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Study of Helium Abundance in Low-Speed Solar Wind Streams by the Data of *Prognoz-7* and *Prognoz-8* Satellites

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Abstract—Data from the *Prognoz-7* and *Prognoz-8* satellites are analyzed with respect to the relative helium abundance, n_α/n_p, of the low-velocity solar wind in the Earth-orbit region. On the basis of the whole data set, the conclusion is confirmed that n_α/n_p experiences a considerable decrease when a satellite traverses a region where the interplanetary magnetic field changes sign. This line corresponds to the neutral line of the global magnetic field (the projection of the symmetry plane of the low-latitude streamer) in the solar corona (in particular, at the so-called source surface located at a distance of 2.5 solar radii from the center). A possible interrelation between n_α/n_p peaks and their sources at the Sun, which are located near the places of sign change of intermediate-scale magnetic fields, is noticed.

1. INTRODUCTION

The direct measurement of characteristics of heavy ions in the solar wind gives unique information on both the conditions in the outflow source and processes in interplanetary space. This information includes the relative abundance of various elements and their temperatures in the outer layers of the corona, the state of ionization, and acceleration efficiency for various ions [1, 2]. Due to the transition from the coronal layers, where plasma ionization is determined by electron impact and the plasma ion composition is formed, to the collision-free flow, ionization states of ions become "frozen," retaining information on the temperature in the formation region [3]. At an MHD approximation, the relative abundance of ions does not vary in interplanetary space after a flow with the identical bulk velocity of ions has been formed [4]. It is significant that the detailed composition of the solar wind is very sensitive to the mechanisms providing ion escape from the solar chromosphere into the solar corona and then into interplanetary space; thus, it can serve as a test to verify our concepts of these processes [5].

Corresponding measurements with instrumentation significantly differing in capability have already been carried out for 30 years (for example, see references in [1, 2, 6]). In general terms, the accumulated data have confirmed the notion of the solar corona as a source of solar wind, the abundance of elements in the corona, and the ionization states. It has been shown that the abundance of heavy ions with respect to hydrogen is low in a low-velocity solar wind and increases by a factor of two to four in the high-speed streams. The maximum abundance of heavy ions is observed in plasma clouds ejected during unsteady phenomena at the Sun. Both the higher and lower degrees of ionization are observed for ions in these clouds.

A detailed interpretation of the observation data was found to be very complicated, particularly the solution of the following problems: What structures in the solar corona are related to the arrival of flows with specific properties to the Earth? Which flow properties are explained by their genesis in one or another solar region, and which arise due to flow propagation through interplanetary space? These problems and ways of their solution are addressed in [7]; some aspects of this work are discussed below.

The most extensive data accumulated to date are on the relative abundance of $^4He^{++}$ ions (α-particles) in the solar wind. The correlations between this parameter and various features of flows are very complicated (see [8–10]). In general, the characteristic behavior of a relative helium abundance is the same as mentioned above for all minor ion components. These peculiarities were taken into account in a preliminary classification of solar wind streams over the whole set of parameters describing these streams [7].

Several circumstances stimulated us to carry out a new and more detailed analysis of the problem of α particle abundance in the wind. In addition to data from the *Prognoz-7* satellite, we included data accumulated by *Prognoz-8*. This allowed us to investigate not only the phase of solar activity maximum but also the onset of the decay phase, when effects related to the large-scale magnetic field of the Sun become significant. Moreover, certain concepts of the solar corona and the wind flowing out from it have changed in the past few years, to a large extent owing to observations by the *Yohkoh* and other satellites. It is important to reveal the more dynamic character of the solar corona, as well as to improve the concepts of mechanisms that form high- and low-speed streams of the solar wind [11]. So, taking account of the results of [7], we have decided that it makes sense to carry out an additional correlation between the peculiarities in relative helium abundance and possible sources of flows in the solar corona; a semi-empirical formula was used for this purpose that links the transport time (the difference between the time of flow ejection from the solar corona and the moment of its detection) with the flow velocity in the near-Earth space. We have restricted our consideration to quiescent flows; moreover, the data measured within the epoch close to the solar activity maximum do not allow us to investigate in detail the high-speed streams related to coronal holes due to their absence in low latitudes. Therefore, we consider below the peculiarities of low-velocity solar wind.

The subject of this paper is to analyze peculiarities of the relative helium abundance in the low-speed streams of the solar wind and their possible relations with structures at the Sun's surface.

2. TECHNIQUE OF MEASUREMENTS AND DATA ANALYSIS

The plasma complex SKS-04 mounted aboard the *Prognoz-7*, which permits the measurement of energy spectra of α particles and protons, as well as of integral ion flux, is described in detail in [12]. To measure energy spectra of α particles and protons aboard the *Prognoz-8* satellite, similar SKS-04 sensors were used; however, the MONITOR instrument sensors [13] were used to measure the ion flux values. The advantage of measurements with the *Prognoz-7* and *Prognoz-8* satellites is the separate measurement of energy spectra of α particles and protons by electrostatic analyzers with Wien filters. In total, more than 11000 and 17000 spectra for both ion components in the solar wind, undisturbed by the Earth's magnetosphere, were accumulated aboard *Prognoz-7* (November 1978–June 1979) and *Prognoz-8* (January–July, 1981), respectively. The time resolution was 8 min.

Hydrodynamic parameters of protons and α-particles (velocities V_p, V_α and temperatures T_p, T_α) as well as the relative abundance of α-particles (n_α/n_p) were determined by the data of a selective analyzer under the assumption of the validity of the convective Maxwellian velocity distribution of ions, while the total ion density was found from measurements of the total flux by integral sensors. When averaging over intervals not shorter than 1 h, estimation uncertainties for these parameters do not exceed 2 to 3% for velocity, 20 to 25% for temperature, 20% for total ion density, and about 80% for the relative abundance of α particles [14].

On the basis of statistical analysis of large-scale variations in a number of hydrodynamic parameters obtained by the *Prognoz-7*, a technique was proposed to select five different types of solar wind flows, which can be linked with known structures and phenomena of the solar corona [7]. One of these types was correlated with crossing of the heliospheric current sheet (the extension of a large streamer into interplanetary space) by a near-Earth spacecraft. On the basis of data accumulated by the *IMP 6–8* satellites during 1971–1978, the authors of [15] have concluded that such crossings of sector boundaries are related to a significant depletion of helium abundance.

One of the difficulties we face in interpreting the data on relative abundance of helium ions is a problem of extrapolation from measurements in the region of the Earth's orbit to conditions in the source inside the solar corona. In this case, we must estimate the transport time τ for specific conditions of low-speed solar wind streams. There is good reason to believe that the velocity of the streams varies with distance only slightly all the way from the Sun to the Earth [16]. However, various radio observations indicate a part of corona where the wind velocity increases up to the values typical for interplanetary space. In the formula for transport time, this segment makes only a small change, compared with the case of low-speed flow with a velocity remaining constant all the way from the Sun to the Earth. We allowed for this effect by introducing a factor A into the formula for transport time, as follows:

$$\tau = Ar/V_p, \tag{1}$$

where V_p is the wind velocity at the Earth's orbit, and $r = 1$ a.u. The use of this formula has demonstrated that it describes fairly well the transfer of structural peculiarities of the solar corona into interplanetary space. The factor A in (1) is about 1.1 (see below).

3. RESULTS OF MEASUREMENTS

We had at our disposal data on the relative helium abundance in the solar wind and its other gas-dynamic parameters. Primarily, overview plots were constructed for the two main parameters: the helium abundance n_α/n_p and proton velocity V_p, separately for the periods 1978–1979 and 1981. Basically, the hourly averaged values were analyzed. Although the total data set was very large, sometimes the analysis was made difficult by gaps in the observational data. Only time periods of a fairly low velocity of wind were of interest for us; i.e., both flare and recurrent high-speed streams were not considered. Unfortunately, the time periods under consideration were characterized by pretty high solar activity; as a result, they were unfavorable for investigations of quiet-wind phenomena.

Using the overview plots, it was possible to identify two classes of phenomena. One of them is the case of monotonous decrease of helium abundance in the wind, well pronounced against the background level before and after the event. Phenomena of another type were characterized by local peaks. For identified events of both types, all the detected gas-dynamic parameters with the required time resolution were considered fur-

Table 1. Events stemming from crossing of IMF sector boundaries

Date	t_0	V_p	n_α/n_p	
			about t_0	$t_0 \pm$ a day
Nov. 30, 78*	30.0	350	2	6
Dec. 3–4, 78	3.9	280	0.5	2.5
Dec. 11–12, 78	11.5	270	0.5	1.5
Dec. 16, 78	16.0	400	1.5	10
March 11–12, 79	12.0	450	2.5	10
May 4–5, 79	5.0	350	3.5	7
May 7–9, 79*	8.5	370	1.5	6
June 5, 79	5.8	270	0.5	1
Jan. 10, 81	10.7	370	1	4
Jan. 26, 81	26.8	350	1	3
March 4, 81	4.3	400	0.5	5
March 25, 81	25.0	330	0.5	2.5
Apr. 30, 81	30.3	360	2	4

ther. This analysis has shown, first of all, that events of the first type are related to crossing of the sector boundaries of the interplanetary magnetic field (IMF) by a satellite.

Events of crossing the sector boundaries are collected in Table 1, where the date, the time t_0 of crossing the sector boundary in accordance with [17], the average wind velocity V_p, and the average values of n_α/n_p at t_0 (as well as those of about one day before and one after the event) are given. In total, eleven events when the satellite crossed the sector boundaries and two events when the satellite approached the sector boundary were analyzed (these events are marked by asterisks in Table 1). The helium abundance in these cases was 0.5 to 3%, which is lower by a factor of two or more than the values detected one day before or one day after the moment of crossing the boundary. A decrease of the relative abundance of α-particles was observed during intervals of 12 h to 2.5 days. The sector boundaries with subsequent arrival of high-speed streams show a distinct decrease of the relative abundance of helium ions. This conclusion is valid for all events of crossing sector boundaries, excluding the May 4–5, 1979, event, where helium abundance depletion is not so clear. The effect mentioned takes place also in cases when the satellite only approaches the current sheet and does not cross it. In other words, a velocity jump is not observed, but the sector boundary can be identified according to [17], or its presence can be discovered from a map of magnetic fields given in [18] (see also below). The two events asterisked in Table 1 are of this class.

As is known, a maximum of the solar wind density is often detected in front of the sector boundary. It would be possible to assume that precisely the absolute increase of n_p causes the decrease of the ratio of helium to hydrogen atoms. However, analysis has not demonstrated a dependence of the n_α/n_p value on the presence or absence of the narrow density peak preceding the sector boundary.

As an illustration, Fig. 1 shows data on the relative abundance of helium ions and proton velocities for an event on March 25, 1981, obtained by measurements of the *Prognoz-8* and averaged over 1 h intervals, as well as the values of angles between the vector of the interplanetary magnetic field and the direction toward the Sun, according to [17]. Before the moment of crossing the boundary on March 25, extremely low values of n_α/n_p were observed at some moments; similar events were detected only a few times during the whole period of observations. The event shown in Fig. 1 covers a little more than a day; several events of this type have durations of 2 to 3 days. As is seen in Fig. 1, certain variations of n_α/n_p near the sector boundary are sometimes observed, and sometimes, during a very quiescent wind, they can be absent. The increase of proton velocity at the boundary is clearly seen, which is specific for undisturbed boundaries of sectors. An original record by [17] of the interplanetary magnetic field azimuth shown on the lower panel in Fig. 1 demonstrates that, until March 25, the interplanetary magnetic field is directed, on average, along the Parker's spiral toward the Sun, whereas it starts to be directed away from the Sun after crossing the sector boundary. We have selected the March 25, 1981, event as an illustration due to clear recording of the sector boundary in both field and velocity, which occurs rarely during the solar activity maximum. Let us note that for other events, primarily decreases of the n_α/n_p value were seen (see Table 1).

The distinctly demonstrated correlation between the n_α/n_p decrease and sector boundaries allows us to analyze the question of which structural features of the solar corona might be associated with the phenomenon under consideration. When using the above formula for the transport time and the synoptic map of the solar corona, we found a point at the "source surface," located at a distance of 2.5 solar radii from its center [18], that is a source of the given flow with a velocity measured by satellite in the region of the Earth's orbit. As was expected, the IMF sector boundaries correspond closely to the change of sign of the global magnetic field at the source surface. The best agreement was achieved by selecting the factor A in (1) equal to 1.1. Such a small difference from unity means that the segment where the quiescent-wind velocity increases near the Sun makes only a negligible contribution to the value of the transport time.

From the point of view of solar physics, the main boundary of the interplanetary current sheet in the corona is the symmetry axis of the helmetlike beam (streamer). These large-scale coronal structures present a source of low-velocity solar wind. The wind velocity increases with distance from the interplanetary current sheet.

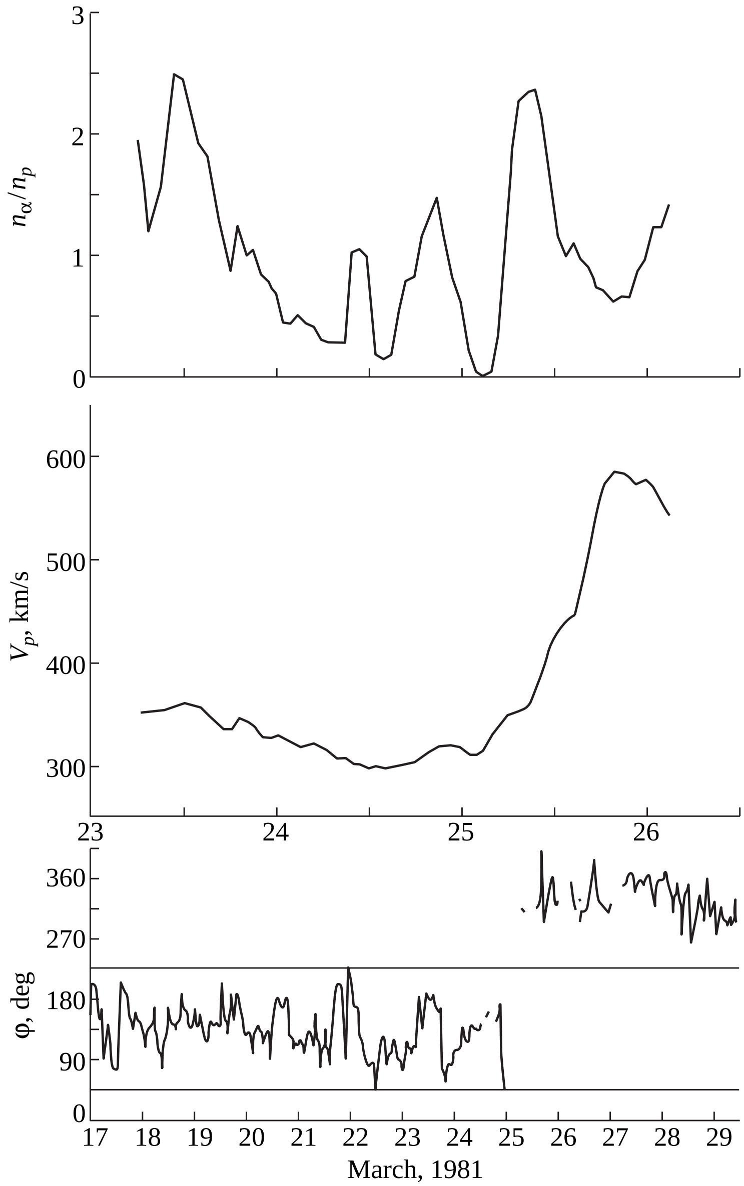

Fig. 1. Relative abundance of helium and proton velocity from the *Prognoz-8* satellite (hourly data) on March 23–26, 1981. A copy of the original record of the IMF azimuth angle φ from [17] for the period of March 17–29, 1981, is given on the lower panel. The change of mean values of this angle by 180°, related to crossings of the interplanetary current sheet, is recorded in the beginning of the day on March 25, 1981.

It is significant that in spite of a sharp increase of velocity (which corresponds to crossing some sector boundaries), it was found that in order to pass from the region of the Earth's orbit to the surface of the wind source in the solar corona, it was necessary to use just the low velocity value in the above-mentioned formula for the transport time. For instance, for the event of March 25, 1981, the flow velocity was 330 km/s before crossing the sector boundary, and the transport time was 5.8 days. If one uses velocity values behind the sector boundary (usually 500–600 km/s), such a correlation of the source of low-velocity wind, depleted in helium, with the boundary of the global field of the Sun (the streamer symmetry axis) is not observed, as the delay time in this case is much smaller.

Thus, our results refine and supplement the conclusions of [15], where the discussed effect of the n_α/n_p decrease related to crossing the sector boundary (the streamer) was first found. In our work, this effect is illustrated by 11 events and shown to be solely a peculiarity of the low-velocity solar wind.

Records of relative helium abundance also include events of the second type with increased values n_α/n_p = 3–10%. This local maximum persists within intervals from 12 hours to one and a half days. More than half of these events are located fairly close to the

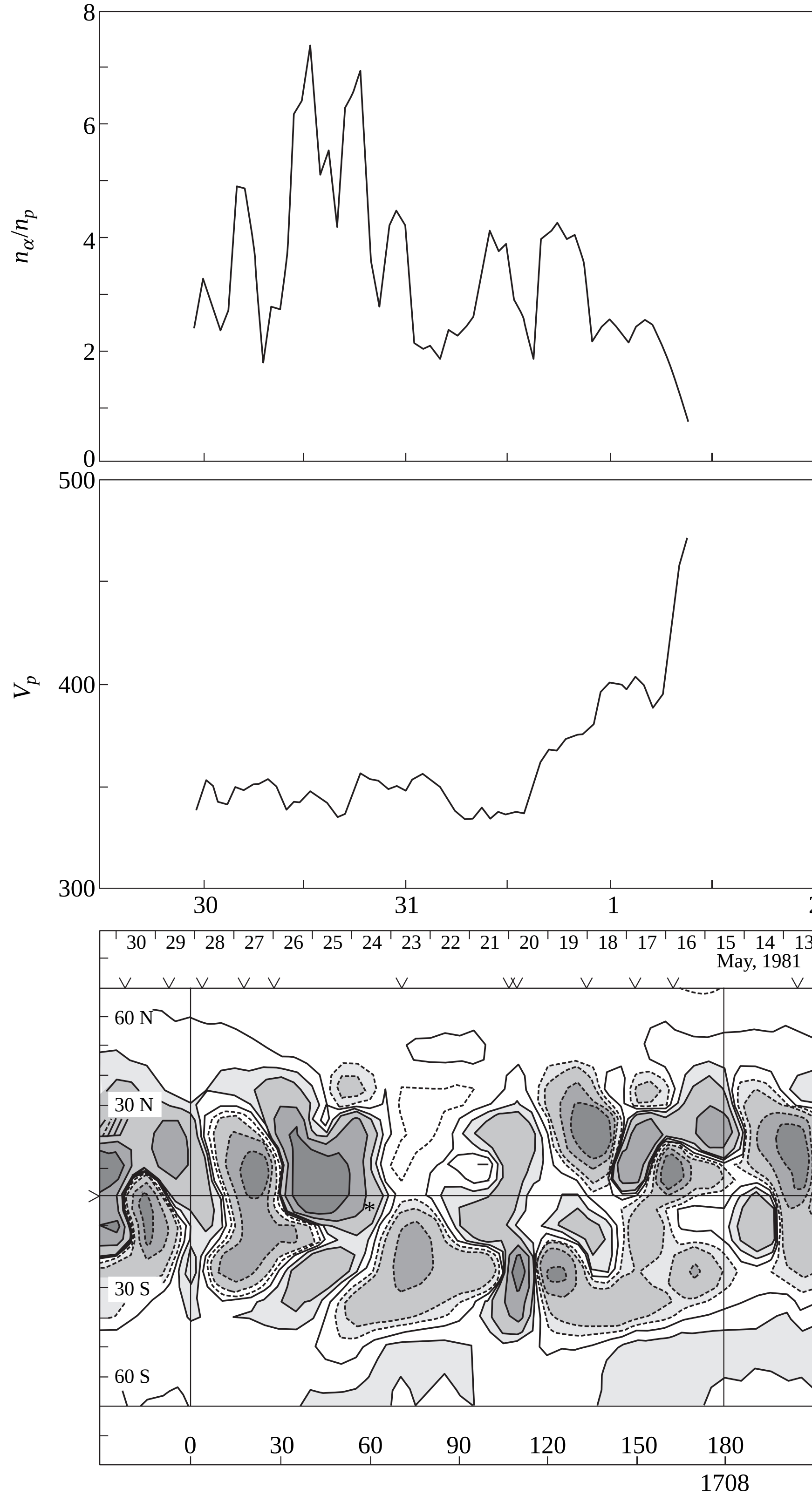

Fig. 2. Relative abundance of helium and proton velocity as measured by the *Prognoz-8* satellite (hourly data) from May 30 to June 1, 1981. A synoptic map of photosphere magnetic fields is given on the lower panel from observations at Stanford Station, USA (from Solar Geophysical Data, Carrington rotation no. 1708). Longitudes and dates are plotted on lower and upper axes, respectively. The position of the source determining the peak in relative helium abundance on May 30–31, 1981, is asterisked near the solar equator at a longitude of 61° (the abscissa).

sector boundaries, although some events are observed that are localized in the middle of a sector. Note that the increases related to the detected solar or interplanetary unsteady disturbances (flares or large transients followed by magnetic storms) were excluded from consideration.

When using the same expression (1) for the transport time with $A = 1.1$, we found the point of flow ejection from the Sun on the synoptic map of photospheric magnetic fields [18]. Already at the first scan of the *Prognoz 7* data, it was discovered that these events are closely adjacent to boundaries of large-scale photospheric fields. Although these fields are prominent on the Stanford maps, they are not seen at all on calculated maps of magnetic fields at the source surface [18]. The average distance between the peaks of these fields was from 30° to 50° in 1979 and a little less in 1981 (within the *Prognoz-8* period). One case of enhanced relative abundance of α-particles is shown in Fig. 2, together with records of the photospheric magnetic fields (Stanford maps). The local maximum of the helium abundance on May 30, 1981, was located in a region of quiescent low-velocity wind. A noticeable velocity increase occurred approximately two days after the event under discussion. The position of the source causing the increase in helium abundance, on the ecliptic projection (noted by ">" and "<" symbols at the left and right on the lower panel in Fig. 2), is marked by an asterisk on the Stanford synoptic map of magnetic fields with a resolution of two angular minutes (Fig. 2).

Local magnetic fields, which cause the development of active regions, large-scale fields as large as tens of heliographic degrees, and fields comparable in size with the Sun's radius, are observed in the photosphere. Higher above, at the surface of the source, only the most recent and large-scale fields are clearly pronounced, which determine the appearance of the sectoral structure in interplanetary space. During most of the activity cycle, the boundary separating the polarity of these fields in the interplanetary space is positioned near the solar equator plane. Both the existence of this surface by itself and its wavy structure influence the propagation of particles and magnetohydrodynamic disturbances in interplanetary space, giving rise to a number of phenomena.

The above-mentioned large-scale photospheric fields of intermediate size decay into isolated "islands" of unipolar fields, which are often located inside the sectors. The lower the activity, the more rarely the "hills" of these large-scale fields are found, and the more reliable the correlation between their polarity boundaries and phenomena observed in the interplanetary space. The periods under discussion were sufficiently close to the maximum of the activity cycle; up to five or six islands of unipolar fields were found on the synoptic map (all longitudes included) at the line of intersection of the solar surface by the ecliptic plane.

Table 2. Events of enhanced relative abundance of helium ions

Date	t_0	V_p	n_α/n_p	$\Delta\lambda$
Nov. 17, 78	17.7	350	3	5
Dec. 16–17, 78	16.8	450	20	5
Dec. 23–24, 78	23.7	450	10	2
Jan. 26–31, 79	28.5	500	10	5
Jan. 17, 79	17.2	400	8	<1
Feb. 6–8, 79	8.0	350	10	<1
March 1, 79	1.0	360	7	2
March 8, 79	8.0	350	10	<1
March 19–21, 79	20.3	370	10	3
Apr. 8–10, 79	9.5	400	10	3
Apr. 13–14, 79	14.2	450	12	<1
Apr. 18–19, 79	18.6	450	8	2
May 11–13, 79	12.5	500	8	5
May 16, 79	16.5	450	7	0.5
Jan. 16, 81	16.5	440	4	2
Jan. 25, 81	25.5	380	3.5	4
Jan. 31, 81	31.5	360	5.5	4
Feb. 4–5, 81	4.5	400	3	2
Feb. 13, 81	13.5	360	5	<1
March 19, 81	19.7	450	3	4
March 31, 81	31.5	400	2.5	<1
Apr. 21, 81	21.5	500	3	<1
Apr. 28–29, 81	28.5	530	3.5	3
May 23, 81	23.5	500	3	5
May 28, 81	28.0	350	4	<1
May 30–31, 81	30.2	340	6	5
June 12–13, 81	12.5	350	5	5
June 28, 81	28.5	450	5	3

Table 2 lists 28 events of enhanced abundance of α-particles. Notation is the same as in Table 1, with the exception of t_0, which means here the moment of a local maximum. The last column displays the distance $\Delta\lambda$ (in terms of heliographic degrees) from the position of a helium-ion source, reduced to the Sun, to the boundary of large-scale photospheric fields. This value was measured along a line—the projection of the Earth's motion onto the photospheric synoptic map—as the distance between a calculated flow source and the nearest boundary of a large-scale photospheric magnetic field. As seen from Table 2, the $\Delta\lambda$ value in specific cases is as large as five heliographic degrees (in absolute value), and its average value is 2.5. The imperfect coincidence of the source of a flow with enhanced helium abundance and the indicated field boundary is related to uncertainties in time of the increase maximum for certain events and in the transport time, as well as the complicated topology of the boundary between magnetic field polarities. Although in some cases, the precision of coincidence between the source of the flow with higher helium abundance and the boundary of polarity of the large-scale photospheric magnetic field is rather poor (about 5° at a typical distance of ~30° between peaks of photospheric fields), the statistical significance of this conclusion for the 28 events considered seems to be sufficiently reliable. This result could not be predicted in advance; however, the regularity found is demonstrated both by the isolated examples and, more clearly, by the total data set.

4. DISCUSSION

Therefore, a decrease of helium relative abundance at the sector boundary is observed with assurance in the data of *Prognoz-7* and *Prognoz-8*. This is a reliable confirmation of the phenomenon discovered earlier [8, 10, 15]. Most often, the source of a low-speed stream is an equatorial streamer—the base of the interplanetary current sheet. Although the wind velocity sharply increases at the sector boundary, it was necessary for the performed correlation to use only a low velocity preceding the arrival of a high-speed stream. Furthermore, the effect was found to be unrelated to the formation of a narrow compaction, which is produced in certain cases in the space behind the sector boundary. The physical origins of the depletion of this region of helium nuclei are still unclear. In principle, diffusion of protons and α-particles during their propagation through the Sun's vicinity can occur in different ways for particles with various charge and mass or charge-to-mass ratio. This process occurs in a magnetic field that decreases toward the streamer symmetry plane and changes its sign behind it. Furthermore, in this case, the field's tangential component, which appears to be due to helix swirling of field lines and development of small-scale instabilities in the streamer, probably may have an effect. Solving the corresponding theoretical problem on the preferential escape of α-particles as compared with protons from the vicinity of the interplanetary current sheet seems to be an urgent problem.

The phenomena that cause an enhanced abundance of helium ions in the wind require further investigation. They are obviously unrelated to flares and transients, although we cannot exclude the possible influence of weak unsteady disturbances. Our analysis has discovered a tendency for sources of these phenomena to be localized in regions positioned above neutral lines of large-scale photospheric magnetic fields of intermediate size. We did not expect such a correlation *a priori*, and its origin is as yet unclear. One can only assume that magnetic fields of such dimension influence the properties of the solar-wind source in the corona above the demarcation line between the polarities of these fields.

Let us note that this work considers the problems of low-velocity solar wind. The wind velocity varies rather slightly with distance, which justifies the use of our formula for transport time. Most likely, the source of this wind is the plasma located above the loops of the inner corona. Magnetic fields of various scales primarily influence the velocity of solar wind and, as a result, determine its decrease in streamers. Our work apparently gives evidence that magnetic fields also affect the relative abundance of helium ions, n_α/n_p, and probably ions of other elements as well; fields of various scales indirectly influence relative helium abundance in different ways. One cannot exclude that weak unsteady processes in the solar corona result in some increase of the relative abundance of helium ions. If so, the role of microflares can be significant for corona heating, wind acceleration, and the relative abundance of helium and heavier elements of the wind.

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