UNIVERSITY OF SOUTHAMPTON

Accretion Disk Winds Across The Mass Scale

by

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in the
Faculty Name
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"Write a funny quote here."

If the quote is taken from someone, their name goes here

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Abstract

Faculty Name
Department of Physics & Astronomy

Doctor of Philosophy

by James Matthews

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...

Acknowledgements

The acknowledgements and the people to thank go here, don't forget to include your project advisor…

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Chapter 1

Introduction

"And now you're asking, I don't know
where to begin"
Mike Vennart, Silent/Transparent

The release of gravitational potential energy as mass falls towards a compact object is the most efficient energetic process in the universe, capable of liberating more rest mass energy than 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). In addition to AGN, accretion discs are seen in X-ray binaries (XRBs), young-stellar objects (YSOs) and accreting white dwarfs (AWDs). Accretion therefore appears to be a universal process; broadly speaking, the physics is the same whether it is taking place in a $\sim 1\ M_{\odot}$ Neutron Star or White Dwarf system, or a $\sim 10^{10}\ M_{\odot}$ black hole – a *quasar*.

Outflows are ubiquitous in accreting systems. We see collimated radio jets in AGN (REF) and XRBs (REF), and there is even evidence of extended radio emission in AWDs (REF). These radio jets tend to appear in specific accretion states (REF), implying an intrinsic connection to the accretion process. Even more intriguing, in XRBs less collimated, mass-loaded outflows or *winds* are observed in the opposite accretion state, possibly emanating from the accretion disc. Evidence for disc winds is widespread across the mass range, but perhaps the most spectacular indication is the blue-shifted, broad absorption lines (BALs) in the rest-frame ultraviolet (UV) seen in high-state AWDs (REFs) and so-called broad absorption line quasars seen in $20-40\%$ of quasars (BALQSOs; REFs).

The astrophysical significance of disc winds extends, quite literally, far beyond the accretion environment. They offer a potential mechanism by which the central accretion engine can interact with the host galaxy and interstellar medium (REFs). This is often referred to as AGN feedback (REF), and is required

This thesis is structured as follows. In the remainder of this chapter, I shall describe the different classes of accretion systems. In chapter 2, I will give the background accretion theory and detail the successes and failures of accretion disc models when compared to observations, before discussing the outflows associated with accretion discs in chapter 3. Chapter 4 outlines the Monte Carlo radiative transfer (MCRT) and photoionization methods I have used in order to investigate the impact of disc winds on the spectra of accreting systems. The science chapters contain three separate submitted papers, in which we investigated the impact of disc winds on the spectra of CVs (Chapter 5), and tested the disc winds quasar unification model (Chapters 6 and 7). In chapter 8, I summarise my findings and their astrophysical significance, and discuss potential avenues for future work.

1.1 Types of Accreting Systems

1.1.1 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 systems this accretion is mediated by a Keplerian disk around the white dwarf (WD). Nova-like variables (NLs) are a subclass of CVs in which the disk is always in a relatively high-accretion-rate state ($\dot{M} \sim 10^{-8}$ M$_{\odot}$ yr^{-1}). This makes NLs an excellent laboratory for studying the properties of steady-state accretion disks.

1.1.2 X-ray Binaries

X-ray binaries are similar to CVs in structure, except that the compact object is either a neutron star (NS) or black hole (BH). The accretion disc emits in the soft X-rays, and an additional hard X-ray power law is also seen in the spectrum (REFs). This hard component is normally attributed to Compton up-scattering of seed disc photons by some kind of 'corona' of hot electrons close to the BH (REFs).

Although I do not discuss XRBs directly in this thesis, it is instructive to discuss some of their observational appearance as it is instructive for understanding the theory of disc winds, as well as their wider significance. The discovery that XRBs follow similar tracks on a hardness-intensity diagram (REFs) is particularly interesting in this regard,

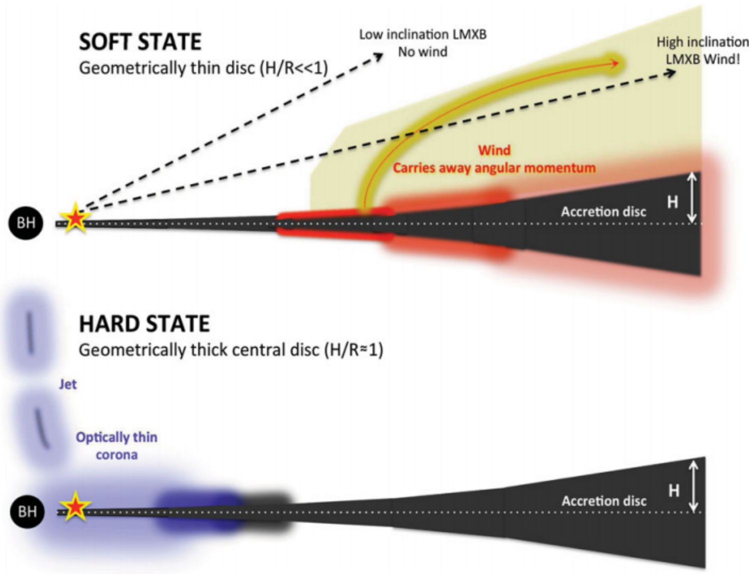

FIGURE 1.1: *Credit: Ponti et al. 2012*

especially since Ponti et al. (2012) showed that broad Fe absorption lines are only seen in the soft-state high-inclination systems, implying that equatorial outflows are intrinsic to the accretion process (see figure 1.1). Although the driving mechanism is almost certainly different to CVs (REFs), the similarity in general structure to models for CVs and quasars is striking.

1.1.3 Quasars and Active Galactic Nuclei

Chapter 2

Accretion Disks and Their Associated Outflows

As described in the Introduction, there are a wide variety of accreting systems with varying degrees of astrophysical significance. Here I will describe the physics of accretion in more detail, before discussing the theoretical and observational basis for accretion disk winds.

2.1 Accretion Disks

2.1.1 The Physics of Accretion

The basic phenomenon of accretion- matter falling into a gravitational potential well- is a ubiquitous one in astrophysics. The details of how and where the energy is released and how angular momentum is transported is subject to a number of different interpretations, mainly depending on the *geometry* of the accretion flow. The so-called α-disk model developed by Shakura and Sunyaev (1973) is currently the leading candidate for explaining how energy and angular momentum is transported through a thin disk of material, an accretion disk.

By considering the energy released through viscous dissipation in the disk it is possible to derive a temperature distribution as a function of radius (Shakura and Sunyaev, 1973, Frank et al., 1992).

$$T(R) = \tag{2.1}$$

It is important to recognise that the work of Shakura and Sunyaev (1973) *does not specify the nature of the disk SED*. What it does do is say where energy is originally released. Typically, accretion disks are modelled as a series of annuli each emitting as blackbodies, but it is possible that a disk atmosphere with frequency-dependent opacity would create a somewhat different spectrum. It is also possible that *neither* of these treatments are realistic. We shall therefore devote a little time to discussing the observational arguments for accretion disks and the current problems

2.2 Observational Appearance

2.2.0.1 Potential Problems with the Thin-disk model

A number of issues have been raised with the thin-disk model and its applicability to accreting systems.

2.2.0.2 Quasar emission region sizes from microlensing

2.2.0.3 Quasar emission region sizes from X-ray lags

2.2.0.4 The 1000Åbreak in AGN

2.2.0.5 The Spectral shape of CV disks

Attempts to fit the observed SEDs of high-state CVs with simple disk models have met with mixed success. In particular, the SEDs predicted by most stellar/disk atmosphere models are too blue in the UV (Wade, 1988, Long et al., 1991, 1994, Knigge et al., 1998a) and exhibit stronger-than-observed Balmer jumps in absorption (Wade, 1984, Haug, 1987, La Dous, 1989, Knigge et al., 1998a). One possible explanation for these problems is that these models fail to capture all of the relevant physics. Indeed, it has been argued that a self-consistent treatment can produce better agreement with observational data (e.g. Shaviv et al. 1991; but see also Idan et al. 2010). However, an alternative explanation, suggested by Knigge et al. (1998b; see also Hassall et al. 1985), is that recombination continuum emission from the base of the disk wind might fill in the disk's Balmer absorption edge and flatten the UV spectrum.

2.3 The Universality of Accretion

Accretion appears to be an important physical processes across ~ 9 orders of magnitude in mass. But is this process the same at all scales? Does any behaviour manifest in all accretion systems?

2.3.1 The RMS-flux relation

2.3.2 Accretion States

2.3.3 Jets and Outflows

2.3.4 A Global Picture

Clearly, accretion physics is relevant to a plethora of astrophysical phenomena. It would also appear that the outflowing material observed in accreting systems has a profound effect on the accretion process itself, as well as acting as a spectral 'filter' – modifying, and sometimes dominating the observational appearance of accretion disks.

2.4 Accretion Disk Winds: Observational Evidence

2.5 Accretion Disk Winds: Driving Mechanisms

2.5.1 Thermal Winds

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Chapter 3

Monte Carlo Radiative Transfer and Ionization

"I'm splashing greys where once was glowing white"
Mike Vennart, Silent/Transparent

In the previous chapters I have given, in fairly broad brush strokes, an introduction to the field and some relevant background relating to accretion discs and their associated outflows. Now it proves useful to discuss some of the specific *methods* one might be able to utilise in order to try and answer some of the questions raised in the previous sections. In particular, I will discuss radiative transfer techniques and their potential applications.

3.1 Fundamentals of Radiative Transfer

The most fundamental quantity of radiative transfer is the *specific intensity*, I_ν, defined as

$$I_\nu = \frac{dE}{d\Omega \; dt \; dA \; d\nu}, \tag{3.1}$$

which has units of erg s^{-1} Hz^{-1} sr^{-1} cm^{-2}. It is useful here to also define the 'moments' of the radiation field

$$I_\nu = \tag{3.2}$$

$$I_\nu = . \tag{3.3}$$

The equation describing the specific intensity change along a path element ds is the radiative transfer equation,

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + j_\nu, \tag{3.4}$$

where κ_ν and j_ν are the absorption and emission coefficients respectively. If we define the optical depth $d\tau_\nu = \kappa_\nu ds$ we can recast this as

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu \tag{3.5}$$

where $S_\nu = j_\nu/\kappa_\nu$ is the source function. This equation is called the *formal radiative transfer equation*, and can be solved to give

$$I_\nu = I_{\nu,0}\ e^{-\tau_\nu} + S_\nu(1 - e^{-\tau_\nu}) \tag{3.6}$$

3.1.1 Spectral Line Formation

From the above equations, it is trivial to show how emission and absorption lines form. Say we have a plasma illuminated by a blackbody of temperature T_0, such that $I_{\nu,0} = B_\nu(T_0)$. The plasma layer then has a different temperature, T, such that $S_\nu = B_\nu(T)$ in that medium. By inspecting equation 3.6 we can see that if we are optically thick within the line, but optically thin in the continuum, then inside the line the source term is dominant and outside the line the first $I_{\nu,0}\ e^{-\tau_\nu}$ term dominates. Therefore, if $T > T_0$ we will see an emission line, and if $T < T_0$ we will see an absorption line. This approach describes line emission in the blackbody limit; for more complicated SED shapes it is necessary to construct simple model atoms.

3.1.2 The Two Level Atom

The two level atom formalism is well described by Mihalas (1978).

3.1.2.1 Einstein Coefficients

Within the two level atom, the rate equation between the two levels in LTE can can be written by invoking detailed balance, such that

$$B_{12}\bar{J}_{21}n_1 = B_{21}\bar{J}_{21}n_2 + A_{21}n_2, \tag{3.7}$$

where B_{12}, B_{21} and A_{21} are the *Einstein coefficients* for absorption, stimulated emission and spontaneous emission respectively. In LTE, the level populations obey Boltzmann statistics, and thus we can also write

$$\frac{n_1}{n_2} = \frac{g_1}{g_2}\exp(h\nu_0/k_BT) \tag{3.8}$$

We can then rearrange equation 3.7 in terms of the mean intensity, and use the fact that, in LTE, $\bar{J}_{21} = B_\nu(T)$ to write

$$\bar{J}_{21} = (2h\nu_0^3)/c^2. \tag{3.9}$$

Since this must be true at all values of T we can also show that

$$A_{21}/B_{21} = (2h\nu_0^3)\ B_{12}/B_{21} = g_2/g_1 \tag{3.10}$$

3.1.2.2 Line Emission and Collisions

3.1.3 The Sobolev Approximation

The Sobolev approximation (SA) is a useful limit originally developed. It is used to treat line transfer in fast-moving flows. Originally the theory was mostly applied to Stellar winds, although since then a wide variety of astrophysical objects have been modelled using Sobolev treatments, such as accreting systems (this work) and Supernovae.

The Sobolev limit

3.1.3.1 Escape Probabilities

3.1.4 Monte Carlo approaches

Simple radiation transfer problems can be solved analytically, but with more complicated geometries it is necessary to utilise Monte Carlo techniques, which are easily solved with modern computing approaches and are intuitively parallelisable problems.

3.2 PYTHON: A Monte Carlo Ionization and Radiative Transfer Code

PYTHON[1] is a Monte Carlo ionization and radiative transfer code. The code has already been described extensively by LK02, SDL05 and Higginbottom et al. (2013; hereafter H13), so here we provide only a brief summary of its operation, focusing particularly on new aspects of our implementation of macro-atoms into the code.

3.2.1 Basics

PYTHON operates in two distinct stages. First, the ionization state, level populations and temperature structure are calculated. This is done iteratively, by propagating several populations of Monte Carlo energy quanta ('photons') through a model wind. The geometric and kinemetic properties of the outflow are specified on a pre-defined spatial grid. In each of these iterations ('ionization cycles'), the code records estimators that characterize the radiation field in each grid cell. At the end of each ionization cycle, a new electron temperature is calculated that more closely balances heating and cooling in the plasma. The radiative estimators and updated electron temperature are then used to revise the ionization state of the wind, and a new ionization cycle is started. The process is repeated until heating and cooling are balanced throughout the wind.

This converged model is then used as the basis for the second set of iterations ('spectral cycles'). In these, the emergent spectrum over the desired spectral range is synthesized by tracking populations of energy packets through the wind and computing the emergent spectra at a number of user-specified viewing angles.

PYTHON is designed to operate in a number of different regimes, both in terms of the scale of the system and in terms of the characteristics of the underlying radiation field. It was originally developed by LK02 in order to model the UV spectra of CVs with a simple biconical disc wind model. SDL05 used the code to model Brackett and Pfund line profiles of H in young-stellar objects (YSOs). As part of this effort, they implemented a 'macro-atom' mode (see below) in order to correctly treat H recombination lines with PYTHON. Finally, H13 used PYTHON to model broad absorption line (BAL) QSOs. For this application, an improved treatment of ionization was implemented, so that the code is now capable of dealing with arbitrary photo-ionizing SEDs, including non-thermal and multi-component ones.

[1] Named c. 1995, predating the inexorable rise of a certain widely used programming language

3.3 Macro-atoms

The macro-atom scheme was created by Leon Lucy and is outlined in his 2002/03 papers. It was implemented in PYTHON *by Stuart Sim, initially for the study of recombination lines in YSO (Sim et al. 2005).*

Lucy (2002, 2003; hereafter L02, L03) has shown that it is possible to calculate the emissivity of a gas in statistical equilibrium without approximation for problems with large departures from LTE. His macro-atom scheme allows for all possible transition paths from a given level, dispending with the two-level approximation, and provides a full non-local thermodynamic equilibrium (NLTE) solution for the level populations based on Monte Carlo estimators. The macro-atom technique has already been used to model Wolf-Rayet star winds (Sim, 2004), AGN disc winds (Sim et al., 2008, Tatum et al., 2012), supernovae (Kromer and Sim, 2009, Kerzendorf and Sim, 2014) and YSOs (SDL05). A full description of the approach can be found in L02 and L03.

The fundamental approach here requires somewhat of a philosophical shift. Normally MCRT is described in the most intuitive way- that is, we imagine real photons striking atoms and scattering, or photoionizing and depositing energy in a plasma. With Lucy's scheme one should instead reimagine the MC quanta as a packets of quantised energy flow, and the scheme as a *statistical* one. The amount of time a given energy quanta spends in a specific atomic level or thermal pool is then somewhat analogous to the absolute energy contained therein.

Following L02, let us consider an atomic species interacting with a radiation field. If the quantity ϵ_j represents the ionization plus excitation energy of a level i then the rates at which the level j absorbs and emits radiant energy are given by

$$\dot{A}_j^R = R_{\ell j}\epsilon_{j\ell} \quad \mathit{and} \quad \dot{E}_i^R = R_{j\ell}\epsilon_{j\ell} \quad , \tag{3.11}$$

Where we adopt Lucy's convention in which Similarly, the rates corresponding to *kinetic* energy transport can then be written as

$$\dot{A}_j^C = C_{\ell j}\epsilon_{j\ell} \quad \mathit{and} \quad \dot{E}_j^C = C_{j\ell}\epsilon_{j\ell} \quad , \tag{3.12}$$

If we now impose statistical equilibrium

$$(\mathcal{R}_{\ell j} - \mathcal{R}_{j\ell}) + (\mathcal{R}_{uj} - \mathcal{R}_{ju}) = 0 \quad . \tag{3.13}$$

we can then obtain

$$\begin{aligned} &\dot{E}_j^R + \dot{E}_j^C + \mathcal{R}_{ju}\epsilon_i + \mathcal{R}_{j\ell}\epsilon_\ell \\ = &\dot{A}_j^R + \dot{A}_j^C + \mathcal{R}_{uj}\epsilon_i + \mathcal{R}_{\ell j}\epsilon_\ell \quad . \end{aligned} \tag{3.14}$$

This equation is the starting point for the macro-atom scheme. It shows that, when assuming only radiative equilibrium, the energy flows through a system depend only on the transition probabilities and atomic physics associated with the levels the energy flow interacts with. By quantising this energy flow into radiant (r-) and kinetic (k-) packets, we can simulate the energy transport through a plasma discretised into volume elements ("macro-atoms"), whose associated transition probabilities govern the interaction of radiant and kinetic energy with the ionization and excitation energy associated with the ions of the plasma.

3.4 Simple-atoms

Prior to SDL05, the relative ionization fractions for all atomic species were estimated via the modified Saha equation (Mazzali & Lucy 1993)

$$\frac{n_{j+1}n_e}{n_j} = W[\xi + W(1-\xi)]\left(\frac{T_e}{T_R}\right)^{1/2}\left(\frac{n_{j+1}n_e}{n_j}\right)^*_{T_R} . \tag{3.15}$$

Here, the 'starred' term on the right represents abundances computed with the Saha equation at temperature T_R, but using partition functions from the dilute blackbody approximation. W is an effective dilution factor, ξ is the fraction of recombinations going directly to the ground state, and T_R and T_e are the radiation and electron temperatures, respectively. This simple ionization scheme produces reasonable results when the photoionizing SED can be approximated by a dilute blackbody. This is the case for high-state CVs. (As noted above, an improved, but more complex treatment of ionization that is appropriate for more complex SEDs is described in H13.)

Similarly, the relative excitation fractions within each ionization stage of a given species were estimated via a modified (dilute) Boltzmann equation,

$$\frac{n_{jk}}{n_j} = \frac{W g_k}{z_j(T_R)} \exp(-E_k/kT_R), \tag{3.16}$$

where n_{jk} is the population of level k in ionic stage j, E_k is the energy difference between level k and the ground state, g_k is the statistical weight of level k and $z_j(T_R)$ is the partition function of ionic stage j. This equation is approximate, and in general this approximation is not good. We therefore endeavour to treat any species in which the excitation state of the ions is thought to be important in determining either the ionizing radiation field, or emergent spectrum, as macro-atoms.

Finally, PYTHON originally modelled all bound-bound processes as transitions within a simple two-level atom (e.g. Mihalas, 1982). This framework was used for the treatment of line transfer and also for the line heating and cooling calculations (see LK02). The approximation works reasonably well for resonance lines, such as C IV λ1550, in which the lower level is the ground state. However, it is a poor approximation for many other transitions, particularly those where the upper level is primarily populated from above. Thus an improved method for estimating excited level populations and simulating line transfer is needed in order to model recombination lines and continua.

3.5 Heating And Cooling

3.5.1 Heating And Cooling Balance

3.5.2 Heating And Cooling Estimators

Here I've tried to use Lucy's notation for macro-atom estimators. Take a three level system, in which l and u represent lower and upper levels, and κ represents the continuum level or upper ion. q is the 'absorption fraction' derived below, and q_{ul} and q_{lu} are the collisional rate coefficients.

3.5.2.1 Macro-atoms

In the macro-atom approach, we basically treat two communication pathways. bound-free transitions represent a way for radiant energy to communicate with the thermal pool and bound-bound transitions represent a way for excitation energy to communicate with the thermal pool.

The heating and cooling rates for macro-atom bound-bound transitions are the rates of collisional excitations and de-excitations - i.e. the rate at which thermal energy is converted into bound-bound excitation energy and vice versa.

$$C_{bb,matoms} = \sum_{lines} q_{lu} n_l n_e h\nu_{ul} V \tag{3.17}$$

$$H_{bb,matoms} = \sum_{lines} q_{ul} n_u n_e h\nu_{ul} V \tag{3.18}$$

For bound-free transitions, we define the normal photoionization and recombination rate coefficients γ and α, where α includes stimulated recombination as we do in the code. Note this differs to the approach in Lucy (2003), where it is instead included as a negative photoionization term, hence the notation $\widetilde{\gamma}$. We also need to define two 'modified rate coefficients' which are the rates at which b-f transitions add and remove energy to the radiation field. These are denoted γ^E and α^E.

The rate at which recombinations convert thermal *and* ionization energy into radiant energy is then $\alpha^E h\nu_{\kappa l} n_\kappa n_e$, where $h\nu_{\kappa l}$ is the potential of the b-f transition, or the energy difference between continuum κ and the level l we are recombining too. The amount of this energy which is removed from the actual thermal pool therefore needs a quantity $\alpha h\nu_{\kappa l} n_\kappa n_e$ subtracted from it, giving

$$C_{bf,matoms} = \sum_{bf jumps} (\alpha^E - \alpha) n_e n_\kappa \nu_{\kappa l} V \tag{3.19}$$

where here I have also included stimulated recombination as we do in the code. Note this differs to the approach in Lucy (2003), where it is instead included as a negative photoionization term, hence the notation $\widetilde{\gamma}$. For photoionizations, we write a similar expression. The rate of at which a level l absorbs energy by b-f transitions is given by $\gamma^E h\nu_{\kappa l} n_\kappa n_e$, but the amount $\gamma h\nu_{\kappa l} n_l$ goes into ionization energy, giving

$$H_{bf,matoms} = \sum_{bf jumps} (\gamma^E - \gamma) n_l h\nu_{\kappa l} V \tag{3.20}$$

as the rate at which radiant energy heats the plasma via b-f transitions.

3.5.2.2 Simple-atoms

In simple-ions it is in some ways a little more complicated. First we define q which will be different for each b-b transition, following Nick's thesis, which is given by (NB: I don't actually know how to derive this)

$$q = \frac{q_{ul} n_e (1 - e^{-h\nu/kT_e})}{\beta_{ul} A_{ul} + q_{ul} n_e (1 - e^{-h\nu/kT_e})} \tag{3.21}$$

where β_{ul} is the angle-averaged escape probability. q represents *the probability that an excited bound electron will collisionally de-excite.* Our b-b heating rate is computed during the photon propagation and is a sum over photons which come into resonance with each line, given by

$$H_{bb,simple} = \sum_{photons} \sum_{lines} (1-q)(1-e^{-\tau_S}) w_{photon} \tag{3.22}$$

And our bound bound cooling rate is given by

$$C_{bb,simple} = \sum_{lines} q \left(n_l \frac{g_u}{g_l} - n_u \right) q_{ul} n_e \frac{(1-e^{-h\nu/kT_e})}{(e^{h\nu/kT_e}-1)} h\nu_{ul} \tag{3.23}$$

The bound-free heating rate is given by

$$H_{bf,simple} = \sum_{photons} \sum_{bf\,jumps} w_{photon} e^{-\tau} \frac{\nu - \nu_0}{\nu} \tag{3.24}$$

where ν here is the frequency of the photon in question, and ν_0. The bound-free cooling rate is then

$$C_{bf,simple} = ?? \tag{3.25}$$

3.6 Spectral Synthesis

The primary output from Python is a synthetic spectrum across a range of viewing

The code utilises a variance reduction technique in order

3.7 Clumping

3.7.1 Motivation

Clumping is often invoked in a number of different types of outflow to explain everything from X-ray variability to

3.7.2 Microclumping

To take account of clumping in our outflow we adopt a simple parameterization used in stellar wind modelling. The key assumption here is that typical clump sizes are much smaller than the typical photon mean free path, and thus the clumps are both geometrically and optically thin. This approach is typically known as microclumping and allows one to introduce a 'filling factor', f, which is the fraction of the volume of the plasma filled by clumps. We can then introduce the 'density enhancement', D, which is simply

$$D = \frac{1}{f} \tag{3.26}$$

The densities in the model are then multiplied by this factor. This has the effect of enhancing 'ρ^2' processes such as recombination or collisional excitation, and

3.8 Code Validation

Appendix A

The Effect of Bound-bound Collisional Coefficients on Thermal Conditions of the benchmark CV model

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