HABILITATION THESIS REVIEWER'S REPORT

Masaryk University	
Applicant	Michal Zajaček, RNDr
Habilitation thesis	Mapping galactic nuclei: From the Galactic center to distant quasars and back
Reviewer	Anna Ciurlo, Dr
Reviewer's home unit, institution	University of California Los Angeles

The thesis explores both the detailed spatial information available for the nearby Galactic Center and the temporal studies of mostly unresolved distant AGN, viewing them as complementary approaches. A central theme is the evolutionary connection between these systems, where the current state of the Galactic Center represents an end product of the quasar state, like the "cinder" of a formerly very active supermassive black hole. The work is grounded in a historical context of understanding the Milky Way's structure and the nature of nebulae.

The thesis presents a significant body of work that effectively connects the detailed spatial information available for the Galactic Center with temporal studies of unresolved distant active galactic nuclei (AGN). A key strength is the candidate's ability to bridge these seemingly disparate systems, exploring the evolutionary connection where the Galactic Center can be viewed as an "old or almost dead quasar" state. The research covers a wide range of physical processes, demonstrating a broad expertise in the field. The work utilizes a variety of methodologies, from analyzing and modeling detailed spatial data in the Galactic Center to applying and refining reverberation mapping techniques for distant sources..

Most Important Contributions

The thesis underscores several significant contributions made by the candidate and his collaborators, showcasing both theoretical insights and advancements in observational analysis.

The thesis frames the Galactic Center as an the "cinder" of a once very active SMBH. The candidate's work contributes to understanding this evolutionary connection by:

- **Mapping the Galactic Center's past activity:** By studying the gas and stellar content in the inner parsec, including young stars and dust-enshrouded objects, the thesis infers that the GC was likely much more active at Seyfert-galaxy levels a few million years ago. This inference relies on linking the gas consumed by star formation to that available for accretion, providing observational evidence for past activity cycles in our own galaxy, complementing the understanding gained from studying active systems elsewhere. This local, detailed view provides crucial context for the "dead quasar" state observed today.
- **Investigating Jet-Star Interactions**: The thesis explores how repetitive encounters between a past active jet from Sgr A* and red giant stars could ablate their envelopes. This mechanism, studied using simplified temporal evolution models and referencing stellar evolution tracks, is proposed as a partial explanation for the observed lack of large red giants in the innermost 0.5 pc of the Galactic Center. The thesis notes that this mechanism could have coexisted with others previously proposed in the literature, such as tidal disruption of envelopes and star-disk interactions, which operate on different scales.
- **Studying the Influence of Nuclear Star Clusters:** Building on the detailed environment of the GC, the thesis explores how the distribution of stars in the Nuclear Star Cluster (NSC) might influence nuclear activity. This work suggests that the NSC distribution (cusp-like

versus core-like) affects the size of the stagnation radius, which divides inflow from outflow regions near the SMBH's Bondi radius. This connects the stellar environment directly to the fueling and feedback of the SMBH, a crucial aspect of understanding nuclear activity cycles.

For distant, unresolved AGN, the thesis relies heavily on reverberation mapping (RM). RM replaces spatial resolution with temporal studies, using the light-travel time delays of emission lines responding to continuum variations to probe the Broad-Line Region (BLR) structure, in particular by:

- **Advancing R-L Relations:** A central theme is the application of reverberation mapping to study the inner regions of distant, unresolved AGN. The work focuses on comparing radius-luminosity (R-L) relations for different emission lines, particularly MgII. It is shown that while the Hβ and FeII R-L relations exist, the MgII R-L relation is flatter but still exhibits a significant correlation. This is presented as a valuable tool for measuring SMBH masses in distant quasars using single-epoch spectroscopy. The candidate's work, specifically on luminous sources like HE 0413-4031 and HE 0435-4312, was critical for constraining this relation. The candidate updated MgII R-L relation based on the largest sample used for this purpose, finding it significantly flatter than Hβ, UV FeII, and optical FeII R-L relations. Furthermore, the candidate highlights how the MgII R-L relation can be used to standardize quasars as alternative cosmological probes
- **Refining Spectral Analysis and FeII Modeling:** This work details the crucial impact of a precise redshift determination (using IR [OIII] lines) on the spectral decomposition of UV spectra in quasars, particularly for the overlapping MgII and FeII emissions. This work demonstrated that the choice of FeII template significantly affects the decomposition and potentially the derived properties and time delays. The candidate's comparison with new CLOUDY models suggests that improved FeII templates are necessary for accurate spectral analysis. The finding of slightly different time delays for FeII and MgII in HE 0413-4031 supports previous wavelength-resolved studies indicating stratification in the BLR.
- **Investigating AGN Activity Cycles via Radio-Optical Properties:** This work explores the radio-optical properties of active galaxies, studying the distribution of radio spectral indices within optical diagnostic diagrams (BPT diagram). The finding that Seyfert galaxies typically show steep indices (associated with older radio structures) while LINERs exhibit flatter/ inverted indices (indicating renewed activity with compact cores and jets) is important. This suggests that the optical diagnostic diagram can trace galaxy-evolutionary cycles, specifically recurrent nuclear-jet activity, in the nearby Universe.

A significant contribution highlighted is the use of quasars, specifically the R-L relation, as alternative cosmological probes. Quasars bridge the gap between local distance ladder measurements (Cepheids, SNe Ia) and high-redshift CMB data:

- **Comparing methods for standardizing quasars for Cosmology:** The thesis directly compares two the R-L relation and the relation between X-ray and UV luminosities (LX-LUV). While previous work has used LX-LUV, and noted issues with its independence from cosmological models and samples, the candidate's work for the first time compares luminosity distances derived from both methods for the same sample of X-ray detected, RM quasars.
- **Identifying Extinction as a Systematic Bias:** This comparison revealed significant systematic differences in the luminosity distances derived by the two methods. The thesis provides a crucial interpretation: differential extinction by dust in host galaxies impacts the LX-LUV relation more significantly than the R-L relation, biasing distance measurements and potentially cosmological constraints. This understanding, supported by analysis of the X-ray/ UV color index and comparing results with and without extinction cuts is vital for refining quasars as cosmological tools, particularly as sample sizes grow and systematic errors become dominant over stochastic ones. This work suggests that the RBLR-L relation is more promising for future cosmological applications.

In summary, the thesis successfully integrates studies of nearby and distant galactic nuclei, placing its specific findings within the broader context of long-standing questions in astrophysics: the evolution of galaxies and their central black holes, the processes of accretion and feedback across varying scales

and cosmic epochs, the detailed structure and physics of AGN inner regions (BLR), and the potential of these objects to serve as probes of cosmology.

Future Research Plan

The thesis and supporting documents outline a clear and promising trajectory for future research, building upon the foundation established by the presented work: many questions remain regarding the relationship between the GC and distant quasars. The candidate's research plans include investigating the short-term effects of jet-red giant interactions to better understand how NSCs influence nuclear activity and feedback cycles. The candidate recognizes the need to further address systematic effects like extinction for large quasar samples, aiming to refine quasars as standardizable sources. Acknowledging the impact of FeII templates, future work will focus on improving spectral models, potentially using updated photoionization codes like CLOUDY to create better FeII templates , which is crucial for accurate RM measurements and cosmological applications.

Conclusion and Recommendation

Michal Zajaček's thesis presents a coherent, innovative program that advances both the **spatial** mapping of our nearest SMBH environment and the **temporal** mapping of quasar populations. His identification of jet–star ablation as a partial solution to the red-giant cusp problem stands out as a novel cross-disciplinary insight. Coupled with his work to refine quasar BLR scaling relations for cosmological use, his contributions are both timely and highly relevant.

The candidate career evolution demonstrates a consistent progression through prestigious research institutions and successful acquisition of significant research grants. The listed publications, especially those in high-impact journals and those where the candidate is the first author, attest to the quality and originality of the research. The role as a principal investigator of a Junior Star grant and involvement in multiple collaborations indicate a strong research leadership and continued productivity.

Based on the quality and significance of the research presented in this Habilitation Thesis, the candidate's track record, and the promising future research directions, I support the candidate's habilitation.

Reviewer's questions for the habilitation thesis defence (number of questions up to the reviewer)

What are the main challenges in the Galactic Center determination of on-going and recent star formation? What are some alternative scenarios to the proposed YSO population?

Conclusion

The habilitation thesis entitled "Mapping galactic nuclei: From the Galactic center to distant quasars and back" by Dr. Michal Zajaček, **fulfils** requirements expected of a habilitation thesis in the field of Theoretical Physics and Astrophysics.

Date: 15/05/2025 Signature: