

UNIVERSITY OF SOUTHAMPTON

Accretion Disc Winds Across The Mass Scale

by

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degree of Doctor of Philosophy

in the

Faculty Name

Department of Physics & Astronomy

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Declaration of Authorship

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- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
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Abstract

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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 in models of galaxy evolution

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 disc around the white dwarf (WD). Nova-like variables (NLs) are a subclass of CVs in which the disc is always in a relatively high-accretion-rate state ($\dot{M} \sim 10^{-8} M_{\odot} \text{ yr}^{-1}$). This makes NLs an excellent laboratory for studying the properties of steady-state accretion discs.

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,

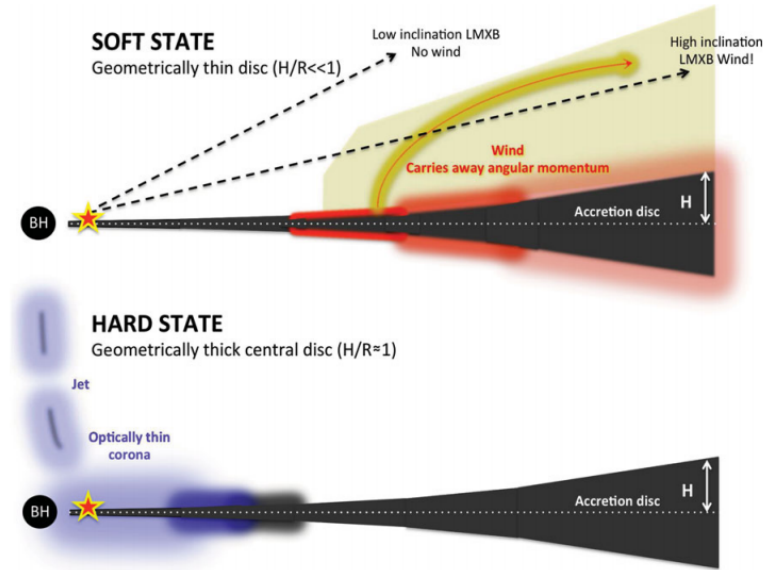


FIGURE 1.1: Credit: *Ponti et al. 2012* Hardness intensity diagram for a WD, NS and BH system

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 discs 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 disc winds.

2.1 Accretion discs

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 -disc model developed by [Shakura and Sunyaev \(1973\)](#) is currently the leading candidate for explaining how energy and angular momentum is transported through a thin disc of material, an accretion disc.

By considering the energy released through viscous dissipation in the disc 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 disc SED*. What it does do is say where energy is originally released. Typically, accretion discs are modelled as a series of annuli each emitting as blackbodies, but it is possible that a disc 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 discs and the current problems

2.2 Observational Appearance

2.2.0.1 Potential Problems with the Thin-disc model

A number of issues have been raised with the thin-disc 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 Spectral shape of CV discs

Attempts to fit the observed SEDs of high-state CVs with simple disc models have met with mixed success. In particular, the SEDs predicted by most stellar/disc 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 disc wind might fill in the disc'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

Broad-band variability is common in all types of accretion disc. It has been known for sometime that there exists a linear relationship between the flux and absolute root-mean-square (rms) amplitude of this variability. This was discovered first in XRBs and AGN (Uttley and McHardy 2001; Uttley et al. 2005; Heil et al. 2012), but it has been shown more recently that the relationship extends to AWDs and even YSOs (Scaringi et al. 2012, 2015). The relationship is not limited to one type of AWD, as it is present in both NLs and DNe (Van de Sande et al. 2015).

The model that best reproduces this behaviour is the so-called ‘fluctuating accretion disc’ model (REFs). It has been shown that additive processes cannot reproduce the behaviour, and a multiplicative mechanism is required (REFs). Regardless of the mechanism, the rms-flux relation is one of the most clear-cut examples of a universal accretion phenomenon. It tells us that at least some of the behaviour in AWD discs is present in AGN and XRB, strengthening the argument that AWDs should be used as ‘accretion laboratories’.

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 discs.

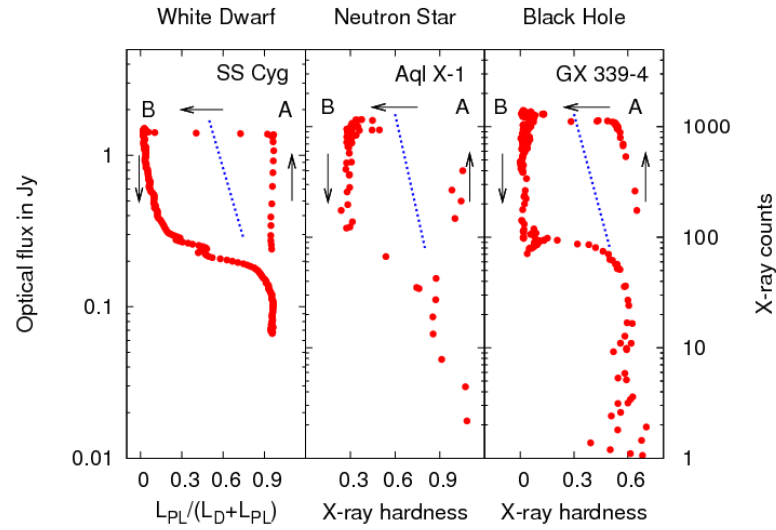


FIGURE 2.1: Credit: Kording et al. XXXX. Caption.

2.4 Accretion disc Winds: Observational Evidence

2.5 Accretion disc Winds: Driving Mechanisms

2.5.1 Thermal Winds

2.5.2 Line-driven Winds

2.5.3 Magneto-centrifugal Winds

2.6 Accretion disc Wind Models

2.7 Wider Perspective

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

$$I_\nu = \frac{dE}{d\Omega \, dt \, dA \, d\nu}, \quad (3.1)$$

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

$$I_\nu = \quad (3.2)$$

$$I_\nu = . \quad (3.3)$$

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

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

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

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu \quad (3.5)$$

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

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

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 be written by invoking detailed balance, such that

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

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

$$\frac{n_1}{n_2} = \frac{g_1}{g_2} \exp(h\nu_0/k_B T) \quad (3.8)$$

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

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

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

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

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 use Monte Carlo techniques, which are easily solved with modern computing approaches and are intuitively parallelisable problems. I will describe

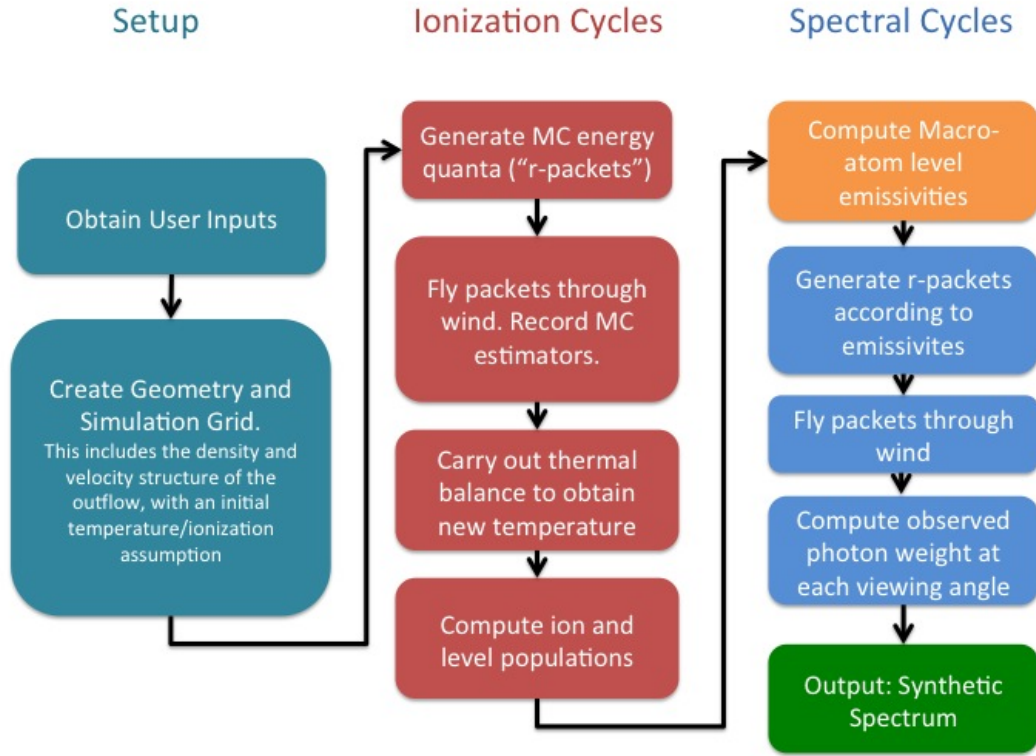


FIGURE 3.1: A flowchart showing the basic operation of PYTHON.

one specific Monte Carlo radiative transfer (MCRT) code, which has been used for the majority of the work in this thesis.

3.2 PYTHON: A Monte Carlo Ionization and Radiative Transfer Code

PYTHON¹ 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

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

geometric and kinematic 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.

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

$$\dot{A}_j^R = R_{\ell j} \epsilon_{j\ell'} \quad \text{and} \quad \dot{E}_i^R = R_{j\ell'} \epsilon_{j\ell'} \quad , \quad (3.11)$$

Where we adopt Lucy's convention in which the subscript ℓ' denotes a summation over all lower states. Similarly, the rates corresponding to *kinetic* energy transport can then be written as

$$\dot{A}_j^C = C_{\ell'j} \epsilon_{j\ell'} \quad \text{and} \quad \dot{E}_j^C = C_{j\ell'} \epsilon_{j\ell'} \quad , \quad (3.12)$$

If we now impose statistical equilibrium

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

we can then obtain

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

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.

Although equation 3.14 assumes strict radiative equilibrium, it is trivial to adjust it to include non-radiative source and sink terms. For example, in an expanding parcel of plasma, adiabatic cooling may be included with a simple modification to the RHS of equation 3.14.

3.3.1 Macro-Atom Estimators

3.3.1.1 Radiation Field Estimators

3.3.1.2 Heating And Cooling Estimators

3.3.2 Ionization Fractions and Level Populations

3.4 Simple-atoms

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.

$$C_{bb,atoms} = \sum_{lines} q_{lu} n_l n_e h\nu_{ul} V \quad (3.15)$$

$$H_{bb,atoms} = \sum_{lines} q_{ul} n_u n_e h\nu_{ul} V \quad (3.16)$$

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 $\tilde{\gamma}$. 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

$$C_{bf,atoms} = \sum_{bfjumps} (\alpha^E - \alpha) n_e n_{\kappa} \nu_{\kappa l} V \quad (3.17)$$

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 $\tilde{\gamma}$. 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

$$H_{bf,atoms} = \sum_{bfjumps} (\gamma^E - \gamma) n_l h\nu_{\kappa l} V \quad (3.18)$$

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)

$$q = \frac{q_{ul} n_e (1 - e^{-h\nu/kT_e})}{\beta_{ul} A_{ul} + q_{ul} n_e (1 - e^{-h\nu/kT_e})} \quad (3.19)$$

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

$$H_{bb,simple} = \sum_{photons} \sum_{lines} (1 - q)(1 - e^{-\tau_S}) w_{photon} \quad (3.20)$$

And our bound bound cooling rate is given by

$$C_{bb,simple} = \sum_{lines} q \left(n_l \frac{g_u}{g_l} - n_u \right) q_{ul} n_e \frac{(1 - e^{-h\nu/kT_e})}{(e^{h\nu/kT_e} - 1)} h\nu_{ul} \quad (3.21)$$

The bound-free heating rate is given by

$$H_{bf,simple} = \sum_{photons} \sum_{bf\ jumps} w_{photon} e^{-\tau} \frac{\nu - \nu_0}{\nu} \quad (3.22)$$

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

$$C_{bf,simple} = ?? \quad (3.23)$$

3.6 Spectral Synthesis

The primary output from PYTHON is a synthetic spectrum across a range of viewing angles. The code utilises a variance reduction technique in order to minimise the amount of time spent in the portion of the code.

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

$$D = \frac{1}{f} \quad (3.24)$$

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

The main challenge for high performance scientific computing can be elegantly summarised by Ferland’s (2002) epitaph, ‘Reliability in the face of complexity’. We have already delved into some of the complexity in this case, so it is important to assess whether our code effectively

3.8.1 Testing against Cloudy

3.8.2 Testing against Tardis

Appendix A

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

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