Accretion Disk Winds Across The Mass Scale: PhD Transfer Report

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ABSTRACT

Broad Absorption Lines (BALs) in the Ultraviolet are seen in $\sim 20\%$ of Quasi-Stellar Objects (QSOs), and are also prominent in spectra of Cataclysmic Variables (CVs) and some X-ray Binaries. Blue-shifted BALs are the most direct evidence of accretion disk 'winds' in such systems; mass loaded outflows emanating from the disk, which may be driven by line forces or magnetic processes. Here I present an eighteen-month transfer report on a PhD project that involves using a Monte Carlo radiative transfer code capable of modeling a variety of systems. The aim is to both help inform our understanding of the profound connection between accretion and mass loss processes, and test unification models in QSOs, CVs and X-ray binaries. The code produces synthetic spectra for different viewing angles in a biconical disk wind model by passing photons through a wind geometry with a self-consistently computed temperature and ionization structure. In addition to presenting some relevant background and results so far, I give an outline of projects and timescales for the remaining work that will contribute to the final thesis.

1 INTRODUCTION

Outflows are crucial to our understanding of accreting systems and are close to ubiquitous across approximately 10 orders of magnitude in mass. These outflows can take the form of highly collimated radio jets (Belloni 2010), but can also manifest in more mass-loaded 'winds' emanating from the accretion disk. The most spectacular evidence of disk winds is blue-shifted broad absorption in spectral lines, a phenonomenon observed in Active Galactic Nuclei (AGN) and Quasi-Stellar Objects (QSOs; Turner & Miller 2009, Weymann et al. 1991), Cataclysmic Variables (CVs; Cordova & Mason 1982) and X-ray Binaries (Ioannou et al. 2003).

It is therefore clear that outflows present a unique opportunity to probe the proposed *universality* (e.g. Mchardy 2006) of the accretion process across the mass scale, whilst also providing potential *unification* models for (see e.g. Elvis 2000) each class of object. Despite this, the full effect of a disk wind on the observational appearance of an accreting system remains unclear, and even the fundamental theoretical questions relating to the origin and driving mechanism for mass loss are unsolved (see Proga 2000 and Proga 2010 for two theoretical reviews). These problems affect a variety of astrophysical phenonena. Disk winds provide a possible source of AGN feedback, which is a crucial component in galaxy formation and evolution models (e.g. Silk & Rees 1998). Cataclysmic variables are one possible progenitor for Type Ia Supernovae, standardisable candles used to predict the accelerating expansion of the universe, and so the role of accretion in the evolution of these systems must be understood. Clearly, answering the questions relating to the theory and observational imprint of accretion disks and their winds is of wide-ranging significance.

Our team has recently embarked on a project in which a state of the art radiative transfer code, previously used to model resonance lines in CVs, has been enhanced and improved to be able to model a wider variety of astrophysical objects and emission mechanisms. The aim of the project is to answer the questions identified above, and to try and understand the full extent to which the disk wind acts as a spectral 'filter' in AGN/QSOs, CVs and X-ray Binaries. The near ubiquity of outflowing material in accreting systems also implies a deep connection between accretion and mass loss, so a natural focal point of our work is to assess the true extent to which accretion disks follow the so-called 'α-disk' treatment outlined by Shakura & Sunyaev (1973). Here I present an eighteen-month transfer report for a PhD project. In section 2 I briefly describe the code, and some of the methods we employ. In section 3 I provide a description of work carried out so far, and in section 4 I provide a plan of remaining work including a thesis outline. Finally, I conclude in section 5.

2 METHOD AND APPROACH

Python is a Monte Carlo radiative transfer code which uses the Sobolev approximation to treat line interactions, and utilises techniques outlined by Lucy & collaborators (Lucy & Abbott 1993; Lucy 1999a,b). To compute the temperature and ionization structure of the wind photons are flown through a user-defined wind geometry, and Monte Carlo estimators are recorded. The temperature is then adjusted to balance heating and cooling in the wind. The process is repeated until the code converges on a solution. Once the ionization and temperature is known, then a spectrum is obtained by tracking photons through the wind and collecting them in user-specified viewing angle bins. The code is first introduced by Long & Knigge (2002), who synthesized the UV spectra of CVs, successfully reproducing P-Cygni resonance line profiles whilst solving for ionization balance according to the method of Mazzali & Lucy (1993). Python has since been used with application to QSO wind modeling (Higginbottom et al. 2013), which involved a new ionization scheme to deal with the more complex power-law spectrum, and the inclusion of processes such as Compton scattering in order to correctly treat X-ray radiation transfer. In addition, Sim et al. (2005) used Python to model Hydrogen recombination line profiles in Young Stellar Objects, which involved implementing a 'macro-atom' line transfer mode.

2.1 Macro-atoms

Previously, Python used a two-level atom approximation (see e.g. Mihalas 1982) for its treatment of lines. This approximation is fast, and works well when treating so-called 'resonance lines' (such as C IV , OVI), in which the excited electron is strongly coupled to the ground state, but when a level is primarily populated from above then this becomes a poor representation. To reproduce recombination lines, it is therefore important to use an improved line transfer technique and level population solver.

By quantising matter into 'macro-atoms', and radiant and kinetic energy into energy packets (r- and k- packets respectively), Lucy (2002, 2003; hereafter L02, L03) showed that it is possible to asymptotically reproduce the emisssivity of a gas in statistical equilibrium without simplifying the treatment of line transfer. A full description of the scheme is well beyond the scope of this report (consult L02, L03), but the 'take-home' message is that the macro-atom scheme allows a full treatment of recombination cascades, with all possible transition paths available to an excited electron. While Sim et al. (2005) applied this technique to a Hydrogen-only model, we are now able to adopt a hybrid scheme. Any species in which recombination is expected to be an important process can be treated as full macro-atoms with transition probabilities available along all physically allowed channels. The other species are treated as so-called 'simple-ions'; They still follow the indivisible packet constraint but are simplified to two level atoms. This allows one to preserve the fast treatment of resonance lines by produce an improved representation of recombination, which is import for both the lines and also the recombination *continuum*

2.2 Code Validation

Python has previously been tested against a number of radiative transfer and photoionization codes. Comparisons of ionization balance with Cloudy (Ferland et al. 2013) can be found in LK02 and H13 showing excellent agreement, we have also conducted comparisons of ionization and spectral synthesis with the Supernova code Tardis. Tardis is described by (Kerzendorf & Sim 2014) and the spectral comparisons can be found therein.

In addition to these code validation efforts, I have also conducted tests of the macro atom scheme in Python to verify that it does indeed solve for level populations correctly and produces the correct level emissivities. The left panel of figure 1 shows a comparison between our level emissivities for the Balmer series compared with analystic calculations by Seaton (1959), showing good agreement in both the Case A and Case B limits (see Osterbrock 1989 for a discussion of these two commonly used approximations). The right panel of figure 1 shows a comparison of Helium I level populations (the most complex ion we currently treat as a macro-atom) between Python and Tardis models. Considering the two codes use different atomic data and Tardis, unlike Python, currently has a complete treatment of collisions between radiatively forbidden transitions, the factor of < 2 agreement is encouraging.

3 THE DISK WIND CONTRIBUTION TO THE OPTICAL SPECTRA OF CATACLYSMIC VARIABLES

Cataclysmic variables (CVs) are systems in which a white dwarf accretes matter from a donor star via Roche-lobe overflow. In non-magnetic, disk-dominated systems this accretion is mediated by an accretion disk which forms around the white dwarf. Nova-like (NL) variables are a particular subclass of object in which the accretion disk is in a permanent state of relatively high accretion rate ($\dot{M} \sim 10^{-8}$ $M_{\odot}$ yr^{-1}), making them the perfect laboratories to test the α-disk model.

For over three decades, it has been known that winds emanating from the accretion disk are important in shaping the

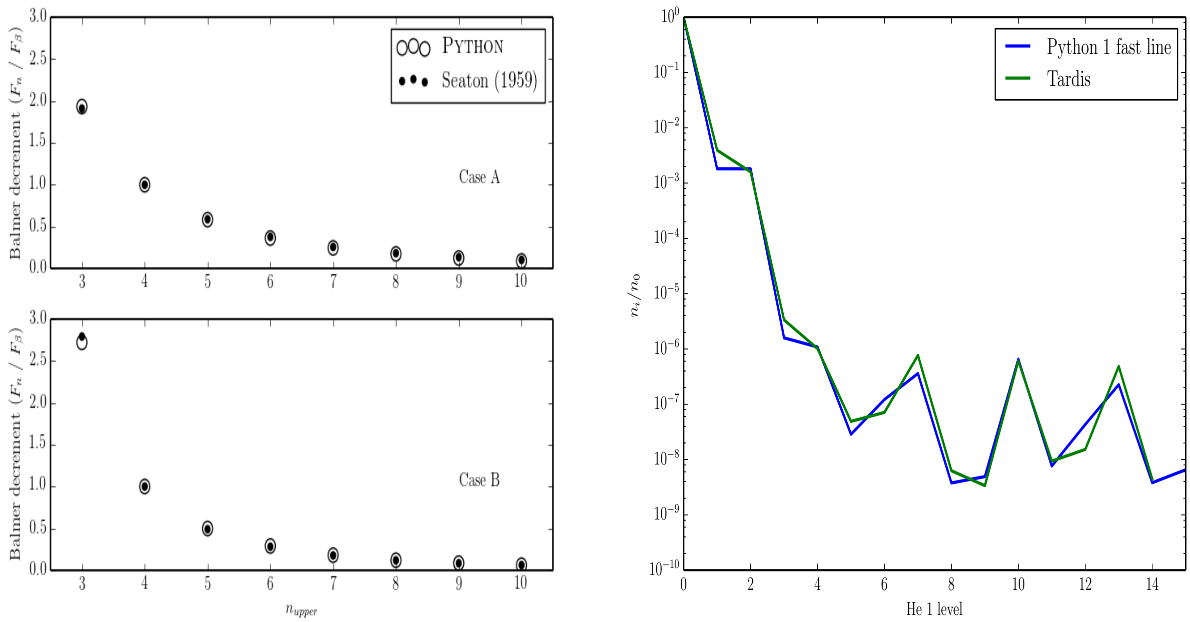

Figure 1. Left: Balmer decrements (level emissivities as a fraction of the $H\beta$ $4 \rightarrow 2$ transition) for a Hydrogen only model in the case A and case B limits. Large open circles show the test model in PYTHON , and filled circles show Seaton's predictions. Right: Level populations of an example cell with bound-free processes to excited levels disabled compared to a TARDIS calculation with the same physical conditions. The cell in question has $n_e = 10^8$ cm^{-3}, $T_e = 30,000$ K, $T_R = 40,000$ K and a dilution factor of $W =$???. We also adopt $\tau_{sobolev} = 0$ (optically thin limit). The level data for this comparison is obtained from Topbase.

ultraviolet spectra of high-state CVs (Heap 1978), the most spectacular evidence being the P-Cygni like profiles of resonance lines such as CIV (see e.g. Cordova & Mason 1982).

While the effect of the wind on the UV is at least partially clear, it may also have more subtle effects across the spectral range. It has been proposed that an accretion disk wind can cause single-peaked emission line profiles in the optical (Murray & Chiang 1996), such as those seen in Nova-like variables and SW Sex stars (Honeycutt et al. 1986; Dhillon & Rutten 1995). It is particularly telling that single-peaked lines can be seen even in eclipse, suggesting that a spatially extensive wind may be the source of emission (see Figure 3). In addition, Knigge et al. (1998) suggested that recombination continuum emission from a disk wind or atmosphere could be responsible for filling in the Balmer absorption edge, explaining the absence of a pronounced 'Balmer jump' in optical spectra of CVs.

We took the type of geometries and kinematics used to explain wind features in the ultraviolet (such as those used by LK02, but see also Shlosman et al. 1996; Noebauer et al. 2010) and applied our new, hybrid macro-atom radiative transfer scheme. The aim was to see if these models could reproduce some of the prominent optical lines, and if the recombination continuum emission was sufficient to mask the Balmer jump.

3.1 A Biconical Wind CV Model

We follow LK02 in adopting a biconical wind geometry originally outlined by Schlosman & Vitello (1993; SV93). This geometry is shown in figure 2. A smooth, biconical disk wind rises from the accretion disk between radii r_{min} and r_{max}. The covering fraction of the wind is controlled by the opening angles of the wind, θ_{min} and θ_{max}. As in LK02, we follow SV93's power law velocity profile.

3.2 Results

The synthetic spectrum from a model similar to that described by LK02, but with a slightly more slowly accelerating wind can be seen in Figure 4. We find that, at high inclinations the Balmer jump is filled in by recombination lines, and we successfully reproduce the Balmer emission lines. In addition, treating Helium as a macro-atom allows us to produce strong emission in He I & II lines. This can be seen in the UV spectrum () The results will be described in detail in an upcoming publication (Matthews et al., in prep).

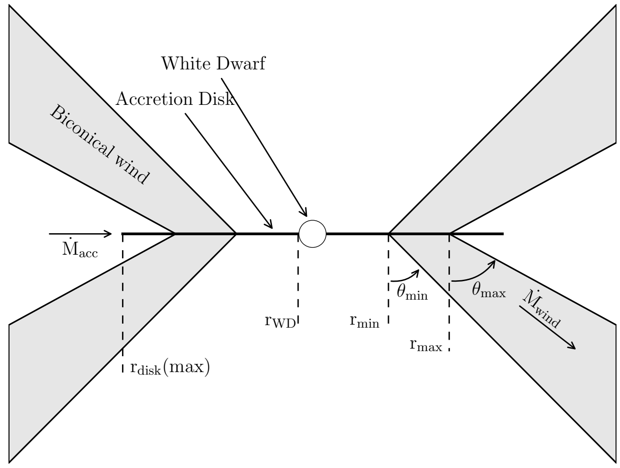

Figure 2. Cartoon illustrating the geometry and kinematic properties of the CV wind model.

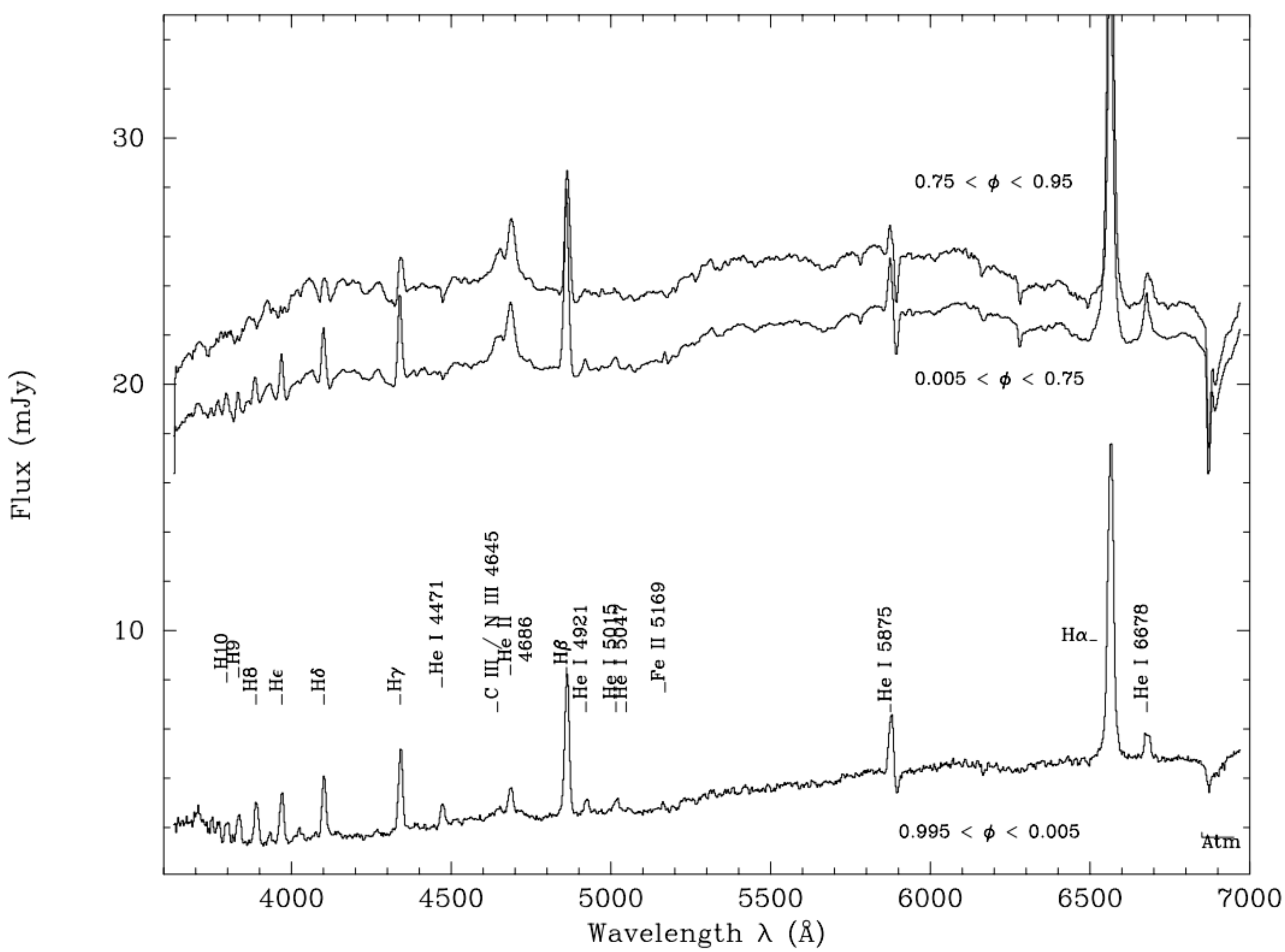

Figure 3. Optical Spectra of the high inclination Nova-like variable RW Triangulis. Single peaked lines can be seen even in eclipse, suggesting that a wind may be responsible for the emission in these lines (figure from Groot et al. 2004).

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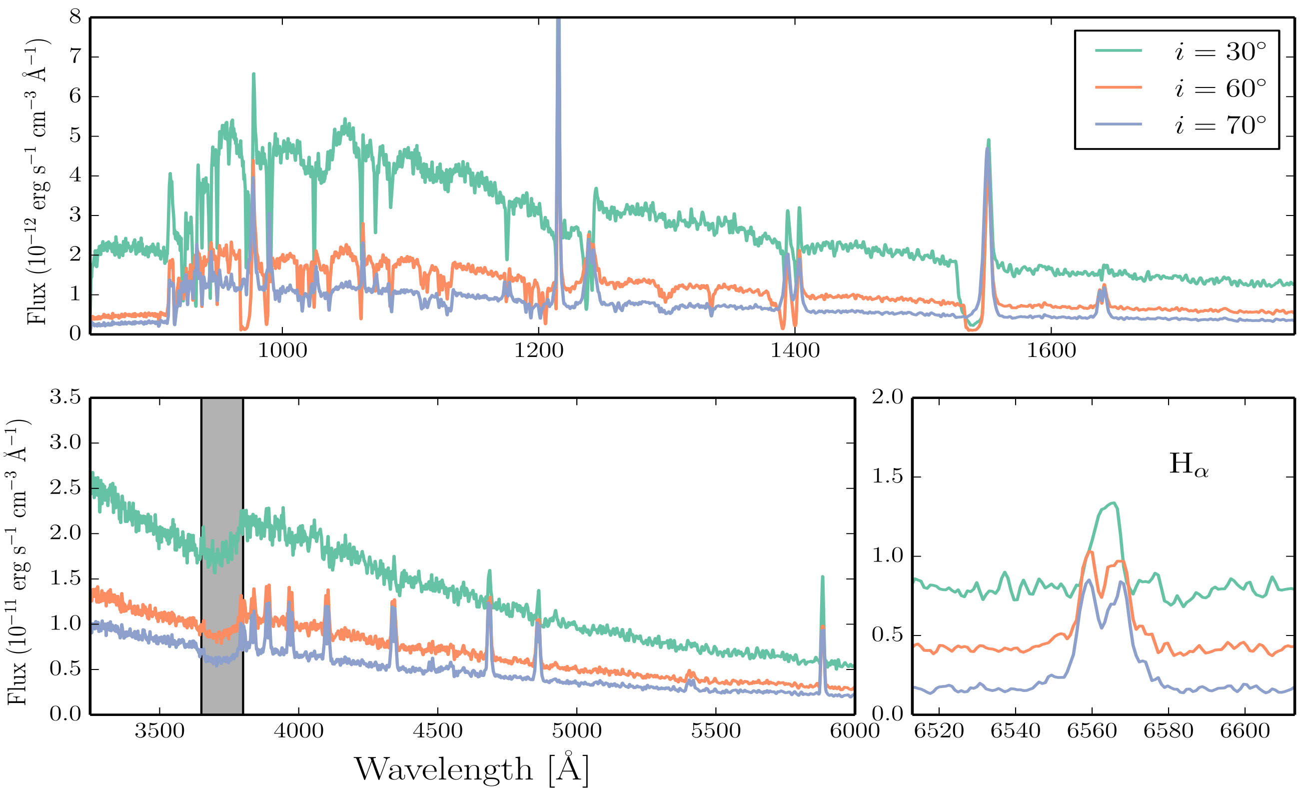

Figure 4. Optical (*bottom left*) and UV (*top*) spectra from a Cataclysmic Variable model calculated with Python for three viewing angles corresponding to inclinations of 30 (blue), 60 (green) and 70 (red) degrees. The transition from a P-Cygni like line profile to broad emission line in CIV can be clearly seen, and there is also a noticeable dependence on inclination in the shape of the Balmer jump. The grey shaded area shows an artificial dip caused by only using a ten-level Hydrogen atom. The bottom right panel shows a zoom-in on the H_α line profile, with an offset applied for clarity.

4 A UNIFIED QSO WIND MODEL

H13 present a benchmark disk wind model which successfully reproduces some aspects of BALQSO spectra (see figure 5). However, inspection of the model reveals three key shortcomings. First, the X-ray luminosity of the model is too weak for non-Bal angles. In addition, X-rays are attenuated by the disk wind and mean that for BAL angles the luminosity observed is low for a BALQSO. Second, the model fails to reproduce BELs, as not enough thermal line emission is produced. Third, the fiducial model fails to correctly model the Ly-α line, because it uses the two-level atom approximation. Fortunately, some progress has been made in addressing these three problems.

I have now improved the macro atom mode so that it can also deal with compton processes using the framework implemented by Nick Higginbottom. This simply involved adding an extra k-packet destruction channel for Compton heating, and k$\rightarrow$r process for Compton cooling. It is now also possible to run the code in hybrid macro/simple-ion mode using the improved ionization scheme presented by H13, and we hope that it may produce similar results to the CV case when modeling the Hydrogen lines in QSOs.

Here I will write something on QSO models I've run so far with more line emission and include a relevant figure.

5 THESIS PLAN & SUMMARY

Remaining work will be split between a number of projects, forming a thesis with a planned structure as follows.

Chapter 1: Introduction. Context and relevant background.
Planned Completion Date: *January 2016.*

Chapter 2: Accretion Disks and Their Winds. A theoretical and observational overview of the evidence for accretion disk winds, and a review of our current understanding of disk and wind physics.
Planned Completion Date: *January 2016.*

Chapter 3: Macro Atoms and Radiative Transfer. A description of radiative transfer techniques used in PYTHON including an outline of the macro-atom scheme and why it is so important.
Planned Completion Date: *January 2016.*

Chapter 4: The Disk Wind Contribution to Optical Spectra of Cataclysmic Variables.
Planned Completion Date: *June 2014.*
Details: Some results from this project are shown in Section 3. The broad conclusions are that when a full treatment of recombination is included then the emission from the wind is able to produce strong lines in Hydrogen and Helium, as well as providing sufficient continuum emission to mask the Balmer jump at some inclinations.

Chapter 5: A Disk Wind Unification Model for Quasi-Stellar Objects
Planned Completion Date: *January 2015.*
Details: See section 4. This project is a natural progression from previous work. Our team has already produced a proof-of-concept for the macro atom method in a CV context, and also presented a benchmark model for BALQSOs (H13). I will apply the macro atom method to our benchmark QSO model, and coupled with a geometry parameter search this will provide insights into whether or not a simple biconical wind geometry can produce Broad emission lines in resonance lines such as Carbon IV and lines such as Lyman-α. This project also provides the opportunity for collaboration with Francesco Shankhar who has identified a way in which our code could be used in conjunction with his work on the X-ray and optical properties of BALQSOs (see Morabito et al. 2013).

Final Science Chapter (Potential): Disk Wind Modeling of X-ray Binaries
Planned Completion Date: *October 2015.*
Details: P-Cygni line profiles in CIV have been observed in X-ray binaries, offerring a tantalising hint of outflowing material (Ioannou et al. 2003). I am a Co-I on the HST proposal 13630 which involves taking UV observations of the 'missing-link' pulsar PSR J1023, designed to assess the state of the wind when the system is in the accreting or radio pulsar stage of evolution. Modeling the system would provide an intriguing insight into the amount of mass loss and potential effects on the accretion disk, and would also allow us to constrain the wind geometry. Even a wider-ranging, proof-of-concept investigation into X-ray binary geometries would prove informative in both this context and more generally, using the groundwork on X-ray systems in our code carried out by H13. This project offers the opportunity for collaboration with the Co-Is on proposal 13630: Diego Altamarino, Rene Breton and Juan Hernandez Santisteban.

Final Science Chapter (Potential): Reverberation Modeling of Active Galactic Nuclei.
Planned Completion Date: *October 2015.*
Details: Reverberation mapping is an important technique in understanding the geometry of AGN systems (Peterson 1998). Incorporating predictions for reverberation mapping into our code is relatively straightforward; one simply has to track each individual photon's path length and origin as they travel through the wind. Once this is carried out, predictions for reverberation responses can be made for various wind geometries, and a direct comparison to reverberation mapping results will yield informative results and provide a well-defined project.

Chapter 7: Conclusions. A summary of the work carried out and its implications for the field.
Planned Completion Date: *January 2016.*

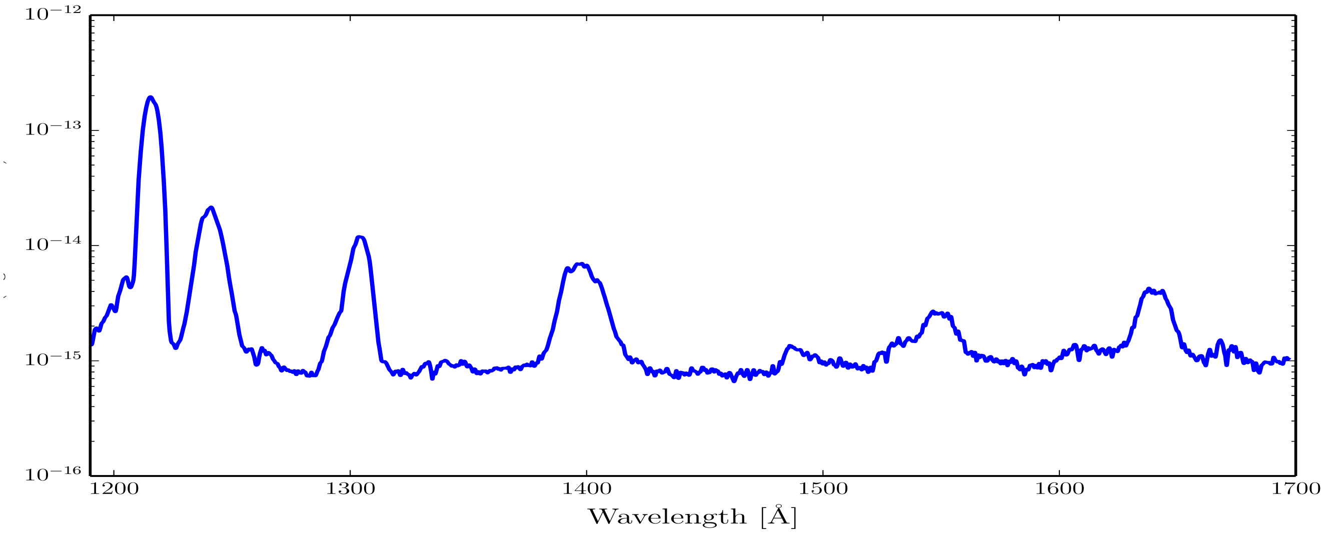

Figure 5. UV spectrum of PSR J1023.

5.1 Summary

At a bare minimum, I believe projects 1 & 2 would provide sufficient original research to constitute a thesis, providing that project 2 involved significant development of the benchmark H13 model and produced the anticipated high-impact work. However, given the time available, it is feasible that *at least* one of the remaining projects will be completed in time for the final thesis. The choice of project undertaken will depend on a number of factors:

- The conclusions we can draw from the data from HST proposal 13630, and the implications for modeling of X-ray binary winds
- The ability of our model to produce BELs, as this impacts whether including reverberation mapping is possible, and indeed relevant.
- The success of project 2 and the number of separate papers that come out of the study.

I believe a combination of the above projects presents a robust thesis plan. The Phd will involve the application of Monte Carlo techniques to a number of different types of system, with the theme of unification and universality providing a scientific link between projects which cover systems with masses ranging from one, to billions, of solar masses.

ACKNOWLEDGEMENTS

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