Skoltech
Skolkovo Institute of Science and Technology

Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Galina Chikunova

PhD Program: Engineering Systems

Title of Thesis: Coronal dimmings associated with coronal mass ejections: evolution, lifetime, and relation to the directivity

Supervisor: Associate Professor Tatiana Podladchikova

Name of the Reviewer: Dr. Stefan Hofmeister

I confirm the absence of any conflict of interest (Alternatively, Reviewer can formulate a possible conflict)	**Date: 13-11-2023**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense. *If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.*
Reviewer's Report
Reviewers report should contain the following items: • Brief evaluation of the thesis quality and overall structure of the dissertation. • The relevance of the topic of dissertation work to its actual content • The relevance of the methods used in the dissertation • The scientific significance of the results obtained and their compliance with the international level and current state of the art • The relevance of the obtained results to applications (if applicable) • The quality of publications The summary of issues to be addressed before/during the thesis defense

Ms. Chikunova's PhD thesis, titled *Coronal dimmings associated with coronal mass ejections: evolution, lifetime, and relation to the directivity*, studies the relationship between solar coronal dimmings and coronal mass ejections (CMEs). In her thesis, she uses state-of-the-art satellite data and methods to tackle this topic, and she developed several novel analysis methods herself and achieved important scientific results. A highlight is that a direction-dependent analysis of coronal dimmings can be used to constrain the properties of Earth-directed CMEs, as this will improve space weather forecasts and thus will serve the society. Ms. Chikunova has published her results in two first-author publications and two co-author publications, which are of high quality at an international level, in the internationally renowned journals *The Astrophysical Journal* and *Astronomy and Astrophysics*. For all of these reasons, I recommend to award her the title Doctor of Philosophy (PhD).

The following first summarizes the structure of her PhD thesis, then discusses the methods and datasets used, and evaluates the importance of her scientific results.

The PhD thesis was well-written, and the structure of the thesis matches the topic of her thesis. Chapter 1 starts with an overview on the field of heliophysics, with an emphasize on the Sun and space weather. In Chapter 2 and 3, she gave a deeper introduction to CMEs and coronal dimmings. These chapters explained in a well understandable way the essential background for the thesis. In Chapter 4, she discussed in detail the mathematical and computational methods for the analysis of coronal dimmings in her thesis. She adapted several methods of Dissauer et al. (2019) for off-limb dimmings, and she developed a novel methodology to account for projection effects close to the limb. In the following three chapters, she discusses the main questions of the PhD thesis:

Chapter 5, she studies the question of *How can we use coronal dimmings detected off-limb to estimate the mass and speed of coronal mass ejections?* She built a statistical dataset of 43 events, extracted the parameters of the off-limb coronal dimmings as described in Section 4, and related it to the CME parameters. She found that the CME mass is strongly correlated to the area and brightness of coronal dimmings, and that the CME speed is well correlated with the area growth rate of the coronal dimmings. The study follows the results of Dissauer et al. (2019), but for off-limb coronal dimmings, and was performed at a high quality. The results have been published in *The Astrophysical Journal* in 2020.

Chapter 6 studies the question *How and when does the solar corona recover after a CME eruption?* She developed two methods to measure the recovery time of the corona after a coronal dimming, measured the recovery time for the set of 43 dimmings, and studied the recovery for 4 coronal dimming events in detail. The results of this study are published by Ronca et al. (*Astronomy and Astrophysics*, 2023, under review), where she is co-author. The analysis and discussion in this chapter are scientifically sound. But unfortunately, it is not clear if she describes her part of the analysis within this overall study – then the relation to the overall goals of the study is missing, or if she describes the results of the entire study – then, a clarification of her contribution to the study is missing. This issue should be resolved by the time of her PhD defense.

In Chapter 7, she studies the question *'How is the evolution and morphology of dimmings connected to the early propagation direction of CMEs?'* The analysis consists of two parts. 1) She analyzed this question on a case study on the 28 October 2021 event, which involved an X1.0 flare, a filament, and a coronal mass ejection. Here, she developed a novel analysis tool for the directional evolution of coronal dimmings; she tracked the kinematics of the filament eruption using projective trigonometry; and derived the kinematics of the associated CME using the Graduated Cylindrical Shell (GCS) modeling. The highlight of this study are the results that the main direction of the evolution of the coronal dimming represents the direction of the filament eruption, and that the overall structure of the dimming closely resembles the inner part of the CME reconstruction. These results are of high importance for the forecast of Earth-directed CMEs, and have been published in *Astronomy and Astrophysics* in 2023. 2) She contributed to the DIRECD software package, which aims at deriving the CME parameters from the coronal dimming parameters. This software package enables future statistical studies on the relationship between the directional evolution of coronal dimmings and the direction of CMEs, as well as can be used directly for CME forecasts. This software package is published by Jian et al. (*Astronomy and Astrophysics*, 2023, under review), where she is co-author.

Finally, Section 8 summarizes her scientific results and gives a future outlook.

The methods and datasets Ms. Chikunova used are state-of-the-art and of high relevance to her project. She has developed several novel analysis methods herself, e.g., the segmentation of off-limb dimmings, methods to derive the lifetime of coronal dimmings, and the direction-dependent analysis method for coronal dimmings. She has successfully applied projective trigonometry to derive the kinematics of a filament eruption and GCS modeling to track the kinematics of a CME. She has worked with the state-of-the-art instruments, such as the novel Extreme Ultraviolet Imager (EUI) onboard Solar Orbiter (which only has launched In 2020), the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO), the Extreme Ultraviolet imagers (EUVI) onboard the Stereo satellites, and the Large Angle and Spectrometric Coronograph (LASCO) onboard the Solar and Heliospheric Observatory (SOHO). Furthermore, she contributed to the Python package DIRECD which enables the community to derive CME parameters from coronal dimmings. This python package will be a valuable analysis and forecast tool for Earth-directed CMEs.

The scientific results of Ms. Chikunova's PhD thesis are also of great importance. Confirming the relationship between coronal dimmings and CMEs for off-limb coronal dimmings is an important contribution to the field, particularly in view of ESA's planned L5 mission *VIRGIL*, which will allow to study off-limb coronal dimmings related to Earth-directed CMEs on a regular basis. The four case studies on coronal dimming recovery times gave insight into the recovery of the solar corona. And the direction-dependent analysis of coronal dimmings gave insight into the physical causes and effects between filament eruptions, CMEs, and coronal dimmings. Her results advance our scientific understanding of coronal dimmings at a high level.

Concluding, Ms. Chikunova has submitted a high-quality PhD thesis and published her results in international renowned journals. She has developed several novel analysis methods herself; worked with state-of-the-art satellite data and analysis techniques; and found important scientific results on the relationship between coronal dimmings and coronal mass ejections. These results will also have an impact on the CME prediction for space weather forecasts and thus benefit the society at large.I recommend to award her the title Doctor of Philosophy (PhD).

Besides the changes in Chapter 6, i.e., to make her own contribution clear and relate it to the rest of the study, I give in the following a list of mostly minor, mostly typographic comments which should be incorporated into her thesis.

- Citation brackets missing:
  - Page 13, 'Chapter 6', Ronca et al.
  - Page 49, starting from Nitta et al.
  - Page 54, Vanninathan et al.
  - Page 71: Hurlburt et al.

- Page 20, perceived as sunlight: reformulate, it is not clear what that means within the Sun's atmosphere
- Most of the solar photosphere, the magnetic field is a few Gauss: that is only partially correct; it is a result of HMI's low resolution. Within the supergranular cells, there is almost no significant magnetic field, that is correct. But the magnetic fields in magnetic elements in the supergranular lanes have magnetic field strength of about 1-1.5 kG – but only diameters of about 100 km, which cannot be resolved by HMI. HMI actually measures not the field strength in Gauss, but the magnetic flux per pixel (area). As HMI has only a plate scale of 0.5", 1-1.5 kG * 100km^2 * pi gives roughly 50-75 Gauss per 0.5"x0.5" HMI pixel. Therefore, be careful when talking about weak quiet Sun magnetic fields. Better say the average magnetic field density is small instead of the magnetic field density low:
  - page 21, 'For most of the solar photosphere…',
  - page 27, first sentence
  - page 28, 'Typical magnetic field strength'
- page 22, 1st paragraph: the density in the transition region decreases by about 4 orders of magnitude, while the temperature increases by 2 orders of magnitude. See also Figure 1-2.
- Try to avoid the discussion of wave heating and reconnection heating of the corona. Both models have their advantages and disadvantages, and both are still studied by different parts of the community. Wave heating using Alfven waves works well if we do not assume a uniform corona but one which has density fluctuations – and measurements show that we have these. Also, some scientists argue that microflare heating cannot provide sufficient power. You are also right about that your arguments are in the scientific debate; it is a controversial topic. For a PhD thesis, I would advise to not take any side here.
- Page 28, the table: What do you mean with unipolar in *ephemeral (unipolar) active regions*? Ephemeral active regions are typically bipolar. Maybe you mean pores in the sense of ephemeral sunspots?
- Page 31, Paragraph 'It takes several days for shocks in the solar wind to reach the Earth. ….. . It feels like not fitting in the text flow. Wasn't that also discussed in more detail already in the above paragraphs?
- Page 41: *CME fronts reveal an angular width of about 30-65 degrees*; but in the next sentence you write *Halo CMEs extending to nearly 360 degrees*. I guess that the extension does not relate here to the angular width described above. This should be made clear as it appears to relate to the angular width.
- Page 42, *In general, the mass of a CME falls…*: averaged at -> with an average of. Averaged at means that you or someone averages something; but here you mean the average of the CME mass, so the physical average of features.
- Page, 2.2.5: Can also be the pushing slow solar wind behind the CMEs be a driver so that slow CMEs below the escape velocity leave the Sun?
- Some figures are not at the top of the page, which appears strange: Figure 2-4, 2-8, 2-9, 2-10
- Page 54: 'transitional coronal holes' or 'transient coronal holes'? Look up the exact term, transient means something different than transitional.
- Page 57, Fe XVI and Mg IX …, representing temperatures of 1 and 2 MK. The order is wrong. Fe XVI -> 2 MK, Mg IX: 1 MK. Make the relation clear.
- General: Units are written in roman, variables in italic:
  - Page 58, 1 arcmin2
- Page 66, "Key features of the SDO mission": verb missing.

- Page 69, description of STEREO instruments. WAVES, IMPACT, PLASTIC are mentioned, but the description is indifferent. Although they are not used in the thesis, they should either be described with a meaningful sentence, i.e., how the instrument generally works, or the instruments should be entirely skipped.
- Page 74, 'were located on the other side of the solar sphere' -> on the back side of the solar sphere.
- Page 76: 'median filter can be applied to the obtained seed pixels (3x3 square)'. Physicists who know about image processing can guess what you mean with (3x3 square), but others not. Describe that in a better way, using an additional sentence.
- Page 86, formula 4.14: why Phi+ + abs(Phi-) /2? I.e., why /2? I guess since you assume closed loops. If so, that should be stated.
- Page 86, threshold of 10 Gauss for the magnetic flux estimation. It is not clear whether you use the HMI 45s or 720s magnetograms. For the 45s magnetograms, the noise level at disk center is about 7 Gauss, at the limb, it is even higher (I guess 10-20 Gauss). Thus, the threshold corresponds to less than 1.5 sigma, which seems quite a low threshold. If you use such a low threshold, you should reason why this is still fine without affecting the flux derivation in your study.
- Page 87, Section 4.3.5: I understand that you want to introduce the analysis methods for the recovery times later; but if you mention it here, a bit more information, at least in 1-2 sentences, would be helpful. E.g., give a very general description of the approach here, and then say details will be discussed later.
- Page 88, 'P is a pixel the area which we'. This sentence seems wrong.
- Page 126, Figure 6-6. I think you mean Figure 6-1.
- In several chapters, you repeat paragraphs with almost identical information. It looks like some of them were still from a previous version of your PhD thesis which you forgot to delete. Or maybe you wanted to give an introduction to a subsection, but forgot that you gave the same information in the paragraphs right before. Please revise your thesis by removing paragraphs containing information that was given already (right) before.
- Page 198: 'to investigate the investigate'. Double investigate.
- Particularly Section 3.4 gives too less information on dimming-CME relationship. At the moment, it is a list of statements from papers, but without explaining the physical causes and effects. Why did you choose not to do that like in the previous Sections and Chapters, where you really gave nice descriptions on the physics? I would recommend to rewrite this section, not using a list style – you will discuss some of these papers anyway again in the introductions of Section 4, 5, and 6 – but in a narrative style where you explain the physical causes and effects of the dimming-CME relationships.

Provisional Recommendation

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*
☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*