DOCTORAL PROGRAM IN ASTRONOMY

PROGRESS REPORT

2017-2018

Towards Exoplanetary Atmospheres: new data reduction methods for the nIR

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Overview

Exo-atmospheres, one of the forefronts of exoplanetary science, has shaped science and scientific instrumentation for the last decade. Over the past years we have been exploring methodologies and software tools for the extraction of minute signals from the NIR (near-Infrared) spectra of Brown dwarfs companions, with the aim of extending towards exoplanets. With contrast ratios between the Brown Dwarf and star below 1% provided by the NIR wavelength range, a clear detection would be a step towards the direct detection of exoplanet atmospheres, which are smaller, cooler and have a lower contrast ratio.

The exploratory methods have been unsuccessful in a positive detection but a thorough exploration of the methods and some detection limits have recently been submitted in a paper.

To further assess high spectral fidelity we have been investigating the theoretical radial velocity precision of NIR spectra and how they compare to real spectra of M-dwarfs. This is made possible by release of the CARMENES library in late 2017. This work is still ongoing and will likely only be completed/published after the thesis is submitted.

This report covers the work performed during the academic year 2017-2018 in further detail and outlines the plan for completion of the PhD thesis in 2018. The thesis document has started to be written with a goal to be completed as soon as possible. Ideally the defense would occur before I return to New Zealand in December.

Brief Description of the Work Done

Here I discuss the two main bodies of work address this year. The first being the spectra of Brown Dwarf companions and the second being the NIR RV precision.

Recovery of Brown dwarf companions

We recently submitted a paper exploring the spectral recovery of BD companions, which is based on the last three years of work. In this paper we detail the reduction of the CRIRES spectra, the application of differential subtraction method attempted in 2016, and the brute force χ^2 fitting of synthetic model spectra to the observations which was started in early 2017. The completion of applying χ^2 fitting of two synthetic spectra to the observed spectra was the main focus of the current year. Eventually, after many struggles we came to the conclusion that a successful detection with this method on this dataset was not possible. A upper limit on the temperature of the companions was determined by injecting synthetic companion spectra and attempting to recover them. Having a non-detection made the completion of this work significantly harder, creating some self doubt in the work performed. We state the main issues and results addressed in the paper below and also directly address the issues we highlighted in last years report below

Inherent synthetic flux ratio and continuum normalization

We adjusted how we combined the synthetic spectra of the host and companion. Instead of choosing or varying the flux ratio between the host and companion and add normalized spectra in that ratio we use the inherent flux ratio present in the model spectra. We do this by adding the spectral together in absolute flux, multiplying each component by its respective surface area, using the components effective radii. This sets the flux ratio of the companion directly from the models, and correctly normalizes both components as they are observed. One issue with this method that we note is that the radii used is the effective radius obtained from the Phoenix-ACES models themselves derived and use when generating the stellar atmospheres. We are aware that using these radii radii has its limitations, as there is degeneracy in BD mass, age, and luminosity of the companion, and in particular a combination of radius-mass and radius-age relationships (Sorahana et al. 2013).

We continuum normalize the combined model spectra to flatten it to the the observations. We also allow for a slight scalar re-normalization in the range of 1 ± 0.05 to be applied between to the observations as a free parameter, taking the value that gives the smallest χ^2.

Other Spectral models

We investigated using the BT-Settl models (Allard 2013). We observed that even though there are some slight differences between the two models they are sufficiently similar in contrast to the observations with both having many lines that were not observed. Also the temperature at the limit of our detection limits is significantly higher than the PHOENIX-ACES cutoff at 2300K to benefit from exploring the BT-Settl models which go below this temperature. The BT-Settl spectra are also still slightly more difficult to work with than the PHOENIX-ACES models. An example showing the similarity between the to models and an observation are shown in Fig. 1 E.

Main paper results/discussion

We applied a single and a binary component χ^2 fits to both simulations and observations. Fitting to simulations would return results similar to the expected result, while the observations would not. They would often fit the secondary companion far away from the expected results, usually hitting the edge of the constraining box (Fig.1 C). There are a number of reasons we believe is the cause of this:

- Mismatch between models and reality
  The spectra of the companion tries to fit/compensate for the difference between the spectra of the host and the model of the host rather than fitting the companion spectra. This can be seen in Fig.1 (D) where the purple residuals are the difference between fitted model (limited to the defined grid) and the observations, while the red line is the difference between the fitted model and a model with the companion at the expected values of 3200K.

- Narrow wavelength region of these specific observations
  The observed wavelength was chosen for its lack of telluric lines, rather than the presence of key spectral lines that break the degeneracy in stellar parameters as done in (e.g. Passegger et al. 2016)

- Actual line depths are smaller than assumed
  E.g. If the continuum of the two components flux ratio of 1% then the spectral lines that are 10% in the companion are 0.1% deep when blended and below the SNR level.

- A χ^2 asymmetry leading to a upper temperature threshold of detection at 3800K see Fig. 1 (A and B)

We discuss these points in further detail in the submitted paper.

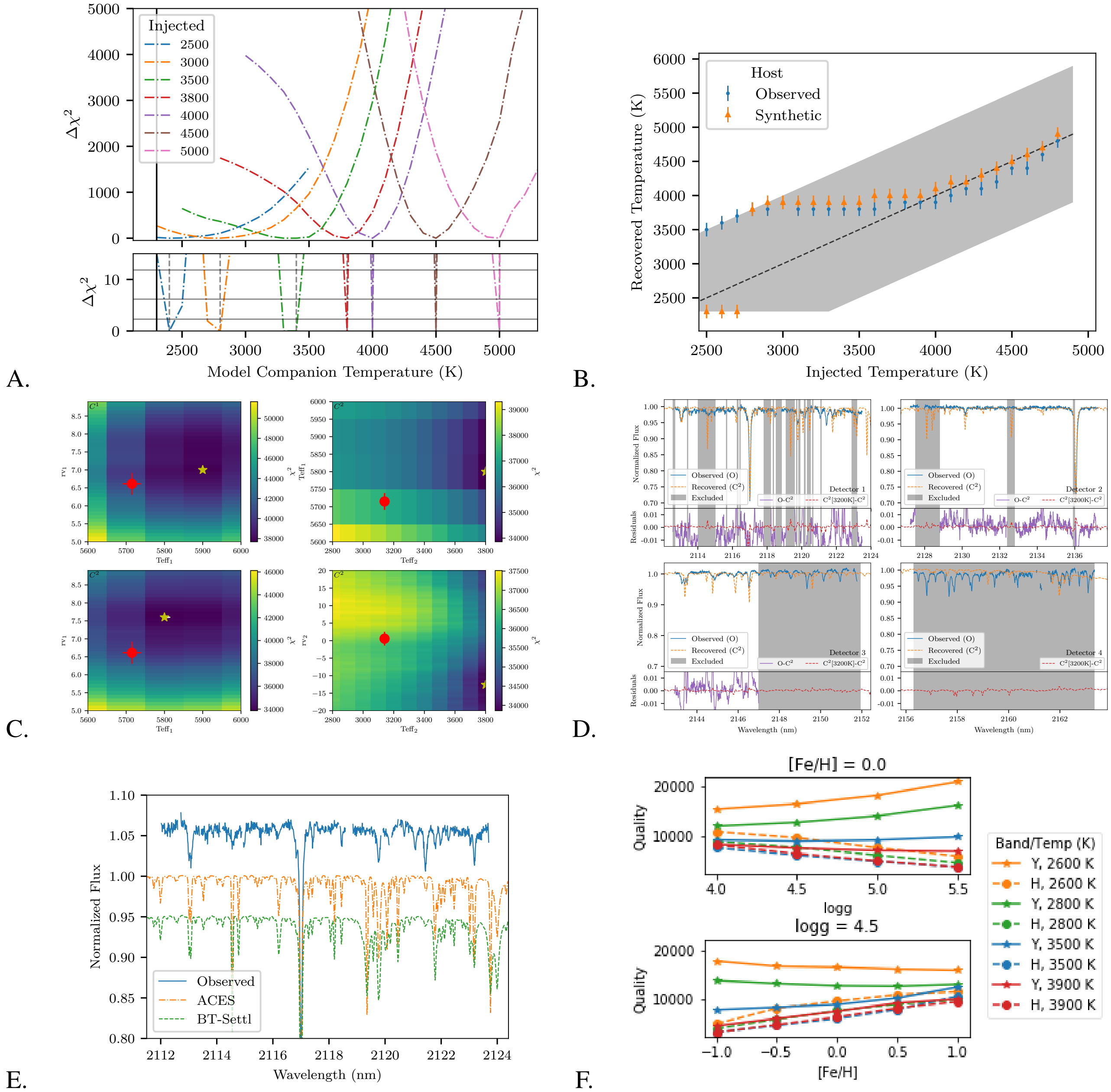

Figure 1: Images produced for this work A-D are included in the submitted paper. A: χ^2 shapes for recovering injected companion spectra. An asymmetry is observed for lower temperature injected companions. B: Injected verse recovered companion temperature on observed and synthetic spectra. C: Poor χ^2 result grid for the second observation of HD 211847. The bottom right panel if the grid for the companion temperature showing the application to the observation results in a minimum value (yellow star) far from the expected value (red circle). D: Comparison between the observed HD 211847 spectrum (blue) and the best fit (3800K companion) synthetic binary model (orange dashed) for each detector. The bottom panel contains the residual between the observation and best fir model (purple). E. Comparison between a BT-SETTL (green) and PHOENIX-ACES (orange) model spectra and one observed spectra (blue). F. Spectral quality of synthetic spectra against logg and metallicity in the Y and H bands.

NIR radial velocity information content

With the submission of the faint companion work I have now shifted focus to the RV information content work. We addressed last year that we were waiting on the release of the CARMENES NIR spectra to extend the NIR information content analysis of (Figueira et al. 2016) on real NIR spectra. The release finally occurred in November 2017 with Reiners et al. (2018). Also, Artigau et al. (2018) performed a comparison between archival optical and NIR observations of Barnard's star to models showing that there is significant differences between models an reality in the NIR regions. We are extending these comparisons across the whole M-dwarf region by selecting 8 CARMENES spectra across the M-dwarf spectral types to compare to the model spectra. The targets we have recently selected to analysis are provided in Table 1. One of our selected stars is Barnard's star allowing for direct comparison to Artigau et al. (2018).

Code Modifications

Two more modifications of the code were performed to make it more general and usable. A script is available to calculate the precision of any spectra in the PHOENIX-ACES library, with the SNR be defined for any band. The original version of the code was hard-coded to calculate only 4 spectra from the library while referenced to SNR=100 at the center of the J band. Along with the RV precision the spectral quality Q is now separately calculated. The quality is flux independent which allows for the comparison between the observations and models as done recently in Artigau et al. (2018).

SPIRou and NIRPS ETC

In September 2017 and May 2018 we were contacted to calculated modifications of the Figueira et al. (2016) RV previsions. These were and will be used for the Exposure Time Calculators for SPIRou (Artigau et al. 2014) and NIRPS (Bouchy et al. 2017), two new NIR spectrographs. We provided previsions relative to different bands (compared to Figueira et al. (2016)) and for NIRPS provided all precision values for the whole temperature range between 2500 and 4000 K.

The increased performance and the bugs corrected in the previous year have been beneficial to providing the requested precision calculations in a timely manor and with the precision values corrected for telluric masking error.

Table 1: CARMENES library target selection spanning the M-Dwarf spectral range. Spectral parameters were obtained from SIMBAD.

Karmn	Name	SpT	SNR_{NIR}	Temp (K)	logg	[Fe/H]	vsin i (km/s)
J20533+621	BD+61 2068	M0.5	257	3772	NaN	-0.01	2.66
J04290+219	BD+21 652	M0.5	212	4037	3.99	-0.21	1.11
J07274+052	Luyten's Star	M3.5	254	3467	NaN	-0.11	NaN
J17578+046	Barnard's Star	M3.5	236	3247	NaN	-0.32	NaN
J11055+435	WX UMa	M5.5	140	3304	NaN	NaN	NaN
J10564+070	CN Leo	M6.0	133	2960	NaN	NaN	NaN
J18356+329	LSR J1835+3259	M8.5	50	2578	NaN	-0.4	37.6
J04198+425	LSR J0419+4233	M8.5	42	NaN	NaN	0.22	NaN

Complementary activities

This year I have not attended international schools or conference or performed observations. I was solely focused on trying to complete the work for the paper and PhD. The 3 things I did participate in were

- Monitoring the, 13^{th} Escola de Verao de Fisica, 3 - 8 Sept. 2017, Porto, Portugal
- IAON-4 30-31 October 2017
- Cookie Seminar, Non-recovery of the faint nIR spectra from Brown Dwarf companions around FGK stars., 27 February 2018

Open Source Contributions

Throughout my PhD I have continued to openly publish most of the code I develop to my publicly available GitHub repositories. I have continued to try and apply software development practices of "continuous integration" and "automated testing" to help the maintenance and correctness of the software created. This approach has been very important in catching many bugs present in the codes I have created. Not only in the initial creation and addition of new components/features of my code, but also in checking the validity of inherited code.

The main repositories that I have focus on this year are companion_simulations which contains most of the work from my recently submitted paper Neal et al. (2018). As well as eniric which is the information content repository and work has been spent on spectrum_overload, a class for handling spectra. I have even published spectrum_overload to pypi so it is available to install using the pip package manager.

I have also made a small number of contributions to open source software (plotting and astronomy related). This has grown my confidence and comfortably to contribute to other open software projects in the future. The main contributions were to PyAstronomy: PR #33, PR #30; Starfish: PR #90, PR #93; Matplotlib: PR #11043; and mpld3: PR #447

During the end of 2017 I also worked with a fellow student to create and updated web site for SWEET-CAT (Santos et al. 2013) a database of parameters for stars with planets maintained by the exoplanet team. This provides some neat plotting ability directly in the browser and ability to search the table, It also combined the SWEET-CAT database with planetary parameters from exoplanet.eu . A prototype is available at https://sweetercat.herokuapp.com. My contributions were bringing the automatic testing experience and identifying problems with the site.

Collaborations

The CRIRES spectra I reduced last year has been used in a publication Ulmer-Moll et al. (2018, in review). This was the data reduced for *Janis Hagelberg*. There has been no news on the status of his use of the reduced spectra.

The observations I performed last year have been used in a paper (Lillo-Box et al. 2018, in review) of which I am a co-author on. No Trojans (asteroids) around other stars have been detected but tighter constraints have been placed on their sizes.

Publication summary

- Published
  - A. Santerne, B. Brugger, D. J. Armstrong, V. Zh. Adibekyan, J. Lillo Box, H. Gosselin, A. Aguichine, J.-M. Almenara, D. Barrado, S. C. C. Barros et al. (including: E. Delgado Mena, O. Demangeon, J. P. S. Faria, P. Figueira, S. Hojjatpanah, J. J. Neal, N. C. Santos, S. G. Sousa), 2018, An Earth-sized exoplanet with a Mercury-like composition, New Astronomy, 2, 23
  - S. C. C. Barros, H. Gosselin, D. Bayliss, E. Delgado Mena, B. Brugger, A. Santerne, D. J. Armstrong, V. Zh. Adibekyan, J. D. Armstrong, D. Barrado et al. (including: O. Demangeon, J. P. S. Faria, P. Figueira, S. Hojjatpanah, J. J. Neal, N. C. Santos, S. G. Sousa), 2017, Precise masses for the transiting planetary system HD 106315 with HARPS, Astronomy and Astrophysics, 608, 14
- Upcoming
  - (Lillo-Box et al. 2018, accepted) - The TROY Project: II. Multi-Technique Constraints on Exotrojans in Nine Planetary Systems
  - Ulmer-Moll et al. (2018, in review) - Telluric Correction in the Near-Infrared: Standard Star or Synthetic Transmission?
  - Neal et al. (2018, in review) - Towards the Near-Infrared Detection of Brown Dwarf Companions: Exploring Methods to Detect Low Mass Stellar Companions from Blended Spectra
  - Andreasen et al. (????) - High resolution near-IR spectroscopic stellar characterization: Refining an iron line list

Ongoing and future Work

NIR information content

There are numerous steps to complete still as this work is ongoing. I have one telluric corrected spectra (Barnard's star) of to being applying the processes below.

- Determine/find the missing parameters in Table 1 for the selected targets. (To identify corresponding synthetic models.)
- Telluric corrections to the 8 NIR spectra. (Tasked to a colleague)
- Post telluric correction processing for bad pixels etc. (code is complete)
- Calculate spectral quality Q for models and observations.
- Analysis between synthetic models and observed spectra.
- Analysis of spectral parameters Fe/H, logg on the theoretical precision values.

One thing that has not been looked into significantly is the effect of metallicity and logg on the spectral quality/precision. Adapting the code to be used with all PHOENIX-ACES models I have started exploring the effect of metallicity on the spectral quality. We will then compare models to the spectra of selected targets. From a preliminary look at the synthetic models there is a effect of a metallicity impact that depends on spectral type and wavelength. An example is shown in Fig. 1(F) where the spectral quality against Fe/H and logg is shown for two different spectral bands and across the M-dwarf temperature range. For the H band (dashed lines) all temperatures follow the same linear trend, but in the J band there is a clear divergence/convergence in the quality with increasing logg/[FeH] respectively.

We have drafted the Introduction and Methods section for this paper already. This paper will also contain the corrections to the Figueira et al. (2016) precision table which has already been created.

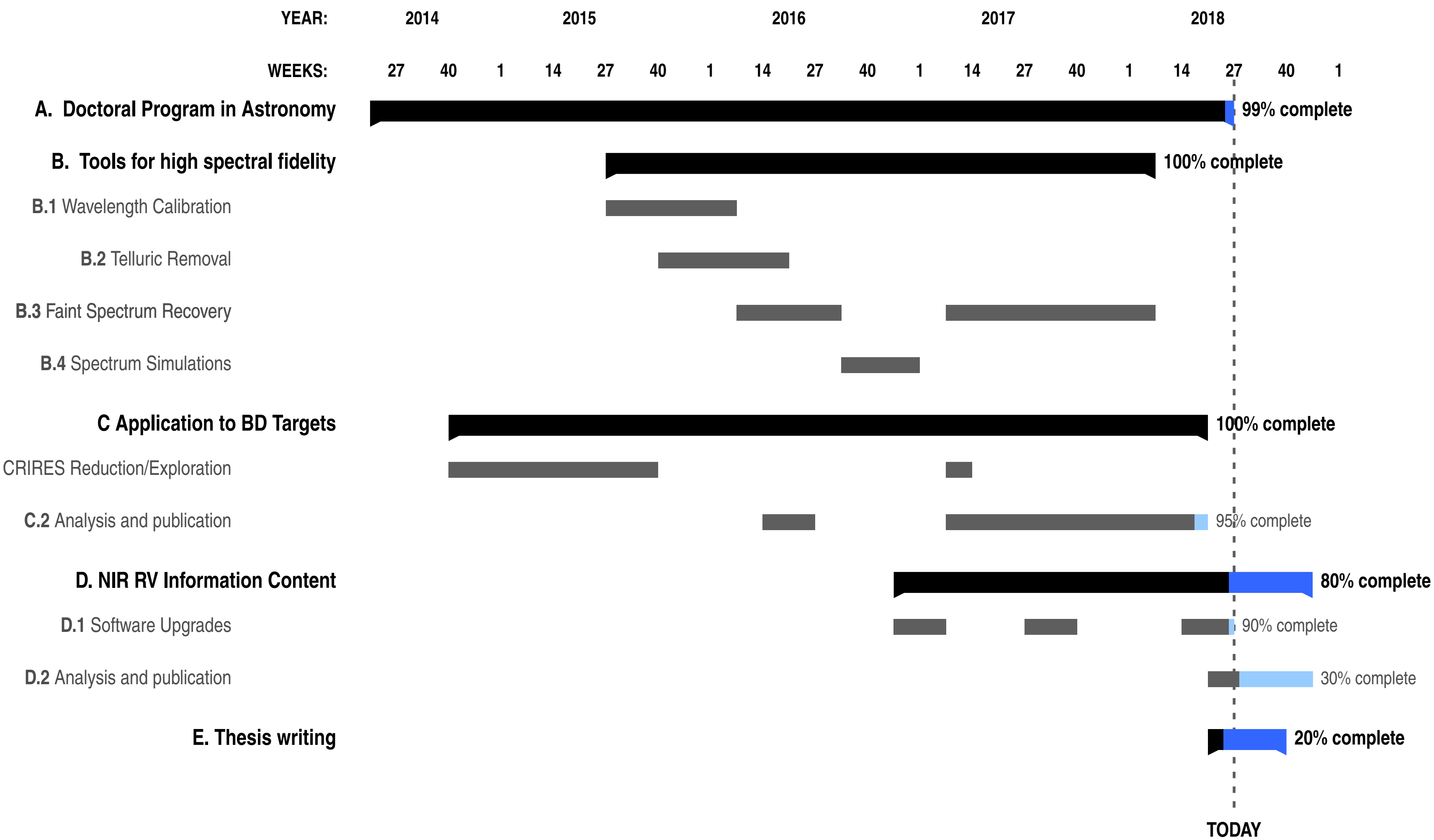

Figure 2: Updated time-line showing the current progress. The publication for section D will likely appear after the thesis is finished.

Thesis writing

So far I have made some progress on the thesis, but not a huge amount. I plan to use a majority of the text from the recently submitted paper (23 pages) but this will all needs edited, and expanded upon. I have currently been focusing my attention to the chapter about NIR precision, while I revisited this work. The goal is to submit as soon as possible although I do not have a clear plan of when that is likely to occur. I do however have a fix deadline of being back in New Zealand for Christmas.

The layout of the thesis contents page is expected to look something like this after completion.

1 Introduction:
   - Stellar bodies - Stars/B-Dwarfs/planets/binaries
   - Compositions/Atmospheres
   - Towards planetary atmospheres
   - Detection methods
   - High resolution NIR
   - NIR information content for RV instruments

2 NIR Reduction
   - NIR reduction overview
   - Key reduction steps
   - DRACS / ESO pipeline comparison
   - Data selection
   - Post reduction steps
     * Wavelength calibration
     * Telluric correction
     * Bad pixel correction

3 Differential Subtraction Method
   - Subtraction technique
   - Application
   - Observational issues

4 Companion recovery
   - Outline χ^2 Method
   - Application to Simulations
   - Application to Observations
   - Injection - recovery
   - Limitations
   - Synthetic model differences
   - Faint companion line depths
   - Wavelength limitations

5 NIR precision
   - Derivation of NIR precision
   - Preparation of Models and CARMENES spectra
   - Synthetic and Observed quality
   - Metallicity/ logg impacts on precision
   - Usage in ETC's
   - Improvements implemented

Conclusion

This year finally saw the submission of the long promised paper. The difficulty in detection and lack of important/interesting results drew out time line (Fig. 2) longer than expected. Moving beyond the paper progress has started on the newer section of work and progress has started on the thesis document.

References

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Ulmer-Moll, S., Figueira, P., Neal, J. J., Santos, N. C., & Bonnefoy, M. 2018, in review