

# Spatial Evolution and Structure of High-Speed Flows of Solar Wind from Coronal Holes

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**Abstract**—The nature of high-speed flows from coronal holes and mechanism of their corotation with the source are analyzed. It is shown that the widespread view of high-speed flows from coronal holes as flows of corotating with the Sun particles contradicts observations. A model is proposed in which the spiral structure and corotation of high-speed flows from coronal holes are explained in terms of kinematics.

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## 1. INTRODUCTION

The existence of regions of compression and rarefaction at the boundaries of fast and slow streams in the solar wind became known after the first interplanetary missions in the 1960s (primarily IMP-1 and Mariner 2). The properties of the regions were qualitatively described by Parker (1965), Dessler (1967), Carovillano and Siscoe (1969). Those models used the assumption that the solar wind had inhomogeneities that underwent variations with the rate of the solar rotation. The reasons for the occurrence of such variations were not yet known, but their existence was confirmed by observations by the end of the 1960s. Shortly after the discovery of coronal holes (Krieger et al., 1973 and references therein), a connection was established between corotating flows and coronal holes. Based on the data of multi-spacecraft observations (IMP-8, Pioneer-10, 11), it was found that the variations in energetic protons occurred with the rate of the solar rotation. The time shift in their detection by various spacecraft corresponded to the times of their intersection with some spiral corotating with the Sun, and the base of the spiral at the Sun was located inside a coronal hole (Barnes and Simpson, 1976).

The boundaries between fast and slow streams are called stream interaction regions (SIRs); those that live longer than one rotation around the Sun are called corotating interaction regions (CIRs). Historically, the second concept was introduced first and the classification then became more complex. According to modern views, high-speed flows from coronal holes (HFCHs) are huge magnetic and plasma tubes emerging from coronal holes and descending to low latitudes

far from the Sun (Khabarova et al., 2021a). SIRs/CIRs represent their boundaries.

After the discovery of HFCHs, researchers began to raise questions regarding the nature of their helical shape and corotation with the source. For more than 20 years, two points of view have coexisted. The first one is that HFCHs are wave disturbances caused by nonstationary effects near the Sun. The second one is that HFCHs are corotating plasma jets. In the latter case, we are talking about the corotation of the particles constituting the plasma and, as a consequence, the occurrence of corotation of HFCHs as a set of particles. The first point of view is the development of the corotating stream models of the 1960s and early 1970s (Parker, 1965; Dessler, 1967; Carovillano and Siscoe, 1969; Hundhausen, 1973). It was also supported by Burlaga's discovery (Burlaga, 1983). Based on the analysis of Voyager-1 and 2 data, it was shown that there is a connection between corotating streams and total pressure waves:  $2nT + B^2/8\pi$ , where  $n$  is the concentration of plasma,  $T$  is the temperature, and  $B$  is the magnetic field magnitude. Further, Burlaga together with Klein constructed a model illustrating the propagation of spiral pressure waves in the heliosphere (Burlaga and Klein, 1986). The model does not answer the question of how these waves occur, but it describes the observations, in particular, the propagation of forward and reverse shock waves at the HFCH boundaries. The authors assume that the waves occur due to the interaction of fast and slow streams near the Sun and, in this sense, they are *dynamic structures*. The waves further propagate unchanged, and due to the addition of the waves released by the rotating source, a spiral is formed. The mechanism of wave formation remains unclear. At the

same time, the presence of waves is not necessary for the formation of a spiral corotating structure. In a series of papers, Pizzo and coauthors (Pizzo, 1978, 1980, 1982, 1991; Pizzo and Gosling, 1994) constructed numerical MHD models, most of which took into account shock waves. As a consequence of non-isotropic boundary conditions, obtained solutions describe heliospheric perturbations which corotate with the Sun and can form the spirals. However, the study of the nature of HFCHs and the mechanism of their corotation was not the main task of modeling. Therefore, almost no attention was paid to the reasons that the numerical solutions had these properties. It was mentioned in the review (Gosling and Pizzo, 1999) that HFCHs can be interpreted as dynamic structures formed by particles that were released at different times from different regions at the Sun. Some authors also probably adhered to this point of view before, but it was not formulated clearly. Soon, the main attention was drawn to another interpretation of HFCHs. The results of Geiss (1995) and Wimmer-Schweingruber (1997) showed that the ratios of concentration of multiply charged ions ( $O^{7+}/O^{6+}$ ,  $Mg/O$  and others) in SIRs/CIRs change in the same way as during the transition from fast to slow solar wind. Since these ratios depend on the conditions at the corona, it was concluded that HFCHs are corotating plasma jets from coronal holes. In other words, the choice was made in favor of the second interpretation. At the same time, HFCHs as a dynamic structure, i.e., one formed by the interaction of waves, continued to be considered in the study of the evolution of shock wave fronts (Richardson, 2018).

Thus, an HFCH is currently interpreted as a flow of matter, which physically rotates around the Sun like the hand of a clock, corotating with the source coronal hole and twisting into a spiral. Formally, corotation and spiral shape of the flow in MHD models are obtained as a consequence of the boundary conditions. Most modern studies pay no attention to what exactly corotates with the source: substance or structure. However, this question is important for understanding the nature of HFCHs. As we will show below, the plasma and the boundaries between fast and slow streams rotate around the Sun with speeds that differ by an order of magnitude. Therefore, the common interpretation of HFCHs is not entirely correct. In this paper, we show that the corotation of HFCHs and the coronal hole, as well as the spiral shape of the HFCHs, can be explained in terms of kinematics. In other words, a new interpretation of HFCHs is proposed.

## 2. OBSERVATIONS. A HIGH-SPEED COROTATING FLOW FROM A CORONAL HOLE CANNOT BE REPRESENTED AS A PLASMA JET COROTATING WITH A SOURCE AT THE SUN

The point of view according to which an HFCH is a single flow of particles corotating with a source at the

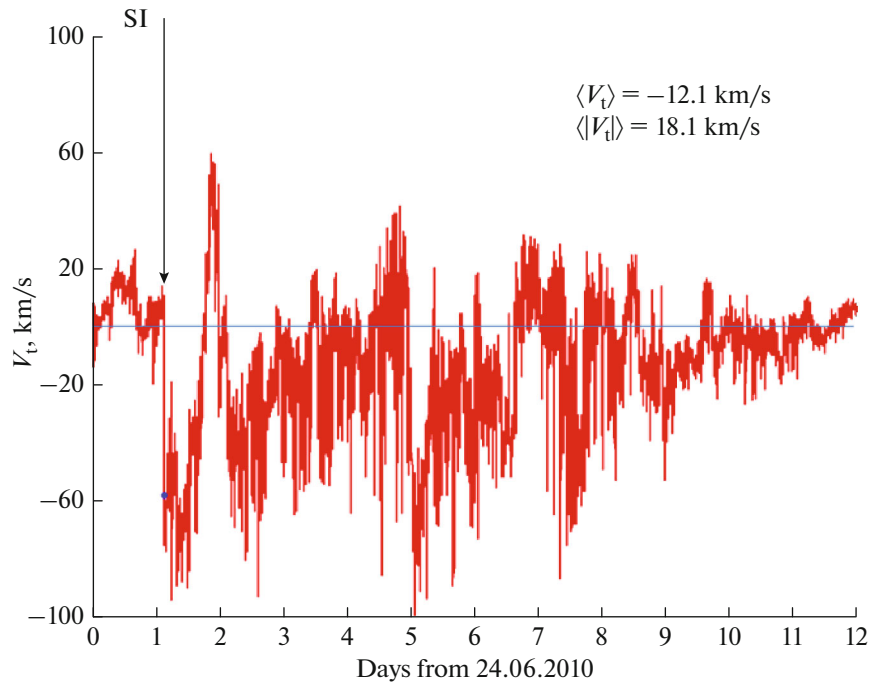
Sun contradicts observations. In order to show this, we compare the speeds of rotation around the Sun of the plasma inside a HFCH and the HFCH itself.

As mentioned in the introduction, there are a number of studies where the angular speed of HFCHs is estimated (Krieger et al., 1973; Burlaga, 1983; Lee, 2000; Crooker et al., 2004; Bochsler et al., 2010). All of them show that the HFCH as a whole corotates with the Sun, i.e., its angular speed is close to  $2.865 \times 10^{-6}$  rad/s (Carrington, 1863). In particular, the angular speed of the HFCHs can be estimated from the motion of the stream interface (SI). The SI represents the HFCH boundary and separates the fast and slow solar wind regions. Khabarova et al. (2021b) identified consecutive intersections of the same SI with the ACE and STEREO A spacecraft. The average angular speed of the HFCH was estimated from the difference in the times of SI arrival to the spacecraft and amounted to  $3.243 \times 10^{-6}$  rad/s. In other words, the HFCH can rotate slightly faster than the Sun at the latitude of the source. There is nothing surprising about this. Observations of the motion of coronal holes at the Sun show that they can have an angular speed 10–20% higher than that of the surrounding plasma (Insley et al., 1995).

The estimate  $\omega = 3.243 \times 10^{-6}$  rad/s is the angular speed of the structural element of the HFCH. It corresponds to the linear velocity of the HFCH in the azimuthal direction  $v_\phi = \omega(1 \text{ AU}) \approx 500$  km/s. It should be noted that the product of the solar angular speed and 1 AU exceeds 400 km/s.

If we assume that 400 or 500 km/s is the speed of the motion of matter in the azimuthal direction, then this is a fantastically large value. Typical values of the azimuthal component of the solar wind velocity at 1 AU are units or tens of km/s (Hundhausen, 1968; Pizzo et al., 1983). Figure 1 shows the values of the tangential component of the solar wind velocity in the RTN coordinate system from the minute-averaged data of the ACE spacecraft. The period of time before and after the passage of the SI (Khabarova et al., 2021b) is considered. The azimuthal  $v_\phi$  and tangential  $V_t$  components of the velocity in the RTN coincide. The open access ACE data for various time periods are available at <https://cdaweb.gsfc.nasa.gov/index.html/>. As can be seen from Fig. 1, the tangential velocity component  $V_t$  varies from  $-60$  to  $60$  km/s. The average  $V_t$  value is  $-12.1$  km/s (against the direction of the solar rotation), the average absolute value of  $V_t$  is  $18.1$  km/s. Thus,  $V_t \ll 500$  km/s everywhere. In other words, the motion of the plasma and the HFCH as a whole at the same points in space differ significantly. Therefore, the HFCH at 1 AU cannot be represented as a single corotating flow consisting of the same particles.

Outside 1 AU, the last conclusion remains valid for large  $r$  as long as the HFCH corotation persists. It is also valid for those distances within 1 AU at which  $\omega r$



**Fig. 1.** The tangential component  $V_t$  of the solar wind velocity from June 24, 2010 00<sup>h</sup>00<sup>m</sup> to July 5, 2010 00<sup>h</sup>00<sup>m</sup>. ACE minute-averaged data, RTN coordinate system. The arrow shows the time of crossing of the Stream Interface (SI) at the leading edge of the flow. The average  $V_t$  values and the average absolute values of  $V_t$  are indicated as  $\langle V_t \rangle$  and  $\langle |V_t| \rangle$ .

exceeds the azimuthal component of the plasma velocity. It is believed that the solar wind plasma corotation with the Sun is disrupted outside the Alfvén surface, which is located at 10–20 solar radii in most models (0.05–0.1 AU (Fahr and Fichtner, 1991)). At small distances, an HFCH can probably move as a solid body.

As noted in the introduction, HFCHs cannot be represented as a pressure wave only. Since the motion of the HFCH does not coincide with the motion of the constituent plasma, it is not a material object. There is a contradiction. It is not clear how the HFCH corotates with the Sun and what its nature is. Below, we propose a solution to this problem.

### 3. A KINEMATIC INTERPRETATION OF COROTATION OF HIGH-SPEED FLOWS FROM CORONAL HOLES (HSCHS) WITH THE SUN

#### 3.1. Kinematic model of HFCHs

Anyone who has seen a rotating garden sprinkler knows that water jets form spirals as they scatter. The reason of their formation is the presence of an azimuthal velocity component of water drops. If we neglect air resistance, this velocity does not depend on the distance to the sprinkler. The angular velocity of the drops is inversely proportional to the distance. In this case, the observer (e.g., a flower) comes under the

spray with the sprinkler’s rotation rate that does not depend on the distance and is multiplied by the number of jets. In other words, the frequency of arrival of perturbations and the frequency of rotation of matter can differ due to the rotation of the source without the presence of any dynamic effects. Unlike the sprinkler example, solar wind flows propagate in all directions, albeit at different velocities, and they can participate in complex interactions with each other. Nevertheless, the fundamental question remains: do dynamic effects cause the formation of a spiral perturbation and its corotation? In order to answer this question, we can study a simplified model of the propagation of matter flows from a coronal hole neglecting any dynamic effects.

We consider a two-dimensional problem in cylindrical coordinates  $(r, \varphi)$  in a plane perpendicular to the solar rotation axis. Let there be a coronal hole with an angular width  $\Delta\varphi$ , and it is a source of plasma with a radially directed velocity  $v$  relative to the Sun that rotates at a frequency  $\omega$ . In the inertial frame of reference, let each element of the fluid move uniformly and rectilinearly at a constant velocity without any external influences.

Under these assumptions, the interplanetary space is a linear medium. If a certain function  $f_{\text{in}}$ , for example, concentration, is supplied to the input from a source at the Sun, then the function  $f_{\text{out}}$  is measured at each moment of time at each point where there is

an observer. The  $f_{in}$  and  $f_{out}$  values are related via convolution:

$$f_{out}(r, \varphi, t) = \int_{-\infty}^{\infty} f_{in}(r', \varphi', t')g(r - r', \varphi - \varphi', t - t')dr' d\varphi' dt', \quad (1)$$

where  $g$  is the propagation function, which is the result of measuring the  $\delta$ -pulse applied to the input. Expression (1) actually describes the addition of a series of input signals  $f_{in}$  with different weight coefficients  $g$ . Let us find the propagation function within the model. As a  $\delta$ -signal, let us consider an arc-like ejection of matter with a speed  $v$  that occurred at a time  $t_0 = 0$  at a distance  $r = r_0$  from the center of the Sun. Such a signal looks like

$$f_{0-in} = \frac{1}{2} A_0 \delta(r - r_0) \delta(t - t_0) (\theta(\varphi) + \theta(\Delta\varphi - \varphi)), \quad (2)$$

where  $\theta$  is the Heaviside step function. The combination of step functions sets the corotation of plasma elements at the initial moment of time and the finite size of the source. Since (2) is an analogue of the  $\delta$ -signal, the integral of it must be equal to 1, therefore,  $A_0 = 1/\Delta\varphi$ . With free rectilinear motion at a velocity  $(v, \omega r_0)$ , the arc-like ejection is converted into

$$f_{0-out} = \frac{1}{2} A \delta\left(r - r_0 - v\left(\varphi - \frac{\omega r_0}{r} t\right) t\right) \times \left(\theta\left(\varphi - \frac{\omega r_0}{r} t\right) + \theta\left(\Delta\varphi - \varphi + \frac{\omega r_0}{r} t\right)\right), \quad (3)$$

where  $\omega r_0/r$  is the angular speed at a distance  $r$ ,  $A$  is the amplitude, and  $v\left(\varphi - \frac{\omega r_0}{r} t\right)$  is the plasma velocity inside the coronal hole in the direction from which the plasma element arriving at the observation point was emitted. It should be noted that  $A$  may depend on  $r$ , but this fact is trivial and does not affect further consideration. However, the choice of  $A(r)$  requires additional assumptions. For example, if  $f$  is the concentration, it may be necessary to consider the law of conservation of matter. We do not specify this point and focus on the remaining factors.

Using (1–3), we can find the instrumental function

$$g(r^1, \varphi^1, t^1) = \frac{A}{A_0} \delta(r^1 - v(\varphi - \varphi^1)t^1) \delta\left(\varphi^1 - \frac{\omega r_0}{r^1 + r_0} t^1\right). \quad (4)$$

To avoid misunderstandings, we note that all parentheses in formula (4) imply dependence on the argument, and do not imply multiplication. The angle  $\varphi$  should be understood as the direction toward the observer. If (3) contains  $A(r)$ , then (4) will include  $A(r^1 + r_0)$ . Let us now consider a source inside a coronal hole of a more general form

$$f_{in} = \frac{1}{2} A_0 F_0 (\varphi - \omega t) \delta(r - r_0) \times (\theta(\varphi - \omega t) + \theta(\Delta\varphi - (\varphi - \omega t))), \quad (5)$$

where  $F_0$  describes the inhomogeneous distribution over the angle of the considered value in the coronal hole. The Heaviside function and  $F_0$  depend on  $\varphi - \omega t$ . Thus, the rotation of the coronal hole is taken into account. The source is assumed to be continuous in time, but it is still localized at a distance  $r_0$  from the center of the Sun. Let  $v = \text{const}$  for simplicity. Then, at the output we obtain the observed value:

$$f_{out} = \frac{1}{2} A F_0(\varphi_1) (\theta(\varphi_1) + \theta(\Delta\varphi - \varphi_1)), \quad (6)$$

where  $\varphi_1$  is the phase of perturbation,

$$\varphi_1 = \varphi - \omega t - \frac{\omega r_0}{r} \frac{r - r_0}{v} + \omega \frac{r - r_0}{v}. \quad (7)$$

If  $v$  depends on  $\varphi$ , then we should replace  $(r - r_0)/v$  in formula (7) with the solution of the equation

$$r - r_0 = v\left(\varphi - \frac{\omega r_0}{r} t\right) t \quad (8)$$

with respect to  $t$ .

Let us consider what the equal-phase surfaces in (7) are.

(1) Let  $\varphi_1$  and  $r$  be fixed. Expression (7) takes the form  $\varphi - \omega t = \text{const}$ , which corresponds to the rotation of the phase surface with the frequency of the source of perturbation. The last one rate equals to  $\omega$ . In other words, the phase surface corotates with the source.

(2) Let  $\varphi_1$  and  $t$  be fixed. The equation describing the shape of the phase surface follows from (7):

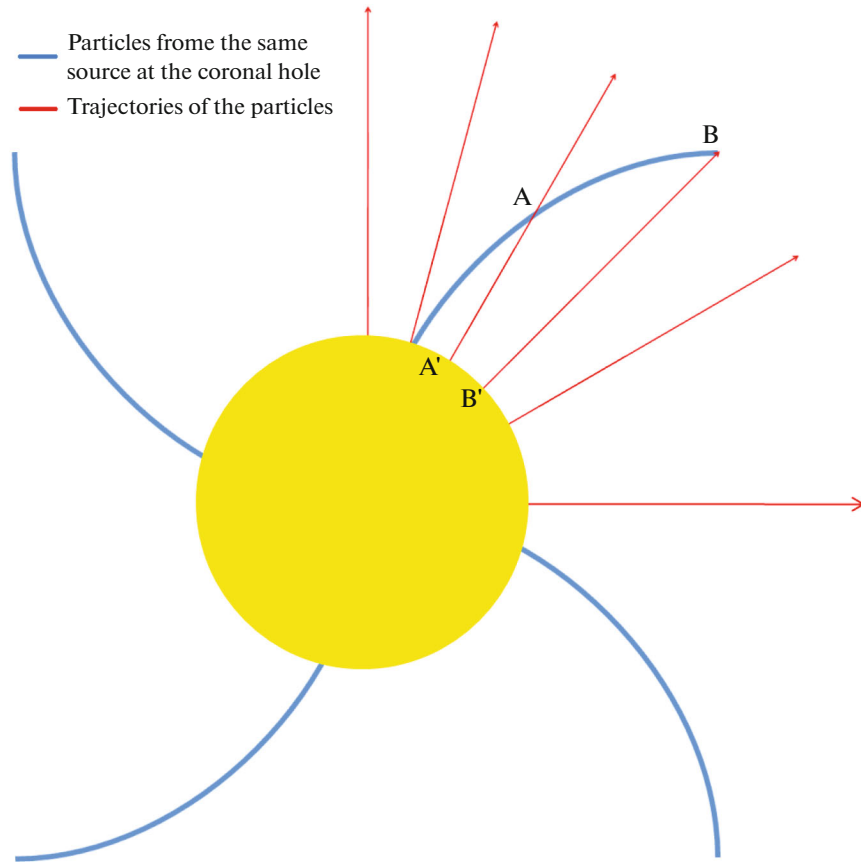
$$\varphi - \omega \frac{r - r_0}{v} \left(1 - \frac{r_0}{r}\right) = \text{const}. \quad (9)$$

Formula (9) describes a spiral, which coincides with the Archimedean spiral at  $r \gg r_0$ . Note that there is no magnetic field in the model, therefore the existence of this spiral is in no way connected with the presence of the Parker spiral. In our case, spiral (9) occurs due to the addition (1) of consecutive arc-shaped plasma ejections from a rotating coronal hole (5). Moreover, the spiral of the magnetic field and the spiral (9) should not coincide near the Sun.

(3) Let  $\varphi_1$  be fixed,  $t = (r - r_0)/v$ . In other words, we consider the rotation of a plasma element that has arrived at a given moment of time at a given point  $r$ .

From (7) we obtain  $\varphi - \frac{\omega r_0}{r} t = \text{const}$ , which corresponds to rotation at a rate  $\omega r_0/r$  and a constant azimuthal velocity component  $\omega r_0$ . In other words, the particles move predominantly radially, as it is specified in the model, (Fig. 2). In fact, the speed of the fast solar wind is 450–900 km/s, and  $\omega r_0 = 2$  km/s at the level of the photosphere, or  $\omega r_0 = 20$  km/s if  $r_0 \approx 10$  solar radii.

Figure 2 allows a better understanding of the difference between “corotating plasma jets” and “corota-



**Fig. 2.** A schematic representation of particle trajectories in the model (red arrows) and regions of space occupied at a fixed time by particles emitted from the same region of the coronal hole at different moments of time (blue spirals). For example, a particle located at point A was released when its source was at point A'. Points B and B' are related similarly. The reference frame is inertial. The axis of the solar rotation is directed toward the reader.

tion of structure.” The red arrows in Fig. 2 show the trajectory of the solar wind particles in the model. As we can see, they move radially. The blue spirals correspond to the regions where the particles ejected from the same part of the coronal hole are located at a fixed moment of time. At each moment of time, the blue spiral rotates around the solar axis with the angular speed of the coronal hole. The solar wind speed in the model depends only on the source (the coronal hole or undisturbed regions of the Sun). This means that at each time point, the particles that have escaped the coronal hole form a “sleeve”. This sleeve differs from the surrounding solar wind by a higher radial velocity component of the plasma and a lower density. Thus, the rotation of spirals is the rotation of perturbations of solar wind parameters. We call the corotation of these perturbations with a source on the Sun “corotation of structure”. “corotation of flows” is an imaginary situation when a flow from a coronal hole at distances on the order of 1 AU rotates around the Sun as a solid body. As shown above, this view contradicts observations; however, it is often found in the literature in an explicit or implicit form.

### 3.2. Discussion of the Kinematic Model

In Eqs. (5)–(9), we take into account the plasma escaping the coronal hole only. However, it is not difficult to take into account the surrounding solar wind as well. Since the model is linear, another source can be added to the nonisotropic source (5):

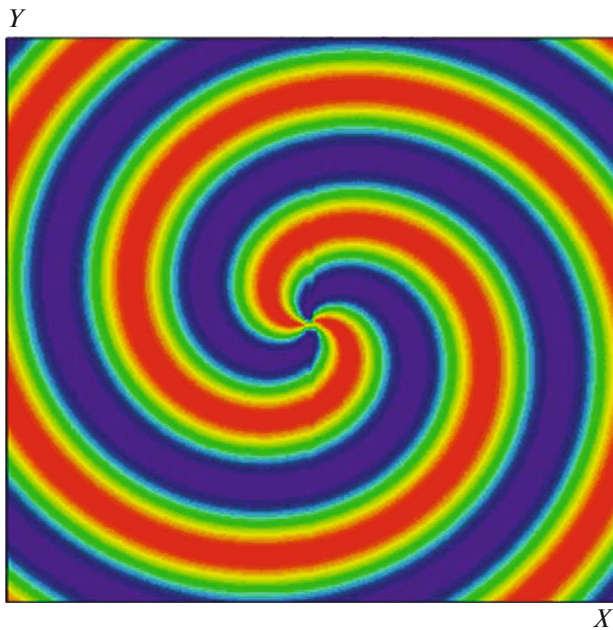
$$f_{in\_1} = \frac{1}{2} A_0 F_1(\varphi - \omega t) \delta(r - r_0), \quad (10)$$

which correspond to

$$f_{out\_1} = A F_1(\varphi_1), \quad (11)$$

where  $\varphi_1$  is defined above. In the case if  $F_1 = \text{const}$ , we obtain an isotropic background, which corresponds to the undisturbed solar wind. If  $F_1$  is a combination of multiple sources of the form (5) with different widths  $\Delta\varphi$  and region boundaries, we obtain several coronal holes and streams from them. In the reality, the number of HFCHs at low heliolatitudes is almost always even (Richardson, 2018).

Expressions (10) and (11) in a linear combination with (2) and (6) make it possible to take into account not only the high-speed flow from the coronal hole,



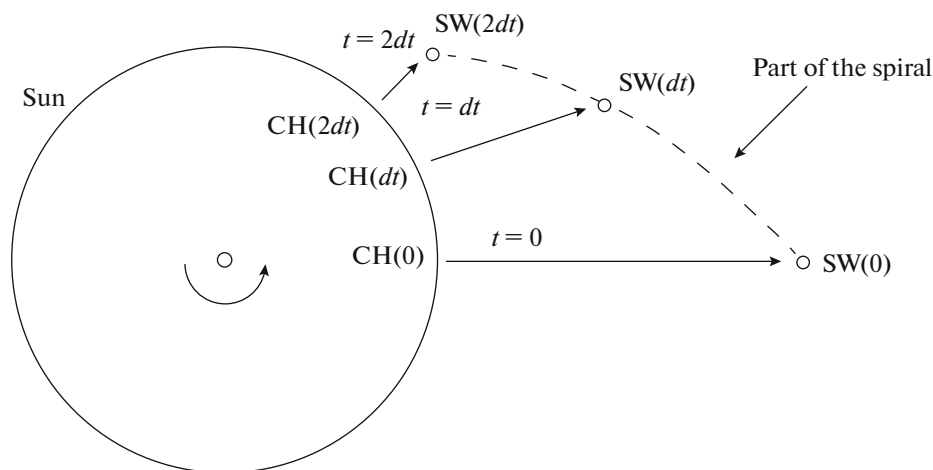
**Fig. 3.** Plasma density, arbitrary units. Alternating regions of compression and rarefaction are marked with different colors. A plane perpendicular to the solar rotation axis (directed toward the reader, Sun is in the center) is shown. The modeling box size is  $4 \times 4$  AU.

but also the isotropic undisturbed solar wind with a non-zero speed. Thus, in the problem, the boundary condition is set not only for the concentration, but also for the speed of the solar wind both inside the source of the high-speed flow and outside it. The boundary condition for the plasma velocity is obligatory, since it enters into the propagation function (5). The presence of velocity inhomogeneity in the model is necessary to obtain a corotating helical structure. This fact is consistent with observations, according to which, if there

is an inhomogeneity of the plasma velocity in the region of the source, then already at 10 solar radii, the helical structure of the HFCHs begins to form (Efimov et al., 2021).

Let us show an example of a calculation with two flows—a fast flow from the coronal hole and a slow isotropic flow in other directions. Figure 3 shows the plasma density in arbitrary units in a plane perpendicular to the solar rotation axis (directed toward the reader, Sun is at the center). The function  $\sin(\varphi_1)$  is chosen as  $F_1$  in (10), (11), where  $\varphi_1 = -\omega t + 2\varphi + \omega r/v + 0.25\pi$  is the modified form of (7). It corresponds to the presence of two identical flows (coefficient 2 in front of  $\varphi$  in the formula), the value  $r_0 = 0$  (large distances from the Sun),  $v = 400$  km/s, the size of the visualization area  $4 \times 4$  AU. The time point  $t = 0$  is chosen. The solution describes a typical density perturbation that has the shape of a spiral. The dependence of the density amplitude versus distance was not taken into account in formula (11) for demonstration purposes. Density perturbations of this type were previously obtained in a number of studies based on other assumptions (Burlaga and Klein, 1986), or in the context of full MHD models (Pizzo, 1978, 1980, 1982, 1991; Odstrčil, 2003; and its generalizations).

Let us consider how corotating spiral perturbations occur in the model. The coronal hole rotates synchronously with the Sun. At each time point, it ejects plasma into a sector with a width  $\Delta\varphi$ . Each ejection is a “fan” of fluid elements. If we fix the element corresponding to the center of the “fan” in each sequence of ejections, these elements are characterized by the same  $f$  value (density or speed) and position relative to the coronal hole at the moment of ejection. Therefore, the line connecting the selected elements can be represented as an equal-phase surface (7). In this case, those ejections that were released from the coronal hole later travel a shorter path and start from a larger



**Fig. 4.** The schematic representation of the formation of a spiral by various jets of matter released at different times ( $0$ ,  $dt$ ,  $2dt$ ). CH is the position of the coronal hole. The length of the arrows corresponds to the path passed by the plasma element. The dashed line marks a part of the spiral.



angle  $\varphi$  due to the solar rotation (Fig. 4). Thus, the equal-phase surface should be a spiral twisted against the direction of rotation of the source (Figs. 3, 4 and formula (8)). This is exactly what is described by the function (6) with phase (7), as well as function (11).

It should be noted that if the series of ejections are shifted by an arbitrary time  $\Delta t$ , the picture does not change as long as the properties of the coronal hole are constant. A series of ejections shifted by time  $\Delta t$  forms a similar spiral. Therefore, we can observe corotation of the spiral with the source in the model.

Similarly, a spiral wave arises when cylindrical or spherical waves are added from a source moving along a closed trajectory. This differs from the sprinkler example in the continuity of the flow and the characteristic ratios between the azimuthal  $\omega r_0$  and radial  $v$  projections of the velocity of spray/plasma flows.

As we can see, the HFCH spiral is a set of independent jets (Fig. 4). It is formed at each point by particles ejected at different times and usually from different points, i.e., an HFCH is not a single flow with a fixed set of particles. On the other hand, all the particles that make up the phase surface (spiral) originate from the same coronal hole, and from the same region of it. Thus, the model corresponds to the data, according to which the ratios of the concentrations of highly charged ions ( $O^{7+}/O^{6+}$  and others (Lepri et al., 2013; Zhao et al., 2016)) are the same as in coronal holes.

### 3.3. Flows from Coronal Holes as Spiral Density Waves

In the model, the spiral is a consequence of the motion of flows, while their interaction is not considered. Therefore, it is not a dynamic structure, as assumed in early models (Parker, 1965; Dessler, 1967; Carovillano and Siscoe, 1969). Nevertheless, shock waves can be formed at the boundaries of HFCHs (Burlaga, 1983; Burlaga and Klein, 1986). Let us show that dynamic structures can form spirals similar to those that occur in the kinematic model.

In astrophysical problems and in modeling of the solar wind, the spiral form of perturbations is often considered as predetermined and the main attention is paid to the properties of such perturbations, their stability, and the consequences of their existence. In the case where time dependence arises in the problem due to violation of axial symmetry and rotation of the central body, the quasistationary formalism is used, in which any function  $f$  has the form  $f(r', \varphi', z')$ , where  $(r', \varphi', z')$  are the coordinates in the rotating reference frame (Beskin, 2006, 2010). Further it is assumed (Balbus and Hawley, 1991) that perturbations in this reference frame are stationary and have the form of spiral waves

$$f = f_0 \exp(i(k_r' r' + m\varphi' + k_z z')), \quad (12)$$

where the wave number  $k_r'$  may depend on time if the angular speed of the perturbation depends on  $r$ . Upon

transition to the inertial reference frame, any perturbation (12) takes the form

$$f = f_0 \exp\left(i\left(\left(k_r + mt \frac{\partial \omega}{\partial r}\right)r + m(\varphi - \omega t) - k_z z\right)\right). \quad (13)$$

If one assumes that in  $\omega = \text{const}$ ,  $k_r = \omega/v$ ,  $m = 1$ ,  $k_z = 0$  formula (13), the phase in (13) coincide with (7) at  $r \gg r_0$  up to a constant. Spiral wave (13) at  $m = 2$  coincides with the kinematic wave shown in Fig. 3. Thus, dynamic waves can propagate synchronously with kinematic waves, forming a single complex structure.

## 4. DISCUSSION AND CONCLUSIONS

This study is concerned with the nature of corotating high-speed flows from coronal holes (HFCHs). Let us summarize the results.

(1) A kinematic interpretation of HFCHs has been proposed. It has been shown that the presence of corotation of high-speed flows from coronal holes with the Sun and their spiral shape can be explained in terms of kinematics without involving hydrodynamics or magnetohydrodynamics.

(2) The historical view of HFCHs as flows of matter that completely corotate with a source at the Sun as a whole entity contradicts observations. At 1 AU, the plasma located at any time inside or near an HFCH rotates around the Sun ten times slower than the HFCH itself. Within the context of the kinematic interpretation, this fact does not lead to contradictions.

(3) At each moment of time, HFCHs consist of different particles released by the same rotating source at the Sun in different directions.

(4) The kinematic model of HFCHs does not contradict the existence of spiral pressure waves and makes it possible to explain the coincidence of the ratios of the heavy ion content inside the HFCH and inside the source inside the coronal hole.

Although there are quite a few HFCH models that are consistent with observations, they do not take into account the significant difference between the velocities of plasma rotation around the Sun and the angular velocity of HFCHs. Despite the fact that the data on the magnitude of both velocities are known, no one has attempted to compare them. The values of the plasma angular velocity shown in Fig. 1 are expected, as well as the fact that the product of 1 AU and the angular velocity of the Sun exceeds 400 km/s. However, the very fact that these parameters differ deserves significant attention.

When it comes to the movement and large-scale structure of HFCHs, sometimes it is not clear from the context how exactly the authors represent its propagation. It is often referred to as "rotation of a flow/stream". There are also discussions about how an SIR/CIR corotating with the Sun collides with another structure from the side (in a nonradial direc-

tion), hitting it like a whip (see the discussion of the point of view by Khabarova et al. (2016)). These views indirectly assume that an HFCH is a single jet. As shown above, this contradicts the observations and can lead to an error in reasoning. The purpose of the new kinematic model is to clearly demonstrate that HFCHs and their constituent structures (SIR/CIR, SI, and others) are objects of a collective nature, essentially the same as traffic jams or spiral arms of galaxies. The only circumstance needed for their occurrence is perturbations that require a continuous source moving along a finite trajectory.

From this point of view, the matter in the solar wind moves predominantly radially, while at 1 AU the surface formed by particles emerging from the same region of the coronal hole has the shape of a spiral and corotates with the source. Therefore, an example of a nonradial collision between a certain structure and an HFCH is possible either due to the presence of shock waves or strong discontinuities (such as a current sheet) moving synchronously with the spiral, or due to the nonradial orientation of the obstacle, or due to the distortion of the HFCH by other flows.

The raised question of the interaction of HFCHs with other objects in a lateral collision is not idle. HFCHs can be geoeffective flows. As noted by Riley (2007) and Khabarova (2007), the HFCH components, SIRs/CIRs, were neglected in space weather forecasting for a long time. The strongest magnetic storms (up to 93%) are associated with powerful coronal mass ejections (CMEs). At the same time, HFCHs are more long-lived structures than CMEs. Long-lived high-latitude HFCHs can have a prolonged regular effect on the magnetosphere at the minimum of solar activity. At the maximum of solar activity, low-latitude HFCHs lie near the the ecliptic plane and almost certainly interact with the magnetosphere. As shown, only one-third of all magnetic storms are associated with CMEs (Gosling et al., 1991; Ermolaev and Ermolaev, 2009; Ermolaev et al., 2009). Riley (2007) and Khabarova (2007) noted that the high geoeffectiveness of HFCHs is associated with the features of their impact on the magnetosphere. A CME makes a sharper impact when the shock wave front arrives, while the density and magnetic field variations that occur in the ULF range near SIRs/CIRs have larger amplitudes; these variations can increase the geoeffectiveness of the high-speed streams, preliminarily oscillating the magnetosphere by falling into resonance with its natural frequencies. We hope that the kinematic interpretation of the HFCHs can facilitate the accelerated development of forecasts based on a larger than usual number of geoeffective parameters.

It should be noted that CMEs are the main sources of magnetic storms at the maximum solar activity, while HFCHs are the sources at the minimum activity (Riley, 2007; Khabarova and Rudenchik, 2002, 2003; Khabarova, 2003).

It is noteworthy that within the context of the above kinematic model, it is not very important what the source at the Sun is. To the same success, instead of a coronal hole, one can consider a continuous flow of the solar wind with direction-dependent perturbations. In this case, it can be similarly shown that any heliospheric structures supported by a continuous source at the Sun can corotate with it. The motion of sector boundaries, heliospheric current sheet, and polar current sheets (Khabarova et al., 2017) should be studied in more detail in the future.

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#### CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest.

#### REFERENCES

- Balbus, S.A. and Hawley, J.F., A powerful local shear instability in weakly magnetized disks. I. Linear analysis, *Astrophys. J.*, 1991, vol. 376, pp. 214–222. <https://doi.org/10.1086/170270>
- Barnes, C.W. and Simpson, J.A., Evidence for interplanetary acceleration of nucleons in corotating interaction regions, *Astrophys. J.*, 1976, vol. 210, pp. L91–L96. <https://doi.org/10.1086/182311>
- Beskin, V.S., *Osesimmetrichnye stacionarnye techeniya v astrofizika* (Axisymmetric Stationary Flows and Astrophysics), Moscow: Fizmatlit, 2006.
- Beskin, V.S., Magnetohydrodynamic models of astrophysical jets, *Phys.-Usp.*, 2010, vol. 53, no. 12, pp. 1199–1234. <https://doi.org/10.3367/UFNe.0180.201012b.1241>
- Bochsler, P., Lee, M.A., Karrer, R., et al., Diagnostics of corotating interaction regions with the kinetic properties of iron ions as determined with STEREO/PLAS-TIC, *Ann. Geophys.*, 2010, vol. 28, no. 2, pp. 491–497. <https://doi.org/10.5194/angeo-28-491-2010>
- Burlaga, L.F., Corotating pressure waves without fast streams in the solar wind, *J. Geophys. Res.*, 1983, vol. 88, no. A8, pp. 6085–6094. <https://doi.org/10.1029/JA088iA08p06085>
- Burlaga, L.F. and Klein, L.W., Configurations of corotating shocks in the outer heliosphere, *J. Geophys. Res.*, 1986, vol. 91, no. A8, pp. 8975–8980. <https://doi.org/10.1029/JA091iA08p08975>
- Carovillano, R.L. and Siscoe, G.L., Corotating structure in the solar wind, *Sol. Phys.*, 1969, vol. 8, no. 2, pp. 401–414. <https://doi.org/10.1007/BF00155388>
- Carrington, R.C.C., *Observations of the Spots on the Sun from November 9, 1853 to March 24, 1861*, London: Williams and Norgate, 1863.



- Crooker, N.U., Kahler, S.W., Larson, D.E., and Lin, R.P., Large-scale magnetic field inversions at sector boundaries, *J. Geophys. Res.*, 2004, vol. 109. <https://doi.org/10.1029/2003JA010278>
- Dessler, A.J., Solar wind and interplanetary magnetic field, *Rev. Geophys. Space Phys.*, 1967, vol. 5, pp. 1–41. <https://doi.org/10.1029/RG005i001p00001>
- Efimov, A.I., Lukanina, L.A., Smirnov, V.M., Chashei, I.V., Bird, M.K., and Paetzold, M., Detection of strongly turbulent regions in the supercorona with the Venus Express and Mars Express satellites, *Geomagn. Aeron. (Engl. Transl.)*, 2021, vol. 61, no. 3, pp. 293–298. <https://doi.org/10.1134/S001679322103004X>
- Fahr, H.-J. and Fichtner, H., Physical reasons and consequences of a three-dimensionally structured heliosphere, *Space Sci. Rev.*, 1991, vol. 58, no. 1, pp. 193–258. <https://doi.org/10.1007/BF01206002>
- Geiss, J., Gloeckler, G., and von Steiger, R., Origin of the solar wind from composition data, *Space Sci. Rev.*, 1995, vol. 72, pp. 49–60. <https://doi.org/10.1007/BF00768753>
- Gosling, J.T. and Pizzo, V.J., Formation and evolution of corotating interaction regions and their three dimensional structure, *Space Sci. Rev.*, 1999, vol. 89, pp. 21–52. <https://doi.org/10.1023/A:1005291711900>
- Gosling, J.T., McComas, D.J., Phillips, J.L., and Bame, S.J., Geomagnetic activity associated with earth passage of interplanetary shock disturbances and coronal mass ejections, *J. Geophys. Res.*, 1991, vol. 96, pp. 7831–7839.
- Hundhausen, A.J., Direct observations of solar-wind particles, *Space Sci. Rev.*, 1968, vol. 8, nos. 5–6, pp. 690–749. <https://doi.org/10.1007/BF00175116>
- Hundhausen, A.J., Solar wind stream interactions and interplanetary heat conduction, *J. Geophys. Res.*, 1973, vol. 78, no. 34, pp. 7996–8010. <https://doi.org/10.1029/JA078i034p07996>
- Insley, J.E., Moore, V., and Harrison, R.A., The differential rotation of the corona as indicated by coronal holes, *Sol. Phys.*, 1995, vol. 160, no. 1, pp. 1–18. <https://doi.org/10.1007/BF00679089>
- Khabarova, O.V., Investigation of variations in the solar wind parameters before the onset of geomagnetic storms, *Cand. Sci. (Phys.–Math.) Dissertation*, Moscow: Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, 2003. <https://www.researchgate.net/publication/320216049>. <https://doi.org/10.13140/RG.2.2.20747.18728>
- Khabarova, O.V., Current problems of magnetic storm prediction and possible ways of their solving, *Sun Geosphere*, 2007, vol. 2, no. 1, pp. 33–38. <https://ui.adsabs.harvard.edu/abs/2007SunGe...2...33K/abstract>.
- Khabarova, O.V. and Rudenchik, E.A., Wavelet analysis of solar wind and geomagnetic field ULF oscillations, Moscow: Preprint of Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, 2002, no. 6.
- Khabarova, O.V. and Rudenchik, E.A., Features of changes in the oscillatory regime of density of the solar wind and the Earth's magnetic field before magnetic storms: Results of wavelet analysis, *Vestn. Otd. Nauk Zemle*, 2003, no. 1. [https://scholar.google.com/citations?view\\_op=view\\_citation&hl=ru&user=JAWj\\_IMAAAAJ&cstart=20&pagesize=80&sortby=pubdate&citation\\_for\\_view=JAWj\\_IMAAAAJ:u\\_35RYKgDlwC](https://scholar.google.com/citations?view_op=view_citation&hl=ru&user=JAWj_IMAAAAJ&cstart=20&pagesize=80&sortby=pubdate&citation_for_view=JAWj_IMAAAAJ:u_35RYKgDlwC).
- Khabarova, O.V., Zank, G.P., Li, G., Malandraki, O.E., le Roux, J.A., and Webb, G.M., Small-scale magnetic islands in the solar wind and their role in particle acceleration. II. Particle energization inside magnetically confined cavities, *Astrophys. J.*, 2016, vol. 827. <https://doi.org/10.3847/0004-637X/827/2/122>
- Khabarova, O.V., Malova, H.V., Kislov, R.A., Zelenyi, L.M., Obridko, V.N., Kharshiladze, A.F., Tokumaru, M., Sokol, J.M., Grzedzielski, S., and Fujiki, K., High-latitude conic current sheets in the solar wind, *Astrophys. J.*, 2017, vol. 836, no. 1. <https://doi.org/10.3847/1538-4357/836/1/108>
- Khabarova, O., Malandraki, O., Malova, H., et al., Current sheets, plasmoids and flux ropes in the heliosphere. Part. I. 2-D or not 2-D? General and observational aspects, space, *Space Sci. Rev.*, 2021a, vol. 217, p. 38. <https://doi.org/10.1007/s11214-021-00814-x>
- Khabarova, O., Sagitov, T., Kislov, R., and Li, G., Automated identification of current sheets: A new tool to study turbulence and intermittency in the solar wind, *J. Geophys. Res.: Space*, 2021b, vol. 126, no. 8. <https://doi.org/10.1029/2020JA029099>
- Krieger, A.S., Timothy, A.F., and Roelof, E.C., A coronal hole and its identification as the source of a high velocity solar wind stream, *Sol. Phys.*, 1973, vol. 29, no. 2, pp. 505–525. <https://doi.org/10.1007/BF00150828>
- Lee, M.A., An analytical theory of the morphology, flows, and shock compressions at corotating interaction regions in the solar wind, *J. Geophys. Res.*, 2000, vol. 105, pp. 10491–10500. <https://doi.org/10.1029/1999JA000327>
- Lepri, S.T., Landi, E., and Zurbuchen, T.H., Solar wind heavy ions over solar cycle 23: ACE/SWICS measurements, *Astrophys. J.*, 2013, vol. 768. <https://doi.org/10.1088/0004-637X/768/1/94>
- Odstrčil, D., Modelling 3-D solar wind structure, *Adv. Space Res.*, 2003, vol. 32, no. 4, pp. 497–506. [https://doi.org/10.1016/S0273-1177\(03\)00332-6](https://doi.org/10.1016/S0273-1177(03)00332-6)
- Parker, E.N., Dynamics of the interplanetary gas and magnetic fields, *Astrophys. J. Lett.*, 1958, vol. 128, p. 664. <https://doi.org/10.1086/146579>
- Parker, E.N., Dynamical theory of the solar wind, *Space Sci. Rev.*, 1965, vol. 4, nos. 5–6, pp. 666–708. <https://doi.org/10.1007/BF00216273>
- Pizzo, V.J., A three-dimensional model of corotating streams in the solar wind. I. Theoretical foundations, *J. Geophys. Res.*, 1978, vol. 83, pp. 5563–5572. <https://doi.org/10.1029/JA083iA12p05563>
- Pizzo, V.J., A three-dimensional model of corotating streams in the solar wind. II. Hydrodynamic streams, *J. Geophys. Res.*, 1980, vol. 85, pp. 727–743. <https://doi.org/10.1029/JA085iA02p00727>
- Pizzo, V.J., A three-dimensional model of corotating streams in the solar wind. III. Magnetohydrodynamic

- streams, *J. Geophys. Res.*, 1982, vol. 87, pp. 4374–4394. <https://doi.org/10.1029/JA087iA06p04374>
- Pizzo, V.J., The evolution of corotating stream fronts near the ecliptic plane in the inner solar system. II. Three-dimensional tilted-dipole fronts, *J. Geophys. Res.*, 1991, vol. 96, pp. 5405–5420. <https://doi.org/10.1029/91JA00155>
- Pizzo, V.J. and Gosling, J.T., Three-dimensional simulation of high-latitude interaction regions: comparison with Ulysses results, *Geophys. Res. Lett.*, 1994, vol. 21, no. 18, pp. 2063–2066. <https://doi.org/10.1029/94GL01581>
- Pizzo, V.J., Schwenn, R., Marsch, E., Rosenbauer, H., Mühlhauser, K.-H., and Neubauer, F.M., Determination of the solar wind angular momentum flux from the Helios data: An observational test of the Weber and Davis theory, *Astrophys. J.*, 1983, vol. 271, pp. 335–354. <https://doi.org/10.1086/161200>
- Richardson I.G., Solar wind stream interaction regions throughout the heliosphere, *Living Rev. Sol. Phys.*, 2018, vol. 15, no. 1. <https://doi.org/10.1007/s41116-017-0011-z>
- Riley, P., Modeling corotating interaction regions: From the Sun to 1 AU, *J. Atmos. Sol.-Terr. Phys.*, 2007, vol. 69, pp. 32–42. <https://doi.org/10.1016/j.jastp.2006.06.008>
- Wimmer-Schweingruber, R.F., von Steiger, R., and Paerli, R., Solar wind stream interfaces in corotating interaction regions: SWICS/Ulysses results, *J. Geophys. Res.*, 1997, vol. 102, no. A8, pp. 17407–17418. <https://doi.org/10.1029/97JA00951>
- Yermolaev, Yu.I. and Yermolaev, M.Yu., Solar and interplanetary sources of geomagnetic storms: Space weather aspects, *Izv., Atmos. Ocean. Phys.*, 2010, vol. 46, no. 7, pp. 799–819. <https://ifz.ru/geofizicheskie-procressyi-i-biosfera/soderzhanie/tom-8-nomer-1-2009/01>. <https://doi.org/10.1134/S0001433810070017>
- Yermolaev, Yu.I., Nikolaeva, N.S., Lodkina I.G., and Yermolaev, M.Yu., Catalog of large-scale solar wind phenomena during 1976–2000, *Cosmic Res.*, 2009, vol. 47, no. 2, pp. 81–94.
- Zastenker, G.N., Khrapchenkov, V.V., Koloskova, I.V., Gavrilova, E.A., Ryazanova, E.E., Ryazantseva, M.O., Gagua, T.I., Gagua, I.T., Šafrankova, J., and Němeček, Z., Rapid variations of the value and direction of the solar wind ion flux, *Cosmic Res.*, 2015, vol. 53, no. 1, pp. 59–69. <https://doi.org/10.1134/S0010952515010098>
- Zhao, L., Landi, E., Fisk, L.A., and Lepri, S.T., The coherent relation between the solar wind proton speed and  $O^{7+}/O^{6+}$  ratio and its coronal sources, *AIP Conf. Proc.*, 2016, vol. 1720, no. 1, p. 020007. <https://doi.org/10.1063/1.4943808>

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