Quasar Emission Lines as Probes of Orientation and Unification:

J. H. Matthews[1]⋆, C. Knigge[1], et al.

[1]*School of Physics and Astronomy, University of Southampton, Highfield, Southampton, SO17 1BJ, United Kingdom*

13 July 2016

ABSTRACT

The incidence of broad absorption lines (BALs) in quasar samples is often explained by a geometric unification model consisting of an accretion disc and an associated outflow. This outflow is assumed to have a covering factor roughly equivalent to the BAL fraction, f_{BAL}. We use the the Sloan Digital Sky Survey quasar sample to test this model by examining ultraviolet (UV) and optical emission line equivalent-widths (EWs), particularly that of the forbidden narrow-line [O III] 5007 Å. We find, as pointed out by previous authors, that the EW distributions of BAL and non-BAL quasars are remarkabaly similar – a property that is inconsistent with a model in which a BAL outflow rises equatorially from a geometrically thin, optically thick accretion disc. To explore this problem in more detail, we discuss accretion disc models, including general realitivistic and disc atmosphere treatments, and establish the expected forms for the angular emissivity function, $\epsilon(\theta)$. We then use this to conduct Monte Carlo simulations, in which we simulate the expected viewing angle distribution of quasars in a flux-limited sample, before computing the expected LoBAL and non-BAL distributions of the EW of [O III] 5007 Å. The results of these simulations are, once again, that the BAL and non-BAL distributions cannot be reproduced by this particular geometric unification model. We then examine the polarisation properties of our LoBAL quasar sample and place the LoBAL quasars on the Eigenvector I diagram. We also explore whether obscuraton or line anisotropy could hide the expected inclination dependence of line EW, and find this is unlikely to be the case. Overall, our work suggests one of the following conclusions, or some combination thereof: (i) the underlying disc continuum is not understood; (ii) BAL quasars are viewed from very similar angles to non-BAL quasars; (iii) geometric unification does not explain the fraction of BALs in quasar samples.

1 INTRODUCTION

The ultraviolet (UV) and optical spectra of type 1 quasars are characterised by a blue continuum and a series of broad and narrow emission lines. Approximately 20% of quasars show blue shifted, broad absorption lines (BALs) in their UV spectra, providing clear evidence that outflowing material intersects the line of sight to the continuum source. The BAL phenomenon is normally explained either by evolutionary models (REFs), in which quasars spend $\sim 20\%$ of their lifetime as BAL quasars or BALQSOs, or by a geometric interpretation, in which BAL fraction roughly corresponds to the covering factor of an ever-present wind. In the latter case, winds would also create the broad emission lines seen in quasar spectra and they thus offer a natural avenue through which the diverse phenomenology of quasars can be *unified* by orientation. This principle of geometric unification is not confined to disc wind models; orientation-based models were also famously invoked to explain the type 1/type 2 and radio-loud/radio-quiet dichotomies in AGN (e.g. **?**Urry & Padovani 1995), as well as the 'Eigenvector I' trend in quasars (Shen & Ho 2014).

Geometric unificiation scenarios require – by definition – that different classes of objects are viewed from different angles. They thus predict that any orientation-dependent observable should vary accordingly between the classes. One empirical example is the clear difference in polarisation properties between type 1 and type 2 AGN (REFs to Marin, Antonucci, others). However, in general, measuring inclinations for quasars and AGN is notoriously difficult (see Marin 2016, for a summary). Obtaining reliable orientation indicators is thus an important observational goal for the community. Perhaps as a result of this problem, directly opposing geometries have been proposed for BAL outflows. Polarisation studies imply that the wind is roughly equatorial (Goodrich & Miller 1995; Cohen et al. 1995; Brotherton et al. 2006), as also suggested by hydrodynamical and radiative transfer simulations (Proga et al. 2000; Proga & Kallman 2004; Higginbottom et al. 2013; Borguet & Hutsemékers 2010). However, there is also evidence for polar

BAL outflows in radio-loud (RL) sources (Zhou et al. 2006; Ghosh & Punsly 2007).

One potential orientation indicator is the EW of the emission lines (e.g. Risaliti et al. 2011). The UV-optical continuum in AGN, known as the big blue bump (BBB), is normally thought to originate from a geometrically thin, optically thick accretion disc surrounding the central black hole. The emission from this disc should be strongly anisotropic due to foreshorteneing (and possibly limb darkening). Emission lines, on the other hand, should emit fairly isotropically, especially if they are forbidden transitions.

The variation of EW with inclination is demonstrated neatly by the behaviour of emission lines in high-state accreting white dwarfs (AWDs), often thought to be reasonable quasar analogues. In these systems, inclinations are fairly well constrained and a geometrically thin, optically thick accretion disc is well established as the continuum source (REFs). High-state AWDs do indeed show a clear trend of increasing line EW with inclination (Hessman et al. 1984; Patterson 1984; Echevarria 1988). This behaviour is also seen in radiative transfer simulations in both AWDs and quasars (Noebauer et al. 2010; Matthews et al. 2015, 2016). The upshot is that, from simple quasar models, we might expect emission line EW should increase with inclination and be largest for edge-on systems. This means that quasar line EWs can be used (i) to test geometric unification models for, e.g., the BAL phenomenon, or (ii) to help *understand the origin of the UV-optical continuum in AGN.* The latter is particularly important given the currently unsatisfactory understanding of the big blue bump (e.g. Koratkar & Blaes 1999, see also section 2).

The ideal emission line to use for this method would be one that is completely isotropic, i.e. *optically thin.* The [O III] 5007 Å narrow emission line fulfils this criteria, since it is a strong, forbidden line formed in the narrow-line region (NLR) of AGN. Any dispersion in the distribution of [O III] 5007 Å EW (EW[O III]) must therefore be driven by some combination of the intrinsic luminosity (Boroson & Green 1992), the covering factor/geometry of the NLR (Baskin & Laor 2005) and the inclination of the disc. In a recent study, Risaliti et al. (2011) showed that the EW[O III] distribution could be well-fitted by a simple model driven purely by disc inclination. In this paper, we apply a similar method in order to provide a fundamental test of BAL and non-BAL quasar unification models in which the continuum source is a geometrically thin, optically thick accretion disc. This is motivated by the remarkably similar emission line properties of BAL and non-BAL quasars – a similarity that would not be expected from simple models in which BALQSOs are viewed from equatorial angles.

This paper is structured as follows. First, we describe the data sample and selection criteria being used. We begin by simply examining the comparing the BAL and non-BAL quasar distributions for three emission lines: the narrow [O III] 5007 Å line, and the broad C IV 1550 Å and Mg II 2800 Å lines. In section **??**, we review the angular distribution of continuum emission one would expect from simple α-disc models, as well as exploring more advanced disc models computed with AGNSPEC. We then use these theoretical angular distributions applied to a simple toy model in section **??**, and conduct MC simulations in an attempt to fit the observed LoBAL and non-BAL quasar distributions of EW[O III], using a similar approach to Risaliti et al. (2011). In section **??**, we discuss the results in the context of radio and polarisation measurements of AGN, and explore the location of BAL quasars in 'Eigenvector 1' parameter space. We also carefully assess the possible role of obscuration, line anisotropy and selection effects and whether any of these can affect the inferences made. Finally, in section **??**, we summarise our results.

REFERENCES

Agol E., 1997, Ph.D. thesis, UNIVERSITY OF CALIFORNIA, SANTA BARBARA
Allen J. T., Hewett P. C., Maddox N., Richards G. T., Belokurov V., 2011, MNRAS 410, 860
Antonucci R., 2013, Nature 495, 165
Baskin A., Laor A., 2005, MNRAS 358, 1043
Borguet B., Hutsemékers D., 2010, A&A 515, A22
Boroson T. A., Green R. F., 1992, ApJs 80, 109
Boroson T. A., Meyers K. A., 1992, ApJ 397, 442
Brotherton M. S., De Breuck C., Schaefer J. J., 2006, MNRAS 372, L58
Caccianiga A., Severgnini P., 2011, MNRAS 415, 1928
Capellupo D. M., Netzer H., Lira P., Trakhtenbrot B., Mejía-Restrepo J., 2015, MNRAS 446, 3427
Cohen M. H., Ogle P. M., Tran H. D., Vermeulen R. C., Miller J. S., Goodrich R. W., Martel A. R., 1995, ApJ Letters 448, L77
Dai X., Shankar F., Sivakoff G. R., 2012, ApJ 757, 180
Davis S. W., Hubeny I., 2006, ApJs 164, 530
Davis S. W., Woo J.-H., Blaes O. M., 2007, ApJ 668, 682
DiPompeo M. A., Brotherton M. S., De Breuck C., 2012, ApJ 752, 6
Echevarria J., 1988, MNRAS 233, 513
Gallagher S. C., Brandt W. N., Sambruna R. M., Mathur S., Yamasaki N., 1999, ApJ 519, 549
Ghosh K. K., Punsly B., 2007, ApJ Letters 661, L139
Goodrich R. W., Miller J. S., 1995, ApJ Letters 448, L73
Green P. J., Aldcroft T. L., Mathur S., Wilkes B. J., Elvis M., 2001, ApJ 558, 109
Green P. J., Mathur S., 1996, ApJ 462, 637
Grupe D., Mathur S., Elvis M., 2003, AJ 126, 1159
Hessman F. V., Robinson E. L., Nather R. E., Zhang E.-H., 1984, ApJ 286, 747
Higginbottom N., Knigge C., Long K. S., Sim S. A., Matthews J. H., 2013, MNRAS 436, 1390
Hubeny I., Agol E., Blaes O., Krolik J. H., 2000, ApJ 533, 710
Knigge C., Scaringi S., Goad M. R., Cottis C. E., 2008, MNRAS 386, 1426
Koratkar A., Blaes O., 1999, PASP 111, 1
Kraemer S. B., Schmitt H. R., Crenshaw D. M., Meléndez M., Turner T. J., Guainazzi M., Mushotzky R. F., 2011, ApJ 727, 130
Lamy H., Hutsemékers D., 2004, A&A 427, 107
Lazarova M. S., Canalizo G., Lacy M., Sajina A., 2012, ApJ 755, 29
Maiolino R., Marconi A., Oliva E., 2001a, A&A 365, 37
Maiolino R., Marconi A., Salvati M., Risaliti G., Severgnini P., Oliva E., La Franca F., Vanzi L., 2001b, A&A 365, 28
Marin F., 2014, MNRAS 441, 551
Marin F., 2016, ArXiv e-prints

Marin F., Goosmann R. W., 2013, MNRAS 436, 2522
Marziani P., Sulentic J. W., Zwitter T., Dultzin-Hacyan D., Calvani M., 2001, ApJ 558, 553
Mathur S., Green P. J., Arav N., Brotherton M., Crenshaw M., deKool M., Elvis M., Goodrich R. W., Hamann F., Hines D. C., Kashyap V., Korista K., Peterson B. M., Shields J. C., Shlosman I., van Breugel W., Voit M., 2000, ApJ Letters 533, L79
Matthews J. H., Knigge C., Long K. S., Sim S. A., Higginbottom N., 2015, MNRAS 450, 3331
Matthews J. H., Knigge C., Long K. S., Sim S. A., Higginbottom N., Mangham S. W., 2016, MNRAS
Mihalas D., 1978, Stellar atmospheres /2nd edition/
Morabito L. K., Dai X., Leighly K. M., Sivakoff G. R., Shankar F., 2011, ApJ 737, 46
Morabito L. K., Dai X., Leighly K. M., Sivakoff G. R., Shankar F., 2013, ArXiv e-prints
Muñoz-Darias T., Coriat M., Plant D. S., Ponti G., Fender R. P., Dunn R. J. H., 2013, MNRAS 432, 1330
Murray N., Chiang J., Grossman S. A., Voit G. M., 1995, ApJ 451, 498
Noebauer U. M., Long K. S., Sim S. A., Knigge C., 2010, ApJ 719, 1932
Nomura M., Ohsuga K., Takahashi H. R., Wada K., Yoshida T., 2016, PASJ 68, 16
Nomura M., Ohsuga K., Wada K., Susa H., Misawa T., 2013, PASJ 65, 40
Patterson J., 1984, ApJs 54, 443
Proga D., Kallman T. R., 2004, ApJ 616, 688
Proga D., Stone J. M., Kallman T. R., 2000, ApJ 543, 686
Risaliti G., Elvis M., 2010, A&A 516, A89
Risaliti G., Salvati M., Marconi A., 2011, MNRAS 411, 2223
Schmidt G. D., Hines D. C., 1999, ApJ 512, 125
Shankar F., Calderone G., Knigge C., Matthews J., Buckland R., Hryniewicz K., Sivakoff G., Dai X., Richardson K., Riley J., Gray J., La Franca F., Altamirano D., Croston J., Gandhi P., Hönig S., McHardy I., Middleton M., 2016, ApJ Letters 818, L1
Shen Y., Ho L. C., 2014, Nature 513, 210
Shen Y., Richards G. T., Strauss M. A., Hall P. B., Schneider D. P., Snedden S., Bizyaev D., Brewington H., Malanushenko V., Malanushenko E., Oravetz D., Pan K., Simmons A., 2011, ApJs 194, 45
Sulentic J. W., Zwitter T., Marziani P., Dultzin-Hacyan D., 2000, ApJ Letters 536, L5
Urrutia T., Becker R. H., White R. L., Glikman E., Lacy M., Hodge J., Gregg M. D., 2009, ApJ 698, 1095
Urry C. M., Padovani P., 1995, PASP 107, 803
Vestergaard M., Wilkes B. J., 2001, ApJs 134, 1
Weymann R. J., Morris S. L., Foltz C. B., Hewett P. C., 1991, ApJ 373, 23
Zhang S. N., Cui W., Chen W., 1997, ApJ Letters 482, L155
Zhou H., Wang T., Wang H., Wang J., Yuan W., Lu Y., 2006, ApJ 639, 716