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James Matthews

Disc Winds Matter

Modelling Accretion and Outflows on All Scales

Doctoral Thesis accepted by
University of Southampton, Southampton, UK

Springer

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"Here, on the edge of what we know, in contact with the ocean of the unknown, shines the mystery and the beauty of the world.

And it's breathtaking."

Seven Brief Lessons on Physics,
Carlo Rovelli

"Good enough for government work."

Christian Knigge

Dedicated to my family—and in memory of Grandpa.

Supervisor's Foreword

The following Ph.D. thesis is the work of James Matthews, who obtained his Ph.D. in Astrophysics from the University of Southampton. Most Ph.D. theses in the UK are likely to be read in full by exactly three people (in addition to the author, hopefully): the supervisor, the internal examiner and the external examiner. As one of these three, I felt this would be a great shame and a terrible waste in this case.

Dr. Matthews' thesis is an outstanding piece of work on all fronts: in terms of its astrophysical significance, in the depth and breadth of understanding it demonstrates, and in the quality and clarity of the writing it contains. Briefly, the thesis describes the application of a state-of-the-art Monte Carlo radiative transfer code to two distinct classes of accreting compact objects: accreting white dwarfs in compact stellar binary systems and accreting supermassive black holes in quasars and active galactic nuclei (AGN). These two types of systems are separated from each other by nine orders of magnitude in mass and size, but they nevertheless share much common physics. More specifically, the thesis is focused on the accretion disc winds that are seen in both types of system, and particularly the imprint these outflows leave on our observations (particularly in spectroscopic data sets). In both settings, the results described in the thesis provide important new insights, while also highlighting the physical connection between the two classes.

In the accreting white dwarf setting, the presence of disc winds has long been inferred from the presence of ultraviolet absorption lines. Here, the thesis shows that the same winds can actually also produce optical emission lines (as well as a recombination continuum), whose origin has been a long-standing problem. In the AGN context, the thesis constructs a simple model of disc winds in quasars that is capable of explaining both the absorption and emission signatures seen in these systems. This is a crucial result that supports a disc-wind based unification scenario for quasars and AGN. Finally, the thesis includes a combined theoretical and observational investigation into the equivalent width distribution of the emission lines in AGN. This reveals a major challenge to all unification scenarios: the equivalent widths of quasars that show broad absorption lines should be different from those that do not show them—but the observed equivalent width distributions are actually indistinguishable. The most likely resolution to this problem is that the dominant emission from quasars and AGN does not arise in a standard, geometrically thin, optically thick accretion disc, as is commonly assumed.

What makes these results particularly remarkable is the depth and breadth of understanding that is necessary to achieve them. The thesis demonstrates this understanding very well, with excellent introductory material on topics ranging from accretion physics and Monte Carlo radiative transfer to compact binaries and quasars/AGN. For example, on the radiative transfer side, the overall Monte Carlo algorithm is outlined clearly and concisely, and key techniques (such as the micro-clumping approximation and the macro-atom approach) are described carefully and in detail. The author's excellent grasp of both the observational and theoretical literature on both accreting white dwarfs and AGN is also evident throughout.

In summary, this thesis is well worth reading not just for researchers interested in its primary results, but for anybody looking for a clear introduction to any of the topics it touches on. Beginning graduate students, in particular, should find it extremely useful, both for its content and as an example of what a great thesis can look like.

Southampton, UK
May 2017

Prof. Christian Knigge
Thesis Supervisor

Abstract

The release of gravitational potential energy as mass falls towards a potential well is the most efficient energetic phenomenon in the universe. This *accretion* process is thought to power the radiative central engines of active galaxies, known as active galactic nuclei (AGN) and is also responsible for the emission from compact binary systems such as X-ray binaries and cataclysmic variables (CVs). Perhaps remarkably, accretion invariably produces *outflow* of material; such outflows are ubiquitous in accreting systems across 10 orders of magnitude in mass, and there is good evidence that mass-loaded winds are launched from the accretion discs of quasars and CVs. Perhaps the most spectacular evidence for accretion disc winds is the blue-shifted, broad absorption lines (BALs) in UV resonance lines, seen in CVs and BAL quasars. As well as imprinting absorption features, disc winds may affect the line and continuum emission from accreting objects. They thus offer a natural way to *unify* much of the phenomenology of CVs and AGN. When one considers that disc winds are also a possible mechanism for AGN feedback, it becomes clear that understanding the physics and true spectral imprint of these winds is of wide-ranging astrophysical significance.

In this thesis, I use the state-of-the-art Monte Carlo radiative transfer (MCRT) code, Python, to conduct a series of simulations designed to test simple biconical disc wind models. I initially give a broad introduction to the field, starting with the basic physics of accretion before describing the observational appearance of accreting systems, from CVs to quasars. Throughout the introduction, I focus particularly on themes of universality and unification, which are central ideas to the work presented here. These themes are explored further in Chap. 2, in which I describe the theoretical and observational status of the current understanding of accretion disc winds. Chapter 3 contains a detailed description of MCRT techniques with particular focus on Leon Lucy's macro-atom scheme and its implementation in Python. This chapter is in some senses the least accessible as it provides a thorough documenting of the Monte Carlo estimators used in the simulations. Such rigour is important, however, and thus I also go on to describe a series of code validation exercises.

Having tested my methods thoroughly, I then explore whether the winds that are responsible for the UV BALs in high-state CVs could also have an effect on the optical spectrum. I find that the wind produces strong emission in the Balmer series, He II 4686 Å and a series of He I lines. The model shows the observed trends with inclination and in some cases produces sufficient recombination continuum emission to fill in the Balmer photoabsorption edge intrinsic to disc atmospheres. The results suggest that disc winds could have a significant impact on the optical spectra of high-state CVs.

The next step was to apply the techniques to quasar winds in a test of disc wind unification models. In previous efforts, the outflow tended to become 'over-ionized', and BAL features were only present if the X-ray luminosity was limited to around 10^{43} erg s^{-1}. The outflow also failed to produce significant line emission. Motivated by these problems, I introduce a simple treatment of clumping and find that it allows BAL features to form in the rest-frame UV at more realistic X-ray luminosities. The fiducial model shows good agreement with AGN X-ray properties and the wind produces strong line emission. Despite these successes, the model cannot reproduce all emission lines seen in quasar spectra with the correct equivalent width (EW) ratios, and I find the emission line EWs have a strong dependence on inclination.

Informed by the quasar wind modelling, I use the Sloan Digital Sky Survey to examine the emission line EW distributions of quasars in the context of geometric unification. I find that the observed distributions are not consistent with a model in which an equatorial BAL outflow rises from a foreshortened accretion disc. I discuss this finding in the context of other observational orientation indicators.

Finally, I summarize my findings and suggest avenues for future work. Overall, the work presented here suggests that *disc winds matter*. They not only act as a spectral 'filter' for the underlying accretion continuum, but may actually dominate the emergent spectrum from accreting objects. As a result, unveiling their driving mechanisms, mass-loss rates and ionization structure is an important goal for the astronomical community.

Acknowledgements

First and foremost, I would like to thank Christian Knigge, for being such an enthusiastic, helpful and stimulating supervisor throughout my Ph.D. Christian, I *always* left our meetings more positive than before—that speaks volumes—and I greatly enjoyed our conversations about science and Explosions in the Sky. I am also extremely grateful to Knox Long for all his assistance, writing the majority of the code and sharing some of his astronomy knowledge with me, and Stuart Sim for being immensely helpful throughout, especially when it comes to radiative transfer. I would also like to thank Nick Higginbottom for hours upon hours of assistance and friendship, and Sam Mangham for his help and input nearer the end of my Ph.D. To all of the above people; thank you for being part of a collaboration that does some great science, but also knew when to discuss a disastrous code bug with a knowing smile and ironic joke. I would also like to thank Daniel Proga, Omer Blaes, Ivan Hubeny, Shane Davis, Mike Brotherton, Mike DiPompeo, Frederic Marin, Daniel Capellupo, Dirk Grupe, Simo Scaringi, Adam Foster, Randall Smith, Chris Done, Anna Pala, Boris Gaensicke, Patrick Woudt and countless others for useful correspondence or stimulating scientific conversations. I am also very grateful to my masters supervisor Rosanne Di Stefano for inspiring me to continue doing research beyond my year in Boston, and to Lance Miller and Poshak Gandhi for being fair, friendly and helpful Ph.D. examiners.

Apart from those who I worked with, I am grateful to everyone who helped make Southampton a happy place to be over 3+ years. There are too many to name, but I will indulge a few. To Cat, thank you for being generally lovely, being so patient with me and having great taste in comedy. To Sam Connolly, you have been ever-present and someone who I can always rely on for good beer, music and knowing looks. Sadie Jones, you were there when I needed you most for a cwtch or wanted to hear you pronounce year or ear. To Rob, Aarran, Juan, Georgios and Poppy, thanks for being true friends throughout the process. Big thanks to everyone else in the department for making it a super cool place to work, my office mates Mari, Judith, Stew and CFro, and my housemates Rich, Stu, Luke, Ollie, Sophie and Szymon. Thanks also go to all the staff for being so friendly and approachable,

particularly Poshak, Diego, Francesco, Mark and Seb who have all helped me at various points through the Ph.D., and to Phil Charles for his sage advice since the early days.

There are also many people, outside of Southampton, who I must thank. Most of all, Mum, Dad, Beth and Nick, and the rest of my family—you have always supported me throughout my studies and just been all round lovely people. Cheers to Nick, Jack and the Hannahs for being great mates and helping me avoid Lemony Snickets. Thank you Josh, James and Alex, and our now manager John, for allowing me to play music that I love in Waking Aida. Eschaton and Full Heal were both released during my Ph.D., and in many ways they are each a thesis within themselves.

This work was supported by the Science and Technology Facilities Council via a 3.5 year Ph.D. studentship. This work made use of the Sloan Digital Sky Survey. Funding for the Sloan Digital Sky Survey has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. I acknowledge the use of the IRIDIS High Performance Computing Facility, and associated support services at the University of Southampton, in the completion of this work. Figures were produced using the matplotlib plotting library. I would also like to thank Padma and Ramon from Springer for helping me through the publication process.

Declaration of Authorship

I, James Matthews, declare that this thesis titled, ‘Disc Winds Matter: Modelling Accretion and Outflow on All Scales’ and the work presented in it are my own.

The first two chapters of this thesis provide a general introduction to the field, and thus are based on the relevant literature. Where a figure is not produced by me, I have acknowledged this clearly with a credit to the relevant publication. Chapter 3 contains a description of the methods used. This is partly a description of the radiative transfer code Python, which was originally developed by Knox Long and Christian Knigge (Long and knigge 2002), but also includes substantial detail on the ‘macro-atom’ technique, which was proposed by Leon Lucy and incorporated into Python by Stuart Sim for a study on young stellar objects (Sim et al. 2005). Although I have put significant effort into testing, fixing and developing this scheme, I did not write the original code to deal with macro-atoms in PYTHON.

Chapters 4–6 were studies I led under the guidance of my supervisor. For these chapters I conducted all simulations and data analysis, produced all the figures and wrote the text. These chapters are adapted from the following three papers with permission from MNRAS:

- Chapter 4: Matthews J. H., Knigge C., Long K. S., Sim S. A., Higginbottom N., ‘The impact of accretion disc winds on the optical spectra of cataclysmic variables’, 2015, MNRAS, 450, 3331.
- Chapter 5: Matthews J. H., Knigge C., Long K. S., Sim S. A., Higginbottom N., Mangham S. W., ‘Testing quasar unification: radiative transfer in clumpy winds’, 2016, MNRAS, 458, 293.
- Chapter 6: Matthews J. H., Knigge C., Long K. S., ‘Quasar emission lines as probes of orientation: implications for disc wind geometries and unification’, MNRAS, DOI:10.1093/mnras/stx231.

The following additional publications are not included in this thesis, although some of the work presented here did contribute towards the respective results:

- Higginbottom N., Knigge C., Long K. S., Sim S. A., Matthews J. H., ‘A simple disc wind model for broad absorption line quasars’, 2013, MNRAS, 436, 2.3.

- Higginbottom, N., Proga D., Knigge C., Long K. S., Matthews J. H., Sim S. A., ‘Line-driven disc Winds in Active Galactic Nuclei: The Critical Importance of Ionization’ and Radiative Transfer, 2014, ApJ, 789, 1.
- Shankar F., Calderone G., Knigge C., Matthews J. H., et al., ‘The Optical–UV Emissivity of Quasars: Dependence on Black Hole Mass and Radio Loudness’, 2016, ApJ Letters, 818, 1.

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Long KS, Knigge C (2002) Modeling the Spectral Signatures of Accretion Disk Winds: A New Monte Carlo Approach. APJ 579:725–740. doi:10.1086/342879. arXiv:astro-ph/0208011

Sim SA, Drew JE, Long KS (2005) Two-dimensional Monte Carlo simulations of HI line formation in massive young stellar object disc winds. MNRAS 363:615–627, 10.1111/j.1365-2966.2005.09472.x, arXiv:astro-ph/0508103

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Abbreviations

ADAF	Advection dominated accretion flow
AGN	Active galactic nuclei/nucleus
BAL	Broad absorption line
BALQSO	Broad absorption line quasar
BBB	Big blue bump
BEL	Broad emission line
BH	Black hole
BI	Balnicity index
BL	Boundary layer
BLR	Broad line region
CDF	Cumulative distribution function
CGS	Centimetre-gram-second
CV	Cataclysmic variable
DN(e)	Dwarf nova(e)
EW	Equivalent width
HERG	High excitation radio galaxy
HMXB	High-mass X-ray binary
HSE	Hydrostatic equilibrium
IP	Intermediate polar
IR	Infra-red
ISCO	Innermost stable circular orbit
LHS	Left-hand side
LINER	Low ionization nuclear emission line region
LMXB	Low-mass X-ray binary
LTE	Local thermodynamic equilibrium
MCRT	Monte Carlo radiative transfer
MRI	Magneto-rotational instability
NAL	Narrow absorption line
NEL	Narrow emission line
NL	Nova-like variable

NLR	Narrow line region
NS	Neutron star
QSO	Quasi-stellar object/Quasar
RHS	Right-hand side
RIAF	Radiatively inefficient accretion flow
RL	Radio-loud
RLOF	Roche lobe overflow
SA	Sobolev approximation
SED	Spectral energy distribution
SFR	Star formation rate
SMBH	Supermassive black hole
sSFR	Specific star formation rate
SXXS	Soft X-ray excess
UFO	Ultra-fast outflow
UV	Ultraviolet
WA	Warm absorber
WD	White dwarf
WHIM	Warm, highly ionized medium
XRB	X-ray binary
YSO	Young stellar object

Physical Constants

Speed of light, c	$2.997\,924\,58 \times 10^{10}$ cm s^{-1}
Boltzmann constant, k	$1.380\,658 \times 10^{-16}$ erg K^{-1}
Gravitational constant, G	$6.672\,599 \times 10^{-8}$ cm^{3} g^{-1} s^{-2}
Solar mass, $M_\odot$	$1.988\,550 \times 10^{33}$ g
Solar radius, $L_\odot$	$6.957\,000 \times 10^{10}$ cm
Thomson cross-section, σ_T	$6.652\,458 \times 10^{-25}$ cm^{2}
Planck constant, h	$6.626\,076 \times 10^{-27}$ cm^{2} g s^{-1}
Stefan–Boltzmann constant, σ	$5.670\,367 \times 10^{-5}$ erg cm^{-2} K^{-4} s^{-1}
Parsec, pc	$3.085\,678 \times 10^{18}$ cm
Proton mass, m_p	$1.672\,621 \times 10^{-24}$ g
Electron mass, m_e	$9.109\,390 \times 10^{-28}$ g
Electron volt, eV	$1.602\,177 \times 10^{-12}$ erg
Electron charge, q_e	$4.803\,207 \times 10^{-10}$ esu
π	$3.141\,593$
e	$2.718\,282$

All constants are given to 6 decimal places, except for the speed of light which is exact. Throughout this thesis I use the centimetre-gram-second (CGS) system of units unless otherwise stated.

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