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Mathematicko-Fyzikalni
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Re: Review of Mr. Robert Klement's PhD Thesis

Dear Prof. Jan Kratochvil,

Thank you for providing the doctoral thesis entitled *Observations and modeling of classical Be stars* by Mr. Robert Klement for review. I really enjoyed reading his thesis! The thesis is well written, logically organized and contains new scientific results important for his field of research.

My research interests on disks surrounding rapidly rotating massive stars, radiative transfer and hydrodynamics overlap significantly with the work presented in this thesis and I am familiar with Mr. Klement's published papers. I was also a co-organizer of an international meeting held in London, Canada in 2014 where Mr. Klement presented a paper entitled *Detailed modeling of β CMi, A Multi-Technique Test of the Viscous Decretion Disk Scenario*. As such, I am well suited to comment on this thesis and the research presented.

Mr. Klement's and my research focuses on a particular kind of massive star called B-emission or Be stars that are surrounded by disks. These objects are ideal laboratories for studying disks and the interaction of stellar winds with circumstellar material. Recent work has demonstrated that viscosity governs the disk density and viscous disk models have been successful at predicting observables once material is ejected from the star. However, despite decades of study, there are still some key details that we still do not know. For example, we do not know the exact mechanism that ejects material from the star into the disk and the viscosity that operates within the disk is poorly understood. At present, finding viable dynamic models to follow disk structure over time represents a major unresolved issue in this field. The rapid rotation of the star certainly helps to propel material off the surface into the disk but we do not think that this quick rotation provides enough of a kick to launch material. Another mechanism combined with rotation must operate to eject the material—perhaps interactions from an orbiting star, a wave or pulsation on the stellar surface or a push from the stellar radiation. Mr. Klement's thesis research tackles some of these key puzzles in this field. His results will also provide valuable insight into important physical processes that are present in many areas of astrophysics.

Mr. Klement's thesis begins with four chapters of background information so that the reader can understand and appreciate the work that follows. Chapter 1 defines Be stars and describes other types of stars with similar characteristics. Next, he describes the importance of studying Be stars and their disks in relation to what they can tell us about other types of astrophysical disks. He also provides a brief description of previous research and meetings in the field. Chapter 2 describes the observational characteristics of Be stars from a wide range of observational technologies. While

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reading this chapter I was impressed by the clear explanations about the observational technologies and especially by the physical interpretation of the observables. For example, he very clearly and concisely describes how the various shapes of the emission lines result from the interaction of the stellar light with the disk. Some of my own students struggle to understand this important diagnostic correctly and it was clear to me that Mr. Klement understood the physical processes important to his work. The understanding of these fundamental processes allows him to interpret the results of his work correctly and this key to conducting successful original research.

Chapter 3 provides an overview of the central star with an emphasis on the effects of rapid stellar rotation, a universal feature of Be stars. Chapter 4 provides a clear summary about Be star circumstellar disks including a short summary on previous models that have been proposed to explain these disks. The chapter ends with a detailed overview of the viscous decretion disk (VDD) model that is the current accepted theory. The VDD model has successfully been able to explain a range of observed features of these disks, and is the focus of subsequent chapters in this thesis.

Chapter 5 focusses on a particular Be star disk system, β CMi. This chapter provides a comprehensive test of the VDD model by predicting observables, using a previously developed code called HDUST, over a large range in wavelength and then constraining these predictions with observations. It is quite an impressive study done in great detail using a variety of observational technologies, such as optical and IR photometry, spectroscopy, interferometry, spectrointerferometry, polarimetry and radio measurements. First he demonstrates the ability of the ultraviolet continuum and polarization data to constrain stellar parameters. Given that the star is the main source of energy to fuel the disk, obtaining accurate stellar parameters is a critical first step in building models of these systems. Interesting they also find that this star is rotating very rapidly and close to critical rotation. A radio measurement at 2cm suggests that the disk could possibly be truncated indicating the presence of a binary companion. In the paper Klement et al. 2015, they find that one single power law description for the density distribution and a steady viscous decretion could not adequately describe the disk. However, in follow-up work with updated codes, the authors successfully match the entire range of observables with a density distribution parametrized with one value of the power law fall-off for the density distribution. This represent a significant finding as it suggests that the VDD model is the correct description for Be star disks. Using their data in the radio regime and other diagnostics, they also confirm the presence of a binary companion that causes the truncation of the circumstellar disk. The analysis suggests that the companion is a subdwarf star, meaning that it must have overfilled its Roche lobe and could have caused the spin-up of the Be star. This finding explains how, in at least some systems, Be disks could be formed. Mr. Klement's work on β CMi represents significant advancement in the understanding of this system and Be star disks, in general.

The work presented in Chapter 6, entitled "Revealing the structure of the outer disks of classical Be stars" focuses on determining the structure of the outermost portion of Be star disks. This work is interesting and original. There has been very little work done using radio measurements for Be stars since the paper by Dougherty and Taylor, 1992 reported the first and only angular resolved image of the Be star, ψ Per in their Nature article. Mr. Klement obtained new data for five disk systems that had previous radio observations reported. For each of these targets, the spectral energy distribution, SED, is constructed over a large range of wavelength. Mr. Klement used data from the ultraviolet, visual and IR photometry, visual spectroscopy and polarimetry to ensure the SEDs for the program stars were well constrained. The VDD model and HDUST is used for the analysis. They confirmed a turnover between the far infrared and radio in the SED for all but one target, and for the first time show that the turndown is too shallow to be the result of a simple truncation demonstrating that disk material must extend past the truncation radius. This research may show that the truncation in these targets is due to the effects of binary companions. This research provides mounting evidence of the success of the VDD model. They also find that for ψ Per that the disk size that reproduces the radio SED does not match the interferometric data. It will be interesting to see the results of Mr. Klement's future work mentioned in his Conclusions with radio flux measurements.

In summary, this thesis contains an ample body of new scientific results important to this field of research. Throughout the thesis, Mr. Klement demonstrates that he has a firm foundation in the physics behind his investigations which will serve him well has he continues his career. I was impressed with the thorough and thoughtful analysis presented in the thesis. In each investigation, he makes use of multiwavelength data and a vast variety of observational techniques to constrain his predictions. The thesis is well-written and this will make his work accessible to other researchers. Mr. Klement has demonstrated that he has great potential for creative scientific work and I wish him well in his future endeavours.

Please ask me if you have any questions.

Sincerely,

Carol E. Jones
Associate Professor