Astronomical and Astrophysical Transactions (*AApTr*), 2019, Vol. 31, Issue 3, pp. 379–388,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

On a method to forecast the registration time of a Coronal Mass Ejection with a coronagraph

O.A. Sheiner*, V.M. Fridman

Radiophysical Research Institute, Nizhny Novgorod State University, Nizhny Novgorod, Russia

We present an algorithm and a short-term forecasting procedure developed on the basis of a statistical analysis of the solar radio emission regularities observed before the "isolated" solar Coronal Mass Ejections registered in 1989, 2009–2013.

Keywords: Sun: coronal mass ejections (CMEs), radio radiation

1 Introduction

It is known that CMEs are characterized by powerful radiation in a wide range of electromagnetic waves, the generation of accelerated charged particles, the formation of shock waves in interplanetary space (Webb et al. 2012). These factors cause many disturbances in the environment. So, perturbations in the magnetosphere and the ionosphere of the Earth, generated by the phenomena of CME, lead to disruptions in the functioning of orientation systems, communications, a number of instruments on board space vehicles, cause numerous disruptions in the work of communication, navigation, tracking and warning on the Earth, can lead to extreme situations in large energy systems, acceleration of corrosion processes in oil and gas pipelines, and also affect weather-forming processes and human health (see, for example, Chumakov 2004, Pulkkinen et al. 2017, Breus et al. 2016, Gal'perin et al. 2001, Libo et al. 2011, Kutiev et al. 2013, Kumar et al. 2010, Tsagouri et al. 2017).

The possibility of preparing and creating measures to protect against natural anomalies and the geo-effective effects of such events in near-earth and terrestrial processes and in many areas of human activity is an actual task of modern science, determined by the CME's forecasting period.

Most of the published work on the CME's forecasting relates to the problem of determining the possible geo-effectiveness of coronal ejections (see for example, Gopalswamy et al. 2007, Dumbović et al. 2015, Scolini et al. 2018), whereas the various algorithms for predicting the fact of the coronal ejection are rather small.

Thus, it is known (Falconer et al. 2008) that for the development of the forecast algorithm for the appearance of coronal mass ejections in the active region, the total

*Email: rfj@nirfi.unn.ru

non-potentiality of the magnetic fields of the active region along the neutral magnetic field line is used during their measurements on a vector-magnetograph. The method of the training algorithm is adapted to develop the CME forecasting algorithm (Qahwaji et al. 2008), using a time comparison of flares in the X-ray range of X and M classes (during time interval of ±150 mins) about maximum of flares. Based on the analysis of eruptive fibers/prominences using neural networks (Omari et al. 2010), the possibility of a CME prediction is also shown.

The advantage of the presented method of forecasting the time of registration of coronal mass ejection is the use of solar microwave radiation data obtained during terrestrial round-the-clock monitoring. This is due to their presence in real time on the Internet and the possibility of applying them with comparatively simple improvements in the methods of processing available information.

2 Description of the forecasting method

The concept of solar coronal mass ejections (CME) as a global phenomenon of solar activity caused by global magneto hydrodynamic processes is generally accepted (Schmieder et al. 2015, Pariat et al. 2017). In this case, the processes accompanying the generation and initial distribution of CMEs occur in different ranges of solar radiation.

The authors have previously shown that the use of radio astronomy data both for identifying the features of the CME and for developing methods for predicting the parameters of CMEs is convenient and promising (Fridman and Sheiner 2009). Actually, the spectral measurements of solar radio emission cover all the heights of the solar atmosphere; the sensitivity and accuracy of measurements allow the recording of even small changes in energy. The registration of radio emission is provided by practically all-weather ground-based observations, and the relatively low cost of obtaining the relevant information is due to the developed and implemented monitoring system of observations (https://www.ngdc.noaa.gov/stp/solar/solarradio.html). Thus, the long-term duration of observations and accumulated material allow us to determine the task of developing methods and methods for determining certain parameters of CMEs and predicting them.

The proposed method, as a method based on empirical data, is a classic combination of a point-based prediction method, when it is indicated whether an event occurs or not, and probabilistic, since the time interval for recording the event is determined.

By its structure, the method is based on an identification scheme, the simplest version of which is the synoptic diagram, when, according to the prehistory, the training sample determines the combination of characteristics that most often preceded the predicted event, which allows us to predict the presence of an event at a certain time interval (Vapnik 1979).

As indicated above, the initial manifestations of solar activity that preceded the phenomena of CME, based on magneto hydrodynamic representations, has spatial scales that cover a significant part of the Sun. That is why the method for predicting the time of CME registration involves procedures that reflect the dynamics of processes on the Sun for a sufficiently long period, at significant time scales (2–3 days), defined as the short-term forecast interval. Whereas with the further development of

activity, the formation of the sources of the CME is concentrated in separate active regions, and the processes that occur are reflected in the features of their spectral composition. This defines the use of a set of several steps in the implementation of the proposed method of forecasting.

The importance of such a forecast is determined by the fact that, on the one hand, it can be served as an alert (indicator) to the intervals of increased attention in observing CME events and their dynamics in the near-earth space with the usage of coronagraphs mounted on space vehicles. On the other hand, this method expands the possibilities of applying methods for assessing the geoeffectiveness of CME events by increasing the time interval for such assessments and precautionary preventive measures of geoeffectiveness of CME.

An analysis of the data of microwave radiation formed in the lower layers of the solar atmosphere is an effective method for identifying features associated with processes already at the stage of formation and initial propagation of CME. The necessary monitoring makes it possible to identify the features of the pre-eruption evolution of CMEs (the evolution of the coronal magnetic topology before destabilization) and their generation. It should be noted that in the development of the forecast method, reliance was made on the totality of all available data on solar radiation obtained by different methods on different instruments, including those not intended for solving forecast problems (Fridman and Sheiner 2017). Let us also emphasize that since the data of monitoring observations by the World Solar Service have been used to fully develop the method, this increases the practical possibilities of implementing the method.

3 Data

A general analysis of the features of the time and spectral dynamics of solar radiation in the microwave range to develop an algorithm for the proposed method for predicting coronal mass ejections was carried out according to the data of the World Solar Service in the radio range for the period 1998–2005. Original data of the Sun Radio Service from the radio astronomy station NIRFI "Zimenki" have also been used; the number of considered periods was 438.

Algorithm and scheme of short-term forecasting of CMEs are developed on the basis of the statistical analysis of the regularities of solar radio emission observed before the registration of "isolated" Coronal Mass Ejections. "Isolated" coronal mass ejections are the events that satisfy the following conditions: the nearest time emissions are not recorded for at least 8 hours before and 6 hours after the event in question. This is due to the fact that the data of the World Solar Service in the considered frequency range were obtained with the help of radio telescopes without spatial resolution. Therefore, it was necessary to be sure that within the considered time interval only one fully defined CME is registered in the coronagraph's field of view, and then the changes in the radio emission observed without spatial resolution will mainly correspond to the activity associated with the formation of the considered coronal ejection.

On the basis of the proposed algorithm according to the established procedure for the development of methods of prediction examination sample analysis of the

data set of The World Solar service and the Catalogues of coronal mass ejections for the periods 1989, 2009–2013 has been carried out (the total number of the periods reviewed is 898).

The data of solar radio emission, obtained during the periods of CME events in radio astronomy observatories, included in the World Service of the Sun (frequency interval of observations from 410 to 15 400 MHz) were analysed. In the analysis, the following characteristics of the radio bursts were taken into account: their intensity I and the duration T of the sporadic component.

Information about the time of coronal mass ejection appearance in the coronagraph' field of view, and the phenomenological type of the event were taken from the catalogues of Coronal Mass Ejections recorded on space vehicles SMM (Burkepile and Cyr 1993), SOHO (https://cdaw.gsfc.nasa.gov/CMElist) and STEREO (https://cor1.gsfc.nasa.gov/catalog). In addition, the data on the position of X-ray and H_α flares on the solar disk were taken into account in order to determine possible sources of radio emission from precursors of coronal mass ejections (http://www.wdcb.ru/stp/data/SolarFlareEvents/FlXXIV.txt and http://www.wdcb.ru/stp/data/FLXXIII.txt).

4 An example of a complete forecast cycle

We give an example of a full cycle of predicting the time of recording solar coronal mass ejections according to the proposed forecasting method for CME event from the examination sample: August 12, 1989. Data on the characteristics of CME are taken from the SMM catalogue. Herewith the loop-type CME was considered as a brighter and faster coronal emission structure, coronal ejection was recorded at the coronagraph at $12:59 \div 14:32$ UT.

5 The first step of the procedure

Earlier, with the participation of the authors of this paper, it has been established (Snegirev et al. 2011) that 2–3 days before a powerful flare there is an observed increase in the amplitude of long-period ($\geq$ 20 min) quasiperiodic pulsations of microwave solar radio emission exceeding two or more times the characteristic level of the non-flare period. This effect takes place at a stage characterized by the appearance of instabilities manifested in wave and fluctuating movements in complexes of activity occupying large parts of the surface of the sun. A decrease in the level of long-period pulsations after the flare event was also recorded. The verification of the events included in the data array used to develop the powerful flare prediction method showed that, when it was possible to compare them with CME data at various phases of the eleven-year solar cycle, flares were associated with CME events.

This fact was the starting point for creating the first step of the algorithm of the considered method of predicting the time of recording solar coronal mass ejections. When considering the events included in our analysis, the effect of increasing the amplitude of long-period ($\geq$20 min) quasiperiodic pulsations of microwave solar radio emission was established for all events of CMEs classified as “loop”, “partial

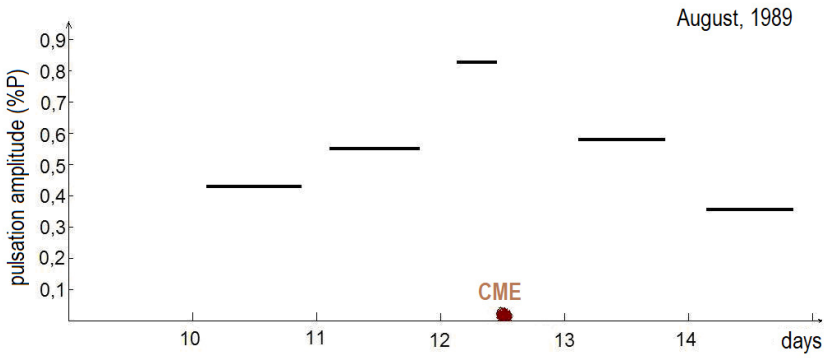


Figure 1 Dynamics of the amplitude of long-period pulsations of solar radio emission at a wavelength of 3 cm before the event of the CME on August 12.

halo" and "halo". At the stage of analysis of wave and fluctuating motions in the activity complexes, one can use the monitoring data of the Sun Service stations (or one of them, taken as the base one) at one wavelength of observations of the radio emission flux from the entire Sun in the form of a time recording (with a resolution of $\leq$1 min) at fixed frequencies of the short-wave part of the microwave range (from 10 to 3 GHz) with a duration equal to the observational session (but not less than 3 hours), which constituted a set of measurement data (set of sessions). Usually, one day of observation is meant as a session. For this CME event on August 12, 1989, 12:59 UT solar radio emission at a wavelength of 3 cm was analyzed in the period from August 09 to August 14, 1989. The current averaging of data for a session with constant averaging $\tau \approx 10$ min was carried out. Thus, only long-period components ($\geq$20 min) of quasi-periodic variations (pulsations) of the radio emission flux were present in the obtained record. Figure 1 shows the dynamics of the amplitude of long-period pulsations of the microwave radiation of the Sun before the event of the CME on August 12, 1989.

The set of considered materials shows that there is an increase in the amplitude of the level of long-period variations of the flux by a factor of 2, at least 24 hours before the registration of the CME, while there is a distribution showing that this growth begins to be observed 2 days before the event.

We note that the decrease in the level of long-period pulsations after the registration of the CME has also been fixed. However, this effect is presented in a small number of events, and it cannot be included in the first step of the prediction procedure. "If the average value of long-period quasiperiodic variations in the radio emission flux expressed as a percentage of the total solar radio flux in a given session is 2 or more times higher than the same average value in the initial session, the forecast is made for the implementation of the CME registration by the coronagraph at its location in 24 to 48 hours."

6 The second step of the procedure

The starting point for the creation of the second step of the procedure for the method for predicting the time of recording solar coronal mass ejections is the spectral investigation of the solar microwave radiation. This led to the detection of a narrow-band radiation component in solar microwave radiation during observations of individual active regions on RT-22CRAO using spectrographs 8–12 and 13–17 GHz (Levin et al. 1989; Levin et al. 1994). It is important to emphasize that such phenomena in the radio range occur at the same characteristic times (several hours) as structural changes in magnetic fields (Zhang et al. 2008; Ugarte-Urra et al. 2007; Chifor et al. 2006). Theoretical calculations confirm the possibility of the appearance of such structures with a band $\Delta f \leq 1$ MHz, as reflections of the topology and dynamics of the emerging magnetic field in the active region, as a process directly preceding the formation of CMEs (Zlotnik and Sheiner 1994; Zlotnik et al. 2007a, 2007b).

Examination of the available set of material from the world's solar service stations and the CME catalogues for the examination sample confirmed earlier results, including the time limits for the appearance of such narrow-band structures, which are 8–3 hours before the CME event is recorded on the coronagraph. Note that at certain times in the radiation, it is possible to detect narrowband structures associated with sporadic microwave bursts lasting several tens of seconds, whereas narrow-band radiation structures associated with changes in magnetic fields in the CME source are stable over the spectrum and in time. For the chosen event of coronal mass ejection on August 12, 1989, as an illustration of the second step of the CME prediction procedure, the data of high-precision spectral measurements carried out in the Crimean Astrophysical Observatory on the RT-22 radio telescope were examined using a spectrograph of the range 14–17 GHz and a spectral resolution of 100 MHz. There was monitoring of radio emission of the local area AR NOAA/USAF 5638 (S18W90), and current (1 time per second) and averaged (per minute) data of the radio emission spectrum in the above spectral range were recorded. The records of radio emission spectra for the CME event on August 12, 1989, are shown in Fig. 2.

About 5 hours before the CME registration, the spectral characteristic begins to appear in the right part of the spectral profile in the region of the Central frequency 15.5 GHz. It is less than 10 % of the total active area flux, and the bandwidth is about 100–150 MHz in the spectral range, the structure is stable in time. When the time of coronal mass ejection registration approaches, its amplitude increases for 2.5 hours before this moment, the flux characteristics are about 1 sfu, and the spectral interval varies from 200 to 400 MHz.

Thus, in order to clarify the time of CME recording, spectral changes in the intensity of the microwave radio emission from the sun obtained from the spectrograph records in the microwave band (8–17 GHz) of solar radiation intensity spectra with a frequency resolution $\leq$ 100 MHz are used. From these records the presence of a narrow-band ($\Delta f \ll$ the general band of the analyzed spectrum) spectral structure in radiation is determined for each consecutive time, the intensity of which is greater up to 10% of the average intensity of the radio emission in the spectrum. At the same time, if the narrow-band structure of the spectrum is maintained for at least 1 hour, it is concluded that the CME will be registered within the next 8–3 hours.

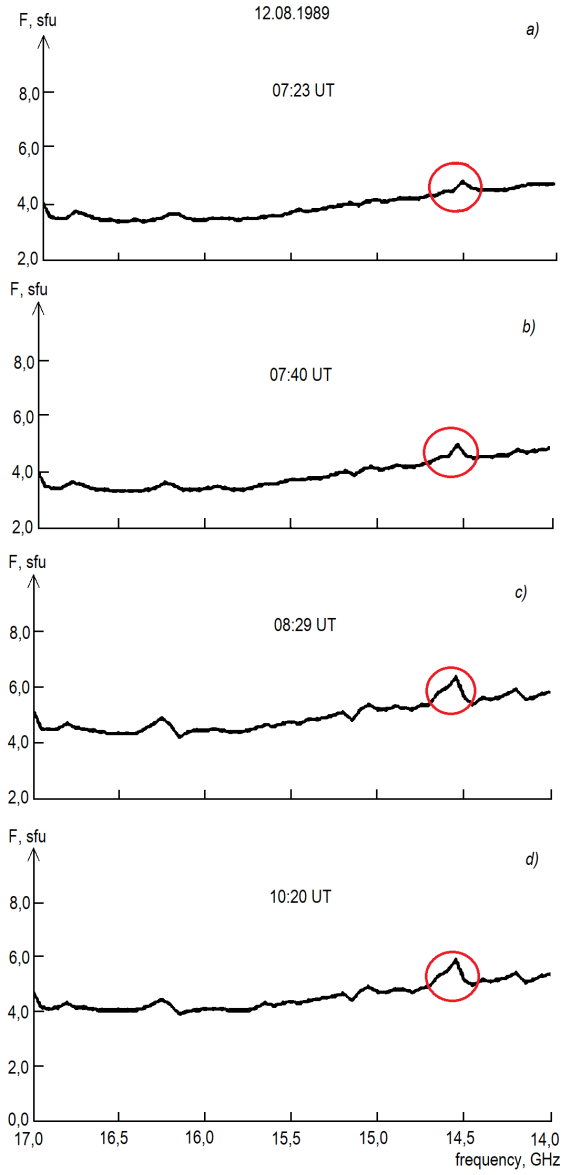


Figure 2 Radio emission spectra of active region AR NOAA/USAF 5638 on August 12, 1989 at fixed moments before coronal mass ejection registration.

7 The third step of the prediction procedure

Previous studies have led to the discovery of the phenomenon of "radio precursors" (Sheiner and Fridman 2010). It was shown that a significant number of CMEs during a two-hour interval prior to their registration on the coronagraph is preceded by sporadic radio emission, which can thus be defined as radio precursors of coronal mass ejections.

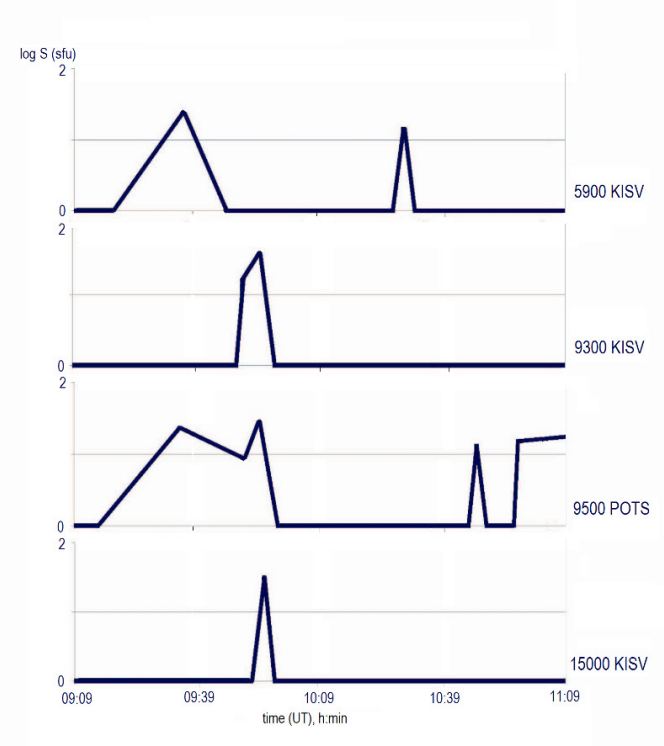


Figure 3 Schematic time profiles of solar radio emission flux before CME registration on August 12, 1989.

This phenomenon was used to form the next step in the prognosis procedure in order to achieve sufficient accuracy of the forecasting time for recording the phenomenon of CME. For this purpose, the data of the Sun Service stations of the radio emission fluxes from the entire Sun in the microwave range (400 MHz–15 GHz), available on the Internet in the form of a temporary recording of radio emission or spectrograms in real time, are compared with the data of the CME catalogues. In analyzing the material under consideration, it was found that when a sporadic radio emission of various types (the radio precursors of CMEs in the form of pulsed, gradual or a series of low intensity bursts, with a duration ≥ 3 min and a value of at least 1–3 units of the solar radiation flux against the background of the total flux), occurs simultaneously and in a significant part of the microwave radiation range (which is characteristic for the local active region of the CME formation), CME event is recorded at the interval ≤ 200 min on the coronagraph. Such dependence shows, in our opinion, the formation and initial extension of CMEs in the lower layers of the solar atmosphere. In Fig. 3, for the event selected to illustrate the scheme for predicting procedure (August 12, 1989), we show the time changes in the radio emission flux S as schematic profiles of solar radio flux records for various solar service stations with a spectral range of observations from 6 to 15 GHz.

On the right-hand side, the observation frequency in megahertz is shown along with the abbreviated name of the corresponding observatory (radio emission data

of the World Sun Service), and on the left-hand side, the values of the fluxes on a logarithmic scale. The method used for visual data representation is described in detail in catalogs (Durasova et al. 2003, Durasova et al. 2004).

At least 3 hours prior to the registration of the CME type Loop on the coronagraph SMM (or 2 hours before the CME type Cloud), a broadband sporadic phenomenon is observed in the analyzed part of the microwave range.

Thereby, for the final correction of the CME registration time in the coronagraph, the current wide-range data of the radio emission fluxes from the entire Sun in the microwave range (400 MHz–15 GHz) are used. When the phenomena of sporadic radio emission of various types occur and exist simultaneously in a significant part of the microwave radiation range, duration $\geq$ 3 min and a value of at least 1–3 solar units of the radio emission flux, conclude that the coronal mass ejection will be registered in a time interval of up to 200 minutes.

Conclusions

On the basis of the proposed algorithm, the analysis of the examination sample of the data set world Solar service and the Catalogues of coronal mass ejections for the periods 1989, 2009–2013 was carried out. It is shown by the example of the CME event 12.08.89, the complex set of prediction steps, including continuous analysis of time and spectral features of solar radio emission over a long time interval provides a forecast of the time of registration of coronal mass ejection.

The method of short-term prediction of the registration time of the phenomenon of coronal mass ejection (CME), including the steps listed above, received the state registration (Fridman and Sheiner 2017).

References

Breus T.K., Binhi V.N., Petrukovich A.A. (2016) Physics-Uspekhi, 59, 502.

Burkepile J.T., Cyr O.C.St. (1993) A revised and expanded catalogue of mass ejections observed by the Solar Maximum Mission coronagraph, NCAR Tech. Note NCAR/TN-369+STR, Natl. Cent. for Atmos. Res., Boulder, Colo.

Chifor C., Mason H.E., Tripathi D., Isobe H., Asai A. (2006) Astron. Astrophys., 458. 965.

Chumakov A.I. (2004) The effect of cosmic radiation on integrated circuits. M.– Radio and communication.– 320p. (in Russian)

Dumbović M., Devos A., Vršnak B. et al. (2015) Solar Phys., 290, 579.

Durasova M.S., Tikhomirov Yu.V., Fridman V.M., Sheiner O.A. (2003) Catalog of solar-activity phenomena preceding coronal mass ejections on the basis of the 1998 data of the World Sun Service in the radio-frequency range. Nizhny Novgorod – NIRFI. –120p. (in Russian).

Durasova M.S., Tikhomirov Yu.V., Fridman V.M., Sheiner O.A. (2004) Catalog of solar-activity phenomena preceding coronal mass ejections on the basis of the 2003 data of the World Sun Service in the radio-frequency range. Nizhny Novgorod – NIRFI. –120p. (in Russian).

Falconer D.A., Moore R.I., Gary G.A. (2008) Astroph. J., 689, 1433.
Fridman V., Sheiner O. (2017) in: Space Weather of the Heliosphere: Processes and Forecasts (IAU Symp,. 335), C. Foullon and O.E. Malandraki, eds, Cambridge University Press, p. 321.
Fridman V.M., Sheiner O.A. (2009) Geomagn. Aeron., 49, 1133
Fridman V.M., Shejner O.A. (2017) Invention RU 2630535C1, Bull. Inv.
Gal'perin Yu.I., Dmitriev A.V., Zelenyi L.M., Panasyuk M.I. (2001) Polyot, 3, 27 (in Russian).
Gopalswamy N., Yashiro S., Akiyama S. (2007) J. Geophys. Res., 112, A06112.
Kumar P., Uddin W., Taor, A., Ramesh C., Shuchi B. (2010) Indian J. Radio Space Phys., 39, 290.
Kutiev I., Tsagouri I., Perrone L., et al. (2013) J. Space Weather Space Clim., 3. A06.
Levin B.N., Fridman V.M., Sheiner O.A. (1989) Izv. Vyssh. Uchebn. Zaved. Radiofiz., 32, 516.
Levin B.N., Fridman V.M., Sheiner O.A. (1994) Astrophys. J. Suppl., 90, 713.
Libo L., WeiXing W., YiDing Ch., HuiJun L. (2011) Chinese Science Bulletin, 556, 1202.
Omari M.Al., Qahwaji R., Colak T., Ipson S. (2010) Solar Phys. 262, 511.
Pariat E., Leake J.E., Valori G. et al (2017) Astron. Astrophys, 601, A125.
Pulkkinen A., Bernabeu E., Thomson A. et al. (2017) Space Weather, 15, 828.
Qahwaji R., Colak T., Omari M.Al., Ipson S. (2008) Solar Phys., 248, 471.
Schmieder B., Aulanier G., Vršnak B. (2015) Solar Phys., 290, 3457.
Scolini C, Messerotti M., Poedts S., Rodriguez L. (2018) J. Space Weather Space Clim, 8, A09.
Sheiner O.A., Fridman V.M. (2010) Radiophys. Quant. Electronics, 53, 281.
Snegirev S.D., Fridman V.M., Shejner O.A. (2011) Invention RU 2 419 821 C1, Bull. Inv. 15.
Tsagouri I., Galkin I., Asikainen T. (2017) Advan. Space Res., 59, 351.
Ugarte-Urra I., Warren H.P., Winebarger A.R. (2007) Astrophys. J., 662. 1293.
Vapnik V.N. (1979) Recovery of dependencies on empirical data. M. – Fizmatgiz – p.448 (in Russian).
Webb D.F., Howard T.A. (2012) Living Rev. Sol. Phys 9, 3.
Zhang Y., Zhang M., Zhang H. (2008) Solar Phys., 250, 75.
Zlotnik E.Ya., Kaltman T.I., Sheiner O.A. (2007a) Astron. Letters, 33, 168.
Zlotnik E.Ya., Kaltman T.I., Sheiner O.A. (2007b) Astron. Letters, 33, 327.
Zlotnik E.Ya., Sheiner O.A. (1994) Space Sci. Rev., 68, 225.