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RECURRENT HIGH-SPEED STREAMS IN THE SOLAR WIND DURING THE DECAY PHASE OF SOLAR CYCLE No. 21: OBSERVATIONS WITH A WIDE-ANGLE ION ENERGY SPECTROMETER ON PROGNOZ-9

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Solar wind measurements were made on Prognoz 9 from July 1983 to February 1984 during the decay phase of solar cycle No. 21. The measurements were made by means of the D-137A wide-angle ion energy spectrometer. During this time period, high-speed streams were observed in the solar wind which were stable for intervals of 5-6 solar rotations. In several of the streams, the speed was as high as 700-800 km/sec. We have compared the Prognoz 9 data with data obtained by analogous measurements in the preceding solar cycle. This comparison leads us to the conclusion that the presence of recurrent high-speed streams is a regular feature during the decay phases of the 11-yr cycles of solar activity, and is one of the manifestations of these cycles.

Systematic direct measurements of the solar wind began in 1964 during the 20th 11-yr cycle of solar activity. From 1964 to 1972 (i.e., for the greater part of the cycle), long-period changes in the solar wind parameters were surprisingly small, despite the fact that the cycle was observed to have its maximum in the period 1968-1970. It was only with the appearance of large stable high-speed streams in the solar wind in 1973-1976 that it became clear that the properties of the solar wind do undergo long period changes [1-3].

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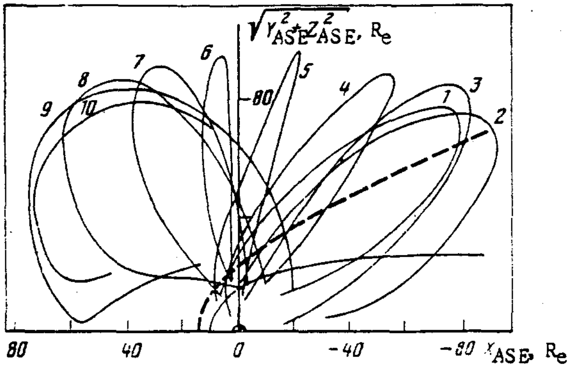

Fig. 1. Trajectory of Prognoz 9. Numerals denote the orbit number, in order.

However, the preceding (20th) solar activity cycle was in many respects unique. For example, in contrast to other solar cycles during the last 100 years, geomagnetic activity during this cycle continued to increase over the greater part of the decay phase of solar activity (~6 yrs), whereas usually geomagnetic activity falls off some 2-3 yrs after sunspot maximum [4, 5].

It is also well known that there are differences between the odd-numbered cycles of solar activity and the even-numbered cycles: there is a 22-yr cycle. In view of the peculiarity of the 20th cycle, it is a matter of particular interest to perform systematic measurements of the solar wind in solar cycle No. 21. In particular, it would be interesting to confirm the prediction made in [6] that stable high-speed streams should resume in the solar wind no later than the end of 1983. Naturally, also, the conclusions about the existence of an 11-yr periodicity in solar wind properties, which were drawn previously on the basis of measurements of solar wind parameters during only a single cycle (No. 20), cannot be entirely convincing unless they can be confirmed or refuted on the basis of measurements in subsequent cycles.

Solar wind measurements were made on Prognoz 9 from July 1983 to February 1984 during the decay phase of solar activity cycle No. 21. These measurements provide one possible way to check the reliability of the conclusions drawn from previous experiments on long period variations in solar wind properties.

1. Description of the Experiment. The basic task of the group of experiments on board Prognoz 9 was to investigate the microwave background radiation. As well as this basic experiment, the satellite also accommodated a small set of instruments which were intended for prolonged systematic measurements of the solar wind, the interplanetary magnetic field, and solar cosmic rays.

Prognoz 9 was launched July 1, 1983 into an orbit which was unusually high for this series of satellites. In the initial period of operations, the height of perigee was $1.93R_e$, and the height of apogee was $111.9R_e$ (where R_e is the radius of the earth). The inclination was 65.3°, and the period of revolution was 25.64 days. In Fig. 1 we show the trajectory of Prognoz 9 for the entire period of active operations of the satellite. The trajectory is plotted in solar-ecliptic coordinate system (ASE), rotated through an angle of 4° about the axis Z_{ASE} to allow for the aberration of the solar wind due to the earth's orbital motion. The positions of the magnetopause and the earth's bow shock are shown in Fig. 1 by solid and dashed lines, respectively. These are taken from the empirical model proposed in [7]. It can be seen from Fig. 1 that, starting with orbit No. 4, Prognoz 9 was situated at practically all times in the solar wind. We should also point out that even on the first three orbits information can be obtained on large-scale structures in the solar wind over a significant fraction of each orbit. The reason is that, at great distances from the earth ($X_{ASE} \lesssim -40R_e$), the bow shock is weak, and the plasma parameters in the transition region are similar to the corresponding parameters in the solar wind.

Measurements of the ion component of the plasma were performed on Prognoz 9 by a modulation method, using a D-137A energy spectrometer. As with previous satellites in this series, Prognoz 9 was stabilized by rotating at an angular velocity of ~3 deg/sec about an axis which coincided (within ~5°) with the solar direction. The sensitive element in the energy spec-

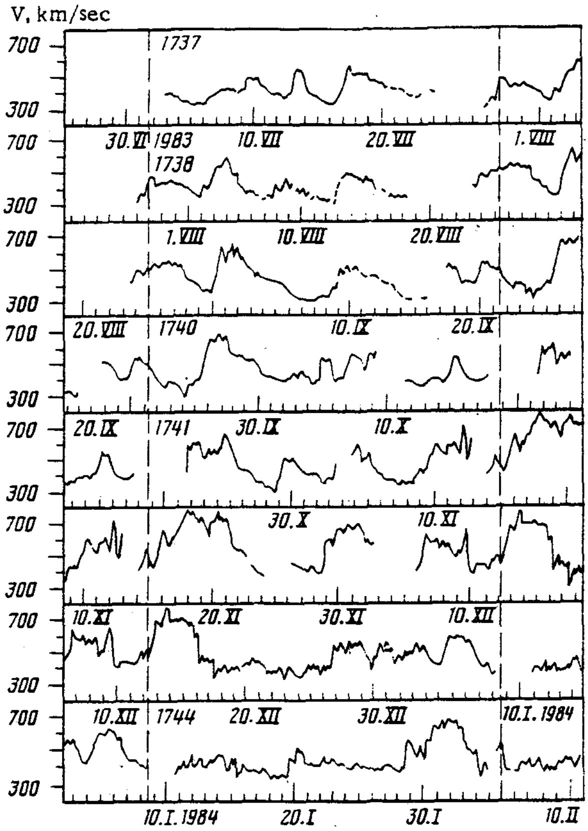

Fig. 2. Solar wind velocity obtained from Prognoz 9 data, July 1983-February 1984. Broken lines denote measurements which were performed in parts of the transition region at great distances from the earth.

trometer was a PL-51 wide-angle modulation detector (a Faraday cylinder). The axis of the PL-51 detector was oriented parallel to the satellite rotation axis.

Analogous detectors (PL-18) have been repeatedly used in earlier satellites to make measurements of the ion component of the solar wind near Mars, Venus, and the earth [8-10]. The difference between these detectors and the modulation detector PL-51 is that, in the latter, spherically shaped directional grids are used. These grids reduce the ambiguity surrounding the determination of solar wind speed: this ambiguity arises because the arrival direction differs from the normal to the aperture. The grids practically eliminate the parasitic modulation by the variable electric fields of the stream of energetic ions which are passing through the directional grids. The effective area of the PL-51 detector was 7.2 cm^2, and the angular width of its directional diagram was ±40°.

In order to measure the differential energy spectra of the ion component of the solar wind with the D-137A energy spectrometer, 16 energy intervals were chosen by varying the voltage on the analyzing grids over a range from 0 to 4400 V.

Taking into account the curvature of the grids, it was possible to determine the migration velocities of protons up to ~900 km/sec. Each energy spectrum required ~164 sec to measure.

Once the energy spectra of protons were measured in those time intervals when Prognoz 9 was situated in the solar wind, we determined the migration velocity, density, and temperature by comparing each measured spectrum with calculated spectra: the latter were obtained for a Maxwellian distribution with known values of these parameters, and allowing for the angular and energy characteristics of the PL-51 detector. In performing the comparison with the calculated spectra, the only measurements of the ion fluxes which were used were those in three energy intervals in the vicinity of that energy interval where maximum ion flux was recorded.

TABLE 1. Characteristics of High-Speed Streams Observed by Prognoz 9

Date of stream onset	v_0, km/sec	v_M, km/sec	A, km/sec	T, days	Date of stream onset	v_0, km/sec	v_M, km/sec	A, km/sec	T, days
6.VII.1983	325	500	175	4	(20.X)	(330)	690	(360)	4
12.VII	360	560	200	0,9	28.X	295	505	210	2,75
15.VII	320	570	250	3.75	1.XI	350	600	250	1,5
1.VIII	345	600	255	2	8.XI	335	725	390	(3)
12.VIII	320	520	200	2,9	13.XI	405	785	380	5,75
(22.VIII)	(320)	555	(235)	(4)	28.XI	380	680	300	(4)
29.VIII	345	655	310	2,75	5.XII	(380)	640	260	3,4
6.IX	280	515	235	4,1	10.XII	370	775	405	3,75
(16.IX)	(300)	530	230	(2)	24.XII	350	565	215	3
19.IX	390	570	180	1,25	29.XII	395	555	160	4,25
23.IX	275	675	400	4,75	4.I.1984	400	610	210	2,1
4.X	365	530	165	1	18.I	310	495	185	1.6
6.X	370	575	205	2,4	27.I	360	670	310	2,75
12.X	345	540	195	1					

Remark. Quantities in brackets were determined approximately.

Further details about the D-137A energy spectrometer, the PL-51 modulation detector, and the method which was used to determine the solar wind parameters have been described in [11].

2. Large-Scale Structure in the Solar Wind during the Period of Measurement. In Fig. 2 we present values of the migration velocity of solar wind protons, V, averaged over 3-h intervals. The data were obtained by the wide-angle energy spectrometer D-137A. In the figure, we have collected the results of measurements of v over the entire period of operation of Prognoz 9, from July 1983 to February 1984. In order to enhance the visibility of the recurrent events, the continuous series of experimental data has been divided into 27.28-day time intervals, corresponding to Carrington rotation numbers 1737-1744. The boundaries of the Carrington rotations are denoted in Fig. 2 by vertical dashed lines.

It can be seen from Fig. 2 that, during the period of time when Prognoz 9 was operational, at least three groups of high-speed streams existed in the solar wind, and they can be observed for ~6 rotations of the sun. In one of these groups (the one which was observed during days 1-9 at the beginning of the Carrington rotations), the solar wind speed reached values of $v_m \approx 700$-800 km/sec.

In order to describe the properties of the structure of the high-speed streams in the period July 1983 to February 1984, and to enable us to compare our data with analogous measurements on other spacecraft, it is convenient to use the formal criteria proposed in [1] for determining the number of high-speed streams, and also their duration and amplitude. Following the authors of [1], we consider a solar wind stream as "high-speed" if its speed increases by 150 km/sec in the course of no more than 5 days. If v_0 is the speed at the beginning of the stream (from which the increase begins), and v_m is the maximum speed which the stream attains, the amplitude of the stream is $A = (v_m - v_0)$, and the duration of the stream T is the time during which the speed remains in excess of $(v_m + v_0)/2$. In Table 1 we present the dates of onset of all of the high-speed streams observed by Prognoz 9. The table also includes the other parameters. During the time period when the satellite was operating in the solar wind, 27 high-speed streams were observed. Of these, 5 had amplitudes ≥350 km/sec, 3 had $v_m \geq 700$ km/sec, and 8 had durations ≥4 days. In the course of 1 yr, the corresponding figures would be ~45, ~8.5, and ~13.5, respectively. For the high-speed streams recorded by Prognoz 9, the mean maximum speed, amplitude, and duration were ~600, ~255 km/sec, and ~3 days, respectively.

In Fig. 3 we compare these characteristics of the high-speed streams observed by Prognoz 9 (asterisks) with data on high-speed streams in the preceding cycle of solar activity. The latter data are taken from [1] (open circles), supplemented by solar wind measurements made by Helios-1 and -2 [6] (filled circles). The results of the Prognoz 9 measurements are displayed in Fig. 3 with an 11-yr shift in time, in order to compare the characteristics of the high-speed streams at corresponding phases of the solar cycle. It can be seen from Fig. 3 that, on the whole, the stream activity and the characteristics of the high-speed streams during the end of 1983 and the beginning of 1984 are similar to the corresponding quantities in the preceding solar cycle.

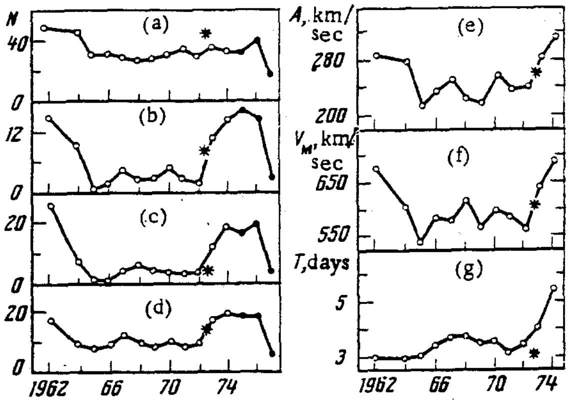

Fig. 3. Yearly averages of the characteristics of high-speed streams. a) Total number of streams observed; b) number of streams with amplitude ≥350 km/sec; c) number of streams with maximum speed ≥700 km/sec; d) number of streams lasting ≥ 4 days; e) amplitude of the streams which were observed; f) maximum velocity; g) half-amplitude duration.

We draw attention to the high degree of recurrence of the high-speed streams in the solar wind observed by Prognoz 9 on the decline phase of the current solar cycle (No. 21; cf. Fig. 2). In other phases of the solar cycle, the high-speed streams are less regular, and they alter substantially in the course of 1-2 solar rotations. Stable high-speed streams were observed previously in the time interval 1973-1976, on the decline phase of the preceding solar cycle (No. 20). Resumption of these stable streams was expected to occur no later than the end of 1983 [6]. In fact, the detection of recurrent high-speed streams by Prognoz 9 is in good agreement with this prediction, indicating that the presence of high-speed streams is a regular feature of the 11-yr solar cycles during the decline phase. The presence of such streams is one of the manifestations of the cycles.

The plasma speed reached values of 700-800 km/sec in some of the high-speed streams observed by Prognoz 9. However, when we compare these with the recurrent high-speed streams observed during the decline phase of the previous cycle in 1973-1974 [12], we find that during the latter time period the high-speed streams were observed to be stronger and more long-lived. It is possible that this difference is associated with the fact that Prognoz 9 made measurements on the solar wind at a time when the stable recurrent streams were beginning to form in the solar wind (cf. Fig. 3).

In the paper following this one [14], the distribution of high-speed streams within individual solar rotations (using Prognoz-9 data) will be compared with the large-scale structure of the interplanetary current sheet. From that comparison the conclusion is drawn that, during the time interval we are considering, the interplanetary magnetic field (IMF) in the ecliptic plane is characterized by a 4-sector structure and that, corresponding to this structure throughout a solar rotation, we can, as a rule, identify four recurrent high-speed streams in the solar wind. On the other hand, when the strong recurrent solar wind streams were observed on the decline phase of the preceding cycle (in 1973-1974), the IMF had a two-sector structure in the ecliptic plane; and, correspondingly, only two streams were observed during a single solar rotation. A consequence of the four-sector structure during late 1983 and early 1984 is apparently a reduction in the half-width of the high-speed streams rather than at the corresponding phase of the preceding solar cycle.

We should point out that on the decline phases of both solar cycles, segments of the interplanetary magnetic field were observed in which the structure was 2-sector and 4-sector. For example, in 1971-1972, during the decline phase of cycle No. 20, 4 sectors were observed in the IMF in the ecliptic plane. And throughout 1982, on the decline phase of cycle No. 21 (but prior to the onset of solar wind measurements by Prognoz 9), the IMF in the ecliptic plane had a 2-sector structure [15]. And two sectors were again observed in the IMF in the ecliptic plane almost immediately after Prognoz 9 stopped taking data [16]. Measurements of the interplanetary magnetic field with the Misha magnetometer on the spacecraft Vega 1 and

2 has shown that, during the first half of 1985, the interplanetary magnetic field in the ecliptic plane continued to have a 2-sector structure.

CONCLUSIONS

Prognoz 9 has made measurements of the solar wind using the D-137A wide-angle energy spectrometer. The measurements were made on the decline phase of solar cycle No. 21. This still-unfinished cycle is only the second complete solar cycle since direct measurements began on the solar wind in 1959 [13].

At the present time, we have not intercalibrated the results from Prognoz 9 with the measurements of solar wind parameters on IMP-8: this would enable us to connect the data obtained by Prognoz 9 with the system of other data concerning the solar wind. Therefore, in this paper and in the following one [14], the only results which we use are the measurements of solar wind speed: these are the most reliable of the parameters which we have determined. The conclusions which are drawn in these papers may be improved subsequently.

From the point of view of investigations of the 11-yr periodicity, the solar wind measurements on Prognoz 9 span a very short interval (8 months). Thus, even after the intercalibration is performed, we will still obtain only a single half-year average value of the solar wind parameters. However, the solar wind measurements on Prognoz 9 were practically continuous, in contrast to the measurements by IMP-8, where the measurements are extremely intermittent. Thus, the information which we have obtained on the structure of the high-speed streams is quite complete.

Summarizing our results of measuring the solar wind on board Prognoz 9 from July 1983 to February 1984 on the decline phase of solar cycle No. 21, we may draw the following conclusions. First, recurrent high-speed streams were observed in the solar wind during this period of time. Second, the streams were stable for periods of 5-6 solar rotations. Third, during one solar rotation, as a rule we observed four high-speed streams corresponding to the 4-sector structure of the interplanetary magnetic field in the ecliptic plane. Fourth, the speed in some of these streams reached 700-800 km/sec.

Thus, the Prognoz-9 observations of the solar wind allow us to conclude that regular high-speed stream structure has resumed in the solar wind during the decline phase of cycle No. 21, in accordance with the prediction made in [6]. The latter prediction was made on the basis of solar wind measurements in the preceding cycle. This indicates that the presence of recurrent high-speed streams is a regular feature of the decline phases of the 11-yr solar cycles, and is one of the manifestations of these cycles.

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SOLAR WIND SPEED AS A FUNCTION OF DISTANCE FROM THE HELIOSPHERIC CURRENT SHEET: DATA FROM PROGNOZ 9

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We compare the large-scale structure of recurrent high-speed streams in the solar wind with the large-scale structure of the heliospheric current sheet. The stream data were recorded by Prognoz 9 in 1983-1984. We perform a quantitative investigation of the solar wind speed V as a function of angular distance λ from the current sheet. Based on the entire data set of V measurements by Prognoz 9, the function $V(\lambda)$ can be approximated by the expression $V\ (\text{km/sec}) = 410 + 305 \cdot \sin^2 \lambda$. We show that the scatter of the experimental points with respect to the approximate curve is reduced if we allow for the fact that the mean velocity of the solar wind on the path from the sun to the earth is smaller than the speed V which is measured at the earth's orbit.

Prognoz 9 made measurements of the solar wind during the time period from July 1983 to February 1984, on the decline phase of solar cycle No. 21. It is well known that during the decline phase of the preceding cycle (No. 20), large recurrent high-speed solar wind streams were observed in the ecliptic plane, lasting 5-6 solar rotations. In the preceding paper [1], we concluded, from Prognoz-9 data, that regular high-speed structure has resumed in the solar wind in the decline phase of the current solar cycle. In the present article, we will compare the large-scale structure of these streams with the large-scale structure of the heliospheric current sheet, and we will investigate how the solar wind speed behaves as a function of angular distance from the current sheet.

The way in which solar parameters behave as a function of angular distance from the current sheet λ manifests itself as a function of heliolatitude at certain phases of the 11-yr solar cycle. This is being discussed actively at the present time (cf., e.g., [2-5]). The dependence of solar wind parameters on λ has not been established reliably. The reasons for this are entirely understandable: direct measurements of the solar wind are limited to the ecliptic plane, measurements of the wind speed by means of interplanetary scintilla-

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