Black Hole Winds at All Scales
Proceedings IAU Symposium No. 378, 2024
G. Bruni, M. Diaz Trigo, S. Laha & K. Fukumura, eds.
doi:10.1017/S1743921323003484

AGN outflows and its variability

Vivek M[1], Akhil Nair[2] and Sapna Mishra[3]

[1]Indian Institute of Astrophysics, Koramangala, Bangalore - 560034, India
email: vivek.m@iiap.res.in

[2]Department of Physics and Astronomy, Clemson University, Clemson, SC 29634, USA

[3]IUCAA, Post Bag 04, Ganeshkhind, Pune - 411007, India

Abstract. The radiative mode of AGN feedback, operated through outflows, plays an essential role in the evolution of galaxies. Quasar outflows are detected as blue-shifted broad absorption lines in the UV/optical spectra of quasars. Thanks to the Sloan digital sky survey, 100,000 broad absorption line quasars are available now for ensemble statistical studies. This rich dataset has also enabled us to identify some peculiar cases of these sources. By quantifying the BAL fraction in radio-loud BAL quasars, our studies demonstrate a clear trend of increasing BAL fraction as the viewing angle approaches an edge-on orientation, favoring the orientation model of BAL quasars. Also, by contrasting the properties of BAL quasars with appearing and disappearing BAL troughs, our analysis suggests that the extreme variations in BAL troughs are driven by ionization changes.

Keywords. Active Galaxies, Quasar outflows, Broad Absorption Lines

1. Introduction

AGN feedback is a self-regulating process that connects the energy released by an Active Galactic Nucleus (AGN) to the surrounding medium, thereby influencing the evolution of the host galaxy and its central supermassive black hole (SMBH). A compelling piece of evidence supporting AGN feedback is the observed tight correlation between the bulge mass of a galaxy and the mass of its central SMBH (Ferrarese & Merritt (2000), Gebhardt *et al.* (2000)). Simulations have demonstrated that AGN can exert "negative" feedback through mechanisms such as heating up or blowing away the interstellar medium (ISM) (Kauffmann and Haehnelt (2000), Di Matteo, Springel, and Hernquist (2005)). There are two primary modes of AGN feedback: the quasar mode (radiative or wind mode) and the radio mode (kinetic mode), as discussed in the review by Fabian (2012). The quasar mode is prevalent in high-luminosity AGN and involves outflowing winds, while the radio mode occurs in low-luminosity AGN and is associated with radio jets. Compared to radio jets, the wide opening angles in quasar winds, deduced from the detection rates of quasar outflows, enable efficient interaction with the surrounding medium. Consequently, comprehending the radiative mode of AGN feedback, particularly the nature of outflows, holds significant importance in constraining various feedback mechanisms and models of galaxy evolution.

The presence of high-velocity outflows can be inferred from blue-shifted broad absorption lines (BALs) observed in the spectra of 10-20% of quasars (Weymann *et al.* (1991)). BAL quasars are categorized into three sub-classes based on the ionization state of the absorbing gas: high-ionization BALs (Hi-BALs), low-ionization BALs (LoBALs), and iron-LoBALs (FeLoBALs) (Filiz Ak *et al.* (2013), Vivek Srianand & Dawson (2018), Vivek (2019)). The fraction of observed BAL quasars can be explained either by an orientation model, where the line of sight intersects with the BAL-absorbing clouds, or an evolutionary model, where the quasar goes through a BAL phase for a certain period (Elvis (2000), Farrah *et al.* (2007)).

2. BALQSO fraction

The fraction of BALQSOs provides valuable insights into the orientation versus evolution models of BALQSOs. Defining BALQSOs is an important consideration in this context. Traditionally, BALs are defined as having C IV absorption troughs broader than 2000 km/s and specific outflow velocities. The fraction of "traditional" BALQSOs in optically selected quasar samples is commonly observed to be approximately 10 percent (Weymann *et al.* (1991); Gibson *et al.* (2008)). While this definition is useful for including nuclear outflows, it excludes a significant portion of genuine BALQSOs. To overcome this limitation, the definition of BALQSO was revised by Trump *et al.* (2006) (Trump et al., 2006) to incorporate absorption features characterized by narrower widths and lower outflow velocities. By employing this revised definition, they discovered a significant augmentation in the BALQSO fraction, reaching 26 percent. Studies utilizing infrared or radio selection have also found the intrinsic fraction to be closer to 20 percent (Ganguly & Brotherton (2008), Dai *et al.* (2012), Morabito *et al.* (2014)).

The nature of BAL quasars is still not fully understood, primarily due to the lack of a reliable orientation indicator for AGN. Statistical indicators based on radio, UV, and optical properties have been used. Studies utilizing simulations have indicated a potential relationship between the velocity offsets and line width ratio of high-ionization C IV and low-ionization Mg II lines, suggesting their potential as indicators of viewing angles (Yong et al., 2020). Studies have also investigated emission line properties, such as the Hβ full width at half maximum (FWHM) and O III equivalent width, as potential orientation indicators for low-redshift quasars (Shen and Ho, 2014).

In the standard AGN unification theory, anisotropic radio emission from relativistic jets suggests orientation-dependent properties. Two commonly used radio indicators are the core-to-lobe flux density ratio (R) and the radio-to-optical ratio of the quasar core (R_I). The R parameter depends on core and lobe radio flux densities, while R_I normalizes the core's radio flux by its optical flux. Both indicators show correlations with orientation, but other factors introduce scatter in the correlations.

In our study Nair & Vivek (2022), our objective was to examine the orientation model of BAL quasars by utilizing a sample of sources that were present in both the SDSS Data Release (DR)-16 quasar catalog and the VLA-Faint Images of the Radio Sky at Twenty Centimeters (FIRST) survey. To accomplish this, we utilized radio cut-out images obtained from the FIRST survey and developed a deep learning model based on convolutional neural networks (CNN). This model enabled us to classify the radio morphologies of quasars into categories such as core-only, young jet, single lobe, or triples. Additionally, we further categorized these radio morphologies into core-dominated and lobe-dominated sources.

With our CNN models, we achieved a high precision of over 98% for classifying the various morphological sub-classes of quasars. The average fraction of BALs in the resolved core, core-dominated, and lobe-dominated quasars aligns with the BAL fraction observed in radio and infrared surveys. Furthermore, we analyzed the distribution of BAL quasars based on quasar orientation using radio core-dominance as an indicator. This analysis was also performed for sub-classes of HiBALs, LoBALs, and FeLoBALs.

Fig. 1 shows the BAL fraction as a function of log(R_I) is examined for different categories of quasars: resolved core quasars (black;dotted), core-dominated quasars

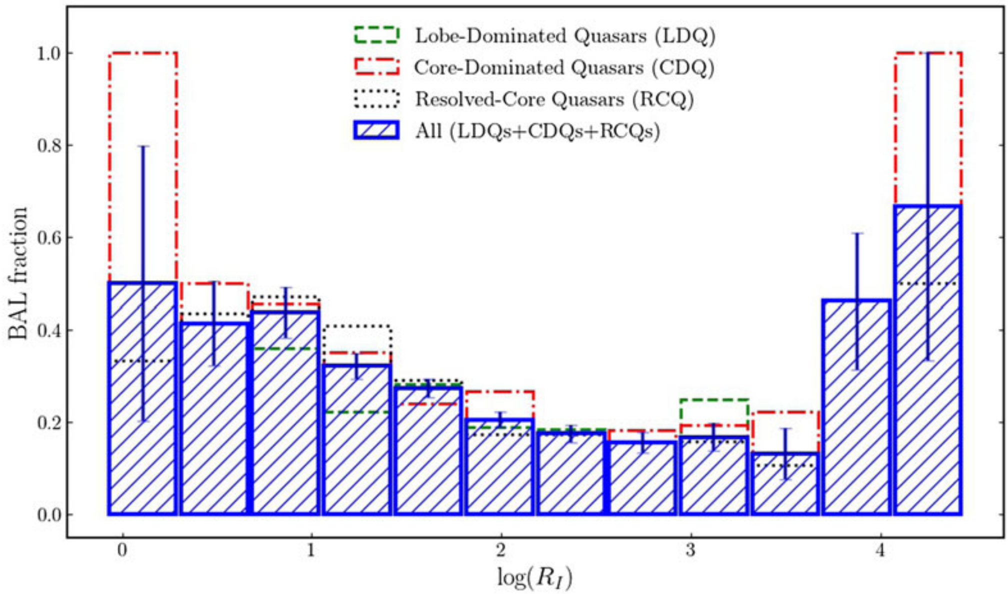

Figure 1. The relationship between BAL fraction and log(R_I) is examined for different categories of quasars: resolved core quasars (black-dotted), core-dominated quasars (red-dot-dashed), lobe-dominated quasars (green-dashed), and a combined sample of resolved core, core-dominated, and lobe-dominated quasars (blue-hatched). Error bars representing 1σ bootstrap errors are included for the combined sample, providing a measure of uncertainty in the BAL fraction.

(red;dot-dashed), lobe-dominated quasars (green;dashed), and a combined sample of resolved core, core-dominated, and lobe-dominated quasars (blue;hatched).

Our findings reveal that all the radio morphological sub-classes and BAL sub-classes exhibit an increased BAL fraction when the jets' orientation angles are closer to the line of sight. This suggests that BAL quasars are more likely to be observed when the viewing angles are in proximity to the equatorial plane of the quasar. However, it is important to note that a pure orientation model alone is insufficient to explain the entirety of the BAL phenomena, and a combination of orientation and evolution is likely the most comprehensive explanation.

3. Variability of BAL troughs

Multiyear variability studies of BAL quasars is crucial in order to gain insights into the location and physical characteristics of the absorbing gas, such as the lifetimes, sizes, and geometries of quasar winds, as well as the underlying mechanisms responsible for these outflows. By examining these variability patterns and their underlying causes, we can gain a deeper understanding of BAL quasars and the physical processes governing their behavior. Various aspects of BAL trough variations, including changes in absorption strength (e.g., equivalent width), the appearance or disappearance of BAL troughs, kinematic shifts in absorption profiles, and alterations in the shape of C IV and Si IV BAL profiles, have been investigated in several cases.

The observed variations in BAL absorption profiles can be attributed to two main factors. Firstly, changes in the covering fraction of the quasar by the absorbing gas can occur as a result of its transverse motions across our line of sight. This has been studied by researchers such as Capellupo *et al.* (2013), Vivek *et al.* (2014). Secondly, variations in the ionizing radiation can lead to changes in the optical depth of the absorbers. This

https://doi.org/10.1017/S1743921323003484 Published online by Cambridge University Press

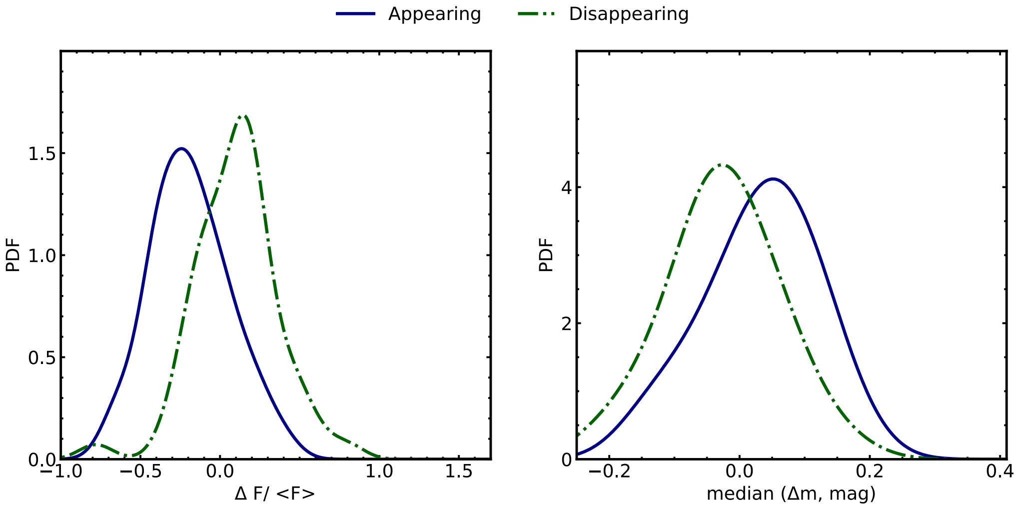

Figure 2. Distribution of (a) change in continuum flux at 1700 Å(b) median of change in V-band magnitudes for Appearing (solid),and Disappearing (dot-dashed) samples.

factor has been explored by Rogerson *et al.* (2018), and Vivek (2019). Additionally, changes in the acceleration profile and/or geometry of the outflow due to alterations in the driving force can also contribute to the observed variability. Studies by Grier *et al.* (2016), and Lu and Lin (2019) have investigated this aspect.

In our recent study, Mishra *et al.* (2021), we presented a new set of 84 broad absorption line (BAL) quasars ($1.7 < z_{em} < 4.4$) that exhibited an appearance of C IV BAL troughs over a span of 0.3-4.8 rest-frame years. To investigate the characteristics of BAL variability, we conducted a comparative analysis using the SDSSDR-7, SDSSDR-12, and SDSSDR-14 quasar catalogues. Our study focused on examining the nature of BAL variability in an appearing BAL quasar sample and contrasting it with a disappearing BAL quasar sample previously studied in the literature. By comparing the two samples, we examined the intrinsic properties, BAL trough characteristics, and continuum parameters of the quasars.

Our findings indicate that the appearing BAL quasars exhibited higher redshift values and shorter probed time-scales in comparison to the disappearing BAL quasars., ensuring that they had comparable distributions of redshift values. We discovered that the appearing BAL quasars were relatively brighter and had shallower and wider BAL troughs compared to the disappearing BAL sample. The distribution of quasar continuum variability parameters exhibited distinct separation between the two samples, indicating that the presence of BAL troughs coincided with a dimming of the continuum, and conversely, the absence of BAL troughs correlated with a brighter continuum. Fig. 2 shows the distribution of change in continuum flux at 1700 Å and the median of change in V-band magnitudes for appearing (solid), and disappearing (dot-dashed) BALQSO samples. The observed spectral index variations in both samples indicated a consistent anti-correlation between the BAL trough and continuum variations, aligning with the well-known trend of "bluer when brighter" in quasars.

We showed that the intrinsic dust model was less likely to be a favorable scenario in explaining BAL appearance/disappearance. Our analysis suggested that the extreme variations of BAL troughs, such as BAL appearance/disappearance, were mainly driven by changes in the ionization conditions of the absorbing gas.

https://doi.org/10.1017/S1743921323003484 Published online by Cambridge University Press

4. Conclusion

By estimating the BAL fraction in radio-loud BAL quasars, we have gained insights into the relationship between BAL fraction and orientation. Our findings reveal a increase in the BAL fraction as the viewing angle approaches a edge-on orientation. This suggests that BAL quasars are more likely to be observed when the line of sight is closer to the equatorial plane of the quasar, favouring the orientation model of BAL quasars. The study of appearing and disappearing BAL quasars provides insights into the nature of BAL variability. Based on our analysis, it can be inferred that the extreme variations observed in BAL troughs, including their emergence and vanishing, are predominantly influenced by alterations in the ionization state of the absorbing gas.

References

Ferrarese, L. and Merritt, D.: 2000, *The Astrophysical Journal* **539**, L9. doi:10.1086/312838.

Gebhardt, K., Bender, R., Bower, G., Dressler, A., Faber, S.M., Filippenko, A.V., and, ...: 2000, *The Astrophysical Journal* **539**, L13. doi:10.1086/312840.

Kauffmann, G. and Haehnelt, M.: 2000, *Monthly Notices of the Royal Astronomical Society* **311**, 576. doi:10.1046/j.1365-8711.2000.03077.x.

Di Matteo, T., Springel, V., and Hernquist, L.: 2005, *Nature* **433**, 604. doi:10.1038/nature03335.

Fabian, A.C.: 2012, *Annual Review of Astronomy and Astrophysics* **50**, 455. doi:10.1146/annurev-astro-081811-125521.

Weymann, R.J., Morris, S.L., Foltz, C.B., and Hewett, P.C.: 1991, *The Astrophysical Journal* **373**, 23. doi:10.1086/170020.

Vivek, M.: 2019, *Monthly Notices of the Royal Astronomical Society* **486**, 2379. doi:10.1093/mnras/stz947.

Vivek, M., Srianand, R., and Dawson, K.S.: 2018, *Monthly Notices of the Royal Astronomical Society* **481**, 5570. doi:10.1093/mnras/sty2712.

Filiz Ak, N., Brandt, W.N., Hall, P.B., Schneider, D.P., Anderson, S.F., Hamann, F., and, ...: 2013, *The Astrophysical Journal* **777**, 168. doi:10.1088/0004-637X/777/2/168.

Elvis, M.: 2000, *The Astrophysical Journal* **545**, 63. doi:10.1086/317778.

Farrah, D., Lacy, M., Priddey, R., Borys, C., and Afonso, J.: 2007, *The Astrophysical Journal* **662**, L59. doi:10.1086/519492.

Gibson, R.R., Brandt, W.N., Schneider, D.P., and Gallagher, S.C.: 2008, *The Astrophysical Journal* **675**, 985. doi:10.1086/527462.

Trump, J.R., Hall, P.B., Reichard, T.A., Richards, G.T., Schneider, D.P., Vanden Berk, D.E., and, ...: 2006, *The Astrophysical Journal Supplement Series* **165**, 1. doi:10.1086/503834.

Ganguly, R. and Brotherton, M.S.: 2008, *The Astrophysical Journal* **672**, 102. doi:10.1086/524106.

Dai, X., Morabito, L.K., Shankar, F., Sivakoff, G.R., and Leighly, K.M.: 2012, *AGN Winds in Charleston* **460**, 120.

Morabito, L.K., Dai, X., Leighly, K.M., Sivakoff, G.R., and Shankar, F.: 2014, *The Astrophysical Journal* **786**, 58. doi:10.1088/0004-637X/786/1/58.

Kimball, A.E., Ivezić, Ž., Wiita, P.J., and Schneider, D.P.: 2011, *The Astronomical Journal* **141**, 182. doi:10.1088/0004-6256/141/6/182.

Mishra, S., Vivek, M., Chand, H., and Joshi, R.: 2021, *Monthly Notices of the Royal Astronomical Society* **504**, 3187. doi:10.1093/mnras/stab782.

Nair, A. and Vivek, M.: 2022, *Monthly Notices of the Royal Astronomical Society* **511**, 4946. doi:10.1093/mnras/stac204.

Shen, Y. and Ho, L.C.: 2014, *Nature* **513**, 210. doi:10.1038/nature13712.

Yong, S.Y., Webster, R.L., King, A.L., Bate, N.F., Labrie, K., and O'Dowd, M.J.: 2020, *Monthly Notices of the Royal Astronomical Society* **491**, 1320. doi:10.1093/mnras/stz3074.

Lundgren, B.F., Wilhite, B.C., Brunner, R.J., Hall, P.B., Schneider, D.P., York, D.G., and, ...: 2007, *The Astrophysical Journal* **656**, 73. doi:10.1086/510202.

Capellupo, D.M., Hamann, F., Shields, J.C., Halpern, J.P., and Barlow, T.A.: 2013, *Monthly Notices of the Royal Astronomical Society* **429**, 1872. doi:10.1093/mnras/sts427.
Vivek, M., Srianand, R., Petitjean, P., Mohan, V., Mahabal, A., and Samui, S.: 2014, *Monthly Notices of the Royal Astronomical Society* **440**, 799. doi:10.1093/mnras/stu288.
Rogerson, J.A., Hall, P.B., Ahmed, N.S., Rodríguez Hidalgo, P., Brandt, W.N., and Filiz Ak, N.: 2018, *The Astrophysical Journal* **862**, 22. doi:10.3847/1538-4357/aabfe5.
Grier, C.J., Brandt, W.N., Hall, P.B., Trump, J.R., Filiz Ak, N., Anderson, S.F., and, ...: 2016, *The Astrophysical Journal* **824**, 130. doi:10.3847/0004-637X/824/2/130.
Lu, W.-J. and Lin, Y.-R.: 2019, *The Astrophysical Journal* **887**, 178. doi:10.3847/1538-4357/ab53d7.