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Subject: Review of Habilitation Thesis by Dr. Josef Durech

Dr. Josef Durech's Habilitation Thesis entitled *Physical Models of Asteroids* is an extensive piece of research into the derivation of models for asteroid spins and shapes. These models are mainly derived from disk-integrated photometric data of asteroids, that is, their brightnesses in a given direction as integrated over the parts of their surfaces both illuminated by the Sun and detectable by the observer. Both dense and sparse sets of photometric data are utilized. The former data comes in as traditional dense lightcurves showing the brightness variation due to the nonspherical shape of the rotating asteroid. The latter data comes in as isolated points well separated in time with no immediate clue on the rotational period.

In addition to photometric data, first, asteroid silhouettes from stellar occultations are incorporated as direct information on the projection of an asteroid's shape on the plane perpendicular to the line of sight defined by the star and the observer. Second, the thermal infrared emission from asteroids is utilized, that is, the disk-integrated brightness in the infrared due to the emission of the radiation originally absorbed by the asteroid in the visible range of the electromagnetic spectrum. Third, disk-resolved adaptive optics, interferometric, and space-mission flyby-observations are incorporated, directly or indirectly, resulting in multimodal inverse problems.

The Habilitation Thesis consists of an introductory part spanning 30 pages as well as 15 peer-reviewed scientific papers, of which Dr. Durech has lead-authored 12 and co-authored 3 papers. In those 3 papers, Dr. Durech is the second author, testifying to the significance of his contribution to the papers. In what follows, I will review all 15 papers **I-XV** in the order of their appearance in the Habilitation Thesis.

I. Durech, J., Grav, T., Jedicke, R., et al. (2005): Asteroid models from the Pan-STARRS photometry. Earth, Moon, and Planets 97, 179-187.

The Pan-STARRS photometric data set promises to provide some 100 photometric points for near-Earth and main-belt asteroids within a time interval of 4-5 years. With the help of realistic simulations, the authors ascertain the scientific potential of the Pan-STARRS project for asteroid spin and shape reconstruction for asteroids. They show that, as compared to obtaining

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traditional dense lightcurve data, sparse photometry provides an efficient way of producing asteroid spin and shape models.

II. Kaasalainen, M., Durech, J., Warner, B. D., et al. (2007): Acceleration of the rotation of asteroid 1862 Apollo by radiation torques. Nature 446, 420-422.

The anisotropic reflection of sunlight and the thermal emission of absorbed sunlight from an asteroid's surface acts as a propulsion engine. For irregular asteroids, the propulsion causes a net torque (the Yarkovsky–O'Keefe–Radzievskii–Paddack or YORP effect) that can change the asteroid's rotation period and its rotational pole orientation. The authors show that, by incorporating a linear time dependence in the rotational frequency of asteroid (1862) Apollo, they are able to consistently model the lightcurves observed for Apollo. They show that an explanation based on the YORP effect is consistent with the modeling. The work constitutes a discovery of the YORP effect for asteroids.

III. Durech, J., Scheirich, P., Kaasalainen, M., et al. (2007): Physical models of asteroid from sparse photometric data. In Milani, A., Valsecchi, G. B., and Vokrouhlicky, D., editors, Near Earth Objects, our Celestial Neighbors: Opportunity and Risk, page 191. Cambridge University Press, Cambridge.

The authors present an overview of their studies of asteroid shape and spin-state reconstruction from sparse photometric data, in continuation of the work presented in Paper I. They show typical examples of physical model reconstruction of main-belt and near-Earth asteroids and discuss the lightcurve inversion of slow and fast rotators, as well as binary asteroids and tumbling asteroids. In agreement with the work by other colleagues, they conclude that simplified shape models can efficiently be used in analyses of sparse photometry.

IV. Durech, J., Kaasalainen, M., Marciniak, A., et al. (2007): Physical models of ten asteroids from an observers' collaboration network. Astron. Astrophys. 465, 331-337.

The authors involve amateur observers for collecting photometric data for asteroids and, using the data, derive shape and spin-state models for ten asteroids. They emphasize the importance of coordinated observational networks to complement the future massive photometric surveys like Gaia. This is because the massive surveys produce sparse photometric data sets and dense lightcurves are required for efficiently determining the rotational period.

V. Durech, J., Vokrouhlicky, D., Kaasalainen, M., et al. (2008): New photometric observations of asteroid (1862) Apollo and (25143) Itokawa - an analysis of YORP effect. Astron. Astrophys. 488, 345-350.

With the help of new photometric data, the authors update the spin and shape model of (1862) Apollo. They show that the refined acceleration of rotation is in complete agreement with the original estimate. The new photometric data removes the original conditionality of the YORP detection on the two lightcurves of the 1998 apparition. They also show that asteroid (25143) Itokawa poses a challenge for the confirmation of the YORP effect. However, the authors are capable of presenting an upper bound for the YORP effect.

VI. Durech, J., Vokrouhlicky, D., Kaasalainen, M., et al. (2008): Detection of the YORP effect in asteroid (1620) Geographos. Astron. Astrophys. 489, L25-L28.

With this work, the authors document the detection of the YORP effect for asteroid (1620) Geographos, the third asteroid for which the effect has been discovered. They showed that the YORP effect retrieved from the linear model of the rotational frequency agreed with that theoretically expected from the shape model.

VII. Durech, J., Kaasalainen, M., Warner, B. D., et al. (2009): Asteroid models from combined sparse and dense photometric data. Astron. Astrophys. 493, 291-297.

The authors show how coarse asteroid models can be derived from data combined from dense and sparse photometric observations. That results in more than 24 new asteroid shape models and pole ecliptic latitudes for another 18 asteroids. In their observational error model, they weighted the sparse data with one third of the dense data. They noted that, in the rotation period determination, the best period (taken to be correct) had at least 10% smaller χ^2-value than that of the second best period.

VIII. Durech, J., Sidorin, V., and Kaasalainen, M. (2010): DAMIT: a database of asteroid models. Astron. Astrophys. 513, A46.

The authors introduce their Database of Asteroid Models from Inversion Techniques, describing its contents and data format. In Paper VII and the present paper, the authors point out that the shape and spin-state models are subject to constant evolution with increasing photometric data sets. As of February 1, 2017, the DAMIT database comprises models for altogether 909 asteroids, some of the asteroids having multiple models. This marks a remarkable 800% increase in the number of models since the paper was published.

IX. Scheirich, P., Durech, J., Pravec, P., et al. (2010): The shape and rotation of asteroid 2008 TC_3. Meteoritics and Planetary Science 45, 1804-1811.

Asteroid 2008 TC_3 provides an exceptional case among asteroids. Soon after its discovery as a near-Earth asteroid it was predicted to impact the Earth. The impact resulted in a fireball, whereafter pieces of 2008 TC_3 were recovered as meteorites. The authors carry out a spin and shape analysis for the object from seriously constrained observational data, showing the tumbling rotation state and obtaining an estimate for the rotational and precession periods.

X. Durech, J., Kaasalainen, M., Herald, D., et al. (2011): Combining asteroid models derived by lightcurve inversion with asteroidal occultation silhouettes. Icarus 214, 652-670.

Continuing their multi-data inversion approach, the authors incorporate occultation silhouette observations as additional constraints to the derivation of asteroid models. With the help of the silhouettes, they are able to obtain equivalent diameters of asteroids and substantially reduce the ambiguities deriving, for example, from multiple pole solutions.

XI. Durech, J., Vokrouhlicky, D., Baransky, A. R., et al. (2012): Analysis of the rotation period of asteroids (1865) Cerberus, (2100) Ra-Shalom, and (3103) Eger - search for the YORP effect. Astron. Astrophys. 547, A10.

With the lightcurve inversion methods, the authors are successful in detecting an acceleration of the spin rate for (3103) Eger and introducing upper bounds for the YORP effect of (1865) Cerberus and (2100) Ra-Shalom. Due to the photometric data at large solar phase angles for Eger, it was necessary introduce a non-convex model for the asteroid's shape. The authors note that only acceleration of rotation presumably due to the YORP effect has been detected. Potentially, Ra-Shalom might become the first asteroid with decelerating spin rate.

XII. Kaasalainen, M. and Durech, J. (2013): What's out there? Asteroid models for target selection and mission planning. In Badescu, V., editor, Asteroids: Prospective Energy and Material Resources, pages 131-150. Springer, Berlin.

The authors review the remote-sensing methods and potential for asteroid modeling, with practical asteroid prospecting and mining in mind. They stress the fact that the a priori knowledge of a given asteroid needs to be maximized before sending practical space missions to the asteroid. It is clear that the success in lightcurve inversion for asteroid spin and shape states will be of key importance for such practical missions to succeed in a cost-effective way.

XIII. Durech, J., Carry, B., Delbo, M., et al. (2015): Asteroid models from multiple data sources. In Michel, P., DeMeo, F. E., and Bottke, W. F., editors, Asteroids IV, pages 183-202. University of Arizona Press, Tucson.

The authors provide a review of asteroid spin-state and shape reconstruction for Asteroids IV, the fourth volume on asteroids in the widely utilized Space Science Series. They discuss the inversion and data fusion from the theoretical point of view, followed by the description of data and models using disk-integrated photometry, disk-resolved images from ground-based or Earth-orbiting telescopes, spacecraft flyby imaging, stellar occultations, interferometry, direct size measurement (Gaia mission), disk-integrated radiometry, and radar. Prospects are outlined for studies of asteroid interiors and asteroid binaries. The sensitivity of the YORP effect on the detailed shape of an asteroid is pointed out.

XIV. Durech, J., Hanus, J., and Vanco, R. (2015): Asteroids@home - A BOINC distributed computing project for asteroid shape reconstruction. Astronomy and Computing 13, 80-84.

The authors involve citizens around the world in their quest for asteroid models using the distributed computing project entitled Asteroids@home. They describe the lightcurve inversion methods and technical details of the project.

XV. Durech, J., Hanus, J., Oszkiewicz, D., and Vanco, R. (2016): Asteroid models from the Lowell photometric database. Astron. Astrophys. 587, A48.

With the help of the Asteroids@home project, the authors succeed in deriving more than 300 new asteroid models using the sparse photometry in the Lowell photometric database, almost doubling the number of asteroid models available. To accomplish this, the authors analyzed the first 100,000 numbered in the database. The authors point out that it is useful to carry out lightcurve inversion simultaneously with the simplified ellipsoid-based method and the convex inversion method: for sparse data, the latter method can result in large numbers of candiate rotation periods, whereas the former method typically gives a single candidate period.

The concise introductionary part of the Thesis preceding the15 papers I-XV contains an introduction followed by the presentation of asteroid shape modeling as an inverse problem. A special section is dedicated on one hand, to, the photometric observations, the principal observations utilized for the inverse problem, and on the other hand, to the thermal infrared observations that also belong to the class of disk-integrated observations. Thereafter, another section is directed for inverse problems involving disk-resolved data on the asteroid. The introductory part of the Thesis then includes an assessment of so-called non-standard cases comprising the excited rotation (tumbling), YORP effect, and binary asteroids. Finally, future prospects are provided in the final section.

Having been actively involved in lightcurve inversion research in the years preceding Dr. Josef Durech's time, I consider myself particularly eligible to evaluate Dr. Durech's scientific achievements. Dr. Josef Durech has been playing a key role in lightcurve inversion for asteroid spin states and shapes for more than a decade. That decade has included major milestone achievements in drastically improving the lightcurve inversion methods and softwares, remarkably increasing the number of asteroids with photometric spin and shape models, discovering new paradigm-shifting radiation effects acting on asteroid rotation, incorporating elegant additional observational data sets in multi-data inverse methods, and in involving citizens around the world in computationally demanding lightcurve inversion tasks. All of these achievements are clearly and concisely described in the present Habilitation Thesis. Based on the Thomson-Reuters ISI Web of Science, Dr. Josef Durech has a fairly high Hirsch-index of 16, showing that the scientific community has noticed his research achievements.

I do disagree with a number of scientific settings in the Habilitation Thesis. First, contrary to what Dr. Josef Durech states, a statistical error analysis using, for example, Markov-chain Monte Carlo methods would have large value, alongside or even overarching the error analysis based on completely changing the shape discretizations, for example. Second, the multi-data weighting procedures utilized appear partially unsubstantiated: it is for example not at all explained why, in the case of combining the dense and sparse photometric data the latter would obtain a weight of one third of the former. Third, I consider the simplification of radiation physics into non-physical approximations (for example, considering the thermal infrared emission process as a reflection process) as a potential obstacle for further applicability and utilization of the spin and shape models. However, considering the focus of the Habilitation Thesis on asteroid spin and shape inversion, I consider these disagreements as deriving from somewhat different schools of science and, as such, as acceptable differences in scientific argumentation subject to further discussion in the future.

It is my recommendation that the applicant be appointed as an associate professor.

Sincerely yours,

Karri Muinonen

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