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Three types of solar wind flow

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Abstract. The origin of the large-scale stream structure of the solar wind flow was studied using an experimental approach. Radio astronomy data obtained in 1997 were compared with SOHO optical observations of the solar corona and magnetic structures derived from the J.Wilcox Observatory Zeeman data. A correlative relation was obtained between the position of the transonic region of the solar wind and magnetic field strength at the solar corona level. This relation falls into three branches corresponding to three types of the magnetic field structure: an open type with the field lines going in the interplanetary space, closed loop-like type and intermediate type including both configurations of field lines. The high-speed streams originate above the open configurations, while closed and intermediate configurations produce low-speed solar wind.

Key words: Sun: corona – Sun: magnetic fields – Sun: solar wind

1. Introduction

This paper deals with the effect of coronal magnetic fields on the formation of the large-scale structure of the solar wind flow. Successful experimental investigations here are comparatively recent. Reccurrent magnetic storms were observed in the Earth magnetosphere in the seventies. It was shown that the source is the high-speed streams of the solar wind produced by a previously unknown type of coronal structure - coronal holes, characterized by a diminished density of the solar matter and open magnetic field geometry (Krieger et al. 1973; Neupert & Pizzo, 1974). Many important details of the mechanisms controlling the intrinsically - nonuniform flow of the solar wind close to the Sun were clarified in the subsequent investigations (Efimov et al. 1990; Schwenn & Marsch 1990; Kojima & Kakinuma 1990; Rickett & Coles 1991; Efimov 1994; Rao et al. 1995; Tokumaru et al. 1995).

In the present paper the effects of these mechanisms are studied for the quiet Sun conditions. The problem is of prime importance because of the fundamental role of the actual flow structure in the solar wind acceleration mechanism (Malara et al. 1992, 1995; Vladimirskii et al. 1996).

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Very important data for the structure of the solar wind flow were obtained from the radio astronomical observations. These data reveal, in particular, a qualitatively different type of flow between the subsonic solar wind area close to the Sun and developed supersonic solar wind at large distances. Regular observations of compact radio sources reveal an extended region of enhanced scattering stretching at solar distances of about 10 to $20R_s$ (Lotova et al. 1985; Lotova 1988). Correlations with the solar wind velocity measurements (Ekers and Little 1971) make it possible to identify this region of enhanced scattering as the transition, transonic region of basic solar wind acceleration. Furthermore, experimental data for the velocity field structure (Armstrong & Woo 1981; Scott et al. 1983) show that the transonic region must be treated as a region of mixed flow, where subsonic and supersonic streams coexist and interact (Lotova et al. 1985; Chaplygin 1964; Trikomi 1923, 1954; Landau & Lifshitz 1989; Frankl 1945; Kogan 1961). At velocities below the Alfven velocity the subsonic to supersonic flow transition proceeds qualitatively similar to that in ordinary compressible media. This is the case which is realized in most of our observations, relating to moderate heliolatitudes. Very different structures of the flow are presented in recent observations of an extremely rapid solar plasma acceleration in polar areas (e.g. Janardhan et al. 1999).

The present study deals with the processes in a broad region of moderate heliolatitudes. The purpose is to classify some flow structures inherent to the solar wind close to the Sun. The radial distance of the internal, nearest to the Sun boundary of the transition region R_{in} is used as a natural characteristic of the acceleration process (intensive acceleration produces supersonic transition closer to the Sun). Experimental data on radio wave scattering were studied in comparison with data on coronal magnetic fields and optical observations of the white light corona (WLC).

2. Radio wave scattering observations

Occultation observations of compact natural sources, quasars and water vapour masers, have been performed regularly since 1987. Large radio telescopes of the P.N. Lebedev Physical Institute at Pushchino were used, DCR-1000 at 103MHz and RT-22 at 22.2 GHz. The observation and data processing methods are described elsewhere (Lotova et al. 1985; Lotova et al. 1989). Prolonged series of daily observations provide radial dependences of scattering, that permit us to determine the positions of both inner and outer boundaries of the solar wind transition region revealed as the region of enhanced scattering. Determination of the inner boundary is facilitated sufficiently by an additional method, the use of a predecessor effect, the narrow region of abruptly reduced scattering that is observed close to the inner boundary of the transition region with its enhanced scattering (Lotova et al. 1985, 1989; Lotova 1988).

These scattering observations cover the range of radial distances of about 5 to $60R_s$ and thus include the entire main acceleration region of 10 to $40R_s$, characteristic outside of the polar areas. Since 1987, several sources passing near the Sun at different heliolatitudes simultaneously or close in time have been observed. As a result, radio maps, i.e. two-dimensional projections of the transonic region, have been constructed allowing us to study the evolution of the large-scale solar wind structure over an 11-year cycle (Lotova & Vladimirskii 1997). These radio maps are by no means "snapshots" of the transition region because of the solar corona evolution during a period of data accumulation. Newertheless, it is a very valuable source of information as to the general shape and asymmetry of the transonic region. As to the experimental errors, scattering level inaccuracy may result in an error of $\pm 0.5R_s$ in R_{in} values.

Fig. 1 presents new results, showing the global structure of the transition region for the year 1997. Deviations from the spherical symmetry are very significant. Circles (o) denote the compact source in the Crab nebula 3C144 and quasars 3C133, 3C152, 3C154, 3C166, 3C208, 3C215, 3C225 and 3C228, passing in June and August. Quasars 3C275 and 3C279, that passed in October, are denoted with □. Maser sources S252A and U ORI passed in June (◇), W 31(2) and IRC-20431 - in December (◇). The transition region is shown with hatching. The open symbols correspond to the inner (closer to the Sun) boundary of the transition region, R_{in}, the filled ones - to the outer boundary. As seen from the figure, the transition region is at a radial distance $R \simeq (10\text{–}40)R_s$ from the Sun.

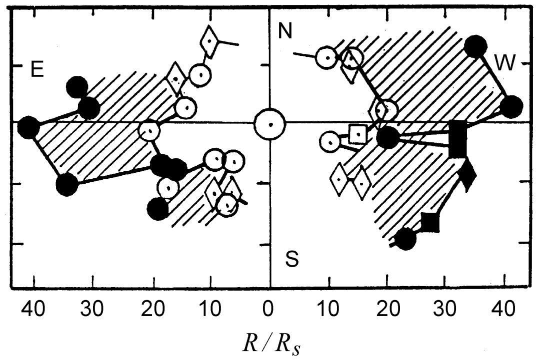

Fig. 1. Radio map of the solar wind transition region for 1997 (for symbols see the text)

3. Plasma flow structure, optical data and solar magnetic fields

In order to reveal specific mechanisms controlling the solar wind flow, the results of the solar plasma acceleration, as seen by the radio wave scattering data, were investigated in relation with solar magnetic fields at small distances from the Sun. Besides these local characteristics, flow structures existing close to the solar surface proved to be of a great importance, so we use the SOHO optical solar corona observations. As a source of magnetic data, the INTERNET information of optical measurements of magnetic fields at the photosphere level were used, obtained by the Wilcox Solar Observatory, Stanford University (htpp: // quake. stanford. edu / wso/ wso. html). On this basis, field equations for $R_s \leq R \leq 2.5R_s$ were solved. Calculations were performed within potential approximation, possible differences introduced by the near - solar medium were disregarded (Hoeksema et al. 1982, 1983; Hoeksema & Scherrer 1986; Hoeksema 1991; Obridko & Shelting 1992, 1999).

The results of the magnetic field calculations were presented in two forms. First, absolute values of the radial component of the fields vector $\mid B_R \mid$ were calculated for $R = 2.5R_s$ and angular coordinates of the occulted source at the day of the radio astronomy observations revealing the transition region inner boundary R_{in}. Radial distance $2.5R_s$ was adopted as a "source surface", initial area of the solar wind acceleration processes. The choice of the angular coordinates mentioned that both $\mid B_R \mid$ and R_{in} values relate to the same streamline of the solar wind flow and characterise the very beginning of the acceleration process ($\mid B_R \mid$) and its result (R_{in}): the higher the intensity of acceleration, the nearer to the Sun proceeds the transition to supersonic velocities.

In a comparison of the $\mid B_R \mid$, R_{in} values with morphology data for optical corona, a problem of resolution of the radio telescope arises. The RT - 22 diagram for $\lambda = 1.35\,cm$ is $2'.6$ wide. Taking into account nearly radial structure of the plasma flow near the Sun, it may be hoped that this will be sufficient for resolution of a flow structure starting from a streamer and observed at a radial distance of about $10R_s$ from the Sun.

Besides ($\mid B_R \mid$) values, topology of the magnetic field at the "source area" was determined using the same Wilcox Observatory data; fieldline diagrams were constructed with a uniform net of points at the solar surface, $R = R_s$ as starting points. These diagrams (see below) are not as easy to interpret as optical images, open field configurations of simple, dipole type arise in polar areas only. At moderate heliolatitudes fieldlines outgoing in space (open type) are combined with a dense sheet of low-lying fieldline loops. A combination of outgoing fieldlines with broad loops, reaching the "source surface", presents an important special case, differing sufficiently from the open type as the plasma acceleration intensity. In spite of these complications, the general result is quite definite: strong magnetic fields only produce fast streams of the solar wind.

The results of 18 experiments, pairs of $\mid B_R \mid$ and R_{in} values are presented in Table 1. The Table gives the name of the occulted source, the date of observation, coordinates of the inner boundary of the transition region: E/W hemisphere, heliolatitude ϕ, and radial distance from the Sun. The last columns give

Table 1. Solar wind flow structures from radio sounding and magnetic data

N	source	date	E/W	ϕ deg	R_{in}/R_s	$B_{2.5R_s}$ μT	field structure	WLC morphology
1	3C144	12.06.97	E	-33	11	2.14	open	lateral lobe of the streamer
2	3C144	18.06.97	W	-15	11	2.75	–”–	–”–
3	3C166	30.06.97	E	-46	9	6.08	–”–	–”–
4	3C228	13.08.97	E	12	15	0.26	–”–	–”–
5	3C275	09.10.97	W	-08	15	0.54	–”–	–”–
6	3C152	20.06.97	E	-63	14	7.32	closed	main body of the streamer
7	S252A	20.06.97	E	-50	15	5.12	–”–	–”–
8	3C208	02.08.97	E	-60	15	6.29	–”–	–”–
9	3C215	12.08.97	W	05.5	20	1.21	–”–	–”–
10	3C225	10.08.97	E	-02	21	1.38	–”–	–”–
11	3C154	21.06.97	E	34	16	3.08	—	–”–
12	3C154	27.06.97	W	50	15	4.96	—	–”–
13	U ORI	22.06.97	W	-50	15	4.89	—	–”–
14	S252A	26.06.97	W	-37	15	3.50	—	–”–
15	3C133	12.06.97	W	38	18	4.24	mixed	area of amorphous luminosity
16	3C152	26.06.97	W	-32	18	3.01	–”–	–”–
17	U ORI	17.06.97	E	-56	16	6.00	–”–	–”–
18	3C208	08.08.97	W	-36	19	3.27	–”–	–”–

the result of more detailed field calculations - open or closed type of the field structure and optical corona morphology data. The Table does not reveal immediately the existence of some definite correlation between field intensity data and transition region geometry. Nevertheless, the use of the magnetic field topology data and optical corona observations allow us to distinguish three physically differing types of flow, which reveal each an obvious field to R_{in} correlation (Fig. 2).

Type 1. Open magnetic field configuration (Table 1, experiments 1–5) with the field lines going away to interplanetary space immediately from the source surface and a transition region located relatively close to the Sun. As shown earlier (Lotova et al. 1995), this structure is characterized by low turbulence and high stream velocities. The comparison with optical data showed that the line of sight of the radio telescope passed here through the plasma stream started at the lateral lobe of the streamer. The result was somewhat unexpected, because in literature (e.g., Watanabe et al. 1996), the flows of streamer type had never been considered among the probable sources of high-speed plasma streams. It is possible that the lateral lobes of the streamers differ essentially in their characteristics from the main body.

Type 2. Closed magnetic field configuration (Table 1, experiments 6–10) with the field lines that form closed loops at (2–3)R_s and a transition region located farther from the Sun. This type of structure is characterised by higher turbulence and lower stream velocities. As was shown by optical observation, the line of sight of the radio telescope passes over the main body of the streamer. In experiments 11–14, the magnetic field structure was not analysed, but the ratio of the measured values

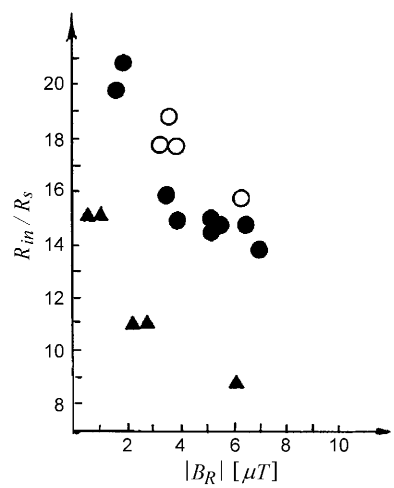

Fig. 2. Correlation relations for the magnetic field intensity $\mid B_R \mid$ at $R = 2.5R_s$ and the inner boundary, R_{in}, of the solar wind transition region

of R_{in} and $\mid \boldsymbol{B}_R \mid$ allows us to classify them as type 2 flows (Fig. 2).

Type 3. Intermediate configuration that comprises both open and closed (loop-like) field lines (experiments 15–18). This case is characterized by the farthermost location of the transition region and the low speed of the solar wind. The line of sight of the radio telescope in these experiments passed over a vast area of strong amorphous luminosity of the solar corona. $\mid B_R \mid$ to R_{in} correlation is obvious for all three groups of data in Fig. 2: decreasing field strength is accompanied by lower intensity of the acceleration process, increasing distance of the transition

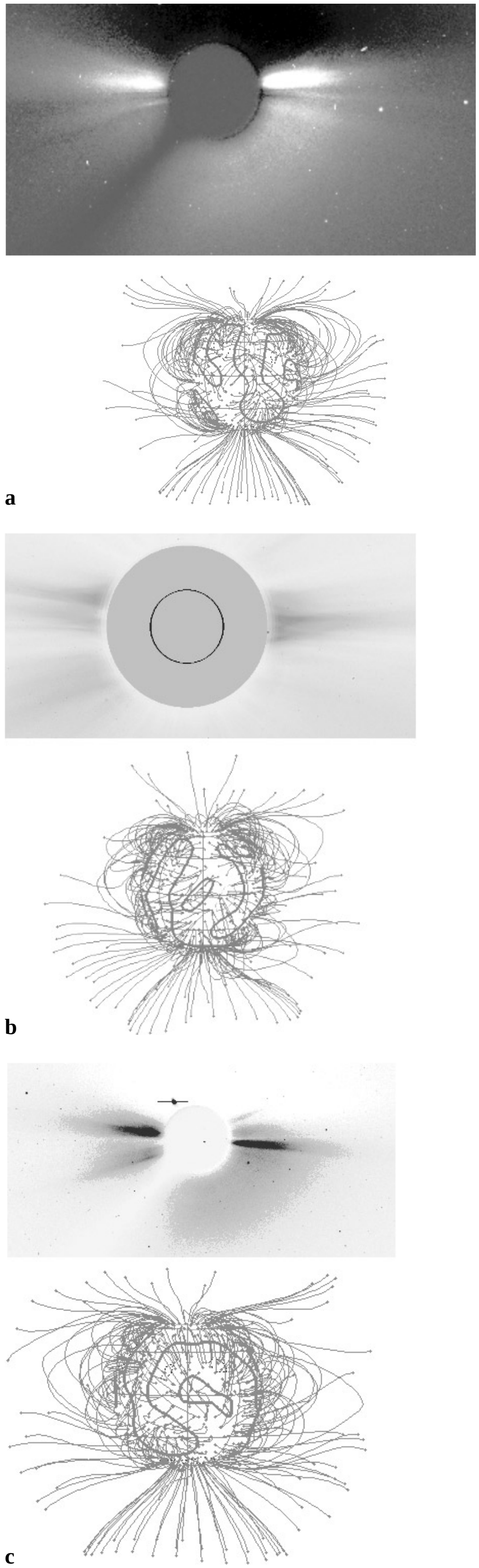

Fig. 3a–c. The solar corona and magnetic field structures for three types of the solar wind flow (Table 1, experiments 3, 9 and 16)

region from the Sun. Though the difference between the group 2 and 3 ordinates in Fig. 2 is not too large, it should be noted that flows arising in the morphologically different regions of the solar corona differ in their structure so that they can be assigned to two different types of the solar wind flow.

Considering the correlation relations reported in Lotova et al. (1995) together with the results described above, one can make a conclusion that generation of the high-speed solar wind is predetermined by the structure of magnetic fields in the vicinity of the Sun. All these correlations are obviously accounted for by the phenomena of frozen-in field, penetration of solar magnetic fields far into interplanetary plasmas. As seen from Fig. 2, the variations of intensity of the magnetic field are not too large, being limited to the range of 1 to 7 μT. This suggests that the topology of the field (open or closed configuration of the fieldlines) is of prime importance, rather than its intensity.

Fig. 3a–c illustrates three types of the flow structure obtained in experiments 3, 9 and 16, respectively (Table 1). Each of three panels shows a SOHO image of the solar corona and the structure of the magnetic field lines, plotted using a uniform net of points on a sphere of radius $R = R_s$ (on the solar surface). The arrows indicate the line-of-sight direction of radio telescope at the crossing the inner boundary of the transition region. The figure shows profound temporal and spatial changes in the structure of flow and magnetic field in the solar environment that are undoubtedly the immediate cause of changes in the stream structure of solar wind. The solar corona being very nonstationary, Figs. 3a–c were obtained for the data in agreement with the days of the R_{in} determinations.

4. Conclusion

The analysis of correlation between the structure of the optical solar corona, the position of the inner boundary of the solar wind transonic region determined by radio astronomy methods and the structure of solar magnetic fields at the origin of the solar wind streamline close to the solar surface revealed the existence of three types of plasma flow, corresponding to three configurations of the magnetic field lines. The open magnetic field with the field lines, going away into interplanetary space, generates high-speed streams of solar wind with a low turbulence and high intensity of acceleration processes. The closed field, with the field lines, that are strongly curved over the source surface and close at (2–3)R_s to form a fan-like structure, gives origin to low-speed plasma streams with high turbulence and relatively low supersonic velocities at large distances from the Sun. The low speed streams occur also in the case of intermediate (open - and loop-like) configuration of the magnetic field. Optical SOHO observations show here regions of intensive amorphous luminosity in the corona.

Optical observations on SOHO provided new information on the particular features in the solar corona that were identified as sources of high- or low-speed solar wind. It turned out that, besides the well-known polar coronal holes, the high-speed solar wind could originate at the lateral lobes of the streamers, observed at medium heliolatitudes, whereas the central part of the streamer structure was the source of the low-speed wind, as suggested before.

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