thus expresses the average change in the particle flux J per day of the 3-day interval.

Apart from the method of expressing the changes in the corona and particle flux, mentioned above, we also made use of its modification. This modified method differs from that described above only in that the length of the interval or box was increased to 6 (i.e. two 3-day interval adjacent to each other) or more days (several 3-day boxes next to one another). In combining two or more adjacent boxes displaying marked changes in coronal intensities, only one condition was imposed on the 3-day boxes: two adjacent boxes had to display the same nature of changes (i.e. either decrease or increase) of coronal intensities. The 3-day boxes were combined regardless of the Bartels rotations. As examples of combining several 3-day boxes we can give boxes 6 and 7 in Bartels rotation No. 1790, or boxes 8, 9 and 1 in Bartels rotations Nos. 1810 and 1811 (see Fig. 2). We thus came up with boxes of different lengths which varied, in terms of days, from 6 to a maximum of 24 (Bartels rotations 1934--1935).

There were several reasons for combining the 3-day boxes into larger units:

1) The fact that the original coronal intensities, which we used as the initial data for creating the 3-day boxes, had already been smoothed by the authors of the Atlas (Letfus and Sýkora, 1982).

2) Our objective was to study large changes in the coronal intensities on a large-scale basis. If manifestations of solar activity such as activity complexes, which are also reflected in the solar corona, are distributed in heliographic longitude over more than 40° (3 days) (Bumba et al., 1982), this procedure conformed to our objective.

3) Of the total number of 264 3-day boxes 135 (i.e. more than 51 %) occurred in groups of two or more boxes adjacent to each other. This is evidence that more than one half of the large changes in the corona take place in areas covering 80° and more in heliographic longitude.

4) Another reason for using the modified method was that the likelihood of determining real changes in the particle flux increased if boxes longer than 3 days were used when data on particle density and solar velocity were not available for all days involved. In using the 3-day boxes, we frequently came across in which only 1 or 2 days of the 3-day interval were covered by particle flux data in both Bartels rotations simultaneously.

5) Yet another reason in favour of combining the boxes was that the time lag between the time of observing the corona and of recording the solar wind particle flux in the vicinity of the Earth (the transit time), which we took to be 4 days for all cases, actually differed from case to case. Although a transit time of about 4 days is the most probable for solar wind particles of a medium velocity (430 km/s), and although this value is frequently referred to in the literature (e.g. Bumba and Hejna, 1985), this transit time may in fact vary for different reasons from 2 to 6 days, which corresponds to velocities of about 870 to 290 km/s.

3. RESULTS, THEIR ANALYSIS AND DISCUSSION

In the period of Bartels rotations 1783-1957 being studied, there were 264 cases in which marked changes in coronal intensity relative to the intensity in the preceding Bartels rotation occurred in the 3-day boxes. However, since the solar wind particle flux data were not available for some of the days, we were only able to analyse 162 3-day boxes of the total number given above after eliminating the days for which no solar wind data were available. Table 3 gives the results of the quantitative analysis based on determining the correlation coefficient (hereinafter referred to as c.c.) between the changes in the coronal intensity and in the solar wind particle flux. The second column of Tab. 3 (marked "absolute changes") gives the c.c. between the changes of coronal intensity and particle flux expressed in absolute value and determined using Eqs (4) and (5), Column 3, marked "relative changes rel1", gives the c.c. between the relative coronal changes, determined on the basis of Eq. (2), and the relative changes of the particle flux, determined from Eq. (6); Column 4 gives the c.c. between the relative changes of the corona (Eq. (2)) and the relative changes of the particle flux, derived from Eq. (7) (marked in the table as "relative changes rel2").

Table 3

Nature of boxes	Correlation coefficients — Nature of changes: absolute changes	relative changes rel1	relative changes rel2
3-day boxes	-0.03	-0.07	0.01
6- or more day boxes	0.03	-0.28	-0.20

As Tab. 3 indicates, the analysis based on calculating the c.c. between the changes in the coronal intensity and the corresponding changes in the particle flux disclosed no unique dependence between these two quantities. Consequently, we also subjected the changes in the corona and solar wind to qualitative analysis which was based on the decisive role being ascribed to the character of the changes and not to their values. In this way we reduced the solution of the problem to determining whether the increase (or decrease) in coronal intensity corresponded to an increase or decrease in the particle flux. The results of this analysis for the 3-day boxes are given in Tab. 4,

Table 4

Character of coronal intensity changes	Number of cases — Character of solar wind particle flux changes		
	increase	decrease	without changes
increase	33	38	6
decrease	44	33	8

Table 5

Character of coronal intensity changes	Number of cases — Character of solar wind particle flux changes		
	increase	decrease	without changes
increase	9	10	1
decrease	11	4	1

and for the 6- or more day boxes in Tab. 5.

The values in Tab. 4 indicate that not even in the cases of increases or decreases of coronal intensity does one of the characters of the changes become statistically significant, although there is a certain indication of asymmetry in the data (33:38 and 44:33). We can thus draw the following conclusion: Statistically there is roughly the same probability that an increase (or decrease) in coronal intensity will result in an increase or decrease (or decrease or increase) of the solar wind particle flux.

This conclusion can be interpreted in two ways:

1) The fact that a particular character of the change in coronal intensi-

ty is responsible, with the same probability, for the same or opposite character of the change in the solar wind particle flux has a realistic physical basis. There is no unique relation between the character of the changes in coronal intensity and particle flux, i.e. we cannot expect and assume a concrete character of the changes in the particle flux just on the basis of the changes in coronal brightness.

2) There is a unique relation between the character of the changes in coronal intensity and particle flux, but the result we obtained does not reflect with sufficient accuracy and correctly the processes in and the mutual relations between the corona and solar wind, which may be caused, e.g., by neglecting to take into account certain mechanisms affecting the relation between the corona and solar wind in the method we used, in the manner of processing the data, the nature of the initial data used, etc.

In an effort to come as close as possible to the correct interpretation of the results mentioned above, we analysed the cases of large changes in coronal intensities over larger areas (80° and more in heliographic longitude) using the modified method. The results obtained with this method are given in the last row of Tab. 3, containing the c.c. between the two types of changes. Table 3 indicates that the absolute values of the c.c. for the relative changes were slightly higher in this case than when the 3-day boxes were used. Since the values of the c.c. -0.28 and -0.20 can still not be considered as values indicative of a marked and unique relation between the changes in the corona and particle flux, Tab. 5 gives the results of the above cases from a qualitative point of view.

This table shows that, although the number of cases analysed is not statistically extensive, there appears to be a more definite tendency in the occurrence of the separate changes of particle flux in dependence on the character of the changes in coronal intensity than in the data shown in Tab. 4. Based on the data in Tab. 5, the following conclusions can be drawn:

1) After an increase in coronal intensity, one cannot expect with certainty and forecast the manner in which this change will be reflected in the solar wind particle flux. It was found that the probabilities of occurrence of either type of change are equal, i.e. an increase as well as a decrease in the particle flux.

2) Under decrease of the coronal intensity, a marked predominance of cases has been recorded of increases in the particle flux as opposed to decreases. Nearly 3 times as many (1:2.75) cases of increase occur than of decrease of the particle flux, whereas the analysis of the 3-day box data indicates a ratio of only 1:1.33 . Thus a marked decrease in the intensity of the green corona is accompanied by an increase in the solar wind particle flux with a probability of more than 70 %.

These two conclusions can be interpreted as follows:

1) If the coronal intensity increases, the particle flux may increase or decrease with equal probability, i.e.

a) If the particle flux decreases after an increase in coronal intensity, there is evidence that the escape of particles has been prevented in some way, and this may, very probably, have been caused by the connecting up of magnetic lines of force in the particular solar region above an emerging or developing active region which is reflected in the green corona by an increase of its intensity.

b) The cases in which the particle flux increased following an increase in coronal intensity are evidence plasma escapes from the corona into interplanetary space even from active regions which are reflected in the corona usually as an increase of the green corona intensity. This escape can take place in various ways, e.g. by means of transients, flares or by continual escape via the apexes (critical points for escape) of coronal rays. Since our data and material reflect the dynamics of large-scale and, from a certain point of view, also long-term processes in the corona, the escape of particles from locations above active regions via the apexes of coronal rays seems to be most probable.

It follows, therefore, that active regions may be responsible for the escape of particles from the corona, as well as for preventing them from doing so, which results in an increase or decrease of the number of particles in the solar wind.

2) The other qualitative conclusion, given sub 2), can be interpreted in accordance with the idea of interaction between a closed and opened configuration of magnetic fields, and the escape of plasma from the corona. A marked decrease in coronal intensity is indeed evidence that the magnetic situation has simplified in a particular area of the solar surface, that the existing magnetic connections have been disrupted and that an open, or less closed configuration of magnetic lines of force, which facilitated the escape of matter from the Sun as opposed to the preceding situation, has been established.

To conclude, we should like to point out that the results presented above may be influenced and to some extent unfavourably distorted with respect to reality for various reasons, which we did not consider in the method of processing we used or in the initial assumptions. We shall mention at least these two:

1) Some studies (e.g. Cuperman and Dryer, 1978; Whang, 1983) indicate connection between high-speed solar plasma streams, recorded close to the Earth, and coronal holes, located at mid or high heliographic latitudes. In this part of the study we assumed that the solar wind particle flux, recorded in the neighbourhood of the Earth, was emitted from the equatorial regions of the Sun. The analysis of the changes of the green corona at higher heliographic latitudes and their reflection in the solar wind particle flux will be the subject of the second part of this study (Part 2).

2) It has been found that coronal holes with a non-radial divergent configuration of magnetic lines of force, which usually enables matter to escape from them and which is usually reflected in the green corona by decreased brightness (at least at some stages of their existence), are usually located close to active regions (e.g. Bohlin and Sheeley, 1978; Kovalenko, 1978; Flaa et al., 1984). There is a physical connection between active regions and coronal holes in their proximity, the active regions playing an important role in

the energy budget of the matter flowing from these coronal holes. However, since coronal holes and active regions reflect differently in the intensity of the green corona (in just the opposite way), these cases of coronal holes located close to active regions may distort considerably and obscure the actual distribution of coronal brightness as a result of averaging the coronal intenstiy over large areas.

ACKNOWLEDGEMENTS

The author´s thanks are due to Dr. V. Letfus of the Astronomical Institute in Ondřejov and to Dr. J. Sýkora of the Astronomical Institute in Tatranská Lomnica who provided him with hitherto unpublished green corona data, and also to the management of the NSSDC/World Data Center in Greenbelt, USA, for making available the solar wind data on magnetic tape. Thanks also go to V. A. Kovalenko and N. P. Korzhov of the Siberian Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation of the Siberian Division of the Academy od Sciences of the USSR in Irkutsk, USSR, for valuable discussions of the problem, and to M. Litavský of the Computer Centre of the Technical University in Košice for his aid with the computer program.

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