Referee report

of the dissertation "Study of coronal mass ejections (CMEs) using STEREO and SOHO observations" written by Anitha Ravishankar in the Astronomical Observatory of Jagiellonian University under the supervision of dr hab. prof. UJ Grzegorz Michałek

The dissertation consists of four scientific articles preceded by a short introduction. The articles have been published in remarkable astronomical journals: Astronomy & Astrophysics (2) and Solar Physics (1) in years 2019 and 2020. The last one, accepted for publication on 15 December 2020 in Astronomy & Astrophysics, is available as a forthcoming paper at the home page of the journal and will be published in March 2021. Miss Ravishankar has been always the first author of the articles. Co-authors: Grzegorz Michałek (4) and Seji Yashiro (1) have submitted statements confirming consistently a leading contribution (60-70%) of Miss Ravishankar. The articles have been prepared in a relatively short time period, which is a good recommendation of dedication and efficiency of collaboration between the Ph.D. student and her Supervisor. Because of relatively short circulation in the scientific community, the articles have got a poor citation yet, but I am sure that it will change!

The dissertation is focussed on kinematics of solar Coronal Mass Ejections especially in context of their geoeffectiveness. This phenomenon shapes our space weather in a crucial way, namely is responsible for all heavy geomagnetic storms. Therefore, investigation of CME expansion throughout the interplanetary space needs a constant progress in observational technics as well as in managing and interpretation of possessed data. Professor Michałek has got an excellent competence to study this topic as a member of a team which has been continuously upgrading a catalog of CMEs observed with the LASCO coronagraph on board SoHO, the longest operating space coronagraph in history. Under guidance of her Supervisor, Miss Ravishankar made in her dissertation a remarkable contribution to the CME science.

In all articles a new method for determining the instantaneous velocities of investigated CMEs has been developed. For this aim, five successive height-time points for a linear fit were employed. This number of points radically smooths uncertainties of individual measurements. In this way, velocities at a given time or distance from the Sun become available, instead of average values which were usually used in statistical approaches. Detailed velocity profiles of CMEs offer an important advantage in every kind of analysis concerning their association with other solar-activity phenomena or their geoeffectiveness.

Miss Ravishankar presented the articles in her dissertation in chronological order, nevertheless I will start with the third article which contains a statistical analysis on CMEs for the largest test sample. The authors recalculated the height-time plots from the LASCO catalog with a time span from 1996 until mid-2017 obtaining velocity and acceleration time profiles for many thousands of events. A very important conclusion of the paper is that almost every CME shows similar two-stages kinematical evolution, in which the initial acceleration phase characterized by a rapid increase of velocity caused by the driving Lorentz force is followed by the residual acceleration (deceleration) phase in which a gradual decrease of velocity occurs due to the fact that the propelling force is balanced by the drag one. This kind of appearance has been reported earlier only for a limited number of examples processed in an extraordinary way (e.g. Zhang et al. 2001). Presented histograms show also how long and how far from the Sun does the Lorentz force drive the expansion of CMEs. I appreciate very much the figures presenting yearly median and average values of investigated parameters that prove that their variability mostly follows shapes and intensities of the individual solar cycles.

My doubts concern the following items. In the discussion of Fig. 10c I disagree that "*only slow CMEs can have a short distance of the initial acceleration*" and "*the faster CMEs are accelerated over larger distances*". In my opinion a scatter of V_{MAX} and R_{MAX} values justifies a traditional dichotomy (e.g. MacQueen & Fisher 1983, Andrews & Howard 2001), in which CMEs associated with flares can be fast and accelerated close to the Sun. On the other hand, CMEs associated with eruptive prominences are continuously accelerated in the whole field of view of the coronagraph. By the way, how many events show equality of maximal (V_{MAX}) and residual (V_{RES}) velocities? A sudden drop of the residual acceleration since 2009 in Fig. 5c makes me uncomfortable especially in context of the note "*that in 2010 [...] the LASCO coronagraph instrument image cadence was doubled*".

The three remaining articles have been managed with definitively less frequent sample of CMEs. The authors paid their attention on halo and partial-halo CMEs in years 2009-2013 investigating their geoeffectiveness (article 1) and their association with Solar Energetic Particles and flares (articles 2 and 4). They used interchangeably images from SoHO/LASCO and STeReO/SECCHI coronagraphs. The chosen time interval, in which the STeReO spacecrafts were in a quadrature position in relation to the Earth, allow them to record parameters of these geoeffective CMEs without uncertainties of a projection effect. Beside coronagraphic images also additional data from other satellites (ACE, GOES, WIND) have been used. Moreover, for clarity of physical interpretation only non-interacting CMEs have been considered. Altogether, the total number of investigated events dropped to several tens, between 25 and 51. The authors made a plenty of correlation diagrams between different parameters describing CMEs and associated observables and concluded the closest connection in case of the best correlation.

In the first article some estimation of arrival time of CMEs in the vicinity of the Earth has been made. By using instantaneous velocities obtained according to the images taken simultaneously by coronagraphs from two satellites (SoHO and STeReO) the authors calculated empirical formulae estimating transition times of CMEs and compared the results to real arrival times from the ACE satellite. They found that the best results were obtained for average velocities determined in the STeReO/SECCHI field of view, because they were able to reduce both, the average absolute errors and the maximum errors of transition time estimations.

In the discussion, why average velocities determined in the STeReO/SECCHI field of view do provide the best results, the authors stress an importance of the number of height–time points, citing Broniarska & Michałek (2018). In my opinion, Fig. 10 in the first article strongly supports a dependence on spatial range (field of view) of observations. In presented figures non-interacting and interacting CMes are marked with different symbols but enclosed fit formulae were calculated only for a total number of points. Does it mean that a fitting of non-interacting CMEs (open diamonds) separately does not offer any progress? The referred paper resembles to some extent the article of Michałek et al. (2004), which was followed by another one (Michałek et al. 2006) considering a connection between halo CME parameters and geomagnetic indexes. Did you try to perform a similar kind of investigation?

The second and the fourth articles can be considered as two chapters of the same topic: which of instantaneous parameters of CMEs is the best for predicting a peak flux of associated SEPs? By checking several candidates the authors found in the second article that the most significant correlation was recorded for CME velocities determined at the SEP peak fluxes. However, similar results were obtained in the case of CME Mach numbers determined at the same times. More comprehensive analysis performed in the fourth article shows a priority of this second indicator. Moreover, a complex and internally consistent picture of particle acceleration by interplanetary shocks is given including the magnetic connectivity from the Sun to the Earth as well as a flare pre-acceleration. The fourth article is also a relevant appendix to remaining articles from the dissertation by presenting illustrations, like Figs. 2 and 12, which allow us to understand better some details of a performed analysis. Very useful are tables in which many details scattered in particular figures are summarized.

Figure 3 from the second article shows that the quadrature configuration of STeReO satellites – of crucial importance for investigations performed in the first, second, and fourth articles – is abused in many cases. Actually, in 2013 a situation of STeReO satellites is closer to the conjunction rather than to the quadrature! It means that CME characteristics obtained for events that occurred after mid-2012 at least should be charged with a projection effect. For sure this perception does not undermine the conclusions presented in these articles but in my expectation de-projected values for this time-interval should even improve the investigated correlations. Did you try to do this by using, for example, the de-projection rules published by Bronarska & Michałek (2018)? Another possibility was to specify in correlation diagrams the charged points with different symbols.

Editorial activities of Miss Ravishankar, her collaborators and journal teams did not exclude completely some print mistakes. My attention paid three of them: (1) a recurrent typo in titles of Figs. 1 and 2 in the first article; (2) a recurrent error in a description of units of the Y-axis in Figs. 8 and 9 in the same article; (3) an almost polar situation of a 19 November 2013 flare in Fig. 1 of the fourth article.

In summary, the submitted dissertation proves a high quality of scientific research made by Miss Anitha Ravishankar. She submitted the four articles published in remarkable astronomical journals. Her conclusions constitute a substantial progress in our knowledge about kinematical evolution of CMEs, allow us also to understand better the association between CMEs and other solar-activity phenomena as well as their geoeffectiveness as a main driver of our space weather. My positive reception does not change a fact that some results probably will not be useful in space weather forecasting. Moreover, the Ph.D.-candidate has demonstrated the comprehensive competences, like managing and processing with a huge stream of data, good knowledge of the solar physics and the statistical analysis, logical and coherent thinking, etc.

I am glad to recommend this dissertation under the public defence.

Wrocław, February 9, 2021

Professor Michał Tomczak
Astronomical Institute,
University of Wrocław