DOCTORAL PROGRAM IN ASTRONOMY

PROGRESS REPORT

2015-2016

Towards Exoplanetary Atmospheres: new data reduction methods for the nIR

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1 | Overview

Exo-atmospheres, one of the forefronts of exoplanetary science, has shaped science and scientific instrumentation for the last decade. Over the past year we have been developing new methodologies and software tools for the extraction of minute signals from the NIR (near-Infrared) spectra of exoplanets.

The two main goals defined in the thesis proposal submitted last year are:

1. Development of tools for high spectral fidelity

2. Application to brown dwarf and exoplanet targets

The tool development has been the main focus of this year using the available brown dwarf spectra to test each step of the process. Good progress towards the the thesis goals has been made this year, although, there was a slight delay due to the birth of my daughter in mid-April, see Figure 1. We are now at a stage to begin identifying the atmospheric absorption lines of the brown dwarf after performing wavelength calibration, telluric line correction, and spectral subtraction.

This report covers the activities performed and the tools developed during the academic year 2015-2016 and outlines the adjusted direction of the PhD.

Figure 1: Amelia Jane Neal

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2 | Brief Description of the Work Done

2.1 Reduction Software

The first task completed involved reducing the CRIRES spectra, this means extracting the spectral information from the raw spectrograph images. There were two options for reducing the data, using the ESO reduction software or a in-house built software called DRACS (Data Reduction Algorithm for CRIRES Spectra). Time was spent reducing the data with both methods to determine which software gave better performance. The top panel of Figure 2 contains a small section of a spectra reduced by both methods to visualize the differences.

There were compromises between the two methods but DRACS was the preferred choice. The line depths of both methods gave comparable results and were used as a consistency check of DRACS. The faster reduction speed, the lack of bad pixels in the reduced spectra were the main advantages for choosing DRACS. Two IRAF scripts were written to extend the DRACS functionality. One to normalize and one to combine the reduced spectra following the decision to use DRACS.

The reduction knowledge obtained has also been used to reduce CRIRES data for collaborations within the exoplanet group. Specifically spectra from Barnard's Star for Daniel Andreasen to determine stellar atmospheric parameters and for Solène Ulmer-Moll to test the performance of different telluric correction software.

2.2 Wavelength Calibration

A wavelength calibration is needed to assign wavelength values to each pixel position of the detectors for the DRACS reduced spectra. I developed Python scripts to calibrate the wavelength of the DRACS reduced CRIRES spectra. We use a different calibration methodology than commonly used. A model of the absorption spectrum of Earths atmosphere calculated for the time of each observation is used to wavelength calibrate each spectra. The telluric line model is fitted with a sum of m absorption lines, while the observed spectra are fitted with a sum of m telluric absorption lines multiplied by a sum of n stellar absorption lines. All absorption lines are fitted as gaussians. A quadratic function is fitted to the central pixel/wavelength values of the matching m absorption lines to assign each pixel value a wavelength (Figueira et al. 2010; Brogi et al. 2016) . Selecting the best lines to fit is a manual process and care is needed due to the presence of shallow lines, noise, blended stellar lines, and unexpected telluric line depth compared to the model.

Currently the calibration fit is performed on each of the 4 CRIRES detectors individually. It is observed that wavelength calibration is poor near the very edges of the detectors, outside of the telluric line positions used for the calibration. This is especially true for detectors that have few telluric lines to calibrate with or have a skewed distribution of lines along the spectra.

A wavelength calibrated DRACS spectra can be found in Figure 2 (top) along with the telluric model used for the calibration and a ESO reduced spectra.

2.3 Telluric Line Correction

The telluric line contamination from Earths atmosphere needs to removed from the observed spectra for us to detect the minute signals from the atmosphere of planets around other stars. This is achieved by dividing the observed spectra by a spectra containing only the telluric absorption lines. In our case we use the exact same telluric line model that we use for wavelength calibration. This is very different from the usual telluric correction method which involves taking observations of a second star with well known and/or featureless spectra (e.g. A0 V star), near in time, close in airmass to the target (Vacca et al. 2003). The observations of the second star is used to obtain the telluric absorption spectrum which can be used to correct the target spectrum. This involves extra costly observation time, with strict observational requirements.

To obtain the model telluric spectra we use the TAPAS (Transmissions Atmosphériques Personnalisées Pour l'AStronomie) web-service (Bertaux et al. 2014). TAPAS performs the atmospheric transmission computation with the standard LBLRTM (Line-By-Line Radiative Transfer Model) radiative transfer code along with atmospheric data. The TAPAS spectra are downloaded for the exact time of each observation, with many other important parameters such as observatory location, pointing direction, instrument resolution, and atmospheric model choice. Note, however, that the atmospheric data used in TAPAS only has a temporal resolution of 6 hours.

Even though there is a nice web interface to request the TAPAS spectra, it quickly became tedious to fill in all the parameters for all the observations. Therefore, I created a Python script to fill out an XML request template (available on the website) with information extracted from the CRIRES observations. The request needs to be copied into the web browser to be submitted, but it still makes it quicker to request TAPAS spectra for each of the observations. This code can be found on my GitHub page `https://github.com/jason-neal/equanimous-octo-tribble` as tapas_xml_request_generator.py. I also created another script to give the results returned by TAPAS more useful names based on the observation and parameters they were generated for. This script tapas_spectra_namer.py is also publicly available on my GitHub.

The telluric correction code currently implements two different corrections. The first applies an exponential airmass ratio scaling ($\beta = \frac{\text{model airmass}}{\text{observation airmass}}$) to the telluric model spectra T^{β} to adjust the line depths (Gullikson et al. 2014). The second first removes the non-H_2O telluric lines, then fits the H_2O scaling factor and removes the scaled H_2O lines. This is because the H_2O lines were not being corrected fully. Bertaux et al. (2014) suggest that the transmission spectra, T, of H_2O lines need to be scaled as T^x, with x an arbitrary scaling factor, at full resolution and then convolved to the resolution of the instrument. This additional H_2O fitting has only just been finished but its preliminary usage suggests that the H_2O fit may be biased towards the few deep lines in our spectra which negatively affects the correction of the weaker H_2O lines. The result of using both the airmass and H_2O scaling methods of telluric correction are shown in the middle panel of Figure 2.

2.4 Atmospheric Feature Extraction

Some work has been done in preparation for extracting the atmospheric signal of the planet/brown dwarf from the reduced spectra. After correcting the telluric lines each spectra need to be shifted to correct for the heliocentric motion of earth. This will align the spectral lines of the star, which, should cancel out when two spectra are subtracted from one-another. This should leave two copies of the planet spectra from the planet/brown dwarf atmosphere with one positive and one negative with a radial velocity offset due to the different times of the observations. The bottom panel of Figure 2 shows the first new results, after subtracting one corrected spectra from another. The highlighted regions indicate where strong stellar and telluric lines were in the original spectrum so are regions to analyze carefully. The next step is to investigate the observed peaks in these results and try and extract the planetary spectra.

2.5 MIR Investigation

During this thesis we wanted to extend our NIR knowledge into the mid-infrared (MIR) to be prepared for the up coming mid-infrared instruments on-board the James Webb Space Telescope due to be launched in 2018. We investigated using a ground based MIR spectrograph on the VLT, VISIR (VLT spectrometer and imager for the mid-infrared), to obtain MIR spectra.

For the ESO proposal call P97 we investigated observing the close, bright and well studied star HD189733 which hosts a hot Jupiter. For the proposal call P98 we investigated trying to observe the atmosphere of a recently discovered very large (msini 15.1 M_J) secondary companion in a wide orbit around HD219828 (Santos et al. 2016). Brown dwarf formation models were analyzed to determine the contrast ratio between the star and the large planet. The calculated signal-to-noise required to detect the planetary atmosphere was of order 10^3 making it unfeasible to observe. The ESO exposure time calculator estimated that we would need hundreds of hours of observing time!

These two proposals would have been possible avenues for the thesis project as we had planned on capitalizing on the upgraded of VISIR to VISIR2.0. Unfortunately, the still low limiting magnitude of VISIR2.0 made it impossible for us to pursue these objectives. At this stage it is not possible to detect extra-solar planet atmospheres from the ground in the MIR.

2.6 Complementary Activities

This year I have attended the lectures and their associated tutorials for a number of advanced courses and other activities held in the department. These include

- Bayesian Statistics - João P. S. Faria
- ESO proposals workshop - Jarle Brinchmann - Worked on the science case for our unfeasible P98 proposal.
- Cosmology with Clusters - Alain Blanchard
- Soft skills - Ana Salgado - Presentation and speaking skills.
- CAUP Hack-day - Created a script that takes articles from arXiv and creates an audio file so that you can listen to journal articles. Not related to my PhD project.

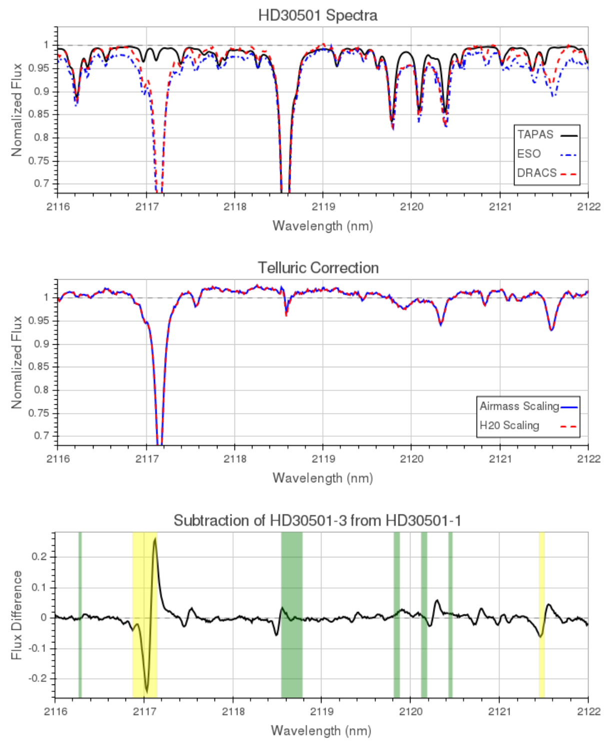

Figure 2: An example spectrum showing the progress made during this year. (top) A reduced CRIRES spectrum of HD30501 from both the ESO reduction software (blue dash-dot) and DRACS (red dashes), along with the TAPAS telluric line model for this observation (solid black). (middle) Telluric correction of the DRACS spectrum from the top panel by dividing it by the TAPAS model spectrum. The two lines represent, standard airmass scaling (red dashed) and the H_2O scaling + convolution method (blue solid). (bottom) The result of subtracting two telluric corrected spectra observed at different times and corrected for Earth's barycentric motion. The locations where telluric and stellar absorption lines were deeper than 5% are highlighted ***green*** are ***yellow*** respectively. It is from this spectrum that we aim to find and extract the atmosphere absorption lines of the brown dwarf.

2.6.1 Codes Developed

Although the code for the main tools I am developing are currently in a private repository there have been other interesting tools/scripts that I have developed over the last year which are publicly available on my GitHub at `https://github.com/jason-neal`. Some of the better ones are listed below.

- snr_calculations.py - Obtain the signal-to-noise of a spectra in different ways
- arxivTTS - Tool to turn papers on arxiv into audio using Text-To-Speech.
- tapas_xml_request_generator.py - Generate XML request for TAPAS given CRIRES fits file or list of files.
- tapas_file_namer.py - Name the returned TAPAS file using value from inside.
- IP_Convolution.py - The improved performance convolution code.

3 | Updated Work Plan

3.1 Spectral Recovery

The first goal of the coming year is to finalize the telluric removal tool developed, continue development of the spectra recovery and apply these all to the Brown Dwarf data on-hand. A technique to find and extract the planetary atmosphere signals (if present) will need to be developed to analyze the recovered spectra. This will likely involve synthetic planetary spectra, wavelength masks, and cross correlation to measure the brown dwarfs radial velocity (RV) offset. This work will result in a paper even if a null detection occurs because it would provide upper mass constraints on these targets, when only a lower limit is given by RV calculations. At this stage the plan is to have a draft by September and to have it submitted to a peer-reviewed journal before the end of 2016.

3.1.1 Spectral Simulations

Depending on the results from spectral recovery, spectral simulations may be needed to determine if there are spectral limitations of the signal recovery. These could include the affects of the wavelength range, resolution or the signal-to-noise. The decision to undertake this will be made once the spectral recovery is complete and as such is indicated as starting after the spectra recovery tool is finalized in the time-line show in Figure 3 below.

3.2 Observing Proposals

The investigation that was done for the previous proposal calls revealed that the currently available instruments are not sensitive enough for our purpose of detecting planetary atmospheres in the MIR. At this stage there is no plan for another proposal attempt but this choice will be re-evaluated when the tools are fully developed, applied, and the publication submitted.

3.3 Change of Focus

It has become apparent that the completion of the CRIRES upgrade to CRIRES+ will not occur before the end of my PhD. The original installation date of CRIRES+ was scheduled to be the beginning of 2017, and thus compatible with the thesis, but it is now Q2 of 2018. There has to be a shift of focus away from obtaining and analyzing CRIRES+ data during the PhD. Although we should be in a good position for when it eventually does come on-line. Two options have been discussed regarding the plan after the tools are finished and the paper is written.The first option is to apply our methodology and tools to try an reproduce published results. In particular we would apply our tools to reduce and analyze high-resolution transmission spectroscopy data presented by (Snellen et al. 2010) and (Brogi et al. 2016) which use carbon monoxide absorption in the NIR to detect planet motions and atmospheric winds of HD209458 b and HD 189733 b respectively. This would be a vigorous test of the tools developed and validate the interesting results presented in these papers.

The second option would be to apply the tools developed to other data available within the exoplanet group. These are spectra for radial velocity calculations though so are outside the original scope of this PhD topic. We plan to allow eight months to determine the feasibility of the first option. If it is not feasible we will move on to the second option for the remaining time of the PhD.

3.4 Team Collaborations

I have joined a large observation program which is very likely to be accepted entitled ”Rocky or gaseous? Exploring the composition of small worlds using K2 and HARPS”. This will require me to perform observations at La Silla, Chile sometime within the next two years. This will be my first professional observing experience and also my first experience being involved in a large collaboration team.

I have also been invited to join a new coding project being started within the exoplanet group called SOAP-opera, an attempt to combine the SOAP stellar activity models with Approximate Bayesian Computation. My growing knowledge with Python may be helpful in the discussions and its implementation. Involvement in this allows me to expand my research experience further.

The PhD project of a fellow student in the group is focused on telluric line corrections. I can potentially contribute to discussions based on the telluric corrections I have performed. I have already reduced and calibrated CRIRES spectra for them and helped them to overcome some software challenges. Hopefully their work will also be able to positively contribute back to my telluric correction as their research progresses.

3.5 Adjusted Time-line

The have been some slight adjustments to the proposal time-line, see Figure 3, to reflect the progress made and changes in direction.

The PDA class AST372 has been added to the doctoral program section to show the progress level of the points collection is slightly behind schedule. I will attend a advanced school in July and the aforementioned paper will push it ahead. I do note this task must be completed by this time next year so that the PhD can be completed before four years.

A separate wavelength calibration task was added as this took a significant amount of time and was separate to the telluric removal. The observing proposals sections were moved to the time in which they were investigated and no extra time has been scheduled at this point in time. Some of the positions and lengths of the bars have been adjusted to reflect the actual time spent on the tasks.

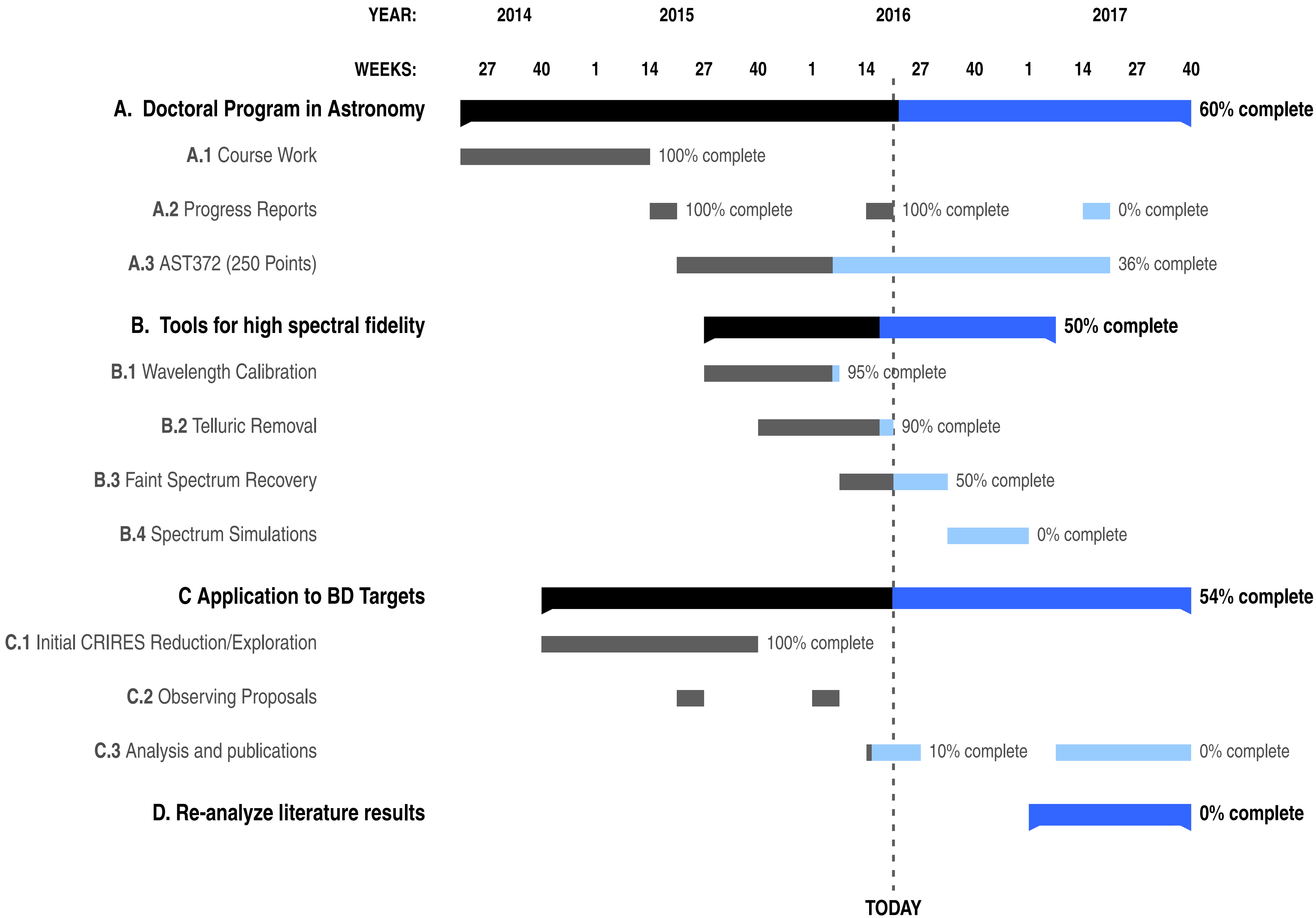

Figure 3: Updated time-line showing the current progress.

4 | Conclusion

In conclusion, good progress has been made over this year, developing the tools to wavelength calibrate, using a model telluric absorption spectra, and to perform telluric line correction. We will now apply these tools to the brown dwarf data available and analyze the resulting spectra for atmospheric features. A paper will be published before the end of the year with the results of this work. A plan has been put in place for the research direction to take after the paper is published with a feasibility milestone determined. Collaborations have also been started with other members of the exoplanet team which involve software development, NIR spectra reduction, telluric corrections and will provide observing experience.

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