Use of the DBM Model to the Predict of Arrival of Coronal Mass Ejections to the Earth

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Abstract—This paper analyzes the results of modeling coronal mass ejection (CME) propagation in 2010–2011 obtained using input data from different sources: CME catalogs SEEDS and CACTus, and predictions of the velocity of quasi-stationary solar wind fluxes, as an environment, through which CMEs propagate. As the model of quasi-stationary solar wind fluxes, the model for predicting the velocity of the solar wind of the Space Weather Forecast Center of the Skobeltsyn Institute of Nuclear Physics of Moscow State University, operating online, is used. The CME prediction is carried out using the Simple Drag-Based Model. A comparison was performed between the ICME arrival time and their velocities obtained when modeling with data from the open ICME catalogs: the Richardson and Cane ICME catalog and the GMU CME List. Based on the comparison, it was concluded that a more accurate prediction for the growth phase of the 24th solar activity cycle was obtained using data on CME parameters from the CACTus database. The obtained errors in predicting the ICME parameters are comparable with the errors of other existing models.

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INTRODUCTION

Coronal mass ejections (CMEs) are ejections of solar plasma, which are characterized by high velocities and densities of plasma and are the main sources of strong geomagnetic storms [1–3].

To ensure the radiation safety of flights and predict magnetic storms, it is necessary to be able to accurately predict the arrival time of coronal mass ejection to the Earth. This problem is nontrivial because of the difficulties in determining the initial conditions and the dependence of the CME evolution in the heliosphere on a large number of factors. The predicted parameters (the velocity and arrival time of interplanetary CMEs) depend on the choice of the model and the initial conditions: the CME ejection time and its velocity and direction of propagation at this time, as well as the general state of the heliosphere (parameters of the ambient solar wind (SW), the presence of high-speed streams (HSS) and other CMEs, which can affect the dynamics of the ejection propagation in the heliosphere) [4].

The term “interplanetary CMEs” (ICMEs) is used to describe CMEs in the heliosphere. Predicting the ICME arrival time and parameters has been carried out for several decades. In [5], the authors compare CMEs, observed with a coronagraph with ICMEs, recorded near the Earth, and note the discrepancy between the initial velocity of the ejection and the velocity of its arrival to the Earth. They propose an empirical model that takes into account the effect of ambient wind velocity on ejection velocity. The influence of the parameters of the interplanetary space, through which the CME propagates, on the propagation mode (deceleration/acceleration) is also noted in [6, 7]: the velocity of ejections at 1 AU is close to the solar wind velocity, while the spread of the initial velocities according to coronagraph data reaches large values. In this case, prediction models that can operate online and use operational data from solar observations from space and ground observatories have also been in demand recently.

For example, in [8], the WSA-ENLIL+Cone model was used to simulate CME propagation in the heliosphere. The magnetohydrodynamic 3D WSA-ENLIL model provides a description of the plasma parameters of the ambient solar wind and interplanetary magnetic field (IMF) depending on time [9]. To simulate CME propagation in the heliosphere, the Cone model proposed in [10] is used. The authors propose to approximate the CME shape by a spherical sector and consider the CME expansion as isotropic and self-similar and the CME propagation as radial.

In the ElEvoHI model proposed in [11], the CME shape is assumed to be elliptical and the CME propagation is calculated using the DBM model. As input data, ElEvoHI uses images from the Heliospheric...
The European system EUHFORIA [12] also makes it possible to predict the time and velocity of CME arrival to the Earth. The large tool of the system makes it possible to simulate the interaction of different solar wind streams and combine different models. In this system, the heliosphere is divided into two regions: the coronal (from the Sun to 0.1 AU) and inner heliosphere (from 0.1 to 2 AU). Each area uses its own data and methods; for example, the input parameters for the coronal model are the topology of the coronal magnetic field, and its solutions serve as input values for the model of the inner heliosphere. The magnetic field is also calculated sequentially: first, for the coronal region and, then, for the region of the inner heliosphere. The input data for modeling the magnetic field are solar magnetograms. To simulate CME propagation, the algorithms proposed in [13] are used, which are based on the numerical solution of hydrodynamic equations.

Currently, there are several online CME prediction systems: for example: the Solar Wind Prediction Center (https://www.swpc.noaa.gov/products/wsa-enlil-solar-wind-prediction), the Integrate Space Weather Analysis system (https://ccmc.gsfc.nasa.gov/iswa/). Both of these systems predict CMEs by combining the WSA-ENLIL heliosphere model and the Cone model for CME propagation.

The synthesis of several models makes it possible to take into account many factors, including the interaction of streams in the heliosphere, to model not only conical CMEs, but also spherical and elliptical ones. However, the use of this system for online prediction requires large computing resources.

This paper presents the results of the analysis of the ICME prediction using various databases of the CME parameters, which are online updated. The study was carried out for the further use of databases to create an online system for predicting the CME time and velocity of arrival to the Earth for the Space Weather Forecast Center of the Skobeltsyn Institute of Nuclear Physics of Moscow State University (http://swx.sinp.msu.ru/models/solar_wind.php?gcm=1). To solve this problem, two models are used together: the DBM model [14] for modeling CME propagation in the heliosphere and the model of quasi-stationary solar wind streams [15] for modeling the velocity of the ambient solar wind. The choice of the DBM model is due to the fact that, according to [16], the DBM model shows prediction results comparable in quality to WSA-ENLIL+Cone, while it is computationally simpler than WSA-ENLIL.

This paper presents the preliminary results of testing the DBM model on the historical database of interplanetary coronal mass ejections recorded in a near-Earth orbit in 2010–2011 in order to study the dependence of the prediction quality on the choice of the initial CME parameters provided by the CME catalogs SEEDS and CACTus.

1. DATA AND MODELS

CMEs in the solar corona are observed using coronagraphs. The images obtained from the LASCO C1, C2, and C3 coronagraphs onboard the SOHO spacecraft located at the Lagrange point L1 (on the Sun–Earth line approximately 1.5 million km from the Earth) clearly show “lateral” CMEs (directed to the West and to East of the Sun), as well as halo CMEs. The STEREO mission was launched with the aim of CME stereoscopic observation. The Stereo A and Stereo B spacecraft (each with a pair of Cor 1 and Cor 2 coronagraphs) move in orbits close to the Earth. In this case, the rotation periods of Stereo A and Stereo B are respectively 346 and 388 days. This movement of the satellites provides the possibility of stereoscopic observation of the Sun: during the time period under consideration, the coronagraphs on Stereo A were directed to the western limb of the Sun, and coronagraphs on Stereo B were directed to the east. Thus, in 2010–2012, using coronagraphs on the Stereo spacecraft, it was possible to observe CMEs directed towards the Earth. Unfortunately, since the STEREO spacecraft varies their position, it is difficult to determine CMEs directed to the Earth with their help at another time, and contact with the Stereo B satellite was lost in 2016.

This study used data from the LASCO coronagraph of the SOHO spacecraft from the CACTus (http://sidc.oma.be/cactus/catalog.php) and SEEDS (http://spaceweather.gmu.edu/seeds/lasco) databases.

The CACTus (Computer Aided CME5 Tracking) database is formed using an automatic program that detects CMEs using images from LASCO C2/C3 coronagraphs and determines the date and time of detection, the duration of the event in hours, the direction of propagation and the angular width of the cone in the picture plane, the front velocity averaged over all directions, and its spread, maximum and minimum values, and each event is assigned a Halo index: degree II, III, or IV depending on the angle of the opening angle of the cone [17]. The database is online and updated every 6 h.

The SEEDS database includes two catalogs: a list of CMEs recorded by the LASCO C2 coronagraph and two CME catalogs recorded by the SECCHI COR2 coronagraphs installed on the STEREO A and B spacecraft. We are interested in the first catalog. The SEEDS database is also formed using an automated program that processes coronagraph images and determines CME parameters from them. The parameters to be determined include the detection time, direction of propagation and angular width of the CME cone in the picture plane, CME velocity obtained using a linear approximation of the CME.
front motion, and acceleration obtained by approximating the front motion by a quadratic function with a sufficient number of event frames in the coronagraph (three or more) [18].

When determining the initial ejection velocity and its acceleration using coronagraph images processing, errors are inevitable due to the fact that we see the ejection in the picture plane; i.e., we can calculate only the projection of the ejection velocity, in this case, the angle between the CME direction and the picture plane is also unknown. This problem can be solved by observing CME from several points (the STEREO mission), but at present, due to the Stereo B malfunction, such measurements do not exist, therefore, we use only data from the SOHO/LASCO spacecraft for online prediction. There are also 3D models of CME propagation, but, for them to be accurate, it is important to know the location of the source in the corona, which is not always possible. For example, the SUSANOO model [19] is based on the calculation of the IMF structure, and the CME propagation in it is represented as the propagation of a magnetic loop in the heliosphere. This model requires magnetograms of the Sun and the exact position of the source. At this stage, we restrict ourselves to the data obtained in the picture plane and a simple model that does not take into account the CME geometry.

To test the model, the time interval from May 2010 to December 2011 was chosen, since from May 2010 the data from the SDO observatory began to arrive, which we use to predict the velocity of quasi-stationary solar wind fluxes.

In this study, we use the Richardson & Cane ICME catalogs [20] and GMU CME List [21]. In these catalogs, ICMEs are determined from the main plasma characteristics of the solar wind: density, velocity, temperature of protons, and ionic ratios according to measurements from the L1 point. For more information on compiling such catalogs, see Richardson et al. [22]. In the indicated ICME catalogs, one can find information about the start of the event (in the Richardson & Cane catalog, the arrival time of the shock wave and the time of arrival of the ICME body are recorded separately, and we took the second one), as well as its duration, average and maximum velocities. We used these data when testing the model.

As a test set of events, we used those ICMEs from the specified catalogs, which had already been compared with the corresponding CMEs, and ICMEs with an undefined source were rejected. Thus, from May 2010 to December 2011, 22 events from the Richardson & Cane catalog and 15 events from the GMU CME List catalog were selected. Taking into account coincident events and not taking into account an event in October 2010, when there is a gap in the LASCO data, we analyzed the propagation of 26 CMEs in total. Their parameters are given in Table 1. They include both events of single CME propagation and events of several CME propagation, for example, events 1 and 2 have different coronal sources, but ejections from different coronal sources entered the near-Earth orbit at the same time and are recorded in the catalogs as one ICME. For each ICME, the catalogs indicated the CME observation time in coronographs or LASCO or STEREO, and for each case, we searched for the corresponding dimming in the Solar Demon database.

The Solar Demon base provides online data on flares and dimmings (sudden decreases in the density of matter on the Sun due to the ejection of matter during the CME formation, manifested as decreases in brightness at the wavelength of 21.1 nm according to SDO/AIA data). Using the dimming base, it is possible to eliminate CMEs directed from the Earth in those cases in which we observe the corresponding dimming not against the background of the solar disk, but behind the limb. The presence of dimming also provides information on the coordinates of the coronal ejection source. We plan to actively use the data from this database in the future to construct a future CME online prediction system.

Focusing on the dimming observation time, where it was possible, or on the time of CME observation in the coronagraph, we found the corresponding CMEs from the CACTus and SEEDS catalogs, since the CME start time is indicated in the ICME catalogs, which does not always coincide with the time from the CME catalogs that we used.

1.1. Description of the DBM Model

As mentioned above, to predict ICMEs, we chose the Drag-Based Model [14], as it is a rather simple computational model, but it is comparable to more complex MHD models in terms of results. In the DBM model approximation, it is assumed that, beginning from a certain distance from the Sun, the CME propagation dynamics is determined only by the CME interaction with the ambient solar wind ($F_d$), i.e., the Lorentz force ($F_L$), and the gravity ($F_g$) can be neglected. Thus, beginning from a certain distance from the Sun (more than 15 solar radii according to [23]), one can consider only the aerodynamic drag force $F_d: F = F_L - F_g + F_d \approx F_d$, at $r > 15R_{\text{Sun}}$.

The resulting acceleration $a_d$ can accelerate or decelerate the ejection, depending on the ratio of ejection velocities $v$ and ambient solar wind $w$:

$$a_d = -\gamma(v - w) |v - w|.$$

The drag parameter $\gamma$ can be considered constant or depend on the CME parameters and calculated by the formula $\gamma = c_d \frac{A \rho_{mw}}{M}$, where $c_d$ is the dimensionless drag coefficient; $A$ and $M$ are the CME cross section and mass, respectively; and $\rho_{mw}$ is the density function of the ambient solar wind.
Table 1. List of investigated events from May 2010 to December 2011. Events taken from GMU CME List are marked with *.

| No. | $T_{start}$ | $T_{end}$ | $V$ | $T_{start}$ | $V_{CME}$ | $a_{CME}$ | $T_{start}$ |
|-----|------------|----------|-----|-------------|-----------|-----------|-------------|
|     | MM DD, YYYY hh.mm | MM DD, YYYY hh.mm | km/s | MM DD, YYYY hh.mm | km/s | km/s | MM DD, YYYY hh.mm |
| 1   | May 28, 2010 19.00 | May 29, 2010 17.00 | 360 | May 23, 2010 17.06 | 240 | May 23, 2010 18.30 | 229 33.5 |
| 2   | May 28, 2010 19.00 | May 29, 2010 17.00 | 360 | May 24, 2010 13.54 | 381 | May 24, 2010 14.30 | 309 2.7 |
| 3   | June 21, 2010 06.00 | June 22, 2010 14.00 | 360 | June 16, 2010 04.06 | 339 | June 16, 2010 04.06 | 287 5.2 |
| 4   | Oct. 31, 2010 05.00 | Nov. 1, 2010 21.00 | 350 | Oct. 26, 2010 11.36 | 349 | Oct. 26, 2010 00.36 | 38 7.0 |
| 5   | Dec. 28, 2010 03.00 | Dec. 28, 2010 15.00 | 350 | — | — | Dec. 23, 2010 05.12 | 152 6.6 |
| 6   | Feb. 18, 2011 09.00 | Feb. 20, 2011 08.00 | 470 | Feb. 15, 2011 02.24 | 469 | Feb. 15, 2011 02.36 | 505 70.8 |
| 7   | March 6, 2011 09.00 | Mar. 8, 2011 06.00 | 430 | Mar. 3, 2011 06.12 | 228 | Mar. 3, 2011 06.36 | 188 —0.5 |
| 8   | March 29, 2011 23.00 | Mar. 31, 2011 04.00 | 360 | Mar. 25, 2011 07.48 | 325 | Mar. 25, 2011 05.36 | 123 4.3 |
| 9   | May 28, 2011 05.00 | May 28, 2011 21.00 | 510 | May 25, 2011 05.48 | 134 | May 25, 2011 05.48 | 290 —14.9 |
| 10  | June 5, 2011 02.00 | June 5, 2011 19.00 | 510 | June 2, 2011 08.12 | 422 | June 2, 2011 09.00 | 91 127.3 |
| 11  | June 17, 2011 05.00 | June 17, 2011 13.00 | 500 | June 14, 2011 07.12 | 456 | June 14, 2011 06.00 | 180 19.2 |
| 12* | July 3, 2011 03.00 | July 4, 2011 15.00 | 396 | June 29, 2011 00.48 | 459 | June 29, 2011 00.25 | 509 —48.1 |
| 13  | Aug. 5, 2011 05.00 | Aug. 5, 2011 14.00 | 430 | Aug. 2, 2011 06.36 | 508 | Aug. 2, 2011 06.48 | 613 33.7 |
| 14  | Aug. 6, 2011 22.00 | Aug. 7, 2011 22.00 | 540 | Aug. 4, 2011 04.12 | 868 | Aug. 4, 2011 03.48 | 384 22.2 |
| 15  | Sept. 10, 2011 03.00 | Sept. 10, 2011 15.00 | 470 | Sept. 7, 2011 06.12 | 419 | Sept. 7, 2011 01.36 | 226 28.9 |
| 16  | Sept. 17, 2011 14.00 | Sept. 18, 2011 06.00 | 430 | Sept. 14, 2011 00.36 | 663 | Sept. 14, 2011 00.00 | 295 —2.3 |
| 17  | Sept. 22, 2011 15.00 | Sept. 23, 2011 03.00 | 390 | Sept. 19, 2011 09.12 | 358 | Sept. 19, 2011 09.12 | 366 6.0 |
| 18  | Sept. 26, 2011 20.00 | Sept. 28, 2011 15.00 | 580 | Sept. 24, 2011 13.25 | 941 | Sept. 24, 2011 12.36 | 920 312.0 |
| 19  | Oct. 6, 2011 10.00 | Oct. 6, 2011 22.00 | 450 | Oct. 2, 2011 01.25 | 578 | Oct. 2, 2011 05.00 | 193 25.6 |
| 20* | Oct. 8, 2011 14.00 | Oct. 9, 2011 10.00 | 328 | Oct. 3, 2011 01.36 | 428 | Oct. 3, 2011 00.48 | 251 16.2 |
| 21  | Oct. 22, 2011 21.00 | Oct. 23, 2011 16.00 | 290 | Oct. 16, 2011 14.24 | 216 | Oct. 16, 2011 12.24 | 619 40.8 |
| 22  | Oct. 24, 2011 22.00 | Oct. 25, 2011 16.00 | 460 | Oct. 22, 2011 11.00 | 694 | Oct. 22, 2011 10.36 | 619 40.8 |
| 23  | Nov. 2, 2011 01.00 | Nov. 3, 2011 04.00 | 380 | Oct. 27, 2011 11.48 | 522 | Oct. 27, 2011 10.12 | 227 5.9 |
| 24  | Nov. 13, 2011 10.00 | Nov. 15, 2011 02.00 | 370 | Nov. 9, 2011 13.48 | 721 | Nov. 9, 2011 13.36 | 649 53.0 |
| 25  | Nov. 29, 2011 00.00 | Nov. 29, 2011 08.00 | 450 | Nov. 26, 2011 07.12 | 672 | Nov. 26, 2011 07.00 | 623 16.6 |
| 26  | Dec. 29, 2011 22.00 | Dec. 30, 2011 09.00 | 400 | Dec. 26, 2011 11.48 | 578 | Dec. 26, 2011 12.00 | 213 31.4 |

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If the ambient solar wind is considered homogeneous and isotropic, then $\gamma$ does not depend from the distance, and this problem is analytically solved and gives the following functions of the CME velocity and the distance traveled versus time:

$$r(t) = \pm \frac{1}{\gamma} \ln \left( 1 \pm \gamma \left( v_0 - w \right) t \right) + wt + r_0,$$

$$v(t) = w + \frac{v_0 - w}{1 \pm \gamma (v_0 - w) t},$$

where $\pm$ depends on the acceleration mode (“+” for deceleration ($v_0 > w$) and “−” for acceleration ($v_0 < w$)) and $v_0$ is the ejection velocity at the distance from the Sun $r_0$.

### 1.2. Selecting the Input Data of the Model

The main input parameters of the model are presented in Table 2. Distance $R_0$ is chosen on the basis of the constancy of parameters $\gamma$ and $w$ during the CME propagation, which simplifies the solution to the problem. It was shown in [14] that it is legitimate to choose $R_0 = 20R_{\odot}$, where $R_{\odot}$ is the radius of the Sun, although, for very fast CMEs, an increase in this value is possible due to the action of the Lorentz force, which is directly proportional to the plasma velocity. Another simplification is the neglect of the dependence of $\gamma$ on the ejection parameters $A$ and $M$. In the implementation of the DBM model [14], it is proposed to consider $\gamma$ as constant for each event and choose its value depending on initial ejection velocity $v_0$: for $v_0 < 500 \text{ km/h}$, $\gamma = 0.5 \times 10^{-7} \text{ km}^{-1}$; for $500 < v_0 < 1000 \text{ km/h}$, $\gamma = 0.2 \times 10^{-7} \text{ km}^{-1}$; and for $v_0 > 1000 \text{ km/h}$, $\gamma = 0.1 \times 10^{-7} \text{ km}^{-1}$. For our testing, we chose the same values for $\gamma$. The velocity of the background solar wind $w$ was determined by the algorithm for predicting the velocity of high-speed solar wind streams based on the areas of coronal holes (CHs) calculated from the AIA instrument of the Solar Dynamics Observatory (SDO) solar images at the wavelength of 193 Å described in [15, 24]. Velocity forecast results are presented on the website (http://swx.sinp.msu.ru/models/solar_wind.php?gcm=1). This model makes it possible to calculate the solar wind velocity at the required distance using empirical dependence $V(S, t) = V_{\text{min}} + A S(t_0)^{\alpha}$, where $S(t_0)$ is the CH relative area that falls into the band in the selected latitude and longitude region at time $t_0$ at wavelength $\lambda_i$ (193 Å); $V_{\text{min}}$ is the minimum SW velocity, which also replaces the periods of absence of solar wind streams from the CH (it was taken equal to 300 km/s); and $t$ is the time of arrival of the SW high-speed stream in the considered orbit according to the velocity prediction (calculated to the ballistic model, in which the SW motion is assumed to be uniform and radial). The coefficients were selected for the wavelength of 193 Å by minimizing prediction errors on the data for 2010–2011: $A_j = 210$ and $\alpha_j = 0.4$. The resulting prediction of SW high-speed streams is the background solar wind or the medium over which CME propagates.

The remaining input parameters of the DBM model, $T_0$ and $v_0$, can be obtained from observations of coronagraphs. For online prediction, only online updated CME databases such as SEEDS and CACTus can be used, however, the parameters of interest to us for the same event in different databases can differ greatly, therefore one of the problems analyzed in this study was the problem of choosing a database that gives the most qualitative prediction result, when using the DBM model for the selected time interval. For the parameters $T_0$ and $v_0$, it is also necessary to recalculate to the distance $R_0 = 20R_{\odot}$, since $T$ indicated in the databases is the CME detection time in the field of view of the LASCO C2 coronagraph. This recalculation was carried out under the assumption of uniform CME motion, which, strictly speaking, is not correct; however, the SEEDS database indicates the CME acceleration calculated from the coronagraph images, which makes it possible to perform recalculation taking into account the accelerated motion. Thus, we obtained three different sets of input parameters $T_0$, $v_0$, and $\gamma$ set 1 from the CACTus base (recalculated to $20R_{\odot}$ in the uniform motion approximation), set 2 from the SEEDS base (recalculated to $20R_{\odot}$ in the uniform motion approximation), and set 3 from the SEEDS base (SEEDS_acc; recalculation to $20R_{\odot}$ in the approximation of uniformly accelerated motion, where it was possible (23 events from 26; otherwise, recalculation in the approximation of uniform motion). The CME velocities at the distance $R_0 = 20R_{\odot}$ for sets 1, 2, and 3 are shown in Fig. 1. As can

### Table 2. Description of input parameters for a simple DBM model

| Parameter | Description |
|-----------|-------------|
| $R_0$     | Distance at which the DBM model approximations begin to operate |
| $T_0$     | Time at which the CME front was at the distance $R_0$ |
| $v_0$     | Velocity of the CME front at time $T_0$ |
| $\gamma$  | Drag parameter |
| $w$       | Velocity of ambient solar wind |
be seen from the figure, CME velocities can differ greatly depending on the database and the algorithm for recalculation to distance $R_0$. The differences are especially noticeable between the recalculation to the distance of 20 solar radii of the SEEDS database with and without acceleration (events 6, 10, 18, etc.). Hereafter, we will consider the use of input parameters based on the data of which database, gives predictions that are closest to the data of the ICME catalog for 2010–2011.

To compare the prediction results with observations, ICME catalogs were used [20, 21]. In total, 26 events were investigated (for the first set 25 events, since the CACTus database did not contain data for December 23, 2010), for each of which three sets of input data were used with different $T_0, v_0$ and $\gamma$ and the same $R_0$ and $w$.

2. RESULTS OF SIMULATION

During modeling, the CME propagation for each event and the dependences of $R(t)$ and $v(t)$ were obtained, while the time and velocity of ICME arrival at the distance of 1 AU were calculated. These values were compared with values from the Richardson & Cane and GMU CME List catalogs and the prediction error was calculated:

$$dt = T_{\text{prediction}} - T_{\text{catalog}},$$

$$dv = V_{\text{prediction}} - V_{\text{catalog}}.$$

Figure 2 shows the dependences of $R(t)$ and $v(t)$ for the event in November 2011 (event 25 in Table 1). From these dependences, it is possible to find the time of ICME arrival at the distance of 1 AU and its velocity at this time. The same event is illustrated in Fig. 3, which also shows the solar wind velocity observed by the ACE spacecraft and the predicted quasi-stationary wind velocity. According to the Richardson & Cane catalog, ICME corresponding to the CME under our consideration was recorded at point L1 on November 29, 2011, at 00:00. Thus, one can see that the predicted arrival time based on sets 1 (CACTus) and 2 (SEEDS) lags behind, and based on set 3 (SEEDS_acc) passes ahead the real time of ICME arrival. The average and maximum ICME velocities according to the Richardson & Cane catalog were 450 and 510 km/s, respectively. The predicted velocities are 519, 506, and 557 km/s for sets 1, 2, and 3, respectively, which is in good agreement with the measured value, especially for sets 1 and 2. The input and output parameters of the model for the case under consideration are given in Table 3.

Having considered all 26 events, we obtained the distribution of prediction errors in terms of velocity $dv$ and time $dt$ for each set of input data. This distribution is shown in Fig. 4. Having estimated the distribution of prediction errors for three sets of input data, we can conclude that set 2 gives a prediction with an underestimated velocity and time lag, while using set 3, on the contrary, leads to a strong overestimation of the ICME arrival velocity, which leads to passing ahead of time. The prediction with the smallest spread of errors is obtained on the basis of input data for set 1. This result can be explained by the difference in the methods for determining the CME velocity from coronagraph images in the CACTus and SEEDS databases. While in the CACTus database (set 1), some velocity averaged over all directions of the ejection is calculated, in the SEEDS database (sets 2 and 3), the initial velocity and acceleration of the leading front of the ejection is calculated based on approximations of its motion by linear and quadratic functions, respectively. Our study shows that the DBM model, which as an input param-

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**Fig. 1.** CME velocities recalculated to distance $R_0$ equal to 20 solar radii for events from Table 1 obtained from three sets from the databases: recalculation without acceleration for CACTus and SEEDS and recalculation with acceleration for SEEDS_acc.
Fig. 2. Dependences of the distance traveled by CME and its velocity on time in the framework of the DBM model calculated for three sets. The black dash-dotted line marks the distance of 1 AU; the vertical dashed lines indicate the CME arrival time at 1 AU for each dataset. Vertical black line indicates the ICME arrival time according to the Richardson & Cane catalog.

Fig. 3. Prediction of the time and velocity of CME arrival in event 25 from Table 1.
Fig. 4. Differences between the taken from ICME catalogs and predicted values of the ICME arrival time and velocity ($dt$ and $dv$) obtained when modeling the CME propagation for the input parameters of the model from different databases for the events from Table 1.

The ICME arrival time and its average velocity in the Earth’s orbit according to the Richardson & Cane catalog:

| No. | Coronograph | DBM input parameters | DBM output parameters |
|-----|-------------|-----------------------|-----------------------|
|     |             | $T_{cor}$, dd.hh.mm | $V_{cor}$, km/s | $A_{cor}$, km/s$^2$ | $R_0$, $R_{Sun}$, dd.hh.mm | $v_0$, km/s | $\gamma \times 10^7$, km$^{-1}$ | $w$, km/s | $T_{prediction}$, dd.hh.mm | $V_{prediction}$, km/s |
| 1   | 26.07.12    | 672                  | —                    | 20                   | 26.11.30                   | 672        | $-0.2$                         | 400      | 29.05.30                     | 519 |
| 2   | 26.07.00    | 623                  | —                    | 20                   | 26.11.39                   | 623        | $-0.2$                         | 400      | 29.08.39                     | 506 |
| 3   | 16.6        | 106                  | 16.6                 | 20                   | 26.10.54                   | 857        | $-0.2$                         | 400      | 28.20.54                     | 557 |

The ICME arrival time and its average velocity in the Earth’s orbit according to the Richardson & Cane catalog:

3. DISCUSSION OF RESULTS

The spread of errors in predicting the ICME arrival time can be seen on the histograms in Fig. 5. The results of approximation by the normal distribution of the difference between the measured and predicted values of the ICME arrival time are presented in Table 4. The approximation gives the best results for the CACTus dataset, which can be seen from the value of determination coefficient $R^2$, which is closer to 1 for the CACTus dataset: 0.99 for CACTus, 0.96 for SEEDS, and 0.95 for SEEDS_acc. For data from the SEEDS database, when using the uniformly accelerated approximation to recalculate the CME parameters observed in the...
coronograph at the distance of 20 solar radii, the median of error distribution $dt$ is shifted relative to zero by $-9$ h, the absolute mean error $\langle dt \rangle$ is 1.1 times smaller, and the spread of errors $dt$ is 1.3 times greater than for the prediction according to data from the CACTus database. At the same time, for data from the SEEDS database without taking into account the acceleration, the median of the distribution is shifted by $+37$ h, the absolute mean error $\langle dt \rangle$ is four times larger and the spread of errors $dt$ is 1.6 times larger than for the prediction based on data from the CACTus database. The median of the $dt$ distribution obtained on the basis of the CACTus data is shifted relative to zero by $+14$ h, and the average error $\langle dt \rangle$ is equal to $+9.24$ h. The absolute mean error in determining the CME velocity $\langle dt \rangle$ for the prediction based on the CACTus data was $20$ km/s: three times better than for the prediction based on the SEEDS database and 4.3 times better than for the prediction based on the SEEDS_acc database.

The detected tendency of “forecast lag” (the median of the $dt$ distribution is equal to $+14$ h, and the average error $\langle dt \rangle$ is equal to $+9.24$ h) when using the CACTus database can be due to a large number of factors: the features of the CACTus automatic system, possible errors in predicting the velocity of quasi-stationary fluxes, not taking into account the interaction of fluxes in the heliosphere (the CME–CME interaction is not taken into account; the CME–HSS interaction is taken into account only at 20 solar radii), and neglecting the CME shape and propagation direction. The study and consideration of these factors are the subject of further research. Based on the conclusions, we focused on the simulation results obtained using data from the CACTus database (set 1).

In the present study, the DBM model gives the average over all three sets of prediction error of the CME arrival time equal to 18 h. This error is quite large, but comparable with the errors obtained when using other models given in Table 5. To compare the simulation results with the results of other models from [16, 25, 26], the following prediction errors were calculated:

$$\langle dt \rangle = \frac{1}{N} \sum_{i=1}^{N} dt_i,$$

$$\text{SD} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (dt_i - \langle dt \rangle)^2},$$

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^{N} |dt_i - \langle dt \rangle|.$$

Table 4. Parameters of approximation of histograms of distribution of errors in determining the ICME arrival time by the Gaussian function

| Parameters of approximation | Set 1 CACTus | Set 2 SEEDS | Set 3 SEEDS_acc |
|-----------------------------|--------------|-------------|----------------|
| $R^2$                       | 0.99         | 0.96        | 0.95           |
| RMS                         | 0.37         | 0.59        | 0.69           |
| Median, h                   | 14.3         | 37.4        | -9.2           |
| Width at half altitude      | 58           | 91          | 72             |
where \( t_i \) is the difference between the predicted ICME arrival time and the values from the ICME catalogs for the \( i \)th event and \( N \) is the number of analyzed events.

In [16], an analysis of predictions for 2013–2018 performed by various groups of scientists using different online models is presented. Comparison of the results obtained with the WSA-ENLIL+Cone and DBM models with our results is shown in Table 5. In Table 5, we also compare our results with the final results from [25], which considered 25 events that occurred in 2013–2014. Of these 25 events, 9 CMEs recorded in the coronagraph did not reach the Earth, therefore, the prediction accuracy can be estimated only for 16 events. Although in the papers selected for comparison, another time interval is investigated, however, this is of interest to us, since either the results of online prediction [16] or using the DBM model [25] are described. This last paper also gives the errors in predicting the ICME velocity: the spread of errors in the observed ICME velocity value and the predicted one, and \( \langle dv \rangle \) (km/s) is the average deviation of the observed ICME velocity from the predicted values.

In the future, we plan to perform a separate analysis of events with large prediction errors to understand when this happens and how we can improve our prediction system for such events.

### CONCLUSIONS

In the paper, we analyzed the possibility of joint use of the model of quasi-stationary solar wind streams, which exists at the Space Weather Forecast Center of the Skobeltsyn Institute of Nuclear Physics of the Moscow State University, with the model for predicting the velocity and time of the ICME arrival in near-Earth orbit. A simple DBM model based on the interaction of the ejection with the ambient solar wind was chosen as the CME propagation model. The prediction was carried out on the basis of CME parameters from the CACTus and SEEDS databases for ICME
events from the Richardson & Cane and the GMU CME List catalogs for 2010–2011, the growth period of the 24th solar cycle. Comparison of the obtained results of the prediction of the arrival time and velocity of the ICME in near-Earth orbit with the ICME databases showed that the use of the CME parameters from the CACTus database as the input parameters of the DBM model allows one, on average, to obtain smaller prediction errors. Best of all, the normal distribution approximates the histogram of deviations of the observed ICME arrival time from the predicted one for set 1 (from the CACTus database): determination coefficient R2, in this case, is the largest, and the root-mean-square error is the smallest; the median value is equal to 14.2 h, and the distribution width at half maximum is 58 h. For set 3 (SEEDS_acc), the median value is closer to zero (−9), but the distribution is flatter; the width at half maximum is 73 h. The distribution of CME arrival time errors for set 2 (recalculation from the SEEDS database without taking into account acceleration) shows the worst approximation parameters: the median value is far from zero, and the distribution width at half maximum is 1.6 times greater than for set 1.

The calculated prediction errors using the CACTus database are comparable with the results obtained by other models without using the data from the STEREO spacecraft, the data of which made it possible to obtain a better ICME prediction due to the possibility of CME stereo observation in 2010–2012. In the future, it is also planned to compare the prediction results for the entire 24th solar cycle in order to determine the quality of the prediction at different phases of the solar cycle and understand which CACTus or SEEDS CME database providing online data is best used for predicting the Drag-Based ICME model.

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