Penetration of Coronal Magnetic Fields into Solar-Wind Streams

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Received February 17, 1999; in final form, February 23, 2000

Abstract—The formation of solar-wind stream structure is investigated. Characteristic features of the solar and coronal magnetic-field structure, morphological features of the white-light corona, and radio maps of the solar-wind transition (transonic) region are compared. The solar-wind stream structure is detected and studied by using radio maps of the transition region, the raggedness of its boundaries, and their deviation from spherical symmetry. The radio maps have been constructed from radioastronomical observations in 1995–1997. It is shown that the structural changes in the transition region largely follow the changes occurring in regions closer to the Sun, in the circumsolar magnetic-field structure, and in the solar-corona structure. The correlations between the magnetic-field strength in the solar corona and the location of the inner (nearest the Sun) boundary of the transition region are analyzed. The distinct anticorrelation between the coronal magnetic-field strength and the distance of the transition region from the Sun is a crucial argument for the penetration of solar magnetic fields into plasma streams far from the Sun. © 2000 MAIK “Nauka/Interperiodica”.

Key words: Sun, corona, magnetic fields, solar wind, transition region

INTRODUCTION

In this paper, we make a comprehensive comparison of experimental data on the large-scale structure of circumsolar plasma and solar-wind streams. Considerable progress has been made previously in investigating the mechanisms that determine the magnetic field and its deviations from the previosly used spherical model. It has been established that the passage from a subsonic flow in the immediate vicinity of the solar surface to a supersonic one at large distances occurs in an extended region. The accompanying changes in the flow mode largely determine the stream turbulence and the acceleration energetics (Lotova et al. 1985, 1995; Wang et al. 1990; Efimov et al. 1990; Schwenn and Marsch 1995; Kojima and Kakinuma 1990; Rickett and Coles 1991; Bird 1991; Efimov 1994; Rao et al. 1995; Torkar and Pätzold 1995; Woo 1996; Lotova and Vladimirskii 1997). However, the basic problems of solar-wind physics, its sources and acceleration mechanisms have not been studied adequately. The irregular structure of circumsolar plasma streams is a major factor in the formation of a supersonic solar wind (Malara et al. 1992; Vladimirskii et al. 1996), but the specific mechanisms of the phenomena in this region are virtually unstudied. The role of magnetic fields in the circumsolar plasma acceleration is also poorly understood. The problem as a whole is far more complex than any studies of laboratory-scale processes. The solar wind begins as a slow expansion of very dense plasma in a strong gravitational field; a stream of tenuous plasma moving radially at supersonic velocities arises far from the Sun. We therefore analyze here the correlations between circumsolar plasma stream parameters during the formation of a supersonic solar wind by using the specific experimental studies carried out in 1995–1997 at the epoch of solar minimum, which completes solar cycle 22. We use radioastronomical data on the scattering of radio emission from compact natural sources by circumsolar plasma, optical observations of the white-light solar corona, and data on the magnetic-field strength and structure at small distances from the solar surface. The distance from the Sun at which the passage to a supersonic flow occurs is used to estimate the acceleration rate. It is important that we also compare the morphological features of the solar corona with the solar-wind flow structure at large distances.

SOLAR MAGNETIC FIELDS

To ascertain the specific mechanisms governing the solar-wind flow, we studied the large-scale flow struc-
STRUCTURAL FEATURES OF THE WHITE-LIGHT CORONA

A comparison of the shape of the white-light corona with the above data on the structure of circumsolar magnetic fields is of great interest in studying the formation mechanism of the solar-wind stream structure. Individual features in the coronal structure extend to distances of up to several solar radii from the solar surface and allow a direct comparison with magnetic data (Rušín et al. 1992; Koutchmy and Livshits 1992).

Figure 2 shows the structure of the white-light corona reconstructed from the observations of the solar eclipse on March 9, 1997. We see helmet streamers extending to 5–6RS, considerable flattening at the poles, and polar coronal holes. We also used similar observations of the October 24, 1995 eclipse (Rušín et al. 1996; Pinter et al. 1997; Gulyaev 1998). Apart from the observations of total solar eclipses, we used SOHO photographs of the white-light corona retrieved via Internet. The dates were chosen in accordance with the time of our radioastronomical observations.

The shape and sizes of the corona (see Fig. 2) are typical of the epoch of solar minimum. The corona is modest in size; it is highly flattened at the poles. A persistent N–S asymmetry, the invariably larger flattening of the corona in the southern polar region, is also typical of the epoch of minimum of solar cycle 22. The latter circumstance is directly compared with the magnetic data: on the same days, enhanced magnetic-field strengths were obtained for the southern polar region. The same direct comparison can also be made for finer structural features.

RADIO-WAVE SCATTERING EXPERIMENTS

Regular experiments on the sounding of circumsolar plasma by radio emission from compact natural sources, quasars, and water-vapor maser sources have been carried out with large radio telescopes in Pushchin (Russian Academy of Sciences) since 1987. The cross-shaped DKR-1000 radio telescope, which operates at meter wavelengths, is used in interferometer mode to measure the apparent angular sizes of sources and the radio-wave scattering angle 2θ. The RT-22 radio telescope is used for observing scintillations of maser sources at 1.35 cm. In both cases, long (of the order of a month) series of observations are carried out, allowing the radial dependence of the scattering of radio emission from sources passing near the Sun to be studied. The main result of these observations is the radial dependence of the radio-wave scattering, from which the locations of the inner (Rin) and outer (Rout) boundaries of the solar-wind transition region can be determined. Against the background of a general falloff of the scattering with increasing radial distance, the transition region shows up as a region of enhanced scattering. A study of the nature of this phenomenon shows that the change in scattering results from a change in...
the flow mode (Lotova et al. 1985; Lotova 1992). In the transition region, the mixed flow mode is realized, where both subsonic and supersonic plasma streams coexist and interact. The enhanced scattering, the enhanced flow turbulence, is associated with the instability of discontinuities in such flows (Syrovatskii 1954). It is important that the transition region is a region in which the main acceleration of solar-wind streams takes place. At \( R > R_{\text{out}} \), the solar-wind stream structure is retained. Revealing the key parameters that can determine the retention of a considerable solar-wind flow irregularity is a research problem of great importance. In particular, as the data presented here indicate, the strength of the magnetic field frozen in solar-wind streams is such a parameter.

The techniques for scattering observations and for experimental data reduction, which allow the transition-region parameters to be studied, were described by Lotova et al. (1985) and Lotova and Nagelys (1988). Determination of the location of the transition-region inner boundary is considerably facilitated by using a characteristic feature of the flow in the supersonic region (Lotova and Vladimirskii 1997). A “precursor” of the transition region, a narrow region of sharply reduced scattering whose distance from the transition region is small and is not subject to significant variations, is observed near the transition-region inner boundary.

In connection with the study of the formation of solar-wind stream structure, we compare here the heliolatitude dependences of the location of the transition-region inner boundary \( (R_{\text{in}}) \) and the coronal magnetic-field strength at a radial distance of \( 2.5R_{\odot} \) \( (B_{\text{R}}) \). In this study, as previously, the angular coordinates were reconciled with the times of observations. As the argument, we use the position angle \( \phi \) \( (0^\circ \leq \phi \leq 360^\circ) \), which is measured counterclockwise from the northward direction. The 1997 results are presented in Fig. 3. The 1995–1996 observations were used in a similar way. To improve the statistics in the dependence of \( |B_{\phi}| \) on position angle, apart from the values calculated for the times of \( R_{\text{in}} \) determination (denoted in Fig. 3 by triangles), we used the values corresponding to the times of \( R_{\text{out}} \) determination (denoted by circles).

A clear anticorrelation between the magnetic-field strength and the radial distance of the transition region from the Sun is directly seen from Fig. 3: a location of the transition region closer to the Sun corresponds to large field strengths \( (\sim 7 \mu T) \). Since such a location of the transition region suggests intense acceleration processes and the probable emergence of high-speed solar-wind streams (Lotova et al. 1995), Fig. 3 can be considered as direct evidence for a major role of solar magnetic fields in the circumsolar plasma acceleration mechanism. The structural features of the magnetic fields and plasma flows emerging at small distances from the Sun are retained during the subsequent acceleration at radial distances of \( (10-40)R_{\odot} \) hence the retention of a considerable irregularity of the flow, the stream structure, in the supersonic region far from the Sun.

**RADIO MAPS OF THE SOLAR-WIND TRANSITION REGION**

To obtain maximum information about the state of the circumsolar medium, the largest possible number of sources is used in sounding experiments. Observations of sources passing near the Sun at various heliolatitudes are of greatest value. Using such sources allowed us to present the results of the observations in the form of radio maps, two-dimensional images of the solar-wind transition region on which the contours of the inner and outer boundaries of the transition region are plotted (Lotova and Korelov 1992; Lotova and Vladimirskii 1997). The number of sources accessible in sensitivity that pass simultaneously or at close times is not enough to obtain images which can be directly compared with...
Figure 4 shows the radio map constructed from the 1997 observations. The open and filled symbols correspond to the locations of the transition-region inner and outer boundaries, respectively. We used several series of observations. The triangles represent the observations of the quasars 3C2 and 3C5 approaching the Sun in March, and the circles represent the observations of the compact source 3C144 in the Crab Nebula and the quasars 3C133, 3C152, 3C154, 3C162, 3C166, 3C172, 3C192, 3C208, 3C212, 3C215, 3C225, and 3C228 (June and August). The quasars 3C273, 3C275, and 3C279 pass in October and are denoted in the figure by squares. The maser sources GGD4, S252, U Ori passing in June, and IRC-20431, W31(2) passing in December are marked with diamonds.

The results presented in Fig. 4 and similar observations in 1995 and 1996 include the year of solar minimum (1996). The evolution of the transition region in previous years was studied by Lotova and Vladimirskii (1997). Basically, this is an increasingly closer approach of the transition region to the Sun as the solar minimum is approached. The 1995–1997 results show that the transition region was closest to the Sun in 1995 rather than in 1996, the year of solar minimum. The years 1995–1997 are characterized by a flattening of the transition region at the poles and by its considerable asymmetry. As in the above results referring to small distances from the Sun, to the coronal region, a considerable N–S asymmetry is retained during all three years 1995–1997. The transition-region structure in 1995 inclined to the heliopole plane engages our attention. The region shape and the inclination closely match the results of solar-corona observations in the eclipse of October 24, 1995. The inclination of the transition region to the heliopole is unnoticeable in 1996 and small in 1997. A comparison of Fig. 4 with Fig. 2 shows that the transition-region shape also largely follows the corona shape here. In general, the study of the large-scale structure of the solar-wind transition region using radio maps suggests that the flow structural features emerging under the effect of coronal magnetic fields near the solar surface are retained during the solar-wind acceleration at distances of $(10–40)R_\odot$.

**CONCLUSION**

We have compared the parameters describing the state of circumsolar plasma and solar-wind streams at the end of solar cycle 22, at the epoch of solar minimum. We used data on the magnetic-field strength and structure, observations of the white-light solar corona, and radioastronomical observations of radio-wave scattering by circumsolar plasma. The magnetic-field structure at small distances from the Sun, in the coronal region, is shown to completely determine the plasma flow pattern near the Sun. The salient features of this pattern are retained during the subsequent solar-wind acceleration at radial distances of $(10–40)R_\odot$ from the Sun. The course of the acceleration itself is largely...
determined by the magnetic-field strength at the base of the solar-wind streamlines, in the coronal region. A location of the inner boundary of the solar-wind transition region closer to the Sun, a low flow turbulence level, intense acceleration processes, and high supersonic-flow velocities far from the Sun correspond to enhanced magnetic-field strengths. The available experimental data indicate that the solar magnetic fields and their penetration into solar-wind streams determine the large-scale solar-wind structure and are a major factor in the solar-wind acceleration mechanism.

ACKNOWLEDGMENTS

The radioastronomical data were obtained with two radio telescopes: RT-22 (registration number 01-10) and DKR-1000 (registration number 01-09). We are grateful to the staffs of the J. Willcox Observatory for the solar magnetic field data retrieved via Internet and to the SOHO staff for the image of the white-light corona also retrieved via Internet. The work of the Russian authors was supported by the State Science and Technology Program "Astronomy" (project no. 4-151), the Russian Foundation for Basic Research (project no. 97-02-16233), and RFBR-NNIO (project no. 96-01-00040G).

REFERENCES


Translated by G. Rudnitskii