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PREFACE

In addition to sunshine, the Sun emits extensively into the interplanetary space of about one trillion tons of ionized hydrogen per second. The phenomenon is known as solar wind. Details of the solar wind acceleration near the Sun are poorly known. The purpose of our book is to elucidate the research of the solar wind acceleration region. Unique scientific information about the solar wind at heliocentric distances up to 3 solar radii obtained from receiving antennas directed almost to the Sun (that is the challenging technical task itself) during telecommunication sessions with "Mars 2", "Mars 4", "Venera 10", "Venera 15", "Venera 16" spacecraft and the solar wind acceleration region modelling underlie the fundamental basis for our book.

The book is based on the lectures given by Oleg I. Yakovlev for postgraduates in the Institute of Radio Engineering and Electronics of the Russian Academy of Sciences, as well as the lectures given by Igor S. Veselovsky for students at the chair of cosmic rays and space physics in Physical Department of Lomonosov Moscow State University and the lectures given by Yuri V. Pisanko for students at the chair of ocean's thermo-hydromechanics in the Department of Aero-physics and Space

Research of Moscow Institute of Physics and Technology. The book's text is not pure lecture notes but rather materials written in preparations for lectures, sometimes not quite suitable for the oral presentation during a lecture. All three courses are directed to familiarize students and postgraduates with the circumsolar "space weather kitchen" physical principles, taking into account the author's scientific interests.

We tried to arrange the book so that each chapter could be read almost separately from the others. It allowed us to introduce the most natural notation system for each chapter: in different chapters, the same symbol could denote different physical or mathematical variables, but inside each chapter, the biunique correspondence between the symbol and the variable (physical or mathematical) remained unchanged.

We suppose that a reader knows the fundamentals of electrodynamics, magneto-hydrodynamics, and solar plasma physics, so there are many equations in the text. Not every equation is numbered to avoid unnecessarily burdening the text; numbered are only those mentioned in the text or used in deriving subsequent equations. We introduce abbreviations for an equation (Eq. (X.Y)) or a set of equations (Eqs. (X.Y)) when it is needed to mention these in the text. The first numeral in parenthesis (X) means the chapter number, the second (Y) means the number of the equation (equations) inside the chapter. When assigning a number to a system of equations, the number stands mainly across the last equation of the system. All variables and equations in the text are written in "italic type", while vectors are marked by an upper arrow in equations and are written in "bold type" in the text.

As a rule, we use the Gaussian system of units everywhere except the cases when the use of other units is dictated by established practice in the area of solar wind research: almost all researchers express the solar wind velocity in kilometres per second while magnetic flux density – in Gauss or SI unit Testa (1 nT = 10^{-5} Gauss). SI unit Hz is used as the frequency unit. In the section devoted to the electric field in the solar wind acceleration region, we use the SI system of units where the electric field is expressed in Volts per meter and the electric charge – in Coulombs. We use the off-system Angstrom unit for light wavelength and the off-system electron-volt unit for charged particle energy.

In Chapter 2, it is convenient to express the heliocentric distance in solar radii. Furthermore, the term "Astronomical Unit (AU)", which means the average distance between the Sun and the Earth, can be found in the book.

We included a few of our papers and books as references. It is stipulated by our desire to touch on subjects well known for us, which are described in detail in our listed publications. We include many references to papers published in Russian because one of our goals is to inform readers who cannot read Russian about the results published in Russian only. Indeed, our references are incomplete, and we, in advance, present our apologies to those who consider that their results are not mentioned in more detail.

We hope that our book could be helpful to young researchers and engineers specializing in solar wind and radio communications in deep space.

We are grateful to all who have read the draft or its parts, improving the text significantly. We express our sincere gratitude to Cambridge Scholars Publishing for the stimulation of writing our book.

CHAPTER 1

INTRODUCTION TO THE PROBLEM

Eclipses and the solar corona

There is no non-catastrophic phenomenon in nature that amazes the human imagination as much as solar eclipses do. Really “the death of the Sun” looked horrible for the primitive who did not understand that this was only a temporary and seemingly phenomenon. Everything begins from the solar disk distortion as if someone gnawed it from its right-hand side. The rest becomes smaller and smaller and, little by little, transforms into the sickle with spikes directed to the west. The sickle becomes as thin as a golden filament, hardly enlightening everything around, so that shadow edges look filamentary too. Eventually, the golden filament disappears, and the black spot surrounded by the mysterious halo of quickly changing rays swims on the sky at night among stars sparkling here and there. It continues for no more than 8 minutes at the equator and for no more than 6 minutes in the middle latitudes. A new golden filament breaks loose from the right-hand side of the black spot, and the light arises. The golden filament becomes thicker and transforms into the sickle with spikes directed to the east; eventually, the whole solar disk recovers.

The ancients considered an eclipse as the evil omen: “the death of the Sun”, they attributed to an unknown supernatural power. The description of the eclipse in Homer’s “The Odyssey” is related to the culmination – the day when Penelope’s suitors decided to kill Odysseus, who had come back to Ithaca. Theoclomenus rescued Odysseus when he intimidated plotters by ominous signs, including the eclipse:

«The Sun is blotted out of the sky look there
A lethal mist spreads all across the Earth!»
(“The Odyssey” by Homer, Book XX, verse 356-357, translated by Robert Fagles)

The book entitled “History of the Peloponnesian War” is devoted to the war between Athens and Sparta in the 5th century B.C. The author – Athenian politician Thucydides – participated in many of described events. Eclipses often occurred during the war. The eclipse, known as the Pericles eclipse, took place in the summer of the first year of the war. Five hundred years after the events that had been described by Thucydides (the political antagonist of Pericles), Plutarch devoted XXXV paragraph of the chapter

“Pericles and Fabius Maximus” of his “Selected Biographies” to this eclipse. Pericles at the head of naval forces was ready to put to sea when the eclipse occurred, and people were frightened. Seeing helmsman’s complete confusion, Pericles cloaked the helmsman and asked him whether he considered this as a misfortune. The answer was “no”. Hearing this answer, Pericles asked about the difference between the two cases other than the cloak size. An adherent of the Democratic Party of Athens, Pericles meant the Moon as a cloak that hid the Sun. He knew about the Anaxagoras (500-428 B.C.) doctrine, considering the Moon as a cover hiding the Sun and the reason for darkness during an eclipse. The distance between the Moon and the Earth is four hundred times shorter than the distance between the Earth and the Sun, and its diameter is four hundred times smaller than the solar one. Therefore, the apparent diameter of both objects is almost the same: the Moon covers the Sun almost completely. During an eclipse, the Moon shadow on the Earth is the round spot of 270 km in diameter. The spot moves on the Earth surface quicker than a bullet (~ 1 km s^{-1}) along the long narrow strip where the eclipse can only be observed. On May 5, 1818, when an eclipse took place, Carl Marx was born in Trier in Germany. The eclipse was not seen in Germany but was seen in Russia, especially clear in Saint-Petersburg.

The marvelous silvery-purl beaming ring around the Sun during an eclipse is the solar corona. It is hardly ever observed during a day: it shines a million times weaker than the sunshine. Byzantine historian Leo Diaconus did the first record of the corona in his book entitled “History”, written in imitation of Thucydides. He described the eclipse of 968 A.D., December 22, 4 p.m., when in calm weather the darkness covered lands and gleam stars were seen on the sky and seen was the solar disk devoid of its shine, and only its border shined faintly as if a narrow band had encircled it.

The snapshot of the corona was taken in 1851. Three components of the coronal emission were separated. The first component is K-corona (from German “kontinuirlich” – continuous), i.e. the solar light scattered on free coronal electrons in the direction of an observer. The second one is F-corona (so-called internal zodiac light), i.e. the solar light scattered on particles of the interplanetary dust slowly moving between the Earth and the Sun. The third one is E-corona, i.e. the emissions of coronal ions in spectral lines of the visible range. Mountain observations of E-corona and the lifting of spectrographs on balloons allow investigating the spectra in detail. Edlen (Edlen 1943, 30-63) identified green (5303 Å), red (6374 Å), and several other coronal spectral lines with lines of highly ionized Fe, Ni, Ca atoms. In the electron impact ionization case, the successful ionization needs the high thermal speed of a free coronal electron and, hence, the high coronal temperature. The estimates showed a temperature value of about a million degrees. Under such temperatures, the coronal gas is ionized almost entirely and is the hydrogen plasma with minor impurities of other chemical elements. Let us follow (Chapman 1957, 1-11). The coronal thermal conductivity is as follows:

$$\kappa = k_0 T_e^{5/2}$$

T_e is the electron temperature, $k_0 \approx 8\times10^{-7}$ (erg s $^oK^{7/2}$) for typical coronal temperatures and electron concentrations. The heat conduction equation for the static spherically symmetric corona without any heat sources and sinks is as follows:

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 k_0 T_e^{5/2} \frac{dT_e}{dr} \right) = 0$$

Here r is the heliocentric distance.

The solution satisfying the condition $T_e \to 0$ for $r \to \infty$ is as follows:

$$T_e = T_{e0}\left(\frac{r_0}{r}\right)^{2/7} \qquad (1.1)$$

Here $T_{e0} = 10^6$ ^oK for $r_0 = 1{,}058$ R, R is the solar radius.

The hydrostatic equilibrium of the corona requires:

$$\frac{dP}{dr} = -\frac{GM_s \rho}{r^2} \tag{1.2}$$

Here P is the pressure, ρ is the coronal gas mass density, G is the gravitational constant, and M_s is the solar mass. The electric neutrality of the coronal plasma implies the equality of electron and proton concentrations on the spatial scale larger than the Debye radius. Therefore,

$$\rho = n\left(m_e + m_p\right) \cong nm_p$$

Here n is the electron concentration, m_e (m_p) is the electron (proton) mass. In the case of the same proton and electron temperatures, the pressure is as follows:

$$P = 2nkT \tag{1.3}$$

Here k is the Boltzmann constant. Substituting Eq. (1.1) into Eq. (1.2), one obtains:

$$\frac{d}{dr}\left(\frac{n}{r^{2/7}}\right) = -\frac{GM_s m_p}{2\kappa T_0 r_0^{2/7}} \frac{n}{r^2}$$

The solution of this equation is as follows:

$$n(r) = n_0\left(\frac{r}{r_0}\right)^{2/7} \exp\left\{\frac{7}{5}\frac{GM_s m_p}{2kT_0 r_0}\left[\left(\frac{r_0}{r}\right)^{5/7} - 1\right]\right\} \qquad (1.4)$$

Here $n_0 = n_0(r_0)$. Eq. (1.1), Eq. (1.3), and Eq. (1.4) give the pressure heliocentric distance dependence as follows:

$$P(r) = P_0 \exp\left\{\frac{7}{5}\frac{GM_s m_p}{2kT_0 r_0}\left[\left(\frac{r_0}{r}\right)^{5/7} - 1\right]\right\} \qquad (1.5)$$

Here $P_0 = 2n_0kT_0$. It is clear from Eq. (1.5) that the pressure monotone decreases with the heliocentric distance up to its asymptotic value at $r \to \infty$, which is:

$$P_\infty = P_0 \exp\left(-\frac{7}{5}\frac{GM_s m_p}{2kT_0 r_0}\right)$$

For coronal temperatures and concentrations, P_∞ is about seven to eight orders of magnitude higher than the total pressure of the interstellar gas, the galactic magnetic field, and cosmic rays. It means that the assumption about the static corona is false.

Comets and the solar corpuscular radiation

Another enigmatic (for the ancients) phenomenon is a comet – a star with the colossal tail sometimes occupying half of the sky and appearing suddenly. Usually, a comet has not only the "tail" but also the "head". The head is the brightest top part of a comet, but the tail appears when a comet approaches the Sun. As far back as the 17th century, Kepler noted that the comet's tails were always directed away from the Sun and assumed this could be because of the sunshine. In the sixties of the 19th century, the director of Moscow astronomical observatory Bredichin (Bredichin 1861, Bd.1291) (Bredichin 1861, Bd.1305-Bd.1306) (Bredichin 1878, Bd.93) created a theory of comets. According to Bredichin, the comet's tails consist of the gas-dust mixture evaporating (due to the sunshine) from comet's heads; for sufficiently small dust particles, the solar light pressure can exceed the gravitation and comet's tails become directed from the Sun. In the eighties of the 19th century, the spectrum analysis of the light of the comet's tails revealed the ionized carbon oxide (CO^+) presence there. In the late thirties and early forties of the 20th century, comets were intensively studied in Germany. Based on observations of the Whipple-

Fedke comet in 1942, Ahnert (Ahnert 1943, 307-308) ascribed the anti-solar orientation of comet's tails to permanent corpuscular radiation of the Sun. von Hoffmeister (von Hoffmeister 1943, 265-287) also studied ionized tails of comets; the crude estimate of the solar corpuscular radiation velocity as ~ 400 km s^{-1} could be derived from his graphs. Biermann (Biermann 1951, 274-286) (Biermann 1953, 291-302) (Biermann 1957, 109-110) investigated accelerations of gas clouds (mainly CO^+) in the comet's tails. He determined the velocity and acceleration of a cloud from the sequence of comet tail snapshots representing the cloud motion along the tail. Many times he revealed accelerations of a hundred times more effective than the local gravitation. It was impossible to explain such accelerations by the solar light pressure: the latter was a few orders of magnitude smaller. Biermann attributed the discovered accelerations to the transfer of the solar corpuscular radiation momentum to the cloud in the comet tail. The carbon oxide molecule ionization he ascribed to the charge exchange reaction with solar protons and concluded that the Sun emitted corpuscles continuously in all directions.

In all fairness, let us note that Lodge (Lodge 1900, 249) wrote that terrestrial magnetic storms were caused by clouds of charged atoms or molecules moving from the Sun. FitzGerald (FitzGerald 1900, 287-288) estimated the speed of such clouds as ~ 500 km s^{-1}. Bartels (Bartels 1932, 1-52) noticed the strong tendency of moderate terrestrial magnetic storms to recur every 27 days, i.e. with the period of rotation of solar equatorial regions. The statistics of delays between the proposed solar source passage over the solar central meridian and the subsequent observation of the terrestrial magnetic storm indicated the travel time of about 3–4 days, implying the corpuscular cloud speed of about 400 km s^{-1}. In series of publications, Chapman alone (Chapman 1919, 61-83) and with Ferraro (Chapman and Ferraro 1931, 77-97) (Chapman and Ferraro 1933, 171-196) (Chapman and Ferraro 1940, 245-268) tried to explain severe magnetic storms and aurorae borealises by the action of electrically neutral clouds of electrically charged solar particles. They used sharp jumps on records of terrestrial magnetic field horizontal component variations (the so-called SSC – storm sudden commencement) as markers. The delay between the solar flare occurrence near the central meridian and the corresponding SSC on ground magnetic records was about 1–2 days, giving the cloud speed of about 1000 km s^{-1}. Forbush (Forbush 1946, 771-772) described a sudden intensity decrease of galactic cosmic rays registered with the help of ground-based ionization chambers. Usually, the ionization electric current in such devices is created by muons appearing in the terrestrial atmosphere due to atmospheric constituents' nuclear reactions with galactic and solar cosmic rays. At the end of February and beginning of March 1942, a day after the solar flare had occurred, the cosmic ray flux decreased. The phenomenon was interpreted as the submersion of the Earth into the magnetized solar plasma cloud, which prevented the penetration of galactic cosmic rays to the land. The plasma cloud speed was of the order of 1000 km s^{-1}.

Vsekhsvyatsky, Nikolsky, Ponomarev, and Cherednichenko (Всехсвятский и др. 1955, 165-176) showed that the flux of matter from the Sun should exist. Their estimate of the flux value was based on the following statements. If the corona were hydrostatic, the ratio of iron and hydrogen scales of height would be 1/56: iron ions would be observed at the coronal base only. However, iron ions radiate in the entire corona. If one assumes that the momentum of ascending flows of protons keeps the iron ions in the "suspension state", one can estimate the flux of solar protons from the observations of E-corona. Their estimates (calculated in 1955) proved to be close to later direct measurements of the solar wind proton flux on spacecraft.

The angular widening of discrete radio sources due to the diffraction and the refraction of radio waves in the near-solar plasma provided an additional research tool (Виткевич 1951, 585-588). The coronal plasma should deflect (on small angles relative to the straight line connecting the

Earth and the Sun) radio waves coming from distant cosmic sources, for example, Crab-like nebula or Taurus A. In 1955, Soviet astronomer Vitkevich (Виткевич 1955, 429-432), and his British colleague Hewish (Hewish 1955, 238-251), realized the first experimental radio-soundings of the near-solar plasma exploiting intermittent radio sources. They discovered that the widening of discrete radio sources was permanent and attributed it to the interplanetary magnetic field, which created plasma spatial inhomogeneity structures at heliocentric distances up to fifty solar radii.

Discovery of the solar wind

In 1958, Parker probably knew both Biermann's hypothesis about the solar plasma permanent outflow to the interplanetary space and Chapman's calculation according to which the backpressure of the local interstellar medium was insufficient to maintain the static solar corona. Classic studies of flows inside tubes of variable cross-sections (for example, the Laval nozzle) alluded to the possibility of the transonic gas outflow into the chamber with the vanishingly slight pressure inside – the local interstellar medium. It suggested that the transonic coronal gas outflow into the interplanetary space was a natural consequence of the high coronal temperature. To demonstrate the idea, Parker (Parker 1958, 644-675) proposed the first hydrodynamic model of the stationary solar corona, rejecting the hydrostatic corona concept. He assumed that the solar gravitation could not confine the hot coronal plasma, and the permanent stationary outflow of the coronal material into the interplanetary space took place. He figuratively named it a “solar wind”. He neglected the solar rotation and assumed (for simplicity) the polytrope linkage between pressure and density in the transonic outflow. The physical process acting in both the Laval nozzle and the solar wind converts thermal chaotic motions into the directed one. In the Laval nozzle, the conversion occurs due to the nozzle face. In the solar wind, the solar gravitation limits the particles’ velocities to escape. For the coronal temperature of 10^6 ^oK, he calculated the supersonic solar wind speed at the Earth orbit slightly higher than 450 km s^{-1}. His result was a close fit with earlier estimates based on observations of comet’s tails, geomagnetic storms, and Forbush’s effects. However, his model was not acknowledged at one stroke: his paper submitted to the Astrophysical Journal was rejected by two reviewers. Only the editor – Chandrasekhar (future Nobel laureate 1983), published the paper in the journal. One of the weak spots of Parker’s construction was his assumption of the polytrope linkage between pressure and density. At the same time, the energy equation could be used to close the set of hydrodynamic equations. Chamberlain (Chamberlain 1961, 675-

687) attempted to fill up this gap and proposed a model based on the set of three hydrodynamic equations, namely, the continuity equation, the motion equation, and the heat transfer equation. He assumed that the heat entered into the corona due to the thermal conductivity at the very coronal base and disappeared at an infinite heliocentric distance converting entirely into the flow kinetic energy. After numerical calculations, he obtained the outflow speed at the Earth orbit of about 20 km s^{-1}. He stated that the coronal material outflow to the interplanetary space resembled a “solar breeze”.

The alternative between Parker’s solar wind concept and Chamberlain’s solar breeze concept was a matter of dispute. The final choice was given only after direct measurements of the interplanetary plasma on spacecraft. The first measurements were conducted on the “Luna 2” and the “Luna 3” spacecraft between 1959 and 1961. Plasma traps with one decelerator mesh were used. According to these measurements, the flux density of positive ions with energies higher than 50 eV per charge unit was several units multiplied by 10^8 cm^{-2} s^{-1} (Грингауз и др 1960, 1301-1304) (Gringauz 1961, 551-553). Launched in 1961, the “Explorer 10” spacecraft had plasma traps with decelerator meshes capable of measuring the flux densities of positive ions with several threshold energies per charge unit. The measured flux density was

$(1\text{-}2)\times10^8$ cm^{-2} s^{-1} (Bonetti et al. 1963, 4061-4063), the flow velocity – of about 280 km s^{-1}, and the proton temperature – $(3\text{-}8)\times10^5$ °K (Scherb 1964, 815-818). While direct measurements registered the plasma flux close to the expected solar wind, the observations overlapped only short intervals. Doubts about the solar wind existence were removed after three months of continuous measurements of the interplanetary plasma on the “Mariner 2” spacecraft in 1962 (Snyder and Neugebauer 1964, 89-113). A set of electrostatic analyzers allowed measuring both the proton concentration and the proton velocity. The average proton concentration proved to be 5.4 cm^{-3} and the average proton velocity – 504 km s^{-1} (Neugebauer and Snyder 1966, 4480-4484). The choice in favour of the solar wind was made owing to direct measurements on spacecraft.

Radio astronomical ground-based observations of fluctuations with frequencies in the range (0.1-10) Hz (so-called “scintillations”) of fluxes from radio sources of minimal angular widths (like quasar 3C 38) (Hewish et al. 1964, 1214-1217) (Виткевич и др 1966, 55-59) revealed that the solar wind velocity increased from the equator to polar regions up to three times (Dennison and Hewish 1967, 343-344).

A phenomenon was discovered: the Sun emitted extensively into the interplanetary space of about one trillion tons of ionized hydrogen per second. In Table 1-1 presented are people contributing significantly to the discovery.

Table 1-1 Chronology of the discovery of solar wind phenomenon

High temperature of the solar corona	Edlen	1943
The anti-solar direction of the comet's tails is caused by solar corpuscular radiation.	Ahnert	1943
The Sun radiates charged particles continuously and extensively	Biermann	1951
Estimates of the solar proton outflow	Vsekhsvyatsky, Nikolsky, Ponomarev, Cherednichenko	1955
The first hydrodynamic solar wind model	Parker	1958
Direct measurements of the solar wind flux	Gringauz	1959
Solar wind direct measurements during three months	Snyder, Neugebauer	1962
Solar wind velocity estimates from observations of scintillations	Hewish, Scott, Wills; Vitkevich, Antonov, Vlasov.	1964 1966

CHAPTER 2

ACCELERATION REGION: RADIO-SOUNDING WITH SPACECRAFT SIGNALS

The pioneers in radio-sounding the near-solar plasma are radio-astronomers who exploit a quasar – the radio-source of minimal angular width. They discovered the increase of the quasar angular width when the radio ray path approached the Sun. The effect was explained by near-solar plasma inhomogeneities that led to the angular width. In 1953–1962, the phenomenon was studied in detail, and the dependence of the angular width on the heliocentric distance of the radio ray path was obtained. It allowed estimating the electron concentration and its inhomogeneities near the Sun (Erickson 1964, 1290-1311). After a few quasars had been discovered, scintillations as fast random quasar intensity variations were found out. For studying the near-solar plasma, giant antennas and special receivers for monitoring scintillations on meter wavelengths were assembled in the USSR, Great Britain, India, and the USA. This way, the near-solar plasma was investigated in the heliocentric distances between 60 solar radii and 180 solar radii. It was shown that the turbulent plasma radially moved from the Sun with the velocity of 300–400 km s^{-1} and its inhomogeneity spectrum was similar to Kolmogorov's (Лотова 1968, 292-307) (Hewish and Symonds 1969, 313-329). A method to estimate the near-solar plasma electron concentration was based on the wave group delay measurements. For pulsar NP052 situated in the ecliptic, the ray path intersects the solar corona in the fixed periods as the Earth rotates around the Sun. It allows calculating the delay and reconstructing the electron concentration heliocentric distance dependence (Hollweg 1968, 771-779). These outstanding studies demonstrated the effectiveness of the radio astronomy sounding. However, such a sounding has a critical limitation: it is based on receiving and analyzing the weak noise-type signal, which should be extracted from the solar radio emission background.

The development of deep-space radio communications opened an opportunity of sounding the near-solar plasma with highly stable monochromatic (or modulated) radio waves under the high signal-to-noise merit.

Spaceflights to Mars initiated the first deep-space radio communication experiments that showed essential group delays, strong fluctuations of frequency and phase, and the spectral linewidth due to the near-solar plasma influence. In 1967–1974, radio-sounding missions were devoted to investigating the near-solar plasma influence on trajectory measurements.

The missions revealed that all effects listed above strongly impeded deep-space communications (Goldstein 1969, 598-602) (Яковлев и др. 1974, 600-605) (Колосов и др. 1978, 555-558) (Колосов и др. 1978, 1829-1839). Spacecraft launched to planets and ground stations for deep-space radio communications allowed carrying out unique experiments on radio-sounding the near-solar plasma. In such experiments, deep-space radio communication ground stations were used as complex radio-physical installations with large parabolic antennas, high sensitive receivers, frequency standards, and precise timing, filtering, measuring and registering signals. The facilities allowed obtaining detailed information on the propagation of decimeter and centimeter radio waves in space and determining plasma parameters in the solar wind acceleration region on this basis. The Russian system of deep-space radio communications used two wavelengths λ_1 = 32 cm and λ_2 = 5.07 cm, the US one – three wavelengths λ_3 = 13 cm, λ_4 = 3.6 cm, and λ_5 = 0.96 cm. For improving the reliability of deep-space communications, two ground stations were organized in the USSR (in Evpatoria and Ussuriysk). The USA built four (in Goldstone, California, in Madrid, Spain, in Canberra and Norciya, Australia). Radio-sounding experiments were carried out using stable monochromatic high-frequency spacecraft signals during radio transmission sessions to the Earth lasting from a few minutes to many hours. Every experiment lasted 2–3 months when the ray path approached the Sun and then moved away from the Sun. Based on these radio propagation data, one may determine coronal plasma parameters at heliocentric distances from 3 to 60 solar radii. To study near-solar plasma characteristics, one uses the experimental data on radio delays and radio fluctuations and the theory of radio wave propagation in an inhomogeneous medium. Exploiting the complex experimental technique along with the statistics of signal processing and the radio wave propagation theory, one derives the information on the velocity, the electron concentration, and the turbulence in the solar wind acceleration region.

This chapter presents an overview of the heliocentric distance dependence of near-solar plasma parameters derived from radio-sounding with spacecraft signals. The heliocentric distance denoted *r* in the following is expressed in solar radii units in this chapter.

The described near-solar plasma parameters are related to heliolatitudes below 60° for relatively low and moderate solar activity.

Solar wind velocity

There are several means to measure solar wind velocity via radio-sounding. These are based on the analysis of radio signals received at one