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Formation of a Steady Supersonic Solar Wind Flow

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Abstract—A consistent study of the solar wind has been extended to a wide region of interplanetary space, up to distances from the Sun $R \geqslant 90\ R_s$. Experiments are carried out with the radio telescopes of the Pushchino Radio Astronomy Observatory (Astrospace Center, Lebedev physical Institute, Russian Academy of Sciences): DKR-1000 ($\lambda \approx 2.7$–2.9 m) and RT-22 ($\lambda \approx 1.35$ cm), respectively. The radio-wave scattering characteristics, the scattering angle $\theta(R)$ and the scintillation index $m(R)$, are studied. The formation of a steady supersonic solar wind is associated with a sequence of four stages whose scale in different solar wind streams changes within the range 10–23 R_s, depending on the initial stream speed. These circumstances should be taken into account when predicting the state of the near space using data on the solar wind in regions of the interplanetary medium close to the Sun.

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INTRODUCTION

Vitkevich (1951) proposed a method for studying the outer regions of the solar corona, the radio occultation method. In this method, the circumsolar, interplanetary medium was sounded by radio emission from 3C 144, a powerful compact radio source in the Crab Nebula. It was established from the first successful observations in 1953 and 1955 (Vitkevich 1955) that the observed increase in the angular sizes of the occultation source 3C 144 during its apparent approach to the Sun is related to the scattering of radio waves by electron density inhomogeneities ΔN_e^2 in the interplanetary medium.

In the first radio occultation experiments, the radial dependence of the radio-wave scattering angle $\theta(R)$ was studied in a narrow range of radial distances from the Sun, $R \simeq 4$–$12\ R_s$ (Vitkevich 1955). As a result, a decreasing dependence of the scattering angle $\theta(R)$ was established (Vitkevich 1955):

$$\theta(R) = CR^{-1.6}. \qquad (1)$$

Parker (1958) developed the model of a magnetohydrodynamic solar wind flow, a continuous slow acceleration of the flow with allowance made for its expansion in interplanetary space. Here, we will note that Parker's model is applicable to the solar wind only in a very narrow zone of radial distances from the Sun ($R \leqslant 10\ R_s$), because the radio occultation experiments in circumsolar space revealed the existence of a narrow region with a sharply reduced level of radio-wave scattering at $R \geqslant 10\ R_s$ (Lotova et al. 2011; Lotova and Pisarenko 1990). Thus, as one recedes from the Sun to larger distances, $R \geqslant 10\ R_s$, the solar wind acceleration mechanism differs significantly from Parker's model.

THE DEVELOPMENT OF RADIOASTRONOMICAL RESEARCH ON THE SOLAR WIND

In the last years, the main interest in studying the solar wind has been associated with the successive extension of radioastronomical methods for studying the circumsolar medium to more distant regions of interplanetary space. The next stage of these studies is related to the investigation of the interplanetary medium at radial distances $R \leqslant 40\ R_s$. The experiments were carried out by invoking two modifications

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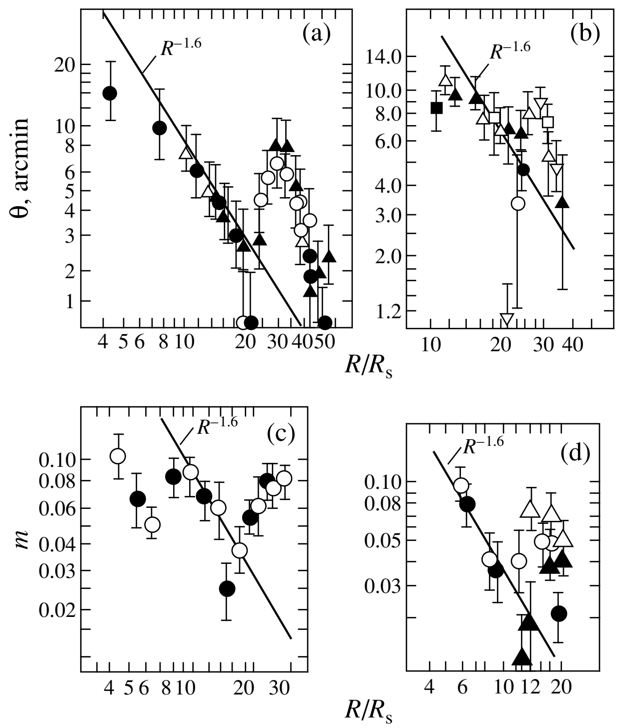

Fig. 1. Radial dependences of the radio-wave scattering angle $\theta(R)$: (a) the occultation sources 3C 225 (O, •), 3C 228 (△, ▲) (August 2001); (b) the sources C 138 (▽, ▼), 3C 144 (△, ▲), 3C 154 (O, •), 3C 166 (□, ■) (June 1991). Radial dependence of the scintillation index $m(R)$: (c) the source IRC-20431 (O, •) (December 1997); (d) the sources IRC-20431 (O, •), W31(2) (△, ▲) (December 1992).

of the occultation method (Lotova et al. 2011; Lotova and Pisarenko 1990; Efimov et al. 1977) with an independent study of various radio-wave scattering characteristics: the scattering angle $\theta(R)$ and the scintillation index $m(R)$. The experiments are carried out at the Pushchino Radio Astronomy Observatory (Astrospace Center, Lebedev Physical Institute, Russian Academy of Sciences) with the DKR-1000 ($\lambda = 2.7{-}2.9$ m) and RT-22 ($\lambda = 1.35$ cm) radio telescopes. In our case, the study of the dependence of the scintillation index $m(R)$ in circumsolar space in the weak-scattering regime ($m < 1$) is based on invoking a new class of occultation radio sources, water-vapor maser sources, $\lambda = 1.35$ cm (Lotova et al. 2011). Using so short wavelengths provides an informative regime of weak scintillations ($m < 1$) in regions of the interplanetary medium close to the Sun ($R \leqslant 40\ R_s$). This allowed the reliability of the main result to be increased. It is related to the detection of two successive narrow zones, $\Delta R \approx 1.5{-}2.5\ R_s$, with a sharply reduced level of radio-wave scattering at radial distances from the Sun $R \leqslant 40\ R_s$ (Figs. 1a–1d). This effect was observed in independent experiments with the study of two different radio-wave scattering characteristics: the scattering angle $\theta(R)$ and the scintillation index $m(R)$.

The data on the solar wind speed based on the *Venera 10*, *Venera 15*, and *Venera 16* measurements (Efimov et al. 1977; Yakovlev et al. 1980, 1987; Armand et al. 1987) were obtained in different years in each case at different radial distances from the Sun in a fairly narrow range of R including only one episode of shock solar wind acceleration. On this basis, it was impossible to reproduce a unified, complex picture of solar wind acceleration. However, comparison of these isolated data with the sequence of spatial solar wind acceleration on the scattering of radio waves reveals good agreement between the results of independent measurements.

The experimental data on the radial dependence of the radio-wave scattering angle $\theta(R)$ and scintillation index $m(R)$ (Fig. 2) suggest the existence of two zones of shock solar wind acceleration in the interplanetary medium. Indeed, comparison of the radial profiles of the scattering characteristics $\theta(R)$ and $m(R)$ with the data on the solar wind speed at the first two stages of solar wind acceleration based on the *Venera 10*, *Venera 15*, and *Venera 16* measurements (Efimov et al. 1977; Yakovlev et al. 1980) showed that the narrow spatial interval $\Delta R \sim 1.5-2.5\ R_s$ corresponding to the shock solar wind acceleration coincides with the zone of a reduced level of radio-wave scattering in the characteristics $\theta(R)$ and $m(R)$.

Further out, an increase in the radio-wave scattering characteristic is observed in the successive development of the shock process behind the shock front, which corresponds to a partial reduction in the flow velocity in the dependence $V(R)$. In this case, however, the velocity $V(R)$ still remains enhanced compared to its initial value. All these interrelated processes of the change in the main characteristics of the solar wind flow (the velocity V, the electron density $\langle N_e \rangle$, and ΔN_e^2) in the shock solar wind acceleration are repeated in all successive episodes of the development of wave processes in the solar wind (Efimov et al. 1977; Yakovlev et al. 1980, 1987; Armand et al. 1987).

THE RADIO OCCULTATION METHOD IN PRESENT-DAY STUDY OF THE SOLAR WIND

In present-day experiments, the solar wind is studied in the continuous regime of sounding the interplanetary medium in a wide range of radial distances from the Sun, $R \approx 40-130\ R_s$. Here, as has been pointed out above, as the occultation source recedes from the Sun to the range of radial distances $R \leqslant 40\ R_s$, the experiments are carried out using two modifications of the occultation method. The study of more distant and rarefied regions of the interplanetary medium, radial distances $R \geqslant 40-90\ R_s$, uses only one modification of the occultation method, the study of the radio-wave scattering angle $\theta(R)$, because quasars are more powerful radio sources. All of the mentioned experiments are carried out at the Pushchino Radio Astronomy Observatory (Astrospace Center, Lebedev Physical Institute, Russian Academy of Sciences). The radial dependence of the radio-wave scattering angle $\theta(R)$ is studied with the DKR-1000 radio telescope ($\lambda \approx 2.7-2.9$ m).

The extension of the methods and the studied solar wind region in the new modification of the occultation method using simultaneously two types of occultation radio sources, quasars (DKR-1000, $\lambda = 2.7$ m) and water-vapor masers (RT-22, $\lambda = 1.35$ cm, Pushchino Radio Astronomy Observatory, Astrospace Center, Lebedev Physical Institute, Russian Academy of Sciences) (Fig. 1), has brought important information about the solar wind acceleration process.

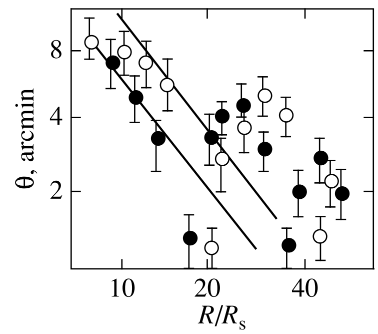

Fig. 2. Radial dependences of the radio-wave scattering angle $\theta(R)$: the source 3C 144, 2010. Here and below, the filled and open symbols correspond to the phase of the source's approach to and recession from the Sun, respectively.

RESULTS OF THE EXPERIMENTAL STUDY OF THE SOLAR WIND IN A WIDE RANGE OF RADIAL DISTANCES FROM THE SUN

In numerous series of experiments, the study of the radial dependence of the radio-wave scattering angle was extended to a wide range of radial distances from the Sun, $R \sim (4-90, 4-130)\ R_s$ (Figs. 3–6).

As a result, it was established that the entire solar wind acceleration process breaks up into four stages, four zones, whose scale is determined by the magnetic field strength in the solar corona and, as a consequence, by the initial velocity of the solar wind streams.

A decay in the level of additional flow acceleration is observed in the sequence of four acceleration stages, i.e., the solar wind acceleration is a decaying process.

For initially high-speed solar wind streams, the extent of the sequence of separate solar wind acceleration stages is $\sim 10\ R_s$; for low-speed streams, it reaches a scale of $\sim 23\ R_s$.

The shock solar wind acceleration process develops in a narrow zone of R, where $R \sim 1.5-2.5\ R_s$ at the end of each of the four solar wind acceleration stages. A decay in the level of additional flow acceleration is observed in the sequence of four acceleration stages, i.e., the four-stage solar wind acceleration is a decaying process. This leads us to conclude that a steady supersonic flow arises at the end of the fourth acceleration stage. Depending on the initial flow velocity in the interplanetary medium, the steady supersonic flow is formed at radial distances from the Sun $R \sim 40\ R_s$ for initially high-speed streams. For low-speed streams, the steady supersonic solar wind flow arises in the range of radial distances $R \sim 92\ R_s$.

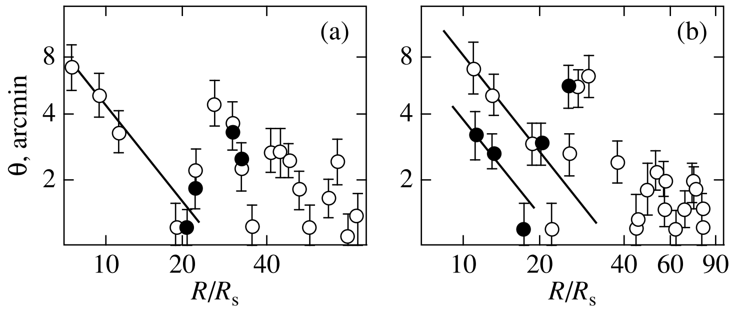

Fig. 3. Radial dependences of the radio-wave scattering angle $\theta(R)$: (a) the source 3C 2, 2010; (b) the source 3C 5, 2010.

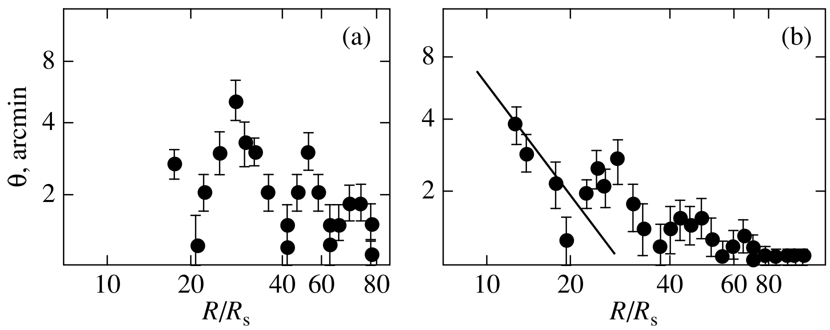

Fig. 4. Radial dependences of the radio-wave scattering angle $\theta(R)$, the source 3C 273: (a) 2010 and (b) 2013.

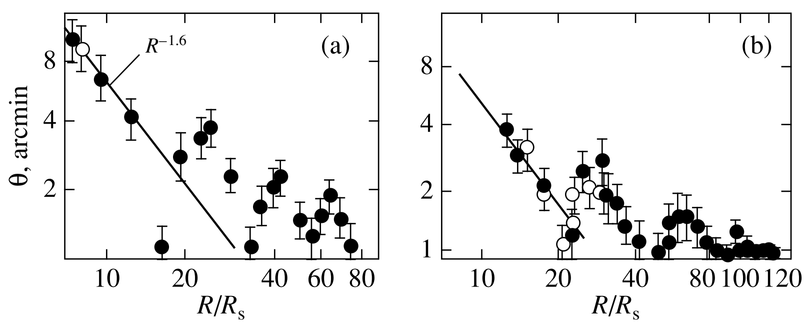

Fig. 5. Radial dependences of the radio-wave scattering angle $\theta(R)$, the source 3C 275: (a) 2011 and (b) 2013.

The solar wind acceleration in circumsolar interplanetary space is the result of a discrete flow acceleration on wave processes of four types in the interplanetary medium. Thus, the results of studying the solar wind lead us to conclude that the steady supersonic solar wind flow formed at the four acceleration stages, irrespective of its initial velocity, arises at radial distances from the Sun $R \approx 90\ R_s$.

Thus, the general supersonic solar wind flow formation process spans a wide range, $R \sim 4{-}90\ R_s$. It breaks up into four stages, four discrete zones differing by the types of wave processes in the interplanetary medium (Baranov and Krasnobaev 1977).

The sequence of wave process development in the interplanetary medium is related to the change in its main characteristics: the magnetic field strength, the temperature and density of the medium.

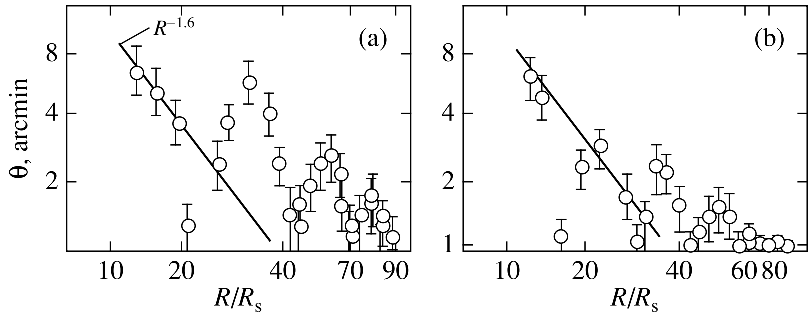

Fig. 6. Radial dependences of the radio-wave scattering angle $\theta(R)$, the source 3C 166: (a) 2010 and (b) 2013.

In the entire variety of solar wind streams differing by their initial conditions (by the structure and magnetic field strength at the base of the streams and, accordingly, by the initial stream speed) in the range of distances up to $\sim 90\ R_s$, the scale of the zone in the sequence of four flow acceleration stages remains constant. In streams of various types, this scale changes within the range $R \sim 10-23\ R_s$.

WAVE PROCESSES IN THE INTERPLANETARY MEDIUM AND THE SOLAR WIND ACCELERATION MECHANISM

A theoretical model for the successive development of wave processes in the interplanetary medium was developed by Baranov and Krasnobaev (1997) under the assumption of a continuous, regular change in the main parameters of the medium in the solar corona—interplanetary medium system. As a result, they substantiated the existence of three types of wave processes in the interplanetary medium: magnetosonic waves, fast and slow, and Alfvén waves. The disregarded factor in the model of Baranov and Krasnobaev (1977) is pulling of the solar magnetic field together with the solar wind flow into the interplanetary medium, which amplifies the magnetic field in the interplanetary medium compared to the asymptomatic corona—interplanetary medium system. Baranov and Krasnobaev (1977) illegitimately extended the asymptomatic solution of the problem of the types of wave processes to the solar corona with its thermal expansion—interplanetary medium with hydrodynamic solar wind flow system. Strictly speaking, this system is not a single-type one, and the asymptomatic solution of the problem of the types of wave processes in the interplanetary medium is not applicable to it. This circumstance returns the problem of wave processes in the interplanetary medium to the known situation in the solar corona, where the existence of wave processes of three types has been established previously: sonic, magnetosonic, and Alfvén waves. Given this remark, the solution of the problem obtained by Baranov and Krasnobaev (1977) should be supplemented with the formation of sonic waves in the interplanetary medium. Thus, the solar wind acceleration mechanism in the interplanetary medium will be associated with the successive development of wave processes of four types: sonic, magnetosonic, fast and slow waves, and Alfvén waves. Their successive acceleration in the interplanetary medium will give rise to a sequence of shock waves of four types, which provide the experimentally established discrete sequence of shock solar wind acceleration.

CONCLUSIONS

For the first time in a present-day study of the solar wind, we have extended the radio occultation method to a wide region of the interplanetary medium to radial distances from the Sun $R \simeq 90-130\ R_s$.

In the range of distances up to $\sim 90\ R_s$, we established the existence of four successive zones with a spatial scale that can vary within the range $\sim 10-23\ R_s$ in different solar wind streams. The solar wind acceleration process is related to the formation of a shock wave at the end of each zone that accelerates the solar wind flow in a narrow range of radial distances, $\Delta R \simeq 1.5-2.5\ R_s$. The repeated shock acceleration processes have a decaying character.

On the whole, the scale of the entire acceleration process in the overall picture of the solar wind determines the largest spatial size in the sequence of four zones in the solar wind streams. It depends on the initial stream velocity in the interplanetary medium and can change within the range of radial distance $R \sim 40-90\ R_s$. As a result, a steady supersonic solar wind flow arises at a radial distance from the Sun $R \simeq 90\ R_s$.

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