



Pre-examination of the doctoral thesis by Katerina Chrbolková:

## **EVOLUTION OF SPACE WEATHERING AND ITS COMPONENTS - EFFECT OF SOLAR WIND AND MICROIMPACTS ON REFLECTANCE SPECTRA OF AIRLESS PLANETARY SURFACES**

### *1. The significance and status of the research within the research field*

Remote sensing of spectral reflectance properties is the only means astronomers have of studying the large number of asteroids we know exist in the main asteroid belt and the near-Earth asteroid population. For the reflectance spectra obtained by ground-based and space-based telescopes to be analyzed correctly, the extent of effects on the surface materials affecting the reflectance spectra must be understood and included. This dissertation probes the effects on silicates expected in the S-class asteroids primarily located in the main-belt and near-Earth asteroids. In particular, Chrbolková examined the timing and extent of the effects of the two main types of space weathering expected to affect asteroids and atmosphereless planets in this region: meteoroidal surface impacts and solar wind surface implantation. She covered both the visible and near-infrared spectral regions in her studies. She addressed the spectral changes and the timing that these changes require to occur on objects. Her work will help future studies delineate what occurred on the surface of an object, and what is its composition. This is a strong contribution to future space science studies, both ground based and space based. This work is relevant to the research conducted by both advisors she has had at both universities; these are internationally recognized scientists in this field.

### *2. The scope of the work and adequacy of the research material, the significance and deficiencies of any manuscripts submitted for publication*

The work is a broad approach to this subject (the specific effects of the causes of lunar-like space weathering), covering first the analysis of remote sensing data of planetary surfaces (here, images of the lunar swirls, which could be used to separate out the effects due to

micrometeoroid impacts only). This was followed by laboratory studies of pulsed laser irradiation to simulate micrometeoroid impacts, and ion irradiation to simulate solar wind effects. The end analyses of these data correlate subsurface changes in amorphous structures with changes in the spectra of the materials.

Three manuscripts have been published as part of this research. The candidate is the first author on these manuscripts, which have been published in reputable scientific journals known for screening their publications thoroughly. I found no deficiencies in these manuscripts when I read them.

### *3. Application and development of the research methods*

The candidate applied both analysis of spacecraft observational data and laboratory measurements of the effects on solid material samples. In order to address the questions she was asking, the candidate not only worked with two universities in order to expand on the approaches she included in her studies, she also built instrumentation at Charles University. She applied known, tested techniques to analyze the results she attained in the laboratory.

### *4. The deduction of results from the material studied*

In the three research papers and supplemental material, the results are deduced in a clear and self-critical manner, meeting a high scientific standard in both her thesis and publications.

### *5. The consistency of the structure of the work*

The dissertation is well structured and organized in a consistent way. By extension, the work described in the three papers is carried out in a consistent and well-structured manner.

### *6. Familiarity with and use of the literature*

The state of the art in the field is well presented in the papers, referencing the fundamental literature addressing space weathering, both the history of research in this field, and work that is immediately relevant to the specific topics addressed with this research. The opening chapter in the thesis is a sound and extensive review of the state of the art in this field. Thus, the candidate demonstrated a deep knowledge of her research field. The dissertation shows that the candidate is up to date with the most relevant literature and uses it correctly.

### *7. The composition of the dissertation (presentation, style and language)*

I have enjoyed a well-presented reading with a very understandable style and language.

*8. The doctoral candidate's contribution to the attainment of the dissertation's research results (if the dissertation includes co-authored publications): has the doctoral candidate made a sufficiently independent contribution to the dissertation as a whole?*

The dissertation includes three publications, all first authored by the candidate. Thus, she has clearly made a sufficiently independent contribution to the dissertation as a whole.

*9. Do you recommend the Faculty of Science to grant the candidate permission to defend?*

Yes, I recommend that the Faculty of Science grant permission to defend, and congratulate the candidate and her advisors on very nice work. I add that I really enjoyed reading the entire thesis; it was a pleasure as well as an honor.

Faith Vilas, Ph.D.  
Senior Scientist  
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## Review of Katerina Chrboalkova PhD Thesis

### Summary:

This work presents important new findings on the mechanisms of space weathering, the timescales over which it operates, and the consequences of this weathering for remote sensing of airless bodies. In particular, the author Chrboalkova has made numerous novel findings:

1) Paper I: By performing PCA analysis of the spectral properties of lunar swirls, Chrboalkova made several important inferences about the nature of space weathering. The first is that swirls on the Moon's near and far sides exhibit differences in spectral slope, which likely reflects the different ion fluxes inside and outside of the Earth's magnetotail, which thereby strongly supports the role of the solar wind in weathering the Moon and swirls. Furthermore, they also found that generally the spectral properties of swirls cannot be described entirely as a mixture of reduced ion bombardment and micrometeoroid weathering. To alleviate this conundrum, they proposed that either fresh material could be added to swirls, or that we do not understand the weathering contribution from micrometeoroids. I think their finding that swirls cannot be neatly described by a mixture of reduced ion flux and micrometeoroid bombardment is very important – in my opinion I think this points to still undetermined processes operating at swirls. My own theory is that different electric charge states on dust grains produce a unique microphysical structure in the upper grain layers, which modifies the albedo. I would be happy to discuss this at some point. But anyway, without identifying these deficiencies in our understanding of swirls, as Chrboalkova has done, we would be in the dark about what is really happening at these important lunar features.

2) Paper II: By irradiating olivine and pyroxene samples with ions and short laser pulses, Chrboalkova demonstrated how the spectral response of olivine differs from pyroxene. This is important in being able to distinguish different asteroid types (mineralogies) with telescopic observations, and even how asteroids may evolve between spectral types in time, as a result of weathering.

3) Paper III: In a follow up study, similar to their first study, Chrboalkova performed additional experiments irradiating olivine and pyroxene with ions and laser pulses. In this new study they identified key changes in the physical properties of the materials that lead to different spectral effects. In particular, they quantified the amorphization of the grain surfaces as a function of mineralogy and type of irradiation. They also reported the production of vesicles, blisters, and other structures. This mechanistic study is essential to understanding how spectral changes are linked to physical changes in the material. In my opinion, such studies are critical in extrapolating laboratory measurements to actual micrometeoroid bombardment and solar wind irradiation.

Answers to specific queries:

### **1. The significance and status of the research within the research field**

As I mentioned in my summary, the research is important in advancing our understanding of space weathering.

### **2. The scope of the work and adequacy of the research material, the significance and deficiencies of any manuscripts submitted for publication**

The scope is sufficiently broad, in that it covers both remote sensing observations and lab experiments. There were no deficiencies in the manuscripts.

### **3. Application and development of the research methods**

The methods were generally very well thought out. The experiments were well planned. The author used numerous types of laboratory instruments in their analysis.

### **4. The deduction of results from the material studied**

The deduction of the results was straightforward from the measurements. The extrapolation of some of the results to explaining weathering timescales and asteroid spectral types was also well done.

### **5. The consistency of the structure of the work**

There is strong consistency in the work based on the common research theme of space weathering, as explored through both experiments and observational data.

### **6. Familiarity with and use of the literature**

The candidate cited many research articles, as appropriate, demonstrating strong familiarity with the literature.

### **7. The composition of the dissertation (presentation, style and language)**

Composition and style are good. I really enjoyed the basic physics review in the Introduction of the thesis, which was very well written. In terms of the journal articles, I also noticed an improvement in time with the papers' organization and clarity of the conclusions.

### **8. The doctoral candidate's contribution to the attainment of the dissertation's research results (if the dissertation includes co-authored publications): has the doctoral candidate made a sufficiently independent contribution to the dissertation as a whole?**

Based on the candidate being first author on three journal articles included in the manuscript, I conclude that the candidate has made sufficiently independent contributions to the dissertation.

### **9. Do you recommend the Faculty of Science to grant the candidate permission to defend?**

Yes

**Deficiencies:** None

Ian Garrick-Bethell