OUR SEARCH FOR AN H-R DIAGRAM OF QUASARS

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1. INTRODUCTION

A NED search for references to one of the hundred brightest AGN (e.g. PG quasars; Boroson & Green 1992, hereafter BG92) will frequently yield $\sim$50-200 “hits”, but among these one will often find only very few papers dealing with optical/UV spectroscopy of that source. This is surprising especially if one considers that such spectra offer the most direct insights into the geometry and kinematics of the central broad and narrow line regions. Multiwavelength astronomy is apparently still in its infancy with most papers dealing with monochromatic measures. While AGN unification schemes are popular–up till recently–no spectroscopic unification has existed for AGN. This is due to at least two things: 1) until relatively recently few sources with moderate to high resolution and S/N spectroscopy existed for AGN and 2) there has been a common belief that AGN spectra are basically the same. The SDSS has ameliorated the former problem, although caution is required if one considers spectra for sources fainter than $g\sim$17.5.

We have been searching for a spectroscopic unification embracing all broad line AGN for the past 10+ years. Our hope was to find a diagnostic space that could serve somewhat the same role as the H-R Diagram serves for stellar studies. The H-R Diagram functions well in 2D although its full power requires exploitation of more parameter dimensions. Certainly an equivalent spectroscopic diagnostic space for quasars will require more than two dimensions if only to remove the degeneracy between source physics and line-of-sight orientation – as drivers of measured source properties. This is a problem that

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does not afflict the stellar H-R diagram. In 2000 we proposed a 4D Eigenvector 1 parameters space \citep{Sulentic2000b,Eigenvector1;BG92} as the optimal vehicle to allow for emphasizing spectroscopic diversity while at the same time contextualizing the diverse types of broad-line emitting sources.

Our 4DE1 parameter space provides a potentially fundamental discrimination between major AGN classes. 4DE1 space \citep{Sulentic2000b} incorporates all of the statistically significant line profile similarities and differences that are currently known. 4DE1 has roots in the Principal Component Analysis (PCA) of the Bright Quasar Sample (Eigenvector 1; BG92) as well as in correlations that emerged from ROSAT \citep[e.g.][]{Wang1996}. 4DE1 as we define it involves BG92 measures: 1) full width half maximum of broad H$\beta$ (FWHM H$\beta$) and 2) equivalent width ratio of optical FeII and broad H$\beta$: $R_{FeII}=W(FeII)/W(H\beta_{BC})$. We added 3) a measure of the soft X-ray photon index ($\Gamma_{sof t}$) and 4) a measure of CIV broad line profile displacement at half maximum ($c(1/2)$) to arrive at our 4DE1 space. Other points of departure from BG92 involve explicit comparison of RQ and RL sources as well as subordination of [OIII] measures \citep[although see][]{Zamanov2002,Marziani2003}. Finally we divide AGN into two populations using a simple division at FWHM $H\beta_{BC}=4000$ km s$^{-1}$ with sources narrower and broader than this value designated populations A and B, respectively. The latter distinction was motivated by the observation that almost all RL sources show FWHM $H\beta_{BC}>4000$ km s$^{-1}$ \citep{Sulentic2000b}. This distinction turns out to be more effective for highlighting spectroscopic differences than the more traditional divisions into: 1) RQ-RL sources and 2) NLSy1-BLSy1 sources defined with FWHM $H\beta_{BC}<$ and $>2000$ km s$^{-1}$, respectively.

Adopted 4DE1 key parameters were chosen with the following two requirements in mind: 1) measures that showed large intrinsic variance ($\Sigma$) and 2) measures that could be made with high precision ($\sigma$). Many most other spectroscopic measures show correlation in 4DE1 and/or population A-B dichotomy \citep[e.g. optical Balmer line asymmetry, UV SIII][1999,1999,1999 ratio, hard X-ray spectral index] but do not show large enough variance, or cannot be obtained for large enough numbers of sources with suitable precision, to permit adoption as key parameters \citep[e.g. $\Sigma>20\sigma$]{Marziani2003}. All line measures involve suitably corrected broad line components (reduction procedures are described in \citealt{Marziani1996,Marziani2003,Sulentic2007}).

The key parameters can be said to measure: 1) the dispersion in (low ionization line) BLR cloud velocities, 2) the relative strengths of FeII and H$\beta$ emission, 3) the strength of a soft X-ray excess and 4) the amplitude of systematic radial motions in (high ionization line) BLR emitting gas. In less simple terms \citep[i.e. more model dependent]{} we likely have: 1) three or four orthogonal variables sensitive to the Eddington ratio, 2) two or three variables sensitive to source inclination, as well as 3) one variable sensitive to black hole mass (FWHM) and another to nebular physics ($n_e$: $R_{FeII}$). Taken together they offer the most direct clues about the geometry and kinematics of the broad line region (BLR).

Source occupation in principal planes of 4DE1 can be found in \citep{Sulentic2000b,Sulentic2007}. These studies have made use of ground based optical spectra for the H$\beta$ region, HST archival FOS/STIS UV spectra for the region of CIV and ROSAT X-ray spectra. We have recently \citep{Zamfir2008} in preparation) exploited the SDSS database which offers major advantages: 1) uniform, high resolution ($\sim 1$A) and high S/N spectra for the 300+ brightest quasars and 2) broad wavelength coverage (3000-9000Å). Our adopted redshift limit $z=0.7$ allows measures of H$\beta$ and neighboring lines. This has greatly expanded the number of bright quasars in the magnitude and color range of the PG. It also provides a sample with the proper ratio of RL to RQ sources. Uniform FIRST radio measures allow us to explore the differences between RQ and RL sources with a highly complete ($\sim 80\%$; see \citealt{Jiang2007}) sample. Figure 1 offers an introduction to the optical plane of 4DE1 in the light of the SDSS era and it is reassuring to note that source occupation confirms our previous work. Similarly we describe preliminary X-ray results that come from the growing XMM-NEWTON spectroscopic sample. We attempt to summarize here the many insights that 4DE1 offers as a diagnostic space that offers a clearer context in which to interpret individual sources.

1) 4DE1 makes clear that broad line emitting AGN show a wide range of spectroscopic properties – they are not all alike – the intrinsic dispersion in 4DE1 parameters is much larger than measurement errors. The cross in the upper right corner of Figure 1 indicates typical (median) measurement uncertainties which correspond roughly to $3\sigma$. FWHM H$\beta$ measures range from 1000 (smallest known $\sim 630$ km s$^{-1}$; \citealt{Grupe1999}) to $\sim 23000$ km s$^{-1}$ in our sample (largest known $\sim 40000$ km s$^{-1}$; \citealt{Wang2005} in H$\alpha$) and $R_{FeII}$ measures from 0 to $\sim 1.8$ (most extreme known $R_{FeII}\sim 6$; \citealt{Lipari1993}).
Note that SDSS calls sources with FWHM Hβ<1000 km s\(^{-1}\) galaxies rather than quasars and FeII emitters with R\(FeII\)rarely found in the SDSS quasar catalog. They are extremely red objects (strong IRAS sources as well; see Lipari et al. 1993; Veron-Cetty et al. 2006) and they require a special analysis of the FeII emission. These objects are therefore not included in our sample. We regard detection of (broad) FeII emission as a requirement for Type 1 quasar status. Our previous work involved many more sources with R\(FeII\),upper limits reflecting the sensitivity of FeII detection to continuum s/n especially for broader line sources (see Marziani et al. 2003a, Figure 3). SDSS spectra for bright quasars reveal less than 1% of broad-line emitting sources with undetected FeII emission suggesting that FeII emission is an ubiquitous property of Type 1 AGN.

Figure 1 tells us that average quasar spectra that do not allow for the wide observed parameter dispersion are somewhat like average stellar spectra involving the entire OBAGFKM sequence (see Sulentic et al. 2002, 2007; Bachev et al. 2004; Zamfir et al. 2008 in preparation) for average spectra in the 4DE1 context).

3) RL sources (blue filled squares/green open circles) occupy one end of the RQ sequence and overlap with about 25% of RQ sources. This domain space separation is highly significant (P\(\sim\)3\(\times\)10\(^{-7}\) that RQ and RL occupy the same domain; Zamfir et al. 2008) and credible because we are dealing with unusually complete/balanced RQ and RL samples. These are therefore the only RQ sources that are spectroscopically indistinguishable from RL AGN. We define a source as RL if log\(L_{20cm}(ergs^{-1}Hz^{-1})=31.5\) (this is approximately a radio/optical flux density ratio R\(K\)=70; Kellermann et al. 1989). This corresponds to the radio properties of the weakest observed
double-lobed (assumed unbeamed in an orientation unification scenario) source in our old and new samples (Sulentic et al. 2003, Zamfir et al. 2008). The probability of radio loudness in Figure 1 increases from $P \sim 0.01$ at the extreme RQ end of the source sequence (where NLSy1 are found; Komossa et al. 2006 estimates $P \sim 0.025$ for NLSy1) to $P \sim 0.15-0.18$ at the opposite end where the vast majority of RL sources are found.

4) Few RL sources are found below $FWHM_{H\beta_{BC}} = 4000 \text{ km s}^{-1}$. Those that do likely involve sources where the putative accretion disk is seen face-on (and radio jets pole-on) (Sulentic et al. 2003, Zamfir et al. 2008). We can infer this because we see a separation between the majority of core-dominated sources (CD–filled squares) and lobe-dominated (LD–open circles) emission. Most RL sources with large and small $FWHM_{H\beta}$ values are lobe- and core-dominated (alternatively steep and flat radio spectrum sources) respectively again as expected from simple orientation unification schemes (e.g. Urry & Padovani 1993; Orr & Browne 1982) where Balmer emission arises in a flattened cloud distribution (usually called an accretion disk) and the radio-jets are aligned perpendicular to the cloud distribution. Red arrows in Figure 1 indicate the median displacement in 4DE1 optical plane coordinates between FRII and CD sources in the old and new source samples (Sulentic et al. 2003, Zamfir et al. 2008). This is consistent with LD sources viewed as the (misaligned) parent population of RL sources and with CD sources as the aligned (near pole-on and Doppler boosted) sources. Some CD (largest $FWHM$) and LD (smallest $FWHM$) sources do not follow the clear trend indicated by the red arrows in Figure 1. These likely represent the (about 10-15% in our RL sample) “misaligned” sources where the radio jets are far from perpendicular to the accretion disk plane.

5) All reasonably resolved LD sources in our SDSS sample show FRII morphology suggesting that FRI sources are rare among broad-line RL emitters. Some weak FRI sources may be present among the RQ sources but they show extreme core/lobe ratios and are effectively filtered out of the FIRST survey (dynamic range limits and spatial frequency attenuation). We find no evidence for a significant radio-intermediate population bridging the RQ and RL sources. While weak radio jets are observed in some RQ quasars (e.g. Ulvestad et al. 2003; Leipski et al. 2006), the majority show radio emission dominated by star formation in the host galaxies (e.g. PG quasars follow the radio-FIR correlation; see Haas et al. 2003). There is no evidence for a continuum of radio jet properties from largely LD RL to largely CD RQ sources although a few RQ show unusually strong radio jet-lobe structures (e.g. García-Baretto et al. 2002). The strongest support for this conclusion comes from 4DE1 (Figure 1) where RL sources show a preferred domain space occupation relative to the RQ majority.

6) There may be two AGN populations: 1) a “pure” RQ population A which shows little overlap with the RL domain (e.g. it includes ~70% of the RQ sample) and 2) a mixed RL-RQ population B (~30% of the RQ sources and almost all RL sources). We recently summarized (Sulentic et al. 2007) the empirical (and inferred theoretical differences) between pop. A and B sources which, in fact, encompass almost all existing multiwavelength measures of AGN. A recent comparison between $FWHM$ and line dispersion (2nd moment of the profile) measurements for $H\beta$ has accidentally confirmed our two population hypothesis (Collin et al. 2006). Focusing on the key 4DE1 parameters we can say that Pop. A sources show relatively narrow single-component Balmer lines, strong FeII emission, a CIV blueshift and a soft X-ray excess. Pop. B sources show broader, and often more complex, Balmer lines, weak FeII emission and absence of a CIV blueshift or soft X-ray excess.

Average Balmer line spectra in the 4DE1 context (Sulentic et al. 2002) require a minimum of two

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Fig. 2. Our bright quasar sample in a UV – X-ray plane of 4DE1 space. Dashed lines are 2σ confidence intervals for zero CIV shift.
Gaussian components for a reasonable model fit. Aside from the relatively unshifted component assumed to be the “classical” BLR we find a broader and redshifted (VBLR- Very Broad Line Region) component. The latter component is dangerous for reverberation studies and BH mass estimation because it responds to continuum changes differently than the classical BLR (Sulentic et al. 2000c). At the upper extreme of optical 4DE1 space we find a very small number (<1%) of sources showing double-peaked Balmer line profiles. While they have been interpreted as a direct signature of accretion disk line emission (Freuches & Halberd, 1994) there are many problems with this hypothesis (Sulentic et al. 1999; Sulentic 2006). The situation is reversed for UV high ionization line profiles like CIV1549. Pop. A sources require unshifted and blueshifted components while pop. B sources show stronger and less shifted line profiles. Extreme pop. A sources are sometimes dominated by the blueshifted component.

CIV measures have been clouded in controversy for many years with much of the disagreement centered on the reality and strength of a narrow CIV emission component (Sulentic & Marziani 1999). We recently presented a recipe for reasonable CIV narrow component subtraction (Sulentic et al. 2007) and show that corrected broad line measures clarify our picture of high ionization line emission properties in AGN.

7) Figure 2 shows the current best CIV-Γsoft 4DE1 plane which illustrates two of the pop. A-B differences summarized above. Figure 2 suggests that pop. B sources show a much stronger domain space concentration than pop. A. RFeII and CIV shift (c(1/2)) measures also show this concentration. While pop. A sources show considerable scatter in all 4DE1 measures, pop B sources show this scatter only in measures of FWHM Hβ. This may be telling us that the physics/geometry/kinematics of pop. B sources is much more similar from source-to-source. This makes some sense if we view pop. B sources as the end phase of quasar evolution when the accretion rate is low.

X-ray measures shown in Figure 2 are based largely on archival ROSAT observations. We have only begun to harvest the new generation of XMM-Newton X-ray measures. Three recent papers have analyzed strongly overlapping samples of PG quasars ranging from 20-40 sources (Porquet et al. 2004; Brocksopp et al. 2006; Piconcelli et al. 2005). These samples allow a preliminary test of earlier inferences that motivated us to adopt Γsoft as a key 4DE1 parameter. Table 1 summarizes a comparison of mean

| Table 1 |
|------------------|------------------|------------------|
|                 | Piconcelli–single power-law fit | Pourquet/Brocksopp/Piconcelli–broken power-law fit |
| Pop. | N | Γ2–12keV | Γ0.3–12keV | N | Γsoft | Γhard |
| A | 22 | 1.94 | 2.71 | 14/14/13 | 2.825/2.86/2.98 | 2.07/2.13/1.39 |
| B | 11 | 1.66 | 1.88 | 7/6/8 | 2.31/2.61/2.75 | 1.795/1.82/1.38 |

XMM measures for PG quasars observed so far. We restrict this preview to low z PG quasars (included in BG92) for the following two reasons: 1) higher redshift PG sources, assumed to have similar intrinsic X-ray luminosity, will yield lower s/n spectra on average and 2) we have no FWHM Hβ or RFeII measures for higher z PG sources precluding a contextualization in 4DE1 space. We immediately distinguish between our so-called population A and B sources. Even if this distinction turns out not to be fundamental in the sense of physically discrete quasar classes it has proven effective for highlighting differences across the 4DE1 sequence.

The largest difference between pop. A and B sources involves comparison over the largest energy range (0.3-12keV). The pop. A-B soft photon index difference is larger than the one reported in the defining papers of the 4DE1 concept (Sulentic et al. 2000a,b). It is also 3× larger than the A-B difference in the “harder” 2-12keV energy range. This was the motivation for suggesting that only pop. A sources show a soft X-ray excess. XMM measures confirm the ROSAT derived pop. A-B difference and Table 1 shows that the mean soft 0.3-12 keV index for pop. B sources is similar to harder pop. A-B indices derived over the 0.3-12keV range. Despite claims that all PG quasars show a soft excess, this result suggests that pop. B sources do not.

Single power-law fits to PG X-ray spectra are generally poor which motivated the above studies to consider broken power-laws providing both hard and soft photon indices as given in Table 1. We see some evidence for a stronger pop A-B difference in the soft band however there is considerable variance among the three studies. If we restrict the Brocksopp et al. 2006 sample to broken power-law fits with the best χ² solutions we find a soft component pop. A-B difference Δ=3.0-2.5~0.5 which supports a pop. A excess at a K-S significance level P=0.002. Sigma values are 0.6 and 0.3 also.
confirming the smaller scatter among pop B sources mentioned above. Clearly we need more X-ray spectra for low z PG quasars.

As also reported earlier (Sulentic et al. 2000b, 2007) a (smaller) difference is seen for harder X-ray measures in the Piconcelli et al. (2003) sample. Pop. B sources show a harder spectrum than pop. A sources in most of the XMM studies. All three XMM studies report correlations between FWHM Hβ and soft/hard measures confirming the correlation that we found with a larger (n=112) ROSAT sample (Sulentic et al. 2000a). The apparently continuous correlation may be telling us that Pop. A-B are simply the ends of single AGN sequence rather than two distinct classes.

The “soft X-ray excess” has been widely interpreted as the thermal signature of an accretion disk (Pounds et al. 1995). This interpretation is reasonable within the 4DE1 context where the strongest soft excess is found among sources with the the smallest black hole masses and highest accretion rates (highest L/L_Edd). Following this reasoning (Piconcelli et al. 2003) explored composite model fits. It is interesting that models employing a power-law+bremstrahlung yielded a much larger pop. A-B difference (kT=0.02 vs. 0.07) than models employing a power-law+black body. If the pop. A-B difference is real then this may be telling us that the thermal disk interpretation is incorrect or too simple. Brocksopp et al. (2006) reached a similar conclusion using a different argument. It has been known for a long time that the pop. A soft excess implies too high temperatures which has motivated some to explore Comptonized disk models (e.g. Haardt et al. 1994).

Two conclusions/comments from the XMM studies (Piconcelli et al. 2003) require a response within the 4DE1 context. A) A RL-RQ difference could suggest the presence of an extra continuum contribution from self synchrotron jet emission (Zamorani et al. 1981). 4DE1: We suggest that the few RL sources in PG preclude statistically useful inferences. However in 4DE1 context we know that RQ pop. B sources show very similar properties to the (largely pop. B) RL sources. Our much larger ROSAT sample shows this statement to be reasonable. This motivated us to opine that since RQ pop. B sources show the same spectra as RL sources there is no evidence for an X-ray component related to a sources radio-loudness. B) None of the two component models gives a satisfactory fit for all sources. This result suggests that the shape of the soft excess is not a universal QSO property. 4DE1: The population A-B distinction is very useful here because it suggests that there are two fundamentally different kinds of X-ray emitting quasars. Their soft X-ray excess is only a property of one of these populations.

8) We recently harvested from the HST archive all UV spectra (n=130 sources) covering the CIV1549 region. We find mean CIV profile shifts (at FWHM) of -677 km s^{-1} and -39 km s^{-1} respectively for pop. A and B sources confirming the original motivation for adopting this measure as a key 4DE1 parameter (Sulentic et al. 2000b, 2007). The blueshift of high ionization UV emission lines is therefore concentrated in sources with FWHM Hβ<4000 km s^{-1}. This means that it is a largely RQ phenomenon (mean CIV profile shifts for RQ and RL sources are -582 km s^{-1} and +52 km s^{-1}, respectively); CIV equivalent width also shows a striking pop. A-B difference: 117A and 57A, respectively. We recently discovered an apparent correlation between CIV EW and FWHM measures, but only for pop. A sources. As mentioned earlier most pop. B sources show CIV shift/EW, R_{Fe/H} and Γ_{soft} measures that are identical within measurement uncertainties. We hope to exploit CIV measures as an orientation indicator using this new correlation. It is now well known that the Baldwin effect is dominated by intrinsic (we would say 4DE1) rather than cosmological effects (Bachev et al. 2004; Baskin & Laor 2004).

**PHYSICAL INFERENCES:** We have described some of the empirical results connected with the four key parameters defining 4DE1 space. 4DE1 is the most effective spectroscopic unifier available, at the same time it emphasizes the differences between AGN. We have also begun to explore the physical implications of 4DE1 (Marziani et al. 2001, 2003b) and suggest the following theoretical inferences from the empiricism; adopting a model where low ionization broad lines (e.g. broad Hβ and FeII emission) arise in a photoionized medium in or near an accretion disk. Simple models then allow us to use: a) line reverberation to infer the radius of the broad line region (Kaspi et al. 2000, 2001, 2004); b) line FWHM or dispersion to infer the BH mass (assuming a virialized medium; Marziani et al. 2003b; Collin et al. 2006; Sulentic 2006) and c) R_{Fe/H} to infer the density of the FeII emitting medium that is as dense as or denser than the region producing Hβ (Marziani et al. 2001 and this volume). The Eddington ratio emerges from b) + source bolometric luminosity. The most useful summary statement here might be a comparison of median inferred properties for pop. A and B sources. Table 2 summarizes
### Table 2

| QUANTITY       | POP–A | POP–B |
|----------------|-------|-------|
| $\log n_E$     | 11.5  | 9.5   |
| $\log U$       | -1.5  | -1.0  |
| $\log M_{BH}$  | 7.7   | 9.0   |
| $L/L_{Edd}$    | 0.3   | 0.08  |

**Fig. 3.** Inferred physical trends along the quasar sequence in the optical plane of 4DE1 space.

The inferred properties in Table 2 are representative of our current understanding of sources with $z \leq 0.8$. Unfortunately the $H_\beta$ spectral region cannot be studied from the ground beyond $z \sim 1.0$ ($z=0.7$ for SDSS spectra) without major effort. Ground based CIV measures have been extensively used to extract $M_{BH}$ and other properties out to much higher redshift ($z \sim 4.0$). Our own studies of the CIV line using the HST archive suggest that CIV cannot be trusted for $M_{BH}$ estimation for many reasons: 1) the obvious Malmquist bias associated with CIV measures for any optically selected sample, 2) the complexity of the CIV profile and properties reflected in pop. A-B profile differences and the lack of a clear correlation between FWHM $H_\beta$ – FWHM (CIV) and 3) especially for the pop. A (majority) of RQ sources - the blueshifted and blue asymmetric profile shapes which must raise doubts that the high ionization UV lines arise in a virialized medium. Sources with a strong narrow line component (likely more common among pop. B sources if lines like $[OIII] \lambda 5007$ are any guide) tend to give a false sense of security because they make CIV profiles look more symmetric to the disk plane where Keplerian rotation dominate. The much smaller velocity dispersion in pop. A sources is consistent with the idea of a highly flattened distribution. Either pop. B sources are much less flattened or there is an additional emission component producing the much higher observed velocity dispersion perpendicular to the disk. A more extreme alternative would see line emission in pop. B sources arising entirely in a non-disk configuration.

Note that the “face-on” value for pop. A sources is set by the lower limit of observed FWHM $H_\beta$ (with FeII emission corroborating that the source is an AGN and that a dense enough medium exists to account for the strong FeII emission). The “edge-on” value of FWHM $H_\beta$ for pop. A is set by the fact that sources with $R_{F_{FeII}} > 0.4$ (unambiguously Pop. A) show FWHM $H_\beta < 4000$ km s$^{-1}$. The situation is less confused for pop. B sources because we can infer the range of FWHM $H_\beta$ from RL sources via radio morphology and core/lobe flux ratios [Rokaki et al. 2003, Sulentic et al. 2003]. We then assume that pop. B RQ sources follow RL pop. B because they are co-spatial in 4DE1. Pop. B sources start to become rare at about FWHM $H_\beta = 10^4$ km/s. If we assume the same range of viewing angle for pop. A and pop. B sources then we observe velocity ranges of a factor of $\sim 5$ and $\sim 2.5$ for pop. A and B respectively, consistent with a flatter pop. A emitting cloud distribution.

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metric and less blueshifted. Recent observations of high z type 2 AGN reveal frequent and reasonable strong CIV narrow line emission (see references in Sulentic et al. [2007]). We have chosen to make a major effort with VLT ISAAC and now have IR spectra of the Hβ region for 50+ sources between z=0.8-2.5. VLT enables us to obtain IR spectra with resolution and s/n similar to ground based spectra for lower redshift sources. Results so far suggest that source occupation in 4DE1 space is similar up to the B= -29 to -30 source luminosity range. Much remains to be done but 4DE1 space continues to offer a useful way to contextualize both empirical and physical properties of quasars. It offers the hope of simplifying or resolving many of the current questions about these most active objects.

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