physical sciences forum

Proceeding Paper

Highly Accreting Supermassive Black Holes as Eddington Standard Candles †

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† 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. These sources can be identified in relatively large numbers from major optical surveys over a broad range of redshifts thanks to selection criteria defined on the basis the so-called Eigenvector 1/quasar main sequence parameter space. 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 extreme quasars should radiate at maximum radiative efficiency for a given black hole mass. This result makes it possible to derive redshift-independent "virial luminosity" estimates from measurements of emission line widths, in analogy to the scaling laws defined for galaxies. In this contribution we summarise 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

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Citation: Marziani, P. Highly Accreting Supermassive Black Holes as Eddington Standard Candles. *Phys. Sci. Forum* **2023**, *1*, 0. https://doi.org/

Published: 15 February 2023

1. Introduction

The Λ-CDM cosmology favors a flat Universe with significant energy density associated with a cosmological constant (see e.g., Ref. [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 one half of the Universe 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. These sources—hereafter extreme Population A quasars (xA) or extreme quasars for brevity—can be identified in relatively large numbers from major optical surveys over a broad range of redshifts thanks to selection criteria defined on the basis the so-called Eigenvector 1/quasar main sequence (E1/MS) parameter space [6,7]. 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 extreme, well defined Eddington ratio with small scatter i.e., at a maximum radiative efficiency for a given black hole mass. This result makes it possible to derive redshift-independent "virial luminosity" estimates from measurements of emission line widths. The method [8–10] relies on the estimate of the virial mass via a photoionization approach and is conceptually equivalent to the luminosity estimates based from line width in early and late type galaxies (i.e., the Faber-Jackson and Tully-Fisher laws), and a sizeable sample of extreme quasars has the potential to yield an independent measure of the main cosmological parameters.

A major issue related to the cosmological application of extreme quasars is the identification of proper emission lines whose broadening is due to a virial velocity field over a wide range of redshift and luminosity. In addition, there are several caveats and missing pieces of informations before a rigorous standardization may become possible. 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, 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 an xA sample that might be exploited for cosmological purposes (Section 2), although large samples of extreme and unredeemed quasars can be built overcoming at least some statistical effects. In the following, we summarise several aspects related to a better understanding of their structure and of the complex interplay between accretion flow and line emitting region. We further overview recent achievements concerning the dynamics of the line emitting regions (Section 3.1), the metal content (Section 3.2) and their 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 group of the author 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 1-dimensional sequence (the E1 main sequence of quasars visible in 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 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. We interpret the blueshifts as related to the signature of outflowing gas from the quasar central engine. The FWHM of Hβ is affected by the 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, there is a strong effect of viewing angle on the Hβ broadening. The relatively large scatter between concordance cosmology and virial luminosity estimates can be reduced (by an order of magnitude) if a correction for orientation effects is included in the FWHM Hβ value; outflow and sample definition yield relatively minor effects [19]. Turning to higher redshift, the most promising surrogate of Hβ is the AlIII doublet. Of 16 xA sources investigated in the survey of Ref. [20], the wide majority shows AlIII blueshift with respect to Hβ. The average shift is rather modest, ≈ -250 for 7 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 blue shifted emission.

3.2. Chemical Composition: How Much Super-Solar?

Metallicity estimates for the broad-line-emitting gas of quasars are subject to a number of caveats; however, xA sources offer several advantages with respect to the quasar general population, as their optical and UV emission lines can be interpreted as the sum of a low-ionization component roughly at quasar rest frame (from virialized gas), and a spectroscopical resolved blueshifted excess (a disk wind), in different physical conditions. Capitalizing on these results, we analyzed the component at rest frame and the blueshifted one, exploiting the dependence of several line intensity ratios on metallicity Z. We found that the validity of diagnostic ratios as metallicity indicators depends on the physical conditions. We therefore utilized a set of ratio to estimate physical properties such as density, ionization, and as well as metallicity of the gas [22]. The two regions (the low-ionization component and the blueshifted excess) of different dynamical conditions also show different physical conditions and surprisingly suggest different metallicity values. 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. We found evidence of an overabundance of Aluminum and Silicon with respect to Carbon. 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 and an interaction between nuclear compact objects and an accretion disk, possibly with the formation of accretion-modified stars [23].

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 Ref. [25] and in Ref. [8] 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 indicators (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 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 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 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.

Conflicts of Interest: The author declares no conflicts 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

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