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Report on

Ms. Anita Ravishankar's PhD thesis

entitled

**Study of coronal mass ejections (CMEs)
using STEREO and SOHO observations**

1 General characteristic of the thesis

The reviewed dissertation is written in English, and it contains the list of publications and used acronyms as well as the table of contents, the description of four original papers and the papers them self. This thesis is logically structured with all chapters clearly linked with each other. The adopted methods and techniques are well described in the attached 4 original papers which have been published in prestigious journals: 1 in Solar Physics

and 3 in Astronomy and Astrophysics. The name of the PhD student is standing on the first place of the lists of authors of these papers. All of these papers are co-authored with the PhD student's adviser, Prof. Grzegorz Michalek, who is the world-known expert in the field undertaken by Ms. Ravishankar. Three papers are co-authored only with the adviser, and one is published with the third name.

The PhD thesis presents new and original results on analytical investigations of the observational data of coronal mass ejections (CMEs). The presented results are important for the diagnostics of CME's arrival time and are in the mainstream of current research efforts in the field of space weather.

In summary, the scientific contents correspond to the required for a PhD thesis.

2 Substantive characteristic of the thesis

The PhD thesis is associated with space weather forecast. The latter is essentially determined by the phenomena originating at the Sun such as CMEs which produce solar energetic particles (SEPs) and interplanetary shocks.

Among four papers included in the doctoral dissertation, three of them focus on the important issues concerning CMEs and space weather and one paper presents the variation of kinematics of CMEs during solar cycles 23 and 24. Using the data of SOHO and STEREO, with the help of GOES-13, the kinematics of CMEs is presented and the relationship between CMEs and the associated SEPs is showed. The obtained original results could be very useful for space weather forecasting.

2.1 Characteristic of the first paper

The first paper aims at estimation of arrival time of CMEs to the Earth. This estimation is one of the most important parameters in determining space weather. The data from SOHO/LASCO and STEREO/SECCHI is used during the ascending phase of solar cycle 24, taking place in between 2009-2013, to obtain the best indicator for prediction of the arrival time of CMEs. The main finding of this paper is to show that maximum velocity of a CME leads to a better accuracy than previous models that are based on instantaneous speed.

2.2 Characteristic of the second paper

The second paper deals with the relationship between the three most intense solar transients, i.e., the solar flares, CMEs, and SEPs. It is commonly known that the latter are essentially generated by two phenomena: (a) solar flares which are triggered by magnetic reconnection and (b) strong shocks associated with CMEs. These SEPs events are of particular interest as their abundance can result in a number of hazardous phenomena such as severe damage in electronics of satellites in space and in electric power grids on the ground. In this paper, the studies on correlation between CMEs speeds and SEPs are extended and this correlation, by using the maximum speeds of CMEs is confirmed.

2.3 Characteristic of the third paper

A statistical study of the kinematics of a number of CMEs, recorded by SOHO/LASCO spacecraft from 1996 until mid-2017, is conducted. The results obtained in this article revealed that the initial acceleration phase is characterized by a rapid increase in CME velocity just after its eruption in the inner corona. This phase is followed by a phase of an almost constant speed of the CME. It is showed that the significant driving Lorentz force

can operate up to a distance of about $6 R_{\odot}$ from the Sun during the first 2 hours of the CME propagation. Additionally, it is found that the considered parameters, such as initial acceleration, maximum velocity and time, at which the maximum velocity is reached, mostly vary with solar cycles and with the intensities of the individual cycle.

2.4 Characteristic of the fourth paper

It was further investigated whether a better parameter, such as instantaneous Mach number, could lead to a higher correlation between SEPs peak intensities and CME speeds. The detailed analysis of 38 non-interacting halo and partial halo CMEs, as observed by SOHO/LASCO, is made. Using the data from STEREO/SECCHI images several kinematic parameters and instantaneous speeds of the CMEs are determined. This analysis leads to the conclusion that SEPs events originating at western limb are well correlated with the maximum of CMEs speeds, while those at eastern limb are anti-correlated. Of the two parameters studied, the Mach number offers higher correlation.

Instantaneous CMEs kinematic parameters such as their maximum speeds, maximum Mach numbers and speeds as well as Mach numbers at SEPs peak fluxes versus SEPs peak fluxes are investigated. Highly positive correlation is observed for Mach number at SEPs peak flux for all events. Additionally, a delay in time and distance between CME, SEP and shock parameters are estimated, and that increase in this delay when SEPs reach peak flux with respect to CME onset, as moving from western to eastern limb, is reported.

2.5 The main findings of the thesis

The most important findings reported in the thesis are:

1. the maximum speed is used to estimate the CME arrival time to show that this speed leads to a better agreement with the observational data

than the average speed;

2. the maximum speed provides a better correlation with intensity of SEPs than its instantaneous counterpart. Additionally, it is showed that the intensity of SEPs does not correlate well with solar flares;
3. parameters such as the maximum velocity, initial CME's acceleration, acceleration time (specified as the time at which maximum velocity is reached) vary from event to event and also with the solar cycle;
4. CME's parameters such as its maximum speed are well correlated with fluxes of solar energetic particles.

In summary, it is my pleasure to state that the results of the reviewed thesis consist the important contribution of Ms. Anita Ravishankar to the research made in the space weather prediction theory.

2.6 Remarks to the editorial side of the thesis

The thesis is well edited. A few minor issues, listed below, do not essentially reduce a high value of this dissertation. Here is the (incomplete) list of a few (minor) issues which could require rephrasing:

1. It would be illustrative to amend, e. g. in Sect. 1.2, a scheme of a typical CME with its well denoted fine structure such as the interplanetary shock, internal cavity, magnetic field lines, etc;
2. Would it be possible to compare the available CMEs data, such as arrival times, resulting from performed numerical simulations of CMEs with the reported analytical findings?;
3. There are few minor misprints and style inconsistencies which could be corrected. Here is the list of few of them:
 - p. 2, the sentence containing the phrase *were by R. C. Carrington*

should be rewritten as *were made by R. C. Carrington*;

p. 7, the sentence starting from *In this dissertation* should begin a new paragraph;

p. 11, the phrase *The model presented in this dissertation* should begin a new paragraph;

4. There is some inconsistency in terminology, e.g. "Sun", "the Sun", "Earth", "the Earth" are used interchangeably.

3 Final remarks

I recognize the PhD thesis of Ms. Anita Ravishankar as a valuable contribution into the problems associated with space weather forecast. This dissertation contains essential novel elements of observational data analysis as well as some background of modelling.

On the bases of the submitted PhD thesis I state with full enthusiasm and without any hesitation that Ms. Anita Ravishankar has revealed her academic achievements which satisfy all requirements described in the act on academic degrees and academic titles for getting the PhD degree. Ms. Anita Ravishankar is a is well-qualified researcher. Her research work is characterized by a high sense of the importance of problems solving and testify to an inquisitive PhD student.

Therefore, with a high level of certainty, I propose to admit Ms. Anita Ravishankar to the next stages of the PhD process.

Sincerely yours,

Krzysztof Murawski