physical sciences forum

Proceeding Paper

Highly Accreting Supermassive Black Holes as Eddington Standard Candles †

Paola Marziani

National Institute for Astrophysics (INAF), Astronomical Observatory of Padova, 35122 Padova, Italy; paola.marziani@inaf.it; Tel.: +39-04-9829-3415

† Presented at the 2nd Electronic Conference on Universe, 16 February–2 March 2023; Available online: https://ecu2023.sciforum.net/.

Abstract: Supermassive black holes accreting matter at very high, perhaps even super-Eddington rates appear in the sky as a special class of luminous active galactic nuclei. The Eigenvector 1/quasar main sequence parameter space allows for the definition of easy-to-implement selection criteria in the rest-frame visual and UV spectral ranges. The systematic trends of the main sequence are believed to reflect a change in accretion modes: at high accretion rates, an optically thick, geometrically thick, advection-dominated accretion disk is expected to develop. Even if the physical processes occurring in advection-dominated accretion flows are still not fully understood, a robust inference from the models—supported by a wealth of observational data—is that these extreme quasars should radiate at maximum radiative efficiency for a given black hole mass. A key empirical result is that lines emitted by ionic species of low ionization are mainly broadened because of virial motions even in such extreme radiative conditions. "Virial luminosity" estimates from emission line widths then become possible, in analogy to the scaling laws defined for galaxies. In this contribution, we summarize aspects related to their structure and to the complex interplay between accretion flow and line emitting region, involving dynamics of the line emitting regions, metal content, and spectral energy distribution.

Keywords: supermassive black holes; broad line emitting region; active galactic nuclei; quasars; observational cosmology; cosmological parameters

check for updates

Citation: Marziani, P. Highly Accreting Supermassive Black Holes as Eddington Standard Candles. *Phys. Sci. Forum* **2023**, *7*, 39. https://doi.org/10.3390/ECU2023-14040

Academic Editor: Mauro D'Onofrio

Published: 16 February 2023

1. Introduction

The Λ-CDM cosmology favours a flat Universe with significant energy density associated with a cosmological constant (see, e.g., [1] for reviews). The inference of a non-zero cosmological constant rests on the use of supernovae [2], galaxy clusters (e.g., [3]), and baryon acoustic oscillations (BAOs; e.g., [4]). The first two methods suffer from a rather low redshift detection limit ($z < 1$–1.5), while thermal fluctuations of the cosmic microwave background (CMB) cover the high redshift window. It may not come as a surprise that the latest observations suggest a tension between H_0 measurements from CMB and BAOs: the CMB constrains the matter energy density at very early cosmic epochs [5], while BAO data sample cosmic epochs from today to around half the Universe's age. It is therefore important that additional lines of investigation are devised today to, at least, provide a fully independent measure of the cosmic matter density Ω_M at $1.5 < z < 4$, where its effect on the Universe expansion is believed to be dominant over the repulsive effect of the cosmological constant and where this parameter has never been measured.

Generally speaking, quasars show properties that make them potential cosmological probes: they are plentiful, very luminous, and are detected at very early cosmic epochs. However, their luminosity is spread over six orders of magnitude, making them antithetical to conventional standard candles. In addition, attempts at providing one or more parameters tightly correlated with luminosity were largely unsuccessful. This is not true, however, for all quasar classes. Supermassive black holes accreting matter at very high, perhaps even super-Eddington rates appear in the sky as a special class of luminous active galactic nuclei. The Eigenvector 1/quasar main sequence (E1/MS) [6,7] makes it possible to select these sources—hereafter extreme Population A quasars (xA) or extreme quasars for brevity. The systematic trends of the MS are believed to reflect a change in accretion modes: at high accretion rates, an optically thick, geometrically thick, advection-dominated accretion disk is expected to develop. Even if the physical processes occurring in advection-dominated accretion flows are still not fully understood, a robust inference from the models—supported by a wealth of observational data—is that extreme quasars should radiate at an Eddington ratio centred on a limiting value (of order unity) with a small scatter, i.e., at a maximum radiative efficiency for a given black hole mass. Measurements of broad low-ionization emission line widths makes it possible to derive "virial luminosity" estimates. The method [8–10] relies on the estimate of the virial mass via a photoionization approach and has a strong analogy with the Faber–Jackson and Tully–Fisher laws, i.e., to the luminosity estimates from absorption and HI line widths in early and late type galaxies, respectively. A sizeable sample of extreme quasars has the potential to yield an independent measure of the main cosmological parameters.

The cosmological application of extreme quasars requires the identification of emission lines whose broadening is mainly due to a virial velocity field. Identification and measurement of these emission lines should be relatively straightforward for sources distributed over a wide range of redshift and luminosity, selected from large surveys. There are, however, several caveats and missing pieces of information before rigorous standardization may become possible. The most relevant issues are the anisotropy of continuum emission and the geometry of the line-emitting regions. Related concerns are the powerful high ionization winds, and the chemical composition of the line-emitting gas. These issues are compounded with circumnuclear and host galaxy star formation that may also reach extreme levels, and with the presence of circumnuclear dust. While extinction due to dust does not seem to affect the rest frame UV and optical spectra of most sources selected because of their blue color, a fraction of them may still be partly embedded in a cocoon of gas and dust, and reddened to various extents. These aspects are reflected in the selection of a xA sample that might be exploited for cosmological purposes (Section 2), although large samples of extreme and unreddened quasars can be built overcoming at least some statistical effects. In the following, we summarize several aspects related to a better understanding of their structure and of the complex interplay between accretion flow and line-emitting regions. We further overview recent achievements concerning the dynamics of the line-emitting regions (Section 3.1), the metal content (Section 3.2), and the spectral energy distribution (Section 3.3). We mention the basis of preliminary attempts to exploit extreme quasars as cosmological distance indicators, as well as the perspective of the method and its extension over a broad range of redshift (Section 4).

2. Sample Identifications: Super-Eddington Candidates

Realistic expectations are now kindled by isolating a class of quasars with some constant property from which their luminosity can be estimated independently of redshift. Physically, in the super-Eddington accretion regime, a geometrically and optically thick advection-dominated structure known as a "thick disk" is expected to develop [11]. Quasars hosting thick disks should radiate at a well-defined limit because their luminosity is expected to saturate close to the Eddington luminosity even if the accretion rate becomes highly super-Eddington. Today we are able to distinguish sources in different accretion states thanks to the exploitation of an empirical correlation set known as the quasar E1/MS [6,12–14]. Over the past 20 years, the author's group has developed an empirical context to interpret the spectroscopic diversity of quasars [7]. Our study began at low redshift ($z < 0.8$) and defined a one-dimensional sequence (the E1 sequence of quasars visible in the upper left panel of Figure 1 Sulentic et al. 2000b). The sequence has since then been expanded to include the most-prominent UV lines observed in high-z quasars [15]. This surrogate Hertzsprung–

Russell diagram for quasars is now understood to be mainly driven by the Eddington ratio [16,17], with the strongest singly-ionized iron emission associated with the higher Eddington ratios. A property consistent with high FeII emission in the UV—the prominence of the AlIII doublet—is helpful to select xA quasars up to $z \approx 4$ [8,18].

3. Results

3.1. Virial Broadening Estimators: Any Line Emission Not Affected by Quasar Outflows?

Blueshifted components in the HI Balmer line Hβ are often revealed in xA spectra. There is a general consensus that blueshifts are due to the Doppler effect associated with outflowing gas approaching the observer. The FWHM of Hβ suffers from an additional broadening by blueshifted emission; however, the effect is not strong ($\approx$ 10%) and the FWHM Hβ can still be used as a "virial broadening estimator" (VBE). More importantly, it is the viewing angle that strongly affects the Hβ broadening. A correction for orientation effects significantly reduces the large scatter between standard Λ CDM cosmology and virial luminosity estimates [19]. Turning to higher redshift, the most promising surrogate of Hβ is the AlIII doublet. Of 16 xA sources investigated in the survey of [20], the wide majority shows AlIII blueshift with respect to Hβ. The average shift is rather modest, ≈ -250, although for seven of them, the blueshift is in excess of -250 km s^{-1}. Six objects show evidence of a strong excess on the blue side of the 1900 blend. The SiIIλ1814 emission line can be of strength comparable to AlIII in the condition of low ionization and high-density derived for the virialized component [21]), but the rather asymmetric line profile suggests that the excess is more likely associated with blueshifted emission.

3.2. Chemical Composition: How Much Super-Solar?

The estimates of metal content of the broad-line-emitting gas of quasars are subject to several caveats; however, the optical and UV emission lines of xA quasars can be decomposed as the sum of a low-ionization component at the quasar rest frame (due to virialized gas), and a spectroscopic-resolved blueshifted excess (due to a disk wind). Profile ratios between high- and low-ionization lines indicate markedly different physical conditions for their respective emitting regions. We analysed several line intensity ratios that are dependent on metallicity Z. These diagnostic ratios useful as metallicity indicators depend on physical conditions. We, therefore, utilized a set of intensity ratios to estimate physical properties such as density, ionization, and metallicity of the gas [22]. The emitting regions associated with the low-ionization component and the blueshifted excess, already known to be in different dynamic and physical conditions, surprisingly showed different metallicity values as well. In both regions metallicities are high, probably among the highest along the quasar MS, with $Z \sim 20 - 50 Z_{\odot}$, and in any case $Z \gtrsim 5 - 10 Z_{\odot}$: the higher value is found for the virialized component, while the outflowing gas should be with $Z \sim 5 Z_{\odot} \lesssim 10 Z_{\odot}$. The discrepancy may reside in the use of different elements for the two estimates. An overabundance of aluminium and silicon over carbon with respect to solar could yield such a high Z. High Z values are likely for xA sources, but Z-values scaled with solar relative abundances of the elements are affected by the possible pollution due to highly-enriched gas associated with the circumnuclear star formation. The effect is exacerbated by the strong enhancement of silicon and aluminium with respect to carbon in type Ib / Ic supernovæ, and ratios involving silicon and aluminium were used only for the virial component. At any rate, high-Z values suggest a complex process involving nuclear and circumnuclear star formation yielding the formation of compact remnants, possibly "sweeping" across the accretion disk with the formation of accretion-modified stars ([23], and references therein).

3.3. Spectral Energy Distribution: A Strong Big Blue Bump and a Steep X-ray Spectrum

The spectral energy distribution (SED) is a correlate of the E1 sequence [13,24,25]. The SEDs shown in [8,25] are in good agreement, and suggest a prominent big blue bump, along with a rather steep decline in the soft and hard X-ray domain [26]. The most recent

SEDs confirm the old scenario that identified the xA sources on the basis of a soft X-ray excess defined by soft-X photon index $\Gamma > 2$ and steeper hard X-ray spectral slope [13,27].

4. The Hubble Diagram

Extreme quasars have the potential to provide a new class of distance indicators covering cosmic epochs from almost present day up to less than 1 Gyr from the Big Bang, much beyond the limits of other optical cosmological indicators such as supernovae. Their redshift distribution can be made statistically unbiased up to $z \approx 3$–4, where the most reliable distance indicators are not available and the effects of the energy density of matter are dominant; data in the broad range $0 < z < 4$ have the potential to assess the dynamical nature of the dark energy. The xA quasars offer a straightforward luminosity indicator (as do spiral galaxies, following the Tully–Fisher law): the luminosity should be proportional to the 4th power of the virial FWHM: $L \propto \mathrm{FWHM}^4$. This relation comes from the virial black mass relation ($M_{\mathrm{BH}} \propto r\mathrm{FWHM}^2$) for the case of an extreme Eddington ratio ($L/L_{\mathrm{Edd}} \sim 1$), and from the assumption of radius of the emitting region scaling exactly as the square root of the luminosity ($r \propto L^{\frac{1}{2}}$), an assumption motivated by the spectral similarity of xA sources [8,18,19]. Preliminary applications of the "virial luminosity" equation to the Hubble diagram have been promising [8,10,28]. The scatter is large, ≈ 0.3 dex, although the coverage of the redshift range between 1 and 3 allows for a precision in the estimate of the cosmic energy density of matter higher than supernovæ alone [8]. To achieve a reliable calibration for precision cosmology, however, several issues related to the non-virial broadening of the emission lines should be solved. The constant of proportionality between L and FWHM depends on SED parameters [8], and it is not as yet clear if the SEDs are all consistent, and X-ray spectral slopes have a small scatter [26]. Nonetheless, with a large sample and the possibility to inter calibrate the optical and UV ranges to estimate the virial broadening over a wide range of redshift, at least a reliable, fully independent estimate of Ω_{M} appears within reach.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BAO	Baryonic Acoustic Oscillation
CMB	Cosmic Microwave Background
E1	Eigenvector 1
FWHM	Full Width Half Maximum
MS	Main Sequence
SED	Spectral Energy Distribution
VBE	VIrial Broadening Estimator
xA	Extreme Population A

References

1. D'Onofrio, M.; Burigana, C. *Questions of Modern Cosmology: Galileo's Legacy*; Springer: Berlin/Heidelberg, Germany, 2009. [CrossRef]
2. Perlmutter, S.; Aldering, G.; Goldhaber, G.; Knop, R.A.; Nugent, P.; Castro, P.G.; Deustua, S.; Fabbro, S.; Goobar, A.; Groom, D.E.; et al. Measurements of Omega and Lambda from 42 High-Redshift Supernovae. *Astrophys. J.* **1999**, *517*, 565–586. [CrossRef]

3. Costanzi, M.; Rozo, E.; Simet, M.; Zhang, Y.; Evrard, A.E.; Mantz, A.; Rykoff, E.S.; Jeltema, T.; Gruen, D.; Allen, S.; et al. Methods for cluster cosmology and application to the SDSS in preparation for DES Year 1 release. *Mon. Not. R. Astron. Soc.* **2019**, *488*, 4779–4800. [CrossRef]
4. Eisenstein, D.J.; Zehavi, I.; Hogg, D.W.; Scoccimarro, R.; Blanton, M.R.; Nichol, R.C.; Scranton, R.; Seo, H.J.; Tegmark, M.; Zheng, Z.; et al. Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies. *Astrophys. J.* **2005**, *633*, 560–574. [CrossRef]
5. Zhao, G.B.; Raveri, M.; Pogosian, L.; Wang, Y.; Crittenden, R.G.; Handley, W.J.; Percival, W.J.; Beutler, F.; Brinkmann, J.; Chuang, C.H.; et al. Dynamical dark energy in light of the latest observations. *Nat. Astron.* **2017**, *1*, 627–632. [CrossRef]
6. Sulentic, J.W.; Marziani, P.; Dultzin-Hacyan, D. Phenomenology of Broad Emission Lines in Active Galactic Nuclei. *Annu. Rev. Astron. Astrophys.* **2000**, *38*, 521–571. [CrossRef]
7. Marziani, P.; Dultzin, D.; Sulentic, J.W.; Del Olmo, A.; Negrete, C.A.; Martinez-Aldama, M.L.; D'Onofrio, M.; Bon, E.; Bon, N.; Stirpe, G.M. A main sequence for quasars. *arXiv* **2018**, arXiv:180205575M.
8. Marziani, P.; Sulentic, J.W. Highly accreting quasars: sample definition and possible cosmological implications. *Mon. Not. R. Astron. Soc.* **2014**, *442*, 1211–1229. [CrossRef]
9. Marziani, P.; Sulentic, J.W. Quasars and their emission lines as cosmological probes. *Adv. Space Res.* **2014**, *54*, 1331–1340. [CrossRef]
10. Dultzin, D.; Marziani, P.; de Diego, J.A.; Negrete, C.A.; Del Olmo, A.; Martínez-Aldama, M.L.; D'Onofrio, M.; Bon, E.; Bon, N.; Stirpe, G.M. Extreme quasars as distance indicators in cosmology. *Front. Astron. Space Sci.* **2020**, *6*, 80. [CrossRef]
11. Abramowicz, M.A.; Czerny, B.; Lasota, J.P.; Szuszkiewicz, E. Slim accretion disks. *Astrophys. J.* **1988**, *332*, 646–658. [CrossRef]
12. Boroson, T.A.; Green, R.F. The Emission-Line Properties of Low-Redshift Quasi-stellar Objects. *Astrophys. J. Suppl. Ser.* **1992**, *80*, 109. [CrossRef]
13. Sulentic, J.W.; Marziani, P.; Zwitter, T.; Dultzin-Hacyan, D.; Calvani, M. Eigenvector 1: An Optimal Correlation Space for Active Galactic Nuclei. *Astrophys. J.* **2000**, *356*, L5–L9. [CrossRef] [PubMed]
14. Shen, Y.; Ho, L.C. The diversity of quasars unified by accretion and orientation. *Nature* **2014**, *513*, 210–213. [CrossRef] [PubMed]
15. Negrete, C.A.; Dultzin, D.; Marziani, P.; Sulentic, J.W. A New Method to Obtain the Broad Line Region Size of High Redshift Quasars. *Astrophys. J.* **2014**, *794*, 95. [CrossRef]
16. Marziani, P.; Sulentic, J.W.; Zwitter, T.; Dultzin-Hacyan, D.; Calvani, M. Searching for the Physical Drivers of the Eigenvector 1 Correlation Space. *Astrophys. J.* **2001**, *558*, 553–560. [CrossRef]
17. Panda, S.; Marziani, P.; Czerny, B. The Quasar Main Sequence Explained by the Combination of Eddington Ratio, Metallicity, and Orientation. *Astrophys. J.* **2019**, *882*, 79. [CrossRef]
18. Martínez-Aldama, M.L.; Del Olmo, A.; Marziani, P.; Sulentic, J.W.; Negrete, C.A.; Dultzin, D.; Perea, J.; D'Onofrio, M. Highly Accreting Quasars at High Redshift. *Front. Astron. Space Sci.* **2018**, *4*, 65. [CrossRef]
19. Negrete, C.A.; Dultzin, D.; Marziani, P.; Esparza, D.; Sulentic, J.W.; del Olmo, A.; Martínez-Aldama, M.L.; García López, A.; D'Onofrio, M.; Bon, N.; et al. Highly accreting quasars: The SDSS low-redshift catalog. *Astron. Astrophys.* **2018**, *620*, A118. [CrossRef]
20. Marziani, P.; Olmo, A.d.; Negrete, C.A.; Dultzin, D.; Piconcelli, E.; Vietri, G.; Martínez-Aldama, M.L.; D'Onofrio, M.; Bon, E.; Bon, N.; et al. The Intermediate-ionization Lines as Virial Broadening Estimators for Population A Quasars. *Astrophys. J. Suppl. Ser.* **2022**, *261*, 30. [CrossRef]
21. Negrete, A.; Dultzin, D.; Marziani, P.; Sulentic, J. BLR Physical Conditions in Extreme Population A Quasars: a Method to Estimate Central Black Hole Mass at High Redshift. *Astrophys. J.* **2012**, *757*, 62. [CrossRef]
22. Śniegowska, M.; Marziani, P.; Czerny, B.; Panda, S.; Martínez-Aldama, M.L.; del Olmo, A.; D'Onofrio, M. High Metal Content of Highly Accreting Quasars. *Astrophys. J.* **2021**, *910*, 115. [CrossRef]
23. Garnica, K.; Negrete, C.A.; Marziani, P.; Dultzin, D.; Śniegowska, M.; Panda, S. High metal content of highly accreting quasars: Analysis of an extended sample. *Astron. Astrophys.* **2022**, *667*, A105. [CrossRef]
24. Ferland, G.J.; Done, C.; Jin, C.; Landt, H.; Ward, M.J. State-of-the-art AGN SEDs for photoionization models: BLR predictions confront the observations. *Mon. Not. R. Astron. Soc.* **2020**, *494*, 5917–5922. [CrossRef]
25. Panda, S.; Marziani, P. High Eddington quasars as discovery tools: current state and challenges. *arXiv* **2022**, arXiv:2210.15041.
26. Laurenti, M.; Piconcelli, E.; Zappacosta, L.; Tombesi, F.; Vignali, C.; Bianchi, S.; Marziani, P.; Vagnetti, F.; Bongiorno, A.; Bischetti, M.; et al. X-ray spectroscopic survey of highly accreting AGN. *Astron. Astrophys.* **2022**, *657*, A57. [CrossRef]
27. Wang, J.M.; Du, P.; Valls-Gabaud, D.; Hu, C.; Netzer, H. Super-Eddington Accreting Massive Black Holes as Long-Lived Cosmological Standards. *Phys. Rev. Lett.* **2013**, *110*, 081301. [CrossRef]
28. Czerny, B.; Martínez-Aldama, M.L.; Wojtkowska, G.; Zajaček, M.; Marziani, P.; Dultzin, D.; Naddaf, M.H.; Panda, S.; Prince, R.; Przyluski, R.; et al. Dark Energy Constraintsfrom Quasar Observations. *Acta Phys. Pol. A* **2021**, *139*, 389–393. [CrossRef]