Fourth semester report, 2026.06.01
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PhD Program: Astronomy and Space Physics
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PhD thesis title:
Multi-wavelength modelling of multi-epoch variability in protoplanetary disks

1 Introduction

The main project of my PhD is the investigation of mid-infrared variability of T Tauri stars. They have been long known to be variable in the optical and near-infrared and with Spitzer observations it became apparent that the same holds true for mid-infrared as well (e.g., Espaillat et al. 2011, Kóspál el al. 2012). Now, with new observations performed on JWST the problem is becoming again the center of attention due to discrepancies between JWST and Spitzer observations (e.g. Gasman et al. 2023). An example from Ábrahám el al. (in prep.) is presented in Fig. 1.

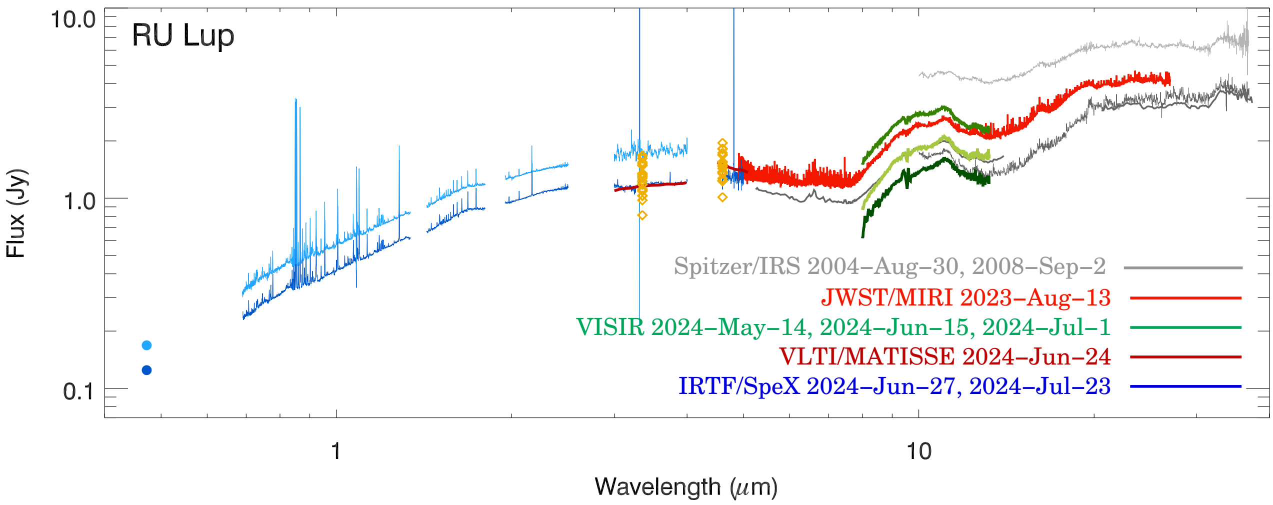

Figure 1: Spitzer, JWST, VISIR, MATISSE and IRTF spectra of RU Lup in 0.5-30 μm range, Ábrahám et al. (in prep.)

Observations on VLT/VISIR and IRTF/SpeX conducted by one of my supervisors, Dr. Péter Ábrahám, in June-July of 2024 revealed that this variability occurs on at least week-month timescale (Fig. 1). My task is to model processes responsible for this behaviour and identify the causes of several cases. The central case of my investigation is the case of DQ Tau (Kóspál et al. 2025), a young close binary with pulsating accretion which has shown significant variation in mid-infrared over its orbital periods. Other cases are represented by less well-studied stars with just 1-2 observed epochs with JWST or Spitzer, such as V1279 Sco or RU Lup. Lastly, I have a third project concerned with explaining through astrochemical modelling the line richness diversity in spectra of eruptive young FU Ori-type stars (Calahan et al. 2024).

2 Summary of work carried out during the previous semesters

The main concern of my previous semesters was fitting of different epochs of JWST observations of DQ Tau (Kóspál et al. 2025) and V1279 Sco (Ábrahám et al., in prep). I have explored

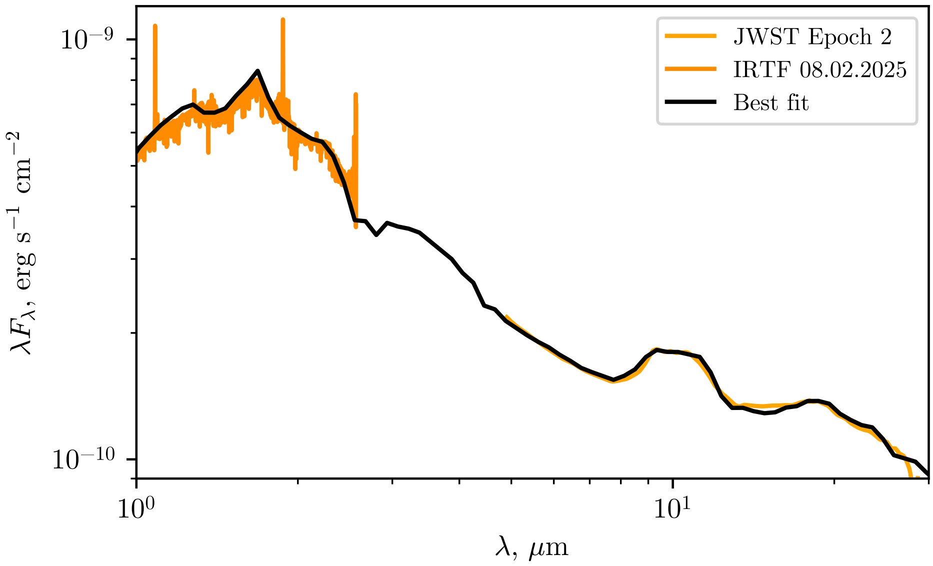

Figure 2: The best fit SED for DQ Tau Epoch 2 together with JWST and IRTF observations

different possible approaches and models that could be applied. In the end, I settled on writing my own classes as an extention to the DiskCheF[1] python package. It then sets up 2D or 3D density distributions of a multi-component dust protoplanetary disk in a form suitable for for the radiative transfer tool RADMC-3D (Dullemond et al. 2012). The package is capable of setting up of virtually any disk with any number of dust populations, get their opacities from `optool` (Dominik et al. 2021) and account for sublimation or settling in a simple parametric manner. With regards to the disk structure, it supports both parametric and hydrostatic equilibrium vertical structure and can introduce any azimuthal asymmetries in the disk, including the misalignment of the inner disk.

Using this package, I explored possible disk structures that give the mid-infrared spectra similar to that observed in DQ Tau. At first, I tested fitting with special fitting methods, such as nested sampling by UltraNest (Buchner 2021), however that proved to be inefficient. Instead, I came up with an investigative method of increasing complexity. First, I run a grid of simple parametric models and then analyse which parameter sets fit not the whole spectrum but parts of it. As different wavelengths trace different disk regions, this way we can get information about distribution of parameter values along the disk. In case of DQ Tau, for example, it has revealed that the vertical structure must be described by a radially decreasing flaring angle, reaching a plateau in the outer disk. When I applied the variable flaring angle structure, I could easily find a fit for the whole spectrum, shown on Fig. 2. That was the main result of the previous semesters.

Additionally, in the first semester I reworked and finished my MSc summer project that I did with my MSc supervisor, Dr. Tamara Molyarova. In this project, I explored how different protoplanetary disk parameters affect the line fluxes of CO isotopologues when we carefully consider grain chemistry. This investigation was highly relevant as CO isotopologues remain one of the main ways of probing the disk gas mass. In that work we showed that inclusion of grain chemistry complicates the picture, no longer allowing to clearly estimate the mass based on just CO isotopologue pairs as was predicted in Williams & Best 2014 or Miotello et al. 2016. It is still possible, however, with additional independent constraints like disk size or dust mass. Finally, our modelling results did not show an order of magnitude underestimation of mass that previous methods had due to absence of processes that deplete CO from the gas. The results

[1] `https://gitlab.com/SmirnGreg/diskchef`

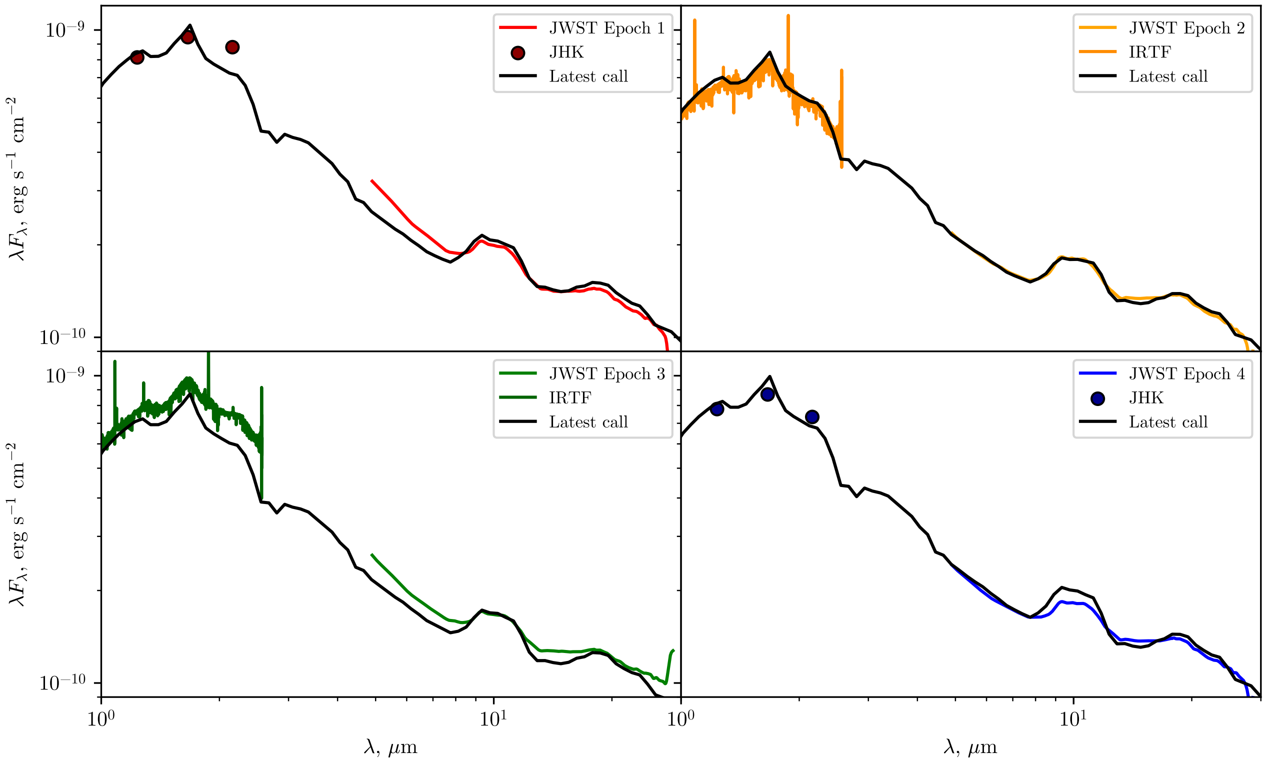

Figure 3: SEDs of DQ Tau Epochs assuming the same disk structure but different stellar spectra and positions

have been published in Zwicky et al. 2025.

Lastly, some preliminary progress was done on the project of FUor line diversity. We run several test models to identify the parameters that affect the line emission the most and we found them. They turned out to be: mass of the envelope that surrounds the disk, initial chemical composition of the disk, disk size and dust maximum size. We agreed upon a grid of models to run for a systematic investigation and I have received computing resources at HUN-REN cloud to carry it out (titled "Molecular line diversity of FU Ori-type stars", approved until November 2026).

3 Work carried out during the current semester

3.1 Mid-IR variability

As I have fitted the quiescent Epoch 2 of DQ Tau, I proceeded to fit the other three. First I have checked the spectra produced without any changes to the structure, only to the stars and their positions. SEDs of those cases are shown on Fig. 3. From there it is apparently clear that some changes beyond stars must be introduced to the disk. For Epochs 1 and 3 there is a severe lack of near-IR and short mid-IR flux, suggesting that there must be a hot dust component close to the binary. In Epoch 4, on the contrary feature, the silicate feature appears too strong and should be instead shadowed.

Given the timescales of the binary orbital period and disk dynamics, it is physically possible to change the structure only in the area between the star positions at periastron (Epochs 1, 3, 4) and apoastron (Epoch 2). Starting with Epoch 1, I added a close wall surrounding the binary with a gap after to avoid adding flux to spectra beyond 8 μm. Adjusting the wall and gap parameters, including azimuthal asymmetry, I managed to fit the Epoch 1. I applied the same

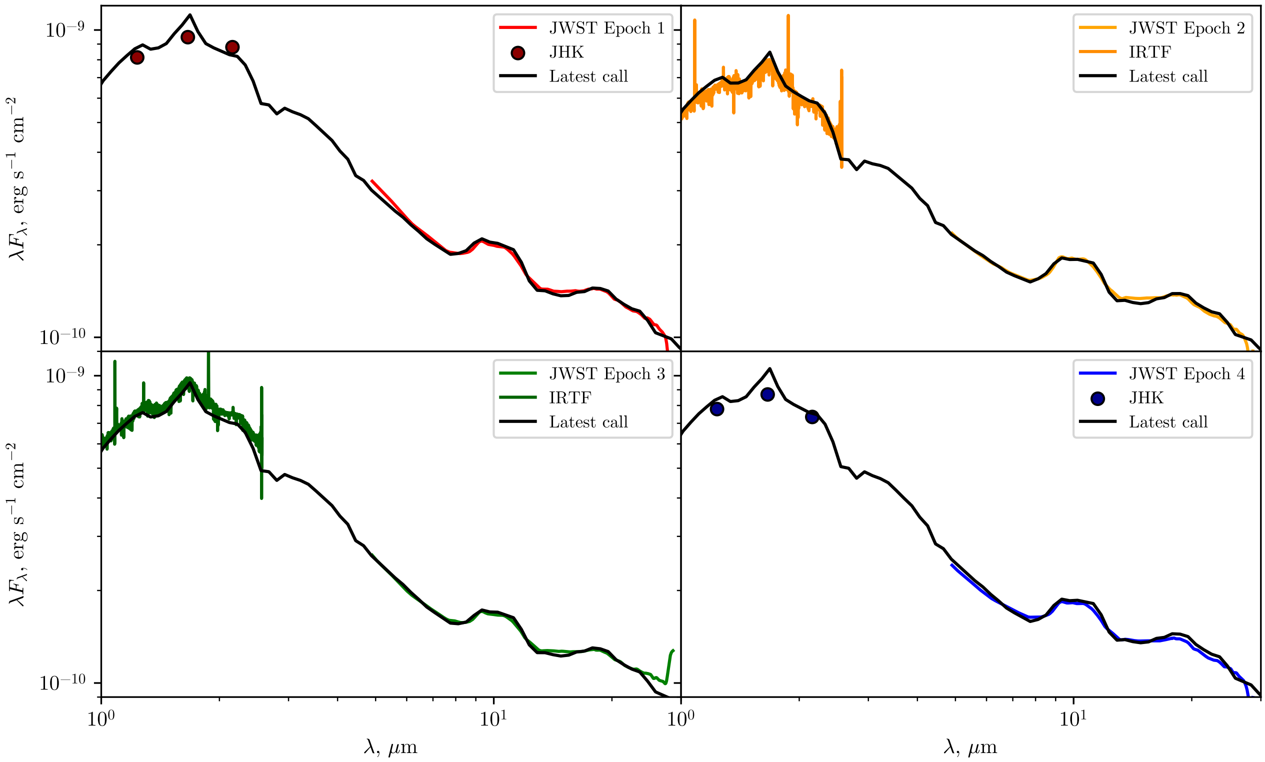

Figure 4: Best fit SEDs of DQ Tau Epochs

structure to other Epochs and they were fitted with only minor adjustments to the structure. Best fit SEDs are shown in Fig. 4.

The structures that ended up fitting the Epochs come in very good agreement with theoretical predictions as from hydrodynamical simulations (Günther & Kley 2004) or schematics from Muzerolle et al. 2019. I have to note, unfortunatelly, that the result is not final as I have uncovered an error in the treatment of dust sublimation. I have resolved this issue with Dr. Mario Flock's advice but the epochs are still to be refitted. However, I think that it will not affect the structure of the fit itself but just give corrections to the parameters.

Now I am adapting the same methodology to fit the Spitzer and JWST observations of V1279 Sco that shows an even more significant variation in mid-IR between two epochs. At the moment I have run the grid of simple models and calculated deviations of the observed spectra from the grid in specific wavelength ranges. They are shown in Fig. 5.

I have varied a total of three parameters: the scale height and flaring angle that define the vertical structure and $\gamma_{\rm in}$ that determines the sharpness of surface density taper at the inner disk. The most interesting detail here is how the spectra around the 10 μm feature in JWST epoch is better fitted with higher flaring angles and smoother $\gamma_{\rm in}$ than for other ranges. This kind of effect is something that can be produced by a gap placed where the feature is emitted most from. More interestingly, it is not present in Spitzer spectrum which suggests a change in this gap.

3.2 FUor line diversity

The grid of models we set to run at the end of last semester has finished calculating. I have analysed our results in terms of peak spectral flux space and how do they compare with observations. Overall, our results cover the space very well and in good agreement with observations. I even found models in the grid that fit the spectra of V1057 Cyg and V1735 Cyg quite well. I found that line-rich spectra are better reproduced by models with more massive envelope

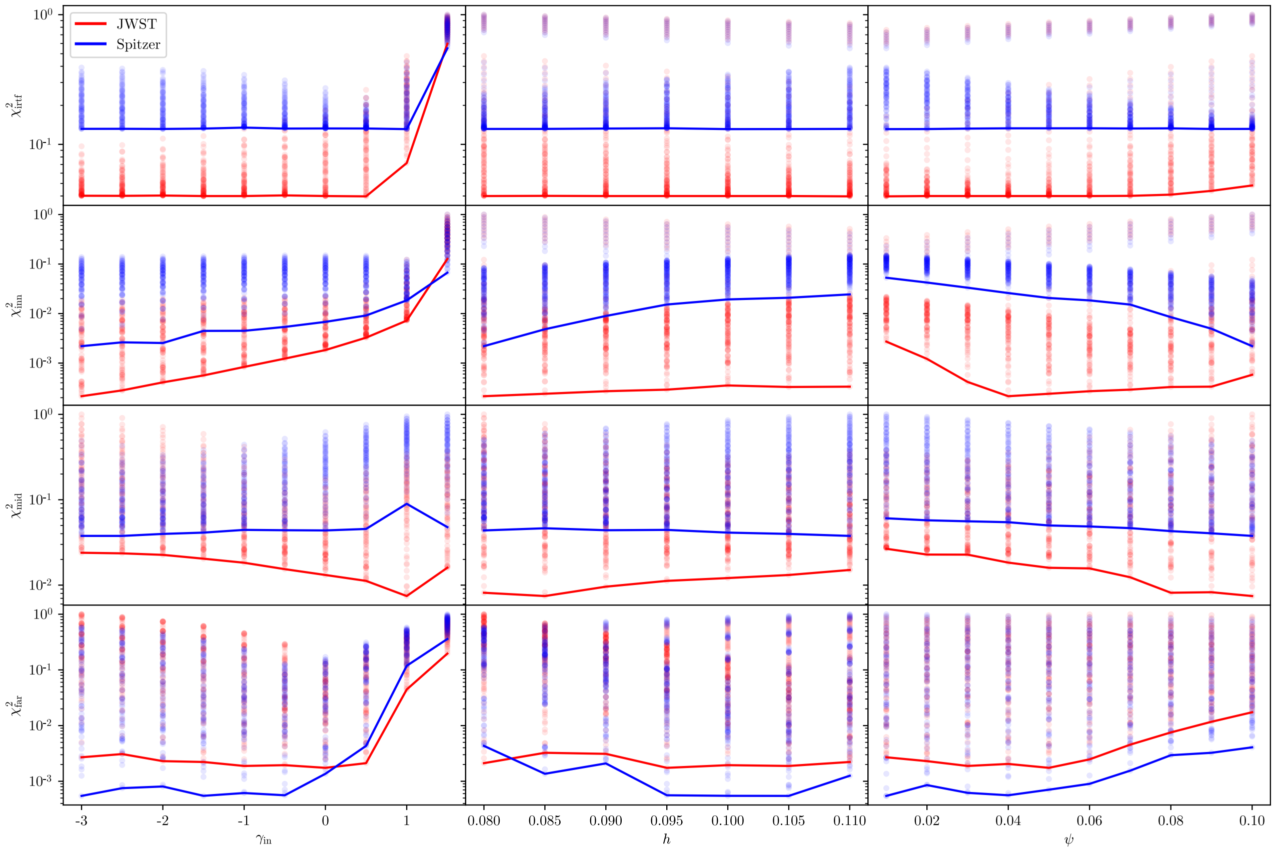

Figure 5: Normalised χ^2 between grid of models and JWST and Spitzer observations. Solid lines follow the lowest χ^2 for the parameter value.

and more grown dust. Additionally, one of the parameters in the model was the inclusion of reactions of photodissociation of ices by cosmic ray induced photons. It is not a parameter that should vary between objects but it does hold information about thickness of ice on the grains. I found that models where those reactions are turned off are in a better agreement with observations, suggesting that dust there possesses a thick mantle mostly impenetrable to photons. These results were presented as a talk on Eruptive YSO Workshop.

The work is quite close to finish but we still need to investigate the chemistry of our models further and explain how dust size and cosmic ray ionisation rate affects it.

4 Publications

1. Varga et al., T CrA has a companion. First direct detection of T CrA B with VLTI/MATISSE, A&A, Volume 695, id.L21, 9 pp., March 2025

2. Zwicky et al., Dancing on the Grain: Variety of CO and its isotopologue fluxes as a result of surface chemistry and T Tauri disk properties, Volume 699, id.A377, 17 pp., July 2025

3. Kóspál et al., Time-resolved protoplanetary disk physics in DQ Tau, A&A, Volume 703, id.A20, 21 pp., October 2025

4. Zwicky et al., Variable inner disk structure of DQ Tau revealed by JWST (preliminary title), in prep.

5. Zwicky et al., FUor molecular line diversity (preliminary title), in prep.

6. Ábrahám et al., Spitzer-JWST variability study of T Tauri disks. I. Archive survey and statistics

7. Bayron et al., The Effect of X-Ray and Accretion Variability on Mid-Infrared Lines in the Young Disk-Bearing Binary DQ Tau, A&A, in prep.

5 Studies

ELTE courses:

1. Solar physics (FIZ/5/057, by Kristof Petrovay)

2. Radio Astronomy II (FIZ/5/010, by Szentirmayné Gabányi Krisztina Éva & Frey Sándor)

Other:

1. Accepted to Les Houches School of Physics Session CXXVII "From the Interstellar Medium to the Formation of Stars: Physics, Tools and Methods.", to be held on 6th — 31st July in Les Houches, France

2. Spring School "Tracking the Evolution of Planetary Systems and Planet", 15th — 22nd April in Liblice, Czech Republic (participated with poster)

6 Conferences

1. Eruptive YSO Workshop, 18th — 22nd May in Budapest, Hungary (member of LOC, chair of session and had a talk)

2. EAS Annual Meeting, 29th June — 3rd July in Lausanne, Switzerland (participation with a talk and a poster)