# Research Proposal

James Matthews, November 12, 2015

**The release of gravitational potential energy as mass falls towards a compact object is the most efficient energetic process in the universe, with a release of rest mass energy higher than that of nuclear fusion. This *accretion* process is thought to power the huge radiative engines at the centres of every galaxy – accreting supermassive black holes known as active galactic nuclei (AGN). These objects offer a unique opportunity to probe the most energetic of environments, while offerring an insight into Einstein's theory of general relativity, due to the strong gravity around the black hole. My research involves detailed modelling of the spectrum of radiation given off by AGN, and in particular the impact that outflowing material may have on this spectrum. Outflows are thought to be crucially important in the co-evolution of black holes and galaxies, as they provide an avenue by which the black hole may interact with its much larger scale environment. Studying the accreting and outflowing plasma around black holes therefore offers a tantalising glimpse into fundamental physics close to the black hole, as well as providing us with information of astrophysical importance on large scales.**

## 1 Introduction

Accretion is a universal process in astrophysics. Accretion discs are observed across approximately 10 orders of magnitude in mass, from white dwarfs to supermassive black holes. Despite being arguably the most important physical process in the universe, many crucial aspects of the physics of accretion discs remain unresolved. In addition to the inflowing accreting material, disc *winds* are ubiquitous in accreting systems. Evidence for these winds is seen in the broad absorption line quasars or *BALQSOs*, which make up about 20% of quasars (see figure 1). As well as being intrinsically linked to the accretion process, outflows offer a unique way for an accreting object to interact with its environment. They are crucially important in regulating the growth of supermassive black holes in galaxies, and can dramatically affect the evolution of galaxies throughout the history of the universe [15].

The physics of outflows also resides on uncertain ground. The driving mechanism of disc winds is still unknown, and the reason why disk winds seem to only appear in certain accretion states is an open question. Factor in the absorbing effect of an accretion disc wind (and implications for black hole 'spin'), and it becomes apparent that understanding outflow physics and the supposed universality of the accretion/outflow interaction is currently one of the most important astrophysical questions to address.

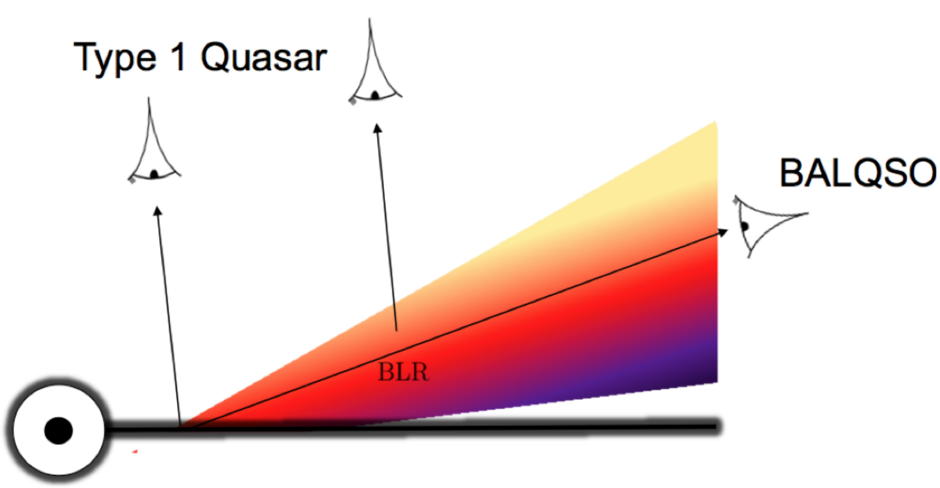


Figure 1: A cartoon describing the broad classes of sightline in a unfication model, illustrating how geometric effects lead to the different emergent spectra. The colour gradient is approximate, but indicates the stratified ionization structure, from highly ionized (yellow) to low ionization (purple) material.

## 2 Past & Current Research

My research career so far has been based around a powerful modelling tool: Monte Carlo Radiative Transfer. Over the past three years, I have been developing and testing a state-of-the-art radiative transfer code which allows one to self-consistently calculate the ionization state of a plasma and resultant emergent spectrum given an illuminating

SED and system geometry. This code has been used with application to YSOs, AWDs and quasars, with notable success.

My first project as part of the PhD involved modelling the wind of AWDs, also known as 'Cataclysmic Variables (CVs)'. P-Cygni profiles are observed in CVs in ultraviolet resonance lines such as C IV 1550 Åand Si IV 1400 Å, but the effect of the wind on the optical region of the spectrum is not well-known. Using radiative transfer and photoionization calculations, we showed that the wind can produce significant line and continuum emission, and may even *dominate* the spectral appearance of accreting objects. *This work is presented in a published paper [8].*

More recently, I have been expanding on the work of Higginbottom et al. [7] to assess the ability of a simple unified wind model to produce the spectra of quasars and BALQSOs, merely as a result of viewing angle effects. To do this, a treatment of clumping was incorporated into the code in order to prevent over-ionization and more realistically model the highly inhomogenous outflows expected in AGN [4, 11, 10]. The results are broadly summarised by figure 2, which shows two synthetic spectra at low and high inclinations compared to relevant observational data. This model is successful in reproducing much of the line and continuum emission phenomenology of quasars, with one main drawback. We find that it is not possible to reproduce the remarkably uniform line equivalent widths between quasars and BALQSOs due to a fundamental constraint based on the anisotropy of line emission and the disk continuum. At high inclinations, a foreshortened disk should lead to dramatically higher line equivalent widths for a moderately isotropic broad line region, but this is not apparent in comparisons between quasar and BALQSO composite spectra [16]. This problem is one of the main motivations for understanding the inclination dependence of line and continuum diagnostics from SDSS (see section 3). *This work is soon to be submitted to MNRAS and has been presented at a number of conferences.*

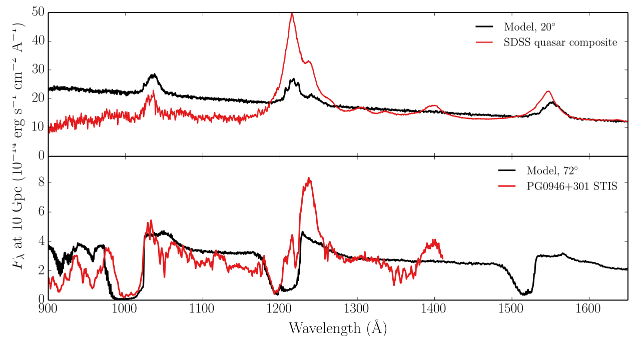


Figure 2: A comparison between a *Hubble Space Telescope* STIS spectrum of PF0946+301 and a synthetic spectrum at 75° from the Matthews et al. 2015 next generation model.

# 3 Future Research

Building on my expertise in radiative transfer and photoionization modelling, I aim to conduct my future research in three main areas, which are described in detail in the following sections.

## 3.1 Predicting Microlensing and Polarimetry Results from Simulations

**Microlensing:** One of the most interesting results of recent years relating to AGN and accretion disks is the discovery that the continuum emission region size is a factor $\sim 3$ larger than predicted by standard Shakura & Sunyaev disk theory [9]. This poses a distinct challenge to our current 'best bet' model for active galaxies. Microlensing analysis has also been carried out on emission lines, allowing the inference of broad line region sizes [6]. Tantalisingly, recent work using lensed BALQSOs finds that an extended reprocessing region is required to explain the magnification of the spectrum [14].

The suggestion that outflows might be crucial in the reprocessing of the continuum and the formation of the emission lines on larger scales than a standard accretion disk presents an obvious avenue for investigation using radiative transfer techniques. With modest alterations to the current code, it will be possible to create image projections on the sky. These images, produced from self-consistent radiative transfer calculation which will fully take into account reprocessing, can then interact with the normal microlensing analysis to discover if an extended outflow can explain any of the current discrepancies between disk theory and microlensing observations. This project offers a unique opportunity to investigate the potential impact of outflows on the emergent AGN spectrum, while simultaneously helping to assess the shortcomings of accretion disk theory.

I am particularly well-placed to undertake this investigation, as it combines my current research in AGN outflows and radiative transfer with my past work on microlensing [1]. In addition, I have identified and made contact with

Dominique Sluse, an expert in microlensing analysis, who has agreed to collaborate on this topic.

**Polarisation:** Spectropolarimetry of BALQSOs shows that the light is polarised, with a polarisation angle that is often offset from the position angle of the radio axis [5]. This measurement is one of the few direct measures currently possible of probing the angular distribution of scatterers around the central object.

I aim to incorporate polarisation into our radiative transfer code using much the same method implemented in similar radiative transfer codes such as SKIRT. This will allow, for the first time, predictions of polarisation signatures from a wind model with a self-consistently calculated ionization and temperature structure. Once this is complete, two main investigations are possible. First, I will compare the polarisation properties of previously published AGN models [2, 7] to understand if the measured BALQSO polarisation angles really are best explained by an equatorial wind. Second, I will expand on the work of Frederic Marin by examining if similar models can naturally reproduce the observed polarisation dichotomy in Type I and II AGN and quasars.

## 3.2 Effectively Modelling X-ray Lines and Compton Humps

When highly ionized plasma is illuminated by an X-ray power law it natural produces a series of high excitation lines and a compton hump caused by compton downscattering of hard X-ray photons (see figure 3 and [3]). Our radiative transfer code has recently been improved to explicitly include compton downscattering via the cold electron approximation, and tests reveal a small compton hump when X-ray photons are scattered off a thin shell of plasma. In addition to the compton hump, X-ray models and observations of X-ray binaries and AGN often show a strong, broad 6.4 keV iron line with a corresponding photoionization K-edge. These features are thought to be caused by reflection off the accretion disk of hard X-ray photons from a 'corona' – hot electrons in a fairly compact region close to the black hole.

The effect of absorption on the iron line and overall reflection spectrum is difficult to model and assess quantitatively. Perhaps unfortuantely, comptonisation of the iron line can lead to a red 'tail' [13] somewhat similar to the signature expect from general relatistic effects. It is therefore critical to understand what effect an outflow may have on the line profile.

We have recently begun work on a number of improvements to our code:

- Adding an option for a 'lamp-post' style geometry for the X-ray source.
- Allowing additional plasma regions so one could self-consistently calculate the vertical and radial ionization structure in a disk atmosphere, and produce resultant reflection spectra.
- Expanding the atomic database of the code to include higher order ions and X-ray lines.
- Incorporating a treatment of general relativity in the code for ray-tracing close o the black hole.

With these improvements we should be able to firstly model the reflection spectrum, which will be a step forward from previous 'illuminated slab' modelling efforts. This will also act as an important input to photoionization calculations. We will also then be able to assess whether comptonisation of the iron line can mimic general relativistic effects. I have been in contact with Maria Diaz-Trigo, a leader in the field of winds in X-ray binaries who is very interested in collaborating on this topic.

## 3.3 Uncovering The True Geometry of AGN disc winds

Orientation indicators are crucially important in ascertaining what inclinations we are viewing systems with evidence of outflows. I aim to utilise the *Sloan Digital Sky Survey (SDSS)* and catalogues of radio-loud quasars and BALQSOs to investigate the following properties.

- $\log(R)$ - the radio core dominance. An alternative parameter would be the radio spectral index.
- EW[OIII] - the equivalent width of the forbidden [OIII] 5007Å emission line, expected to be more or less isotropic.
- $L_{2000}$ - the continuum luminosity which will probe the foreshortening of the accretion disk.
- FWHM$_{H\beta}$ - the full width half maximum of the $H\beta$ 4863 Å line.

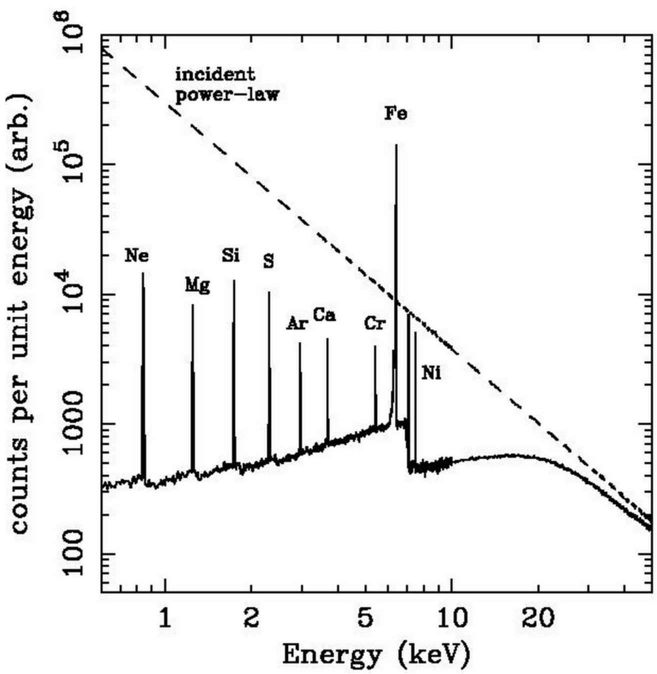


Figure 3: An example spectrum of X-ray reflection from an illuminated slab. The compton hump, high excitation emission lines can be clearly seen, as well as the Fe 6.4keV line Fe K-edge. The dashed line shows the incident continuum and solid line shows the reflected component integrated over solid angle. *Credit: Chris Reynolds PhD thesis, 1996.*

This project is somewhat more open ended than the others – it relies on correlating various line diagnostics informed by radiative transfer modelling. I would also produce equivalent width distributions of emission lines in BALQSO catalogues, and repeat the analysis of Risaliti et al. [12] to ascertain if the distributions are consistent with proposed unification geometries. This project would be complementary to the polarisation studies that currently offer some of the only clues to the opening angles of BAL outflows.

## 4 Summary

I hope that I have convinced the reader that a) this research is of wide-reaching astrophysical importance, and b) I have the requisite experience and expertise to carry it out effectively. I anticipate that the work described here could be completed on a timescale of approximately 3 years, with significant opportunities for expanding on the distinct projects described here. I also expect these projects to be collaborative, both with my existing team but also with new collaborators. Indeed, Oxford is an ideal place to conduct this research. Prof. Rob Fender, an accretion expert who has published work on winds in soft states of X-ray binaries, and Prof. Lance Miller, an expert in radiative transfer modelling of the broad line region, would both offer natural collaborative avenues.

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