Wrocław, February 12, 2021

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Review of the PhD Thesis

Author: **Anitha Ravishankar**
Author's affiliation: **Astronomical Observatory of the Jagiellonian University**
Title: **"Study of coronal mass ejections (CMEs) using STEREO and SOHO observations"**
Supervisor: **dr hab. prof. UJ. Grzegorz Michałek**

The reviewed thesis was written by Anitha Ravishankar, who obtained Master of Sciences diploma in 2016 at the Faculty of Physics at Christ University, Bangalore, India. After that time, she was a PhD student at the Faculty of Physics, Astronomy and Applied Computer Science of the Jagiellonian University.

The main purpose of the reviewed doctoral dissertation by Ms. Anitha Ravishankar is the analysis of the kinematics of Coronal Mass Ejections (CMEs) during their propagation in the Solar System and near the Earth. This analysis was performed using observations from orbital solar observatories. In the case of phenomena propagating towards the Earth (halo CME), energetic particles and the magnetic field contained in CMEs interact with the magnetosphere and the upper atmosphere of the Earth, causing various types of phenomena, including geomagnetic storms that sometimes have a negative impact, e.g. on the operation of artificial satellites of the Earth or causing telecommunications disruptions. These phenomena shape the so-called space weather, which depends mainly on the level of solar activity. The study of space weather is extremely important because it determines the functioning of radio communication, energy networks, and electronic systems in space. It may also be related to other phenomena on Earth, for example to the climate, that are not yet thoroughly known and understood. Therefore, the research presented in this dissertation is important for a better understanding of the mechanisms of the interaction of the cosmos, including the Sun, with the Earth, and may contribute to development of methods of forecasting the state of space weather and its impact on the Earth.

This dissertation is written in English, consists of 4 published articles and a short introduction containing: a) description of the current state of knowledge about CMEs and space weather, b) a guide to the main results of the publications included in the dissertation, c) general conclusions of the whole dissertation and d) list of references. The dissertation is also supplemented with a list of abbreviations. I consider the layout of the doctoral dissertation and the order of chapters appropriate and the dissertation itself constitutes a logical and closed whole. However, I believe that a chapter introducing the subject and presenting the general state of knowledge could be more comprehensive. The same remark applies to the chapter describing the final conclusions, which, although each published work contains its main results, could be more comprehensive, contain a more accurate summary of the results of the entire doctoral dissertation and proposed future directions or research methods that could further enhance our knowledge about CMEs, SEPs (solar energetic particles) and their impact on the Earth and its surroundings.

All publications included in the PhD thesis were published in highly-impacted refereed scientific journals (Astronomy & Astrophysics, Solar Physics) and Ms. Anitha Ravishankar is the first author in each of them. The other co-authors of the papers provided statements, which show that the involvement of her in the preparation of these articles is 70% for 3 publications and 60% for one of them. I believe that this is a significant contribution and shows that it was the PhD student who was the main person in charge of the work contained in the attached publications. All 4 articles were cited (with self-citations) totally 3 times. The small number of citations may be due to the relatively recent publication dates

The PhD thesis of Ms. Anitha Ravishankar is thematically homogeneous and begins with the presentation of the current state of knowledge related to the study of CMEs and SEPs. This chapter, while fairly short, provides basic information about CMEs, the two types of SEPs, and the relationship between them. In this chapter, she also highlights some issues related to these phenomena that have not been well investigated so far and require additional analyzes or observations. It is worth praising the fact that in the description of the current state of knowledge, the PhD student cites many already published articles, the list of which fits well the subject of this thesis. This chapter ends with a short but sufficient description of the instruments from which the observational data used in this dissertation were obtained.

The four published papers (P1 – P4) are the most important component of the PhD dissertation, and each of them contains an analysis of research issues related to the propagation of CMEs and their impact on associated SEPs phenomena in the heliosphere, including an analysis of these phenomena in the vicinity of the Earth orbit. The first paper (P1) entitled "Estimation of Arrival Time of Coronal Mass Ejections in the Vicinity of the Earth Using SOlar and Heliospheric Observatory and Solar TErrestrial RElations Observatory Observations" focuses on determining the CMEs arrival time. For this purpose, observations of 51 halo CMEs or partial-halo CMEs were analyzed. These observations were made mainly by both STEREO satellites, which were in near quadrature configurations with respect to the Earth position. Such configuration of the satellites allowed to observe halo CMEs from a direction perpendicular to the mean plane along which they propagate. This makes possible to more accurately determine the true radial velocity for the CMEs halo due to the negligible projection effect. Unlike the STEREO mission, the orbital location of the SOHO satellite causes the CMEs velocities determined from its observation were highly influenced by the projection effect. The in-situ observations necessary to determine the travel time (TT) of ICMEs were obtained with the Advanced Composition Explorer (ACE) mission. The main and innovative result of this work is the development of a better method of modeling the TT of CMEs, characterized by a smaller maximum error, which is 29 hours. Previous modelling techniques of the TT of CMEs to the Earth were characterized by an error of 50 hours. Reducing this error were possible mainly due to the usage of STEREO data and the use of maximum speed instead of average speed as a main parameter characterizing CMEs.

The second work (P2) entitled "Non-Interacting Coronal Mass Ejections and Solar Energetic Particles near the Quadrature Configuration of Solar TErrestrial RElations Observatory" concerns the relationship between CMEs and SEPs, taking into account two different SEP generation mechanisms. In this paper, the observations from the near-quadrature STEREO probes were used and the maximum speed of CMEs (instead of the average) was used to analyze the correlation with the intensity of SEPs. GOES-13 data in three energy channels were used to determine the intensity of SEPs. Additionally, the observations of the GOES-14 probe were used to establish the relationship between CMEs, SEPs, and solar flares observed in the soft X-ray. Totally, 25 SEP phenomena, associated CMEs and flares were analyzed during the ascending phase of the solar cycle No. 24 (2009-2013). The parameters of the analyzed phenomena are included in Table A.1 of P2. The authors of P2 analyzed, inter alia, correlations between different types of CMEs velocity and the maximum intensities of SEPs phenomena using data from two instruments, STEREO and SOHO. The analysis also showed that the acceleration mechanisms of SEPs may differ depending on the energy to which they are accelerated. The work P2 also analyzes correlations between average and maximum CME speeds, between speeds determined on the basis of data from STEREO and SOHO probes, between the position of the active regions associated with CME and CMEs speeds, and between the Mach number and the peak flux of SEPs phenomena. The most important result of the work of P2 is the achievement of smaller or larger correlations between various parameters of CMEs, SEPs and flares observed in X-rays. Noteworthy is the poor correlation between the CMEs velocity or the intensity of the SEPs, and the intensity of the X-ray flare emission. In summary, the set of these correlations is valuable, extends our information about CMEs and SEPs, and can contribute to better forecasting of the impact of active phenomena on the Earth and its surroundings.

Another paper (P3) entitled "Kinematics of Coronal Mass Ejections in the LASCO Field of View" differs from the previous ones, as it uses data from only one mission – SOHO. In addition, the set of analyzed phenomena is huge: a statistical analysis of as many as 28,894 CMEs observed in the years 1996 - 2017 was carried out. This period covers the entire solar cycle 23 and most of the cycle 24. For each phenomenon containing at least 8 height measurements, it was possible to construct the velocity profile V(r). Totally, 21,492 phenomena met this criterion. Of course, due to the projection effect, these velocities are only tangential components of the true plasma velocities in CMEs. The CMEs velocity evolution was divided into two phases: the initial phase of rapid speed increase to the maximum value, during which the plasma dynamics is controlled by the Lorentz force (initial acceleration phase) and the phase of gradual speed reduction until the solar wind speed is reached (residual acceleration phase). The determined CMEs parameters in both of these phases (acceleration, velocities, times and distances of obtaining maximum and residual velocities by CMEs) were compared with each other and some also with the data from the catalog. This comparison was made for different phases of solar cycles and divided into fast and slow CMEs. One of the more interesting results of P3 is to show that the kinematic properties of CMEs are significantly different in initial acceleration and residual acceleration phases, which is not reflected in the averaged data contained in the CMEs catalog. The values of initial and residual accelerations were also determined and compared with the results of previous publications. Another noteworthy result is the demonstration that the Lorentz force determines the dynamics of CMEs to a distance of about 6 $R_\odot$, during the first two hours of CME propagation. The abrupt decrease in the average residual acceleration during the maximum of the solar cycle 24 is another interesting result that indicates anomalies in the CMEs behavior during the cycle 24. Such anomalies may be related to the solar dynamo and their analysis may contribute to a better understanding of the mechanisms responsible for solar activity. In summary, the work of P3 brings additional information and relationships extending our view on the CMEs and their propagation in the heliosphere. It is worth to notice that the authors (including the PhD student) are aware of numerous simplifications and assumptions concerning, for example, the geometry effects, which may affect the obtained results.

The last paper (P4) entitled "Relationship Between Solar Energetic Particle Intensities and Coronal Mass Ejection Kinematics Using STEREO / SECCHI Field of View" contains a continuation of the research described in P2. In this paper the authors removed analysis of flares because of poor correlations between them and SEPs. Additionally, in order to obtain a higher quality of correlation, observations from only STEREO satellites were used. The aim of this research is to analyze the possibility of predicting the occurrence and intensity of CMEs and SEPs, using some already known relations, e.g. that Mach number of interplanetary shocks is an important parameter controlling the intensity of SEPs. In this study 38 halo CMEs were observed in 2009 – 2013 (ascending phase of solar cycle 24) by both STEREO satellites in their near-quadrature configuration. The CMEs phenomena that were associated with the SEPs were only selected. Similar to P2, in-situ observations were provided by the GOES-13 mission. In this work a very detailed analysis of the distributions of various parameters characterizing CMEs, SEPs and the mutual correlations between them was carried out. A good illustration of the analyzed parameters is provided in Fig. 2, which presents two examples of events with their characteristics used in the analysis. The last section of P4 (Conclusions) contains detailed discussion of the obtained results. One of the significant conclusion is the fact that Mach number is the parameter which offers higher correlation and the CME velocity alone is not enough for a detailed study. Moreover, for space weather forecasting the best CME kinematic parameter that could be used to predict SEPs is the Mach number at SEP peak flux. Another conclusion is that the kinematic studies of CMEs and SEPs can be influenced by a changeable magnetic field in Parker spiral and its disturbances. All the conclusions and results of P4 can provide a significant contribution for future development of the forecasting of space weather.

Small remarks:

1) The caption of Table 1 (paper P1) does not contain a detailed description of all the parameters presented in the table. Such description would make its content easier to read.

2) The use of term quadrature to describe the configuration of STEREO probes is not entirely legitimate due to the definition of this configuration. Quadrature is a configuration in which two celestial bodies (such as the planet, satellite, and the Sun) have an angular separation of 90 degrees as seen from the Earth. Such configuration is possible only if the solar orbit of a planet or satellite lies outside the Earth orbit. Moreover, even applying the term quadrature for STEREO-Sun-Earth configuration it's not precise to say that "The twin spacecrafts STEREO-A and -B are at approx. 90^{O} separation with respect to the Earth". The range from 80^{O} in 2010 to 150^{O} in 2013 can hardly be consider as "approximately 90^{O}" and the observations of most CMEs were obtained when STEREO satellites were not in real quadrature. Instead, the term "near-quadrature" should be rather used but e.g. in 2013 the configuration of satellites was far even from the near-quadrature. Was the effect of projection considered for CMEs observed be STEREO being far from the quadrature?

3) In P1 in Sect. 4 (Summary and Discussion), page 19 of 21, last line: I think Figure 4a is not correct here, maybe should be replaced e.g. by 6a, b?

4) Too small descriptions of axes in some plots, especially in P2 and P4.

5) Acronym DH is not defined.

Final conclusion

Summing up the whole review, it can be concluded that Ms. Anitha Ravishankar has done a huge and important work contributing to a better understanding of the kinematics of CMEs and associated SEPs. In 4 articles included in this dissertation, PhD student demonstrates the knowledge of the analysis and interpretation methods of observational data from two solar orbiting observatories - SOHO and STEREO. The PhD student has done a great work analyzing a large data sets and finding various correlations between the CMEs and SEPs parameters. The PhD dissertation of the Ms. Anitha Ravishankar also shows her knowledge on the publications related to the PhD topic and that she is aware of the state of knowledge in this topic. She could also find mutual relations between various parameters describing phenomena and on the basis of them formulate conclusions. The presented dissertation is an original and innovative solution to a scientific problem and significantly enriches our knowledge about CMEs and associated SEPs. The results of this research may accelerate work on the possibility of predicting the state of space weather and its impact on the Earth. This applies in particular to predicting the intensity of energetic particles emitted from the Sun during eruptive processes and determining the magnitude of their influence on various areas of our life. In this dissertation, Ms. Anitha Ravishankar showed that she had mastered general theoretical knowledge in the field of her research and that she had the ability to conduct scientific work. All attached papers have a clear research purpose, appropriate methodology, presents valuable research results and contribute to problems related with space weather and its forecasting.

Therefore, I declare that the PhD thesis of the Ms. Anitha Ravishankar meets all formal and customary requirements for the doctoral dissertations and I am applying for admission of Ms. Anitha Ravishankar to the following stages of the PhD procedure.

Arkadiusz Berlicki