The last few years have seen the confirmation of several trends associated with the quasar main sequence. The idea of a main sequence for quasars is relatively recent, and its full potential for the observational classification and contextualization of quasars’ properties has yet to be fully exploited. The main sequence drivers are discussed in terms of the properties of extreme objects. We briefly summarize developments that constrain the viewing angle of the accretion disk in a particular class of quasars (extreme Population B, radiating at low Eddington ratio), as well as inferences on the chemical composition of the broad line emitting gas, and on the nature of radio emission along the quasar main sequence.

KEYWORDS:
galaxies: active — quasars: general — quasars: emission lines — galaxies: starburst — radio continuum: galaxies

1 INTRODUCTION: A MAIN SEQUENCE FOR TYPE-1 (UNOBSCURED) QUASARS

The main sequence (MS) concept originated from a Principal Component Analysis on the spectra of Palomar Green quasars that allowed the identification of a first Eigenvector (Eigenvector 1, E1). The E1 was found to be associated with an anti-correlation between strength of the singly ionized iron emission blend centered at \( \lambda 4570 \) (FeII\( \lambda 4570 \)) and the FWHM of \( \text{H}\beta \) (or peak intensity of \([\text{O}III]\ 4959,5007\)). The MS itself can be effectively represented in a plane where the FWHM \( \text{H}\beta \) data are diagrammed against the parameter \( R_{\text{FeII}} \) defined as the flux ratio between FeII\( \lambda 4570 \) and the broad component of \( \text{H}\beta \) i.e., \( R_{\text{FeII}} = \frac{F(\text{FeII}\lambda 4570)}{F(\text{H}\beta_{\text{BC}})} \). Figure [1] shows a sketch of the occupation of the quasar MS in this parameter plane.

The MS has withstood the test of time; from the original 80 sources in the paper by [Boroson & Green, 1992] and the tens of objects in an even earlier study by [Gaskell, 1985], the MS has been detected and studied in sample of \( \sim 200 \) objects ([Sulentic et al., 2002], \( \sim 500 \) [Zamfir, Sulentic, Marziani, & Dultzin, 2010], to \( \sim 20000 \) [Shen & Ho, 2014]). The main trends have been confirmed, extended to multifrequency data related to the accretion process and the accompanying outflows ([Sulentic et al., 2002], [Sulentic, Marziani, & Dultzin-Hacyan, 2000], [Sulentic, Marziani, Zwitter, Dultzin-Hacyan, & Calvani, 2000] see also the summary Table of [Fraix-Burnet, Marziani, D’Onofrio, & Dultzin, 2017]), and revealed also by sophisticated techniques such as locally linear embedding in manifold learning ([Jankov, Ilič, & Kovačević, 2021]).
Why are the seemingly-obscure parameters FWHM Hβ and $R_{\text{FeII}}$ so revealing? FeII emission is self-similar in type-1 AGN but the relative flux to Hβ (parameterized by $R_{\text{FeII}}$) can vary from undetectability to $R_{\text{FeII}} \gtrsim 2$, with values larger than $\approx 2$ being exceedingly rare. The FeII emission extends from UV to the IR and can dominate the thermal balance of the low-ionization broad-line region (BLR; Marinello, Rodriguez-Ardila, Garcia-Rissmann, Sigut, & Pradhan 2016). The FWHM of Hβ is related to the velocity field in the low-ionization part of the BLR (predominantly virialized) and to viewing angle effects. Therefore these two parameters reflect important aspects of the emitting gas physical conditions and dynamical status, along with the orientation (defined as the angle $\theta$ between a putative axis of symmetry and the line of sight at which the AGN is seen). The MS includes only type-1 AGN i.e., sources for which broad lines are visible in natural light. According to the unification schemes, $\theta$ is constrained between 0 and $\sim 45$ — 60 degrees (Antonucci 1993; Urry & Padovani 1995; see also Marin 2016 for a more recent perspective). Effects of changing $\theta$ on the line width are believed to be significant for radio-quiet type-1 AGN as well, although there is not as yet an established view to connect $\theta$ to observed spectral parameters. Orientation definitely plays a role in beam-dominated radio emission (Urry & Padovani 1995), although the effects on the broad optical and UV lines are subject of current debate (more in §3.2).

The elbow-shaped MS allows for the definition of two main populations: Population A and B (Sulentic, Marziani, & Dultzin-Hacyan 2000) hereafter Pop. A and Pop. B respectively) on the basis of a limit on the FWHM of Hβ ($\approx 4000$ km s$^{-1}$ at low and moderate luminosity), as well as of several spectral types in narrow ranges of FWHM and $R_{\text{FeII}}$. The Population A and B spectra are usually so very different that their classification can be recognized by eye: Pop. A sources show sharp Hβ profiles, prominent FeII, and weak [OIII]λ4959,5007 emission; on the converse a typical Pop. B spectrum shows Gaussian-line Hβ profiles, weak FeII, and strong and spiky [OIII] (see the Figures in Sulentic, Marziani, & Dultzin-Hacyan 2000). If one compares a high-ionization line such as CIV $\lambda 1549$ to Hβ, the first shows a significant shift to the blue with respect to the quasar rest frame.$^1$ Summing up decades of works in monitoring and in the study of the spectroscopic properties of quasars, we can say that the emitting region can be heuristically subdivided in two sub-regions: a low ionization, closely associated with the accretion disk, and that has been found to be predominantly in virial dynamical equilibrium, for both Pop. A and B (even with significant differences that are still poorly understood), and an outflow/wind region (Collin-Souffrin, Dyson, McDowell, & Perry 1988; Elvis 2000), by far more evident in Pop. A and especially in extreme Population A (xA, defined by $R_{\text{FeII}} > 1$; see Fig. 1). The aim of this paper is to emphasize the danger of ignoring the trends of the main sequence, by showing how different the objects at the opposite extreme ends are.

Before discussing the interpretation of the main sequence (Section 2), it is helpful to consider why there is a special reason to prefer 4000 km s$^{-1}$, instead of 2000 km s$^{-1}$ for the Hβ FWHM limit. Most studies still distinguish narrow-line Seyfert 1 (NLSy1s, defined from the condition FWHM Hβ $\lesssim 2000$ km s$^{-1}$) as a distinct class, and compare NLSy1s to “broad-line” AGN. However, the Hβ profiles remain Lorentzian-like up to around FWHM(Hβ) = 4000 km s$^{-1}$, and the CIV $\lambda 1549$ blueshifts remain consistent up to around the same FWHM limit (Marziani, del Olmo, et al. 2018). A clear change in the Hβ line profiles occurs at FWHM(Hβ) $\approx 4000$ km s$^{-1}$: composite profiles in the range 3000 km s$^{-1}$ $\lesssim$ FWHM(Hβ) $\lesssim$ 4000 km s$^{-1}$ are best fit with a Lorentzian function, while for 4000 km s$^{-1}$ $\lesssim$ FWHM(Hβ) $\lesssim$ 5000 km s$^{-1}$ a double Gaussian provides a best fit (Sulentic et al. 2002).

The overview of the MS interpretation (Section 2) is followed by an analysis of chemical composition and orientation effects among Pop. B sources (Section 3). The results on chemical compositions are mirrored by the ones obtained for Pop. A (Section 4). In the case of xA, a novel result summarized in §4.2 is the connection between the defining property of strong FeII emission and significant radio power, that mirrors the “jetted” origin of the tremendous radio power of some 20% of Pop. B sources (Zamfir, Sulentic, & Marziani 2008). Our conclusion (Section 5) stresses how the improvement in our understanding of quasar physics might be instrumental in the use of xA quasars as cosmological probes.

### 2 INTERPRETATION OF THE MAIN SEQUENCE

Several approaches consistently support a relation between $L/L_{\text{Edd}}$ and $R_{\text{FeII}}$. For example, the average of the stellar velocity dispersion of the host galaxy in narrow luminosity bins (a proxy for $M_{\text{BH}}$) decreases with $R_{\text{FeII}}$, implying that $L/L_{\text{Edd}}$ increases with $R_{\text{FeII}}$ (Sun & Shen 2015). The $L/L_{\text{Edd}}$ computed from the virial black hole mass $M_{\text{BH}}$ relation for sources with reverberation mapping data is correlated with $R_{\text{FeII}}$ (Du et al. 2016).

A toy model that assumes a virial relation for $M_{\text{BH}}$ in the form:

$$M_{\text{BH}} = f(\theta) \frac{r_{\text{BLR}} \text{FWHM}^2}{G}$$

(1)

where $f(\theta)$ is the viewing-angle dependent virial factor shows that the occupation of the MS optical plane at low-z can

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1. For the sake of simplicity we shall omit the subscript BC from now on.
2. Most precisely traced by low-ionisation narrow emission lines such as [OIII]λ3727 (N. Bon et al. 2020).
be accounted for in terms of Eddington ratio and orientation (Marziani, Sulentic, Zwitter, Dultzin-Hacyan, & Calvani, 2001).

Figure 2 shows the prediction of the toy model overlaid to the shape representing the occupation of the AGN in the optical plane of the MS. A surprising aspect of the MS is that the sources radiating at maximum luminosity-to-black hole mass, at high (possibly super-Eddington) accretion rates (Marziani, Sulentic, Zwitter, Dultzin-Hacyan, & Calvani, 2001), under the standard virial assumption, then the line FWHM can be written as a function of the bolometer:

$$\text{FWHM} \propto \left(\frac{L}{M_{\text{BH}}}\right)^{-\frac{2}{3}} \cdot \sin^{-\frac{1}{2}} a$$

or \(\sim 1\) (Mineshige, Kawaguchi, Takeuchi, & Hayashida, 2000). A change from Pop. B to Pop. A in response to a luminosity increase would improve the current interpretation of the Eigenvector 1 MS, and is not expected.
FIGURE 2 The occupation of MS quasars in the plane $\text{FWHM H}\beta$ vs $R_{\text{FeII}}$ as in Fig. 1 with two grids of $L/L_{\text{Edd}}$ and $\theta$, for $M_{\text{BH}} = 10^8 M_\odot$ (black) and $M_{\text{BH}} = 10^9 M_\odot$ (blue). Eddington ratio increase along with $R_{\text{FeII}}$, while viewing angle $\theta$ decreases toward the bottom.

If $a = 0.5$, one can easily see that $\text{FWHM} \propto M_{\text{BH}}^{-1/2}$ for fixed $\theta$ and $L/L_{\text{Edd}}$, implying that the grid is shifted upwards and that the FWHM increases by a factor $\sim 1.8$ for a ten-fold increase in $M_{\text{BH}}$. Going one step further it is possible to account for the $R_{\text{FeII}}$ values in each spectral bin assuming a systematic increase of density, chemical abundances and Eddington ratio from the low $R_{\text{FeII}}$, high FWHM to the high $R_{\text{FeII}}$, low FWHM end of the MS (Panda et al., 2019), keeping a consistency with the $r_{\text{BLR}}$ values expected from the scaling $r_{\text{BLR}} = L$ (Bentz et al., 2013), and including the correction derived for highly accreting quasars (Martínez-Aldama et al., 2019).

### 3 | EXTREME POPULATION B

The extreme Population B involves by definition sources with broad Balmer profiles (a conventional limit could be set at $\approx 10000 \text{ km s}^{-1}$ of at $12000 \text{ km s}^{-1}$ to include only the most extreme sources, and very low (often undetectable) $R_{\text{FeII}}$ i.e., at variance with Pop. A where the majority of sources have measurable $R_{\text{FeII}}$. A defining feature is the presence of a redward asymmetry, especially prominent in low-ionization lines (Marziani, Zamanov, Sulentic, & Calvani 2003; Wang et al., 2017; Wolf et al., 2020). The $R_{\text{FeII}}$ Parameter is a fundamental one in the definition of the MS, and the FeII flux is expected to be dependent not only on the gas physical conditions but on the chemical abundances as well. It is therefore important to assess the relevance of metallicity $Z$ on the location in optical plane of the MS (Panda et al., 2018; Panda et al., 2019; Punsly, Marziani, Bennert, Nagai, & Gurwell, 2018). A second important result coming from the MS occupation is that, at variance with Pop. A, extreme Pop. B encompasses the largest prevalence of “jetted” sources. It is intriguing that the jetted sources differ from the RQ ones in the distribution of blueshift of high ionization lines, while there is a minor effect of radio-loudness on the low-ionization lines (Richards et al., 2011; Sulentic, Chatzikos, & Hewett, 2021). One of them is the metal content of the line emitting gas. We considered the active galaxy NGC 1275 (a.k.a. 3C 84 or Perseus A, a radio-loud AGN with an optical spectrum of Pop. B), and analyzed the rest-frame optical and UV spectra to measure the chemical abundance of its BLR gas. A full account of the analysis is provided by Punsly, Marziani, et al. (2018). The source has a very faint BLR compared to the prominent narrow-line region emission but, once this difficulty has been overcome via a careful multi-component nonlinear fit, it was possible to gain constraints on the target line flux ratios: $R_{\text{FeII}} \lesssim 0.3$, $\text{FWHM H}\beta \approx 5000 \text{ km s}^{-1}$ (implying a spectral type B1 in the MS context, low [CIV] $\lambda1549$/Heti$\lambda1640$ and CIV $\lambda1549$/H$\beta$ ratios, high Heti$\lambda4686$/H$\beta$. The fit was carried out using a non-linear, multicomponent, minimum $\chi^2$ approach with the same technique described in several previous papers (e.g., Marziani et al., 2010; Sulentic et al., 2015). We exploit here an empirical advantage of the MS: for most of the bins it is possible to consider composites or even a single object as representative of the spectral type (Marziani et al., 2010), as (the only exception being perhaps A1; Panda et al., 2019) the sources scatter around a well defined average.

Recent analyses utilized photoionization computations that cover a six-dimensional parameter space (spectral energy distribution (SED), ionization parameter, density, column density, …)

3.1 | Chemical composition analysis

While the MS emission line trends might be mainly governed by a trend in ionization parameter and density, there are other factors that may play a concomitant role, and whose importance is still debated (see e.g., Temple, Ferland, Rankine, Chatzikos, & Hewett, 2021). One of them is the metal content of the line emitting gas. We considered the active galaxy NGC 1275 (a.k.a. 3C 84 or Perseus A, a radio-loud AGN with an optical spectrum of Pop. B), and analyzed the rest-frame optical and UV spectra to measure the chemical abundance of its BLR gas. A full account of the analysis is provided by Punsly, Marziani, et al. (2018). The source has a very faint BLR compared to the prominent narrow-line region emission but, once this difficulty has been overcome via a careful multi-component nonlinear fit, it was possible to gain constraints on the target line flux ratios: $R_{\text{FeII}} \lesssim 0.3$, $\text{FWHM H}\beta \approx 5000 \text{ km s}^{-1}$ (implying a spectral type B1 in the MS context, low [CIV] $\lambda1549$/Heti$\lambda1640$ and CIV $\lambda1549$/H$\beta$ ratios, high Heti$\lambda4686$/H$\beta$. The fit was carried out using a non-linear, multicomponent, minimum $\chi^2$ approach with the same technique described in several previous papers (e.g., Marziani et al., 2010; Sulentic et al., 2015). We exploit here an empirical advantage of the MS: for most of the bins it is possible to consider composites or even a single object as representative of the spectral type (Marziani et al., 2010), as (the only exception being perhaps A1; Panda et al., 2019) the sources scatter around a well defined average.

Recent analyses utilized photoionization computations that cover a six-dimensional parameter space (spectral energy distribution (SED), ionization parameter, density, column density, …)

The same considerations however apply to extreme Pop. B, considering that those sources show emission line ratios similar to the NGC 1275.
metallicity, micro-turbulence; Panda et al. 2018). Exploration of a parameter subspace in density, ionization parameter U, column density, and metallicity with CLOUDY 17.01 (Ferland et al. 2017) assuming a carefully defined SED on the basis of multifrequency observations (a full description is provided by Punsly, Marziani, et al. 2018) yielded a set of possible solutions in agreement with the diagnostic ratios, and with the observed line luminosity: \(n_H \sim 10^{10} \text{ cm}^{-3}, N_H \sim 10^{23} \text{ cm}^{-2}, 0.1Z_\odot \leq Z \leq 1Z_\odot\) (Punsly, Marziani, et al. 2018). These values are consistent with the ones assumed by Panda et al. 2019 for the Pop. B spectral bins.

### 3.2 Orientation analysis

Type-1 quasars showing a Fanaroff-Riley II morphology are associated with very low Eddington ratio and moderate \(\theta\). Actually the core-to-lobe ratio and the core-to-optical fluxes have been used as an orientation indicator (Wills & Brotherton 1995; Wills & Browne 1986). In the MS context, Fanaroff-Riley II quasars and also jetted sources (satisfying the rather strict condition on the radio-to-optical flux \(R\)) have been used as an orientation indicator (Wills & Brotherton, 1995). In fact, the core-to-lobe ratio and the core-to-optical fluxes have been used as an orientation indicator (Wills & Brotherton 1995; Wills & Browne 1986). In the MS context, Fanaroff-Riley II quasars and also jetted sources (satisfying the rather strict condition on the radio-to-optical flux \(R\)) have been used as an orientation indicator (Wills & Brotherton, 1995).

#### 3.2.1 Moderate-to-high viewing angles

Sources with widely-separated double peaks attracted a lot of attention in the years 1990s and 2000s. Very broad Population B sources that show a double peaked Balmer line profile have been long since considered as candidate accretion disk profiles (Chen, Halpern, & Filippenko 1989). They are rare (~ 2% in the SDSS; Strateva et al. 2003) and, after discounting the hypothesis of a binary black hole (Halpern & Filippenko 1988) on the basis of long-term monitoring (Eracleous, Halpern, Gilbert, Newman, & Filippenko 1997), as well as the possibility of a bipolar outflow (Sulentic, Calvani, Marziani, & Zheng 1990; Zheng, Sulentic, & Binette 1990) for lack of evidence, the present consensus is that the profiles are genuinely representative of disk emission, possibly without strict axial symmetry (E. Bon, Jovanovic, Marziani, Bon, & Otašević 2018; Eracleous, Livio, Halpern, & Storchi-Bergmann 1995). Basically, the radial velocity stability of the double-peaked structure ruled out alternative models. The prototypical source Arp 102B is relatively bright and luminous (\(M_R \approx -25.7\)) but nowadays very similar profiles are being discovered in lower luminosity AGN (Bianchi et al. 2019), thanks to the careful subtraction of the host galaxy continuum made possible by the use of integral field spectroscopy. Models of accretion disks are consistent with viewing angle around 30 — 50 degrees, and show the red wing with redshift amplitude \(\delta z\) consistent with the effect of gravitational and transverse redshift (N. Bon, Bon, Marziani, & Jovanović 2015).

\[\delta z \approx \frac{3}{2} \frac{r_g}{\tilde{r}_{BLR}}\]

where \(r_g\) is the gravitational radius, and \(\tilde{r}_{BLR}\) corresponds to innermost radii of the BLR, if the \(\delta z\) measurement is obtained from the line centroid close to the line base (for example, 0.1 or 0.25 of maximum intensity).

#### 3.2.2 Low viewing angles

The emission line profiles of radio-loud quasars are often characterized by extreme redward asymmetries in the line profiles (Marziani, Sulentic, Dultzin-Hacyan, Calvani, & Moles 1996; Punsly 2010). A recent survey of blazar spectra (Punsly, Marziani, Berton, & Khob 2020) show consistency with a large contribution from the inner region of an accretion disk to the line profiles, with disk inner radius \(\tilde{r}_{BLR} \lesssim 100r_g\). In this case, the model profiles constrain the disk viewing angle to be \(\theta \lesssim 5\) degrees. The accretion disk emission is favored by the low level of the ionizing continuum: if normalized to the optical flux, the emission is about two order of magnitude lower in the FUV domain with respect to NGC 5548, the prototypical Population B source. The flatness of the emitting region added a second element that helped to detect the effect of orientation, if the blazar profiles are compared to the ones of more inclined sources such as Arp 102B.

The detection of gravitational redshift requires efficient illumination of the inner disk, which may be provided by low luminosity or by particular geometries, for example a warped disk (Jiang et al. 2021). As a corollary, it is unclear whether redshifted line wings in all of Population B can be explained as due to gravitational and transverse redshift. The CTV lines shown in Fig. 3 illustrate the point: while the red wing is well reproduced by a disk model, the core and the blue line sides are affected by additional line emission roughly at rest frame, as well as by an outflowing component yielding an excess emission that voids the information from the centroid close to the line base (E. Bon 2008; E. Bon, Popović, Gavrilović, Mura, & Mediavilla 2009; E. Bon, Popović, Ilić, & Mediavilla 2006; Popović, Mediavilla, Bon, & Ilić 2004).
is mainly blueshifted (i.e. wind) emission but Balmer and Paschen lines remain predominantly virialized (Martínez-Aldama et al. 2018). The selection criterion \( R_{\text{FeII}} \gtrsim 1 \) corresponds to an UV selection criterion based on two diagnostic ratios implying strong Aluminium and Silicon lines and weak CIV \( \lambda 1909 \). At the origin of the interest in xA sources (some of which might be highly super-Eddington accretors, Wang et al. 2014) is the fact that xA population quasars radiate close to an extreme Eddington ratio (Marziani & Sulentic 2014), and this property may be exploited to define standard “Eddington candles” for cosmology (e.g., Marziani et al. 2021 and references therein).

4.1 Chemical composition analysis

Emission line ratios in a photoionization context are dependent on the SED of the ionising radiation that is known in turn to depend on Eddington ratio (Ferland, Done, Jin, Landt, & Ward 2020; Laor, Fiore, Elvis, Wilkes, & McDowell 1997), and hence on the location along the MS. Arrays of Cloudy 17.02 (Ferland et al. 2017) photoionization simulations were computed covering the \( U - \) density parameter plane with a step of 0.25 dex, for 12 values of metallicity covering the range \( 0.01 Z_{\odot} \leq Z \leq 1000 Z_{\odot} \), with a SED appropriate for sources radiating at high Eddington ratio, including a prominent big blue bump. A detailed account of the simulation settings and a systematic presentation the physical basis of the method and of the results is provided by Marziani, del Olmo, Perea, D’Onofrio, & Panda (2020) and /uni015 Aniegowska et al. (2021). The simulation results show that diagnostic line ratios CIV \( \lambda 1549/\text{He}\,\text{II} \lambda 1640,\) Al\,\text{III} \( \lambda 1860/\text{He}\,\text{II} \lambda 1640,\) (Si\,\text{IV}+O\,\text{IV} \] \( \lambda 1400/\text{He}\,\text{II} \lambda 1640 \) are monotonically increasing with \( Z \) over a wide range of ionization parameter values, for a fixed SED (Śniegowska et al. 2021). The He\,\text{II} \lambda 1640 emission line is expedient because of unchanging He abundance and of simple He\,\text{II} \lambda 1640 radiation transfer (collisional excitation is negligible, as the lower transition level is at a high energy above ground \( \approx 40 \text{eV} \); Marziani, del Olmo, et al. 2020).

In terms of metallicity, xA sources show very homogeneous properties and extreme values of metallicity (\( Z \gtrsim 10 Z_{\odot} \); \( Z \sim 20 Z_{\odot} \) seems a typical value). For the low-ionizaton BLR, ionization parameter, density, and \( Z \) are constrained within a relatively narrow range for most xA sources (Śniegowska et al. 2021). Systematic differences in the \( Z \) derived from the different ratios may imply over-abundances of Al and Si (\( Z(\text{Al}\,\text{III}/\text{He}\,\text{II}) \sim 20 - 50 Z_{\odot} \) with respect to C, since \( Z(\text{CIV}/\text{He}\,\text{II}) \sim 10 Z_{\odot} \) (Garnica et al. 2021, in preparation). The difference persists over a rather wide range in ionization parameter and density, and is most likely due to scaling by
a fixed factor under the assumption that all relative elemental abundances of the BLR are solar. This approach does not take into account that solar relative abundances are most likely inappropriate in the nuclear and circumnuclear regions of AGN.

### 4.2 Radio properties

An unexpected finding was a high prevalence of radio-intermediate (with radio-to-optical specific flux in the range 10—80) or even radio-loud quasars in xA that can reach very high radio power $P_v \lesssim 10^{25}$ W Hz$^{-1}$, comparable to the low end of the distribution of jetted sources (Zamfir et al., 2008). Moving along the sequence from spectral type from B1$^{++}$ to A4, the fraction of radio-loud and radio-intermediate peaks at the two extremes.

A possible interpretation is the existence of a population of jetted sources of moderate luminosity, associated with small black hole masses (RL NLSy1s, Komossa et al., 2006). However, the xA radio-intermediate might not follow the same relation between radio power and radio-to-optical flux ratio (Fig. 4 and del Olmo et al. 2021). WISE colors indicate that star formation in the host galaxies can give a significant contribution to the radio power (Caccianiga et al., 2015). Ganci et al. (2019) showed that the xA sources with significantly radio power obey the correlation between FIR luminosity and radio power expected for star-forming galaxies and radio-quiet quasars (c.f. Bonzini et al., 2015). A radio power $P_v \sim 10^{25}$ W Hz$^{-1}$ translates into an enormous star-formation rate SFR $\sim 10^4$ M$_\odot$ yr$^{-1}$, implying that most of the host (and not only the circumnuclear regions) might be experiencing a burst of star formation. This might be unlikely at low redshift, but not at the “cosmic noon.”

### 4.3 Orientation effects

The orientation effects on xA sources specifically have been analyzed in several recent papers (Dultzin et al., 2020; Marziani, Bon, et al., 2020; Negrete et al., 2018). xA samples are biased: since they have low line equivalent width (Martínez-Aldama et al., 2018), they are preferentially selected with narrower lines, and narrower lines might imply low inclination. This said, xA sources are accreting at very high rates, implying that their luminosity per unit mass converges toward a limiting value (Wang, Du, Valls-Gabaud, Hu, & Netzer, 2013). This property can be, in principle, used to define “Eddington standard candles,” in which the Eddington ratio, and not the luminosity, has a small scatter around a well-defined value (Marziani & Sulentic, 2014). Since the virial luminosity is derived from the assumption $L/M_{BH} \sim \text{const}$, lower $L$ is implied by narrower line width, and the FWHM decreases with decreasing amplitude of the viewing angle, a relation can be established between viewing angle $\theta$ and the difference between the virial luminosity and luminosity derived from concordance cosmology. The resulting distribution covers the range from $0 \lesssim \theta \lesssim 50$, with a maximum at $\theta \approx 20$ (Marziani, Bon, et al., 2020; Negrete et al., 2018), with a relatively small dispersion. At least the xA sources that were analyzed in the previous works are seen predominantly almost face-on.

### 5 Conclusion

Recent developments strengthen the interpretation of the MS of quasars based on Eddington ratio and orientation. At the Population B extremes, the broad line emitting regions appear as “disk dominated” and the flatness of the emitting region helped detect orientation effects. The MS is not only about spectral parameters; instead, it reflects different evolutionary and environmental situations. In Population B, an estimate of metallicity $Z$ for a fairly typical source suggest solar or
slightly sub-solar metallicity. At the other extreme of the main sequence, extreme of Population A appear to be in highly star forming hosts, very metal rich, possibly with enrichment associated with a circumnuclear Starburst or nuclear accretion modified stars (D’Onofrio & Marziani 2018). Preliminary attempts to build a Hubble diagram with xA sources are still affected by large dispersion in the distance modulus estimates (Czerny et al. 2021; Dultzin et al. 2020). Large samples (ideally recognized via machine learning, Jankov et al. 2021; Peruzzi et al. 2021) could help) reduce the statistical dispersion. However, the additional complexity related to SED and circumnuclear environment needs to be thoroughly analyzed to safely exploit xA sources as Eddington standard candles.

Author contributions

PM wrote the paper. The other authors contributed in various form to several publications summarized in the text. We thank the reviewer whose suggestion greatly contributed to improve the clarity and completeness of the paper.

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REFERENCES

Antonucci, R. 1993, ARA&A, 31, 473-521. doi:
Bentz, M. C., Denney, K. D., Grier, C. J. et al. 2013, April, ApJ, 767, 149. doi:
Bianchi, S., Antonucci, R., Capetti, A. et al. 2019, September, MNRAS, 488(1), L1-L5. doi:
Bon, E. 2008, December, New A Rev., 57, 9-13. doi:
Bon, E., Jovanović, P., Marziani, P., Bon, N., & Otašević, A. 2018, June, Frontiers in Astronomy and Space Sciences, 5, 19. doi:
Bon, E., Popović, L. Č., Gavrilović, N., Mura, G. L., & Mediavilla, E. 2009, December, MNRAS, 400, 924-936. doi:
Bon, E., Popović, L. Č., Ilić, D., & Mediavilla, E. 2006, November, New A Rev., 50(9-10), 716-719. doi:
Bon, N., Bon, E., & Marziani, P. 2018, January, Frontiers in Astronomy and Space Sciences, 5, 3. doi:
Bon, N., Bon, E., & Marziani, P. 2015, December, Ap&SS, 360, 7. doi:
Bon, N., Marziani, P., Bon, E. et al. 2020, March, A&A, 635, A151. doi:
Bonzini, M., Mainieri, V., Padovani, P. et al. 2015, October, MNRAS, 453, 1079-1094. doi:
Boroson, T. A., & Green, R. F. 1992, May, ApJS, 80, 109. doi:
Caccianiga, A., Antón, S., Ballo, L. et al. 2015, August, MNRAS, 451(2), 1795-1805. doi:
Chen, K., Halpern, J. P., & Filippenko, A. V. 1989, April, ApJ, 339, 742-751. doi:
Collin-Souffrin, S., Dyson, J. E., McDowell, J. C., & Perry, J. J. 1988, June, MNRAS, 232, 539-550. doi:
Corbin, M. R. 1995, July, ApJ, 447, 496-. doi:
Czerny, B., Martínez-Aldama, M. L., Wojtakowska, G. et al. 2021, April, Acta Physica Polonica A, 139(4), 389-393, doi:
del Olmo, A., Marziani, P., Ganci, V., D’Onofrio, M., Bon, E., Bon, N., & Negrete, A. C. 2021, January, IAU Symposium, 356, 310-313. doi:
D’Onofrio, M., & Marziani, P. 2018, September, Frontiers in Astronomy and Space Sciences, 5, 31, doi:
D’Onofrio, M., Marziani, P., & Chiosi, C. 2021, September, arXiv e-prints, arXiv:2109.06301. doi:
Du, P., Wang, J.-M., Hu, C., Ho, L. C., Li, Y.-R., & Bai, J.-M. 2016, February, ApJ, 818, L14. doi:
Dultzin, D., Marziani, P., de Diego, J. A. et al. 2020, January, Frontiers in Astronomy and Space Sciences, 6, 80. doi:
Elvis, M. 2000, December, ApJ, 545, 63-76. doi:
Eracleous, M., Halpern, J. P., Gilbert, A. M., Newman, J. A., & Filippenko, A. V. 1997, November, ApJ, 490, 216-. doi:
Eracleous, M., Livio, M., Halpern, J. P., & Storchi-Bergmann, T. 1995, January, ApJ, 438, 610-622. doi:
Ferland, G. J., Chatzikos, M., Guzmán, F. et al. 2017, October, Rev. Mexicana Astron. Astrofis., 53, 385-438.
Ferland, G. J., Done, C., Jin, C., Landt, H., & Ward, M. J. 2020, May, MNRAS, 494(4), 5917-5922. doi:
Fraix-Burnet, D., Marziani, P., D’Onofrio, M., & Dultzin, D. 2017, Frontiers in Astronomy and Space Sciences, 4, 1. Retrieved from http://journal.frontiersin.org/article/10.3389/fspas.2017.00001
Ganci, V., Marziani, P., D’Onofrio, M., del Olmo, A., Bon, E., Bon, N., & Negrete, C. A. 2019, October, A&A, 630, A110. doi:
Gaskell, C. M. 1985, April, ApJ, 291, 112-116. doi:
Halpern, J. P., & Filippenko, A. V. 1988, January, Nature, 331, 46-48. doi:
Jankov, I., Ilić, D., & Kovachević, A. 2021, June, Publications de l’Observatoire Astronomique de Beograd, 100, 241-246.
Jiang, B.-W., Marziani, P., Savić, D. et al. 2021, August, MNRAS. doi:
Kaspis, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., & Giveon, U. 2000, April, ApJ, 533, 631-649. doi:
Komossa, S., Voges, W., Xu, D. et al. 2006, August, AJ, 132, 531-545. doi:
Laor, A., Fiore, F., Elvis, M., Wilkes, B. J., & McDowell, J. C. 1997, March, ApJ, 477, 93-. doi:
Marin, F. 2016, August, MNRAS, 460(4), 3679-3705. doi:
Marinello, A. O. M., Rodriguez-Ardila, A., Garcia-Rissmann, A., Sigut, T. A. A., & Pradhan, A. K. 2016, February, ApJ, 820(2), 116.
Martínez-Aldama, M. L., Czerny, B., Kawka, D., Karas, V., Panda, S., Zajaček, M., & Życki, P. T. 2019, October, ApJ, 883(2), 170. doi:
Martínez-Aldama, M. L., del Olmo, A., Marziani, P. et al. 2018, November, A&A, 618, A179. doi:
Marziani, P., Bon, E., Bon, N. et al. 2020, January, Contributions of the Astronomical Observatory Skalnate Pleso, 50(1), 244-256. doi:
Marziani, P., del Olmo, A., D’Onofrio, M. et al. 2018, April, Narrow-line Seyfert 1s: what is wrong in a name? Revisiting narrow-line Seyfert 1 galaxies and their place in the Universe. 9-13 April 2018. Padova Botanical Garden, Italy. Online at <A href="https://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=328">https://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=328</A>.
Vol. PoS(NLS1-2018), p. 002. SISSA/ISAS.
Marziani, P., del Olmo, A., Perea, J., D’Onofrio, M., & Panda, S. 2020, December, *Atoms*, 8(4), 94. doi:

Marziani, P., Dultzin, D., del Olmo, A. et al. 2021, January, *IAU Symposium*, 356, 67-71.

Marziani, P., Dultzin, D., Sulentic, J. W. et al. 2018, March, *Frontiers in Astronomy and Space Sciences*, 5, 6.

Marziani, P., & Sulentic, J. W. 2014, August, *MNRAS*, 442, 1211-1229. doi:

Marziani, P., Sulentic, J. W., Dultzin-Hacyan, D., Calvani, M., & Moles, M. 1996, May, *ApJS*, 104, 37+. doi:

Marziani, P., Sulentic, J. W., Negrete, C. A., Dultzin, D., D’Onofrio, M., Del Olmo, A., & Martinez-Aldama, M. L. 2014, October, *The Astronomical Review*, 9, 6-25.

Marziani, P., Sulentic, J. W., Negrete, C. A., Dultzin, D., Zamfir, S., & Bachev, R. 2010, December, *MNRAS*, 409, 1033-1048. doi:

Marziani, P., Sulentic, J. W., Plauchu-Frayn, I., & del Olmo, A. 2013, May, *AAp*, 555, 89, 16pp.

Marziani, P., Sulentic, J. W., Zwitter, T., Dultzin-Hacyan, D., & Calvani, M. 2001, September, *ApJ*, 558, 553-560. doi:

Marziani, P., Zamanov, R. K., Sulentic, J. W., & Calvani, M. 2003, November, *MNRAS*, 345, 1133-1144. doi:

Mineshige, S., Kawaguchi, T., Takeuchi, M., & Hayashida, K. 2000, June, *PASJ*, 52, 499-508.

Negrete, C. A., Dultzin, D., Marziani, P. et al. 2018, December, *A&A*, 620, A118. doi:

Padovani, P. 2017, November, *Frontiers in Astronomy and Space Sciences*, 4, 35. doi:

Panda, S., Czerny, B., Adhikari, T. P., Hryniewicz, K., Wildy, C., Kuraskiewicz, J., & Śniegowska, M. 2018, October, *The Astrophysical Journal*, 866(2), 115. Retrieved from [https://doi.org/10.3847%2F1538-4357%2FApJ%2F1538-4357%2F866%2F115](https://doi.org/10.3847%2F1538-4357%2FApJ%2F1538-4357%2F866%2F115) doi:

Panda, S., Marziani, P., & Czerny, B. 2019, September, *ApJ*, 882(2), 79. doi:

Peruzzi, T., Pasquato, M., Ciroi, S., Berton, M., Marziani, P., & Nardini, E. 2021, August, *A&A*, 652, A19. doi:

Popović, L. Ć., Mediavilla, E., Bon, E., & Ilić, D. 2004, September, *A&A*, 423, 909-918. doi:

Popovic, L. C., Vince, I., Atanackovic-Vukmanovic, O., & Kubicela, A. 1995, January, *A&A*, 293, 309-314.

Punsly, B. 2010, April, *ApJ*, 713, 232-238. doi:

Punsly, B., Marziani, P., Bennert, V. N., Nagai, H., & Gurwell, M. A. 2018, December, *ApJ*, 869, 143. doi:

Punsly, B., Marziani, P., Berton, M., & Kharb, P. 2020, November, *ApJ*, 903(1), 44. doi:

Punsly, B., Tramacere, A., Kharb, P., & Marziani, P. 2018, December, *ApJ*, 869(2), 174. doi:

Richards, G. T., Kruczek, N. E., Gallagher, S. C. et al. 2011, May, *AJ*, 141, 167-+. doi:

Shen, Y., & Ho, L. C. 2014, September, *Nature*, 513, 210-213. doi:

Śniegowska, M., Marziani, P., Czerny, B., Panda, S., Martinez-Aldama, M. L., del Olmo, A., & D’Onofrio, M. 2021, April, *ApJ*, 910(2), 115. doi:

Strateva, I. V., Strauss, M. A., Hao, L. et al. 2003, October, *AJ*, 126, 1720-1749. doi:

Sulentic, J. W., Bachev, R., Marziani, P., Negrete, C. A., & Dultzin, D. 2007, September, *ApJ*, 666(2), 757-777. doi:

Sulentic, J. W., Calvani, M., Marziani, P., & Zheng, W. 1990, May, *ApJ*, 355, L15. doi:

Sulentic, J. W., Martinez-Carballe, M. A., Marziani, P., del Olmo, A., Stirpe, G. M., Zamfir, S., & Plauchu-Frayn, I. 2015, June, *MNRAS*, 450, 1916-1925. doi:

Sulentic, J. W., Marziani, P., & Dultzin-Hacyan, D. 2000, *ARA&A*, 38, 521-571. doi:

Sulentic, J. W., Marziani, P., Zamanov, R., Bachev, R., Calvani, M., & Dultzin-Hacyan, D. 2002, February, *ApJL*, 566, L71-L75. doi:

Sulentic, J. W., Marziani, P., Zwitter, T., Dultzin-Hacyan, D., & Calvani, M. 2000, December, *ApJL*, 545, L15-L18. doi:

Sulentic, J. W., Zamfir, S., Marziani, P., Bachev, R., Calvani, M., & Dultzin-Hacyan, D. 2003, November, *ApJL*, 597, L17-L20. doi:

Sun, J., & Shen, Y. 2015, May, *ApJ*, 804, L15. doi:

Temple, M. J., Ferland, G. J., Rankine, A. L., Chatzikos, M., & Hewett, P. C. 2021, August, *MNRAS*, 505(3), 3247-3259. doi:

Urry, C. M., & Padovani, P. 1995, September, *PASP*, 107, 803. doi:

Wang, J.-M., Du, P., Brotherton, M. S. et al. 2017, October, *Nature Astronomy*, 1, 775-783. doi:

Wang, J.-M., Du, P., Hu, C. et al. 2014, October, *ApJ*, 793(2), 108. doi:

Wang, J.-M., Du, P., Valls-Gabaud, D., Hu, C., & Netzer, H. 2013, February, *Physical Review Letters*, 110(8), 081301. doi:

Wills, B. J., & Brotherton, M. S. 1995, August, *ApJ*, 448, L81. doi:

Wills, B. J., & Browne, I. W. A. 1986, March, *ApJ*, 302, 56-63. doi:

Wolf, J., Salvato, M., Coffey, D. et al. 2020, March, *MNRAS*, 492(3), 3580-3601. doi:

Zamfir, S., Sulentic, J. W., & Marziani, P. 2008, June, *MNRAS*, 387, 856-870. doi:

Zamfir, S., Sulentic, J. W., Marziani, P., & Dultzin, D. 2010, February, *MNRAS*, 403, 1759. doi:

Zheng, W., & Sulentic, J. W. 1990, February, *ApJ*, 350, 512. doi:

Zheng, W., Sulentic, J. W., & Binette, L. 1990, December, *ApJ*, 365, 115-118. doi:

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