RevMexAA (Serie de Conferencias), **28**, 83–88 (2007)

EIGENVECTOR 1: TOWARDS AGN SPECTROSCOPIC UNIFICATION

Jack W. Sulentic,[1] Deborah Dultzin-Hacyan,[2] and Paola Marziani[3]

RESUMEN

Presentamos una introducción al espacio de parámetros conocido como “Eigenvector 1”, en el que se busca encontrar una unificación, a partir de propiedades espectrales, de los diversos tipos de AGN con líneas anchas de emisión. Este es un parámetro 4D que utiliza mediciones en el óptico, UV y rayos–X para distinguir entre diferentes clases de AGN. Las diferencias en la ocupación del espacio de parámetros sugieren que las fuentes de radio–fuertes son fundamentalmente diferentes a la mayoría de las fuentes radio–calladas. Esto se deriva de nuestra sugerencia de que pueden existir dos poblaciones distintas de AGN con líneas anchas de emisión. Sugerimos que la exploración del espacio de parámetros “Eigenvector 1” a altos corrimientos al rojo y fuentes luminosas podría ser un programa valioso para los nuevos telescopios propuestos en San Pedro Mártir.

ABSTRACT

We present an introduction to the Eigenvector 1 parameter space, which is an attempt to find a spectroscopic unification for broad-line emitting AGN. It is a 4D parameter space that uses optical, UV and X–ray measures to discriminate between different classes of AGN. Differences in parameter space occupation suggest that radio-loud sources are fundamentally different from the radio-quiet majority. This is a derivative of our suggestion that two distinct populations of broad-line emitting AGN may exist. We suggest that exploration of Eigenvector 1 space at higher redshift and source luminosities would be a valuable program for the proposed new telescopes at San Pedro Mártir.

Key Words: **GALAXIES: ACTIVE — GALAXIES: QUASARS: GENERAL — GALAXIES: SEYFERT**

1. INTRODUCTION

As a long time user of San Pedro Mártir I can attest to the quality of the sight and the frequency of clear skies there. We have been waiting for a long time to see a larger telescope on San Pedro and hope the present project will be a success. Our own work at San Pedro has involved spectroscopy of bright quasars and we think our results offer one interesting way to utilize the proposed 6.5-m class instruments.

Unifications are popular in studies of Active Galactic Nuclei (AGN), such as the one that sees type 1 and type 2 AGN as the same kind of source viewed at different orientations. Strangely, there is no real spectroscopic unification, due in part, perhaps, to a prevailing idea that the broad-line spectra of all AGN are basically the same. Nothing could be further from the truth, and our efforts are directed toward recognizing and quantifying AGN spectral diversity.

[1]Dept. of Phys. and Astron., University of Alabama, Box 870324, 206 Gallalee Hall, Tuscaloosa, AL 35487, USA (giacomo@merlot.astr.ua.edu).

[2]Instituto de Astronomia, Universidad Nacional Autónoma de México, Apartado Postal 70-264, 04510 México DF, México.

[3]Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122, Padova, Italy.

The H-R Diagram provides both optimal discrimination between the principal classes of normal stars and isolation of important states of stellar evolution. Most of this is accomplished with a simple 2 parameter space although H-R power can be increased by adding additional measures to create an “H-R space” that takes into account different physical conditions of stellar gas in different parts of the diagram. We are searching for an equivalent diagram that might help clarify the phenomenology of AGN and lead to a better understanding of the physics that drives them. It was clear from the outset that more than two dimensions (2D) would be required in order to remove the degeneracy between physics and source orientation, a complication that does not affect the stellar H-R diagram. Do we need an H-R Diagram for AGN or will an average quasar spectrum tell us all that we need to know? We find that AGN exhibit a large phenomenological diversity that suggests a parameter space equivalent to the H-R diagram would be invaluable. We introduce a 4D “Eigenvector 1” (E1) parameter space that may serve as a surrogate H-R Diagram for AGN. Results so far are very encouraging and virtually every observational conundrum that has arisen concerning broad-line AGN in the past ten years is simplified when interpreted within

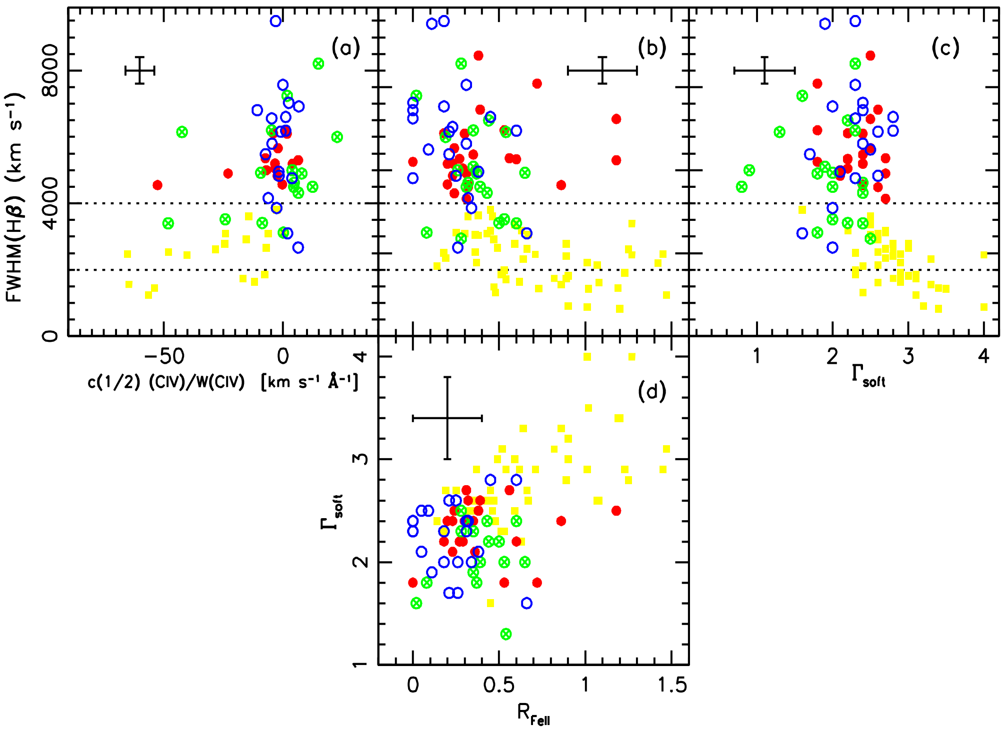

Fig. 1. *a-d:* Parameter planes of E1 involving UV, optical, and X–ray measures for low-z (z $\lesssim$ 0.8) AGN. Solid symbols are RQ sources (grey boxes: Population A, black circles: Pop. B). Open symbols are RL sources (open: core-dominated, crossed: lobe-dominated). Error bars indicate typical 2σ uncertainties for a source at FWHM(H$\beta_{\rm BC}$) $\approx$ 4000 km s^{-1}and RFe $\approx$0.5. The error on $\Gamma_{\rm soft}$ is equal to the median of errors for which $\Gamma_{\rm soft}$ was available.

the E1 context. Rather than mass, which drives the stellar H-R relation, we suggest that $\dot{m} = \dot{\rm M}/\dot{\rm M}_{Edd}$ ($\propto$ accretion rate) may be the principal driver of E1. The next most important variables are thought to involve black hole mass and source orientation. San Pedro data has contributed significantly to our E1 studies and we think that exploration of E1 space would be an ideal line of research especially with the proposed 6.5-m telescope dedicated to wide-field, multi-object spectroscopy. This introduction is "reality based" meaning that we focus on the empiricism rather than physical models. It is our philosophy that the observations must lead theory and we hope that San Pedro observations will lead future E1 studies.

1.1. *Beyond an Average Quasar Spectrum*

If one searches for citations of a typical bright AGN using the NASA Extragalactic Database (NED) one often finds 100-200 hits. Yet it is surprising that one rarely finds more than 2 or 3 hits to papers providing reasonable quality optical/UV spectra for the sources. In part this reflects the time cost involved in obtaining spectra with good resolution (1-10Å) and S/N (30-50 in the continuum near Hβ). It may also reflect the above mentioned belief that a few good spectra tell us all that we need to know about quasar spectroscopic phenomenology. The science value of rest-frame optical/UV data is two-fold: 1) it drives studies of AGN nebular physics now facilitated through systematic improvements of the photoionization codes (for example, the CLOUDY package now includes models of Fe^{+} and Fe^{++} ions (Ferland 2005) and 2) it provides a source contextualization via measurements that "resolve" the broad-line region (BLR) geometry and kinematics. Perhaps the lack of "hits" also reflects the frustration with efforts in the first vein (Baldwin et al. 2004 and references therein) aimed at modeling detailed BLR physics. We suggest that a contextualization like E1 can facilitate efforts toward understanding all aspects of the AGN phenomenon.

The Eigenvector 1 (E1) parameter space provides a potentially fundamental discrimination between major AGN classes. E1 space incorporates all of the statistically significant line profile similarities and differences that are currently known (Sulentic et

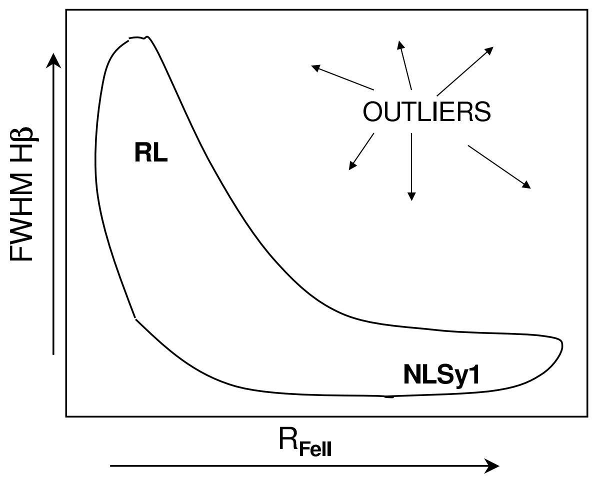

Fig. 2. Schematic of the zone of principal source occupation (i.e.,"main sequence") in the optical E1 plane. Approximate loci of radio-loud and narrow-line Seyfert 1 sources are indicated. Very few sources are found in the outlier region.

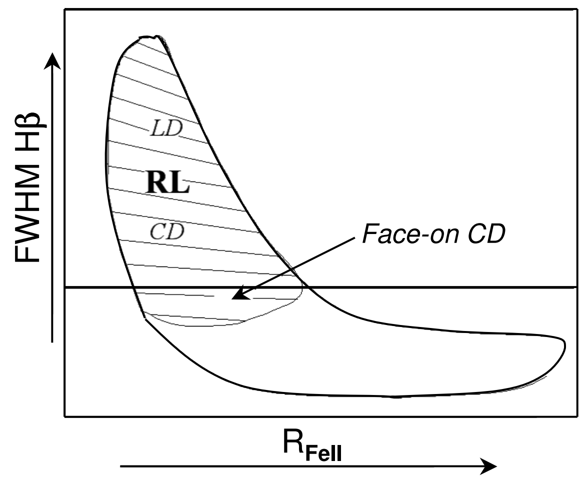

Fig. 3. Schematic of the zone of principal source occupation in the optical E1 plane showing the more restricted zone occupied by radio-loud (RL) AGN. Horizontal line indicates the approximate lower boundary for RL sources. The separation into lobe- and core-dominated (LD and CD, respectively) sources is also shown — a first hint about the role of source orientation in driving E1 occupation/correlation. BLLACs (when they show broad lines) and other RL sources thought to be oriented with radio jets along our line of sight (i.e., face-on) fall towards the bottom of the RL domain.

al. 2000a,b). The first hints of E1 emerged from a principal component analysis (PCA) of the correlation matrix for quasars in the Palomar-Green (PG) sample (Boroson & Green 1992, hereafter BG92). Figure 1a-d shows 2D projections of E1 parameter space as we define it. The current best E1 parameters are: (1) FWHM Hβ, (2) R_{FeII}= EW FeII λ4570 blend/EW Hβ, (3) soft X–ray photon index Γ_{soft}, and (4) c(1/2)= centroid shift at FWHM of CIV λ1549. All line measures are for suitably corrected broad-line components. In simplest terms they can be said to measure: (1) the dispersion in BLR cloud velocities, (2) the relative strengths of FeII and Hβ emission, (3) the strength of a soft X–ray excess, and (4) the amplitude of systematic radial gas motions. In less simple terms (i.e., more model-dependent) we likely have: (1) three orthogonal variables, sensitive to the Eddington ratio, (2) two variables, each sensitive to source inclination and broad-line gas motions, and (3) one variable, sensitive to black hole mass and nebular physics (electron density).

AGN spectroscopic measures plotted in Figure 1 come from three data sources: (1) Optical measures from our spectral atlas of more than 215 low-z AGN, including a large number of observations from San Pedro Mártir (Marziani et al. 2003a); (2) UV spectral measures from the HST archive for about 100 low-z sources (Sulentic et al. 2000b; Bachev et al. 2004); (3) soft X–ray photon indices for a large fraction of the sample, coming from many sources (Wang, Brinkmann, & Bergeron 1996; Brinkmann et al. 1997; Siebert, Brinkmann, & Yuan 1998; Yuan, Siebert, & Brinkmann 1998). Radio-quiet (RQ) sources are indicated by solid symbols in the figures while open and crossed circles indicate flat (core-dominated) and steep (lobe-dominated) spectrum radio-loud (RL; as defined by Kellermann et al. 1989), respectively. E1 as shown in figure 1a-d tells us some fundamental things about AGN:

- 1) All broad-line emitting AGN are not alike — the intrinsic dispersion in E1 parameters is much larger than measurement errors. Average quasar spectra that do not allow for these differences are somewhat like average stellar spectra involving the entire OBAFGKM sequence (see Sulentic et al. 2002 and Bachev et al. 2004 for the first average spectra in the E1 context).

- 2) The RQ majority of AGN show a restricted E1 domain occupation. Individual E1 parameters show a wide dispersion but combinations of the parameters are much more restricted, suggesting an L-shaped "main sequence". Figure 2 illustrates this distribution schematically.

- 3) RL AGN show a much more restricted domain occupation that is displaced from the ma-

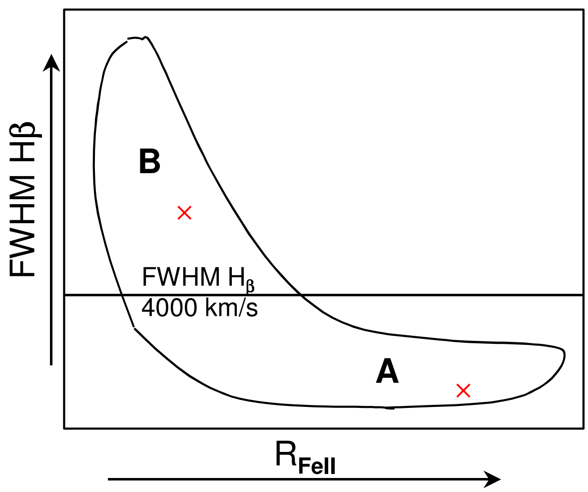

Fig. 4. Schematic optical plane of E1 showing the regions of occupation for so-called population A and B sources. Nominal boundary between the two populations is indicated by the horizontal line. See also Figure 5.

jority of radio-quiet sources (see Figures 2 and 3). In other words, RL sources occupy only one end of the RQ main sequence. We think that this is *prima facie* evidence for a fundamental difference in physics and/or BLR geometry between RQ and RL sources. Only about 25% of RQ sources are co-spatial with the RL domain while the remainder occupy an almost pure-RQ zone. The probability of radio-loudness is near 50% for sources that fall within the RL zone. It is less than 1% in other parts of this plane (e.g., Narrow-line Seyfert 1; NLSy1). Radio intermediate sources distribute the same as RQ sources, again implying that they are not the same as RL sources (see also Sulentic et al., 2003)

- 4) There is evidence for parameter correlations especially among the RQ sources (see Tables 1 and 2 of Sulentic et al. 2000b for details of the correlation analysis). The strongest intercorrelations appear to involve the RFe, $\Gamma_{\rm soft}$ and CIV line shift parameters.

- 5) There may be two AGN populations: 1) a pure RQ population A (filled boxes) which show little overlap with the RL domain (65% of the BG92 RQ sample) and 2) a mixed RL-RQ population B (filled circles) (25% of the BG92 RQ sources). A best guess for the boundary between the hypothesized population A and B sources is FWHM Hβ=4000 km s^{-1} (see Figure 4 for a schematic). The shape of the main sequence of source occupation in Figures 1 and 2 provides evidence for the population A-B parameter space dichotomy. It is not yet clear if this represents a true source dichotomy or opposite extremes of a single phenomenological/evolutionary sequence. At the least it is useful for emphasizing source differences.

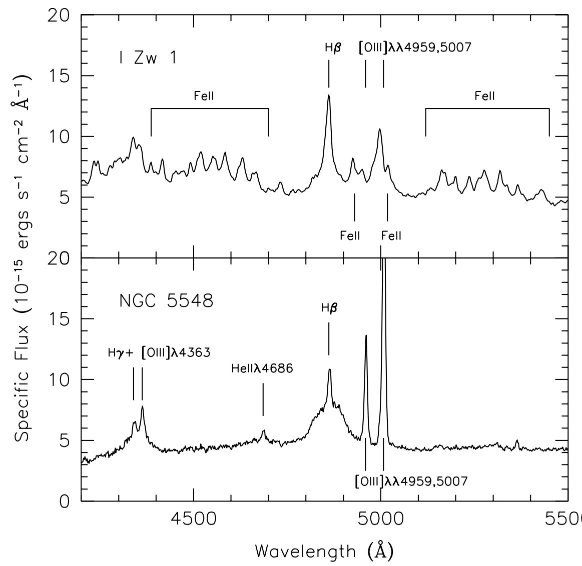

Fig. 5. Examples of spectra for two well known Type 1 AGN: Population A I Zw 1 and Population B NGC 5548 that illustrate quasar spectral diversity. Their positions in the optical E1 plane are indicated with red X's in Figure 4.

Whatever the relation between the two proposed AGN populations, their line profiles show striking differences (Sulentic et al. 2002; Marziani et al. 2003b; Bachev et al. 2004). Figure 5 shows a comparison of the H$\beta_{\rm BC}$ and C IVλ1549$_{\rm BC}$ line profiles for prototype NLSy1 source I Zw 1 and NGC 5548 which is a typical Seyfert 1 galaxy. Differences between the Balmer profiles and Fe II strength are striking. However the most impressive difference involves the apparent kinematic *decoupling* of the C IVλ1549 and Hβ profiles in population A sources like I Zw 1. Previous work (Marziani et al. 1996) suggested that properly NLR corrected C IVλ1549 in RQ sources (see Sulentic & Marziani 1999) is always blue-shifted relative to Hβ and the AGN rest frame. We have normalized the C IVλ1549 shift by W(C IVλ1549) in Figure 1a because we see a complementary trend for W(C IVλ1549) to be smallest in the NLSy1 population. Figure 1a confirms that essentially all population A RQ sources show a C IVλ1549 blue-shift while RL (and RQ pop. B) sources show no trend and amplitudes generally less than $\pm 10^3$ km s^{-1}. Correlations of C IVλ1549 shift with RFe and $\Gamma_{\rm soft}$ confirm that is an important E1 parameter.

1.2. *Toward Understanding the Physical Drivers of Eigenvector 1*

E1 correlates AGN spectroscopic data in a way that removes much of the apparent "randomness" of line properties. It also redefines input parameters for photoionization and kinematical models. Accumulating evidence from numerous studies suggests that the domain space occupation and correlations in E1 involve at least two principal independent parameters (convolved with source orientation) : 1) L_{bol}/M_{BH} ($\propto$ L/L_{Edd}) and 2) accretion rate ($\dot{m}$). The role of black hole angular momentum is unclear at least as far as the optical, UV and soft X–ray properties are concerned. One possible explanation for the population A-B dichotomy involves black hole spin (Bachev et al. 2004). Iron abundance and disk magnetic fields are likely to play lesser roles.

Available evidence suggests that the central source luminosity to black hole mass ratio (the Eddington ratio) may be systematically higher in population A sources (Marziani et al. 2001; Boroson 2002). A role for L/M is supported by the existence of a soft X–ray excess, particularly in NLSy1 sources, that has been related to: (a) a higher accretion rate (Pounds, Done, & Osborne 1995), and (b) the thermal signature of an accretion disk (Page et al. 1999; Puchnarewicz, Mason, & Siemiginowska 1998). Figure 6 shows our first attempt at deriving black hole masses and L/M values for our sample (see figure caption and Marziani et al. 2001, 2003b for details). Apparently super-Eddington RQ sources and RL sources in the population A domain are likely luminosity-boosted due to a near face-on orientation. If corrected to an average inclination (~30°) they become sub-Eddington and normal population B, respectively.

C IVλ1549 shows the largest blue-shifts in NLSy1 sources consistent with the idea that high ionization line emission arises in a disk wind (e.g. Murray et al. 1995; Chiang & Murray 1997; Bottorff et al. 1997). The observations are consistent with the idea that L/M is only high enough to trigger a radiation pressure driven outflow in population A RQ sources. The Balmer profiles and strong Fe II emission found in population A sources are most easily explained if both are produced in an optically-thick illuminated accretion disk (see, e.g., Sulentic et al. 1998).

RL sources show no evidence for a soft X–ray excess which may reflect a real absence of this component or that it is swamped by a power-law component that is stronger in RL sources. We favor the former interpretation because population B sources that are RQ appear spectroscopically identical to RL sources and also do not show a soft X–ray excess. The absence of a soft X–ray component in RL+RQ population B sources coupled with the absence of the C IV blue-shift are consistent with weak or absent disk wind signatures in these sources. The broad lines may arise in a bi-conical structure in some of RL sources (Marziani et al. 1993; Sulentic et al. 1995), but it is not clear how far inferences based on double-peaked or peculiar profiles can be extended.

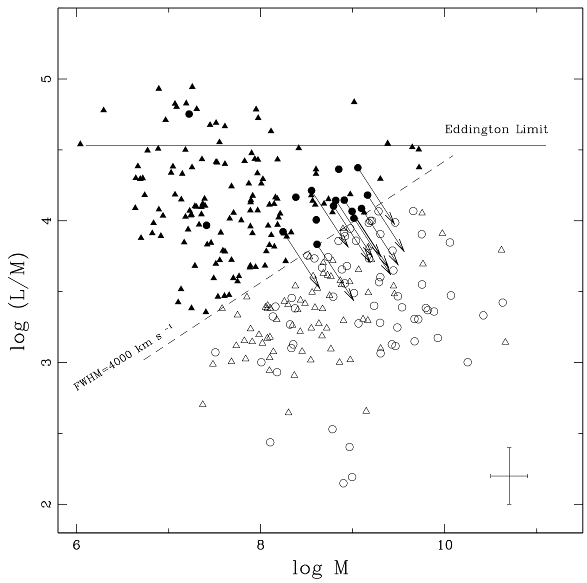

Fig. 6. The physical parameter plane of log M vs. log L/M for our low redshift sample, where M is the black hole mass and L the bolometric luminosity of the source (L/M $\propto$ L/L_{Edd}). Lines indicate the Eddington limit and FWHM Hβ=4000 km s^{-1} as the nominal boundary between so-called population A (open symbols) and B (closed symbols) sources. Triangles are RQ and circles RL sources. Arrows correct near face-on RL sources to an average inclination which moves these "RL interlopers" out of the RQ population A domain. The cross in the lower right corner indicates typical estimated uncertainties.

One of the many E1 related challenges for the new San Pedro telescopes will involve extending studies to higher redshift and luminosity sources. Previous work indicates that E1 space occupation and correlations are independent of source optical luminosity. In fact they have even shown that the Baldwin effect is intrinsic to Eigenvector 1 physics. This must be tested and luminosity indicators must be found if quasars are ever to play a role as cosmological standard candles.

JS gratefully acknowledges support from the conference hosts. Graduate students A. Durbala and S. Zamfir provided valuable assistance in the preparation of the power point presentation and printed manuscript preparation.

REFERENCES

Bachev, R., et al. 2004, ApJ, 617, 171
Baldwin, J. A., et al. 2004, ApJ, 615, 610
Boroson, T. 2002, ApJ, 565, 78
Boroson, T., & Green, R. 1992, ApJS, 80, 109 (BG92)
Bottorff, M., Korista, K., Shlosman, I., & Blandford, R. 1997, ApJ, 479, 200
Brinkmann, W., et al. 1997, A&AS, 323, 739
Chiang, J., & Murray, M. 1997, ApJ, 474, 91
Ferland, G. 2005, BAAS, 37, 477
Kellermann, K., Sramek, R., Schmidt, M., Shaffer, D., & Green, R. 1989, AJ, 98, 1195
Marziani, P., et al. 1993, ApJ, 410, 56
Marziani, P. Sulentic, J., Dultzin-Hacyan, D., Calvani, M., & Moles, M. 1996, ApJS, 104, 37
Marziani, P., Sulentic, J., Zwitter, T., Dultzin-Hacyan, D., & Calvani, M. 2001, ApJ, 558, 553
Marziani, P., et al. 2003a, ApJS, 145, 199
Marziani, P., Zamanov, R., Sulentic, J., & Calvani, M. 2003b, MNRAS, 345, 1133
Murray, N., Chiang, J., Grossman, S., & Voit, G. 1995, ApJ, 451, 498
Page, M., Carrera, F., Mittaz, J., & Mason, K. 1999, MNRAS, 305, 775
Pounds, K., Done, C., & Osborne, J. 1995, MNRAS, 277, L5
Puchnarewicz, E., Mason, K., & Siemiginowska, A. 1998, MNRAS, 293, L52
Siebert, J., Brinkmann, W., & Yuan, W. 1998, Astron. Nachr., 319, 35
Sulentic, J., et al. 1995, ApJ, 438, L1
Sulentic, J., Marziani, P., Zwitter, T., Calvani, M., & Dultzin-Hacyan, D. 1998, ApJ, 501, 54
Sulentic, J. W., & Marziani, P. 1999, ApJ, 518, L9
Sulentic, J. W., Marziani, P., & Dultzin-Hacyan, D. 2000a, ARA&A, 38, 521
Sulentic, J. W., et al. 2000b, ApJ, 536, L5
Sulentic, J. W., et al. 2002, ApJ, 566, L71
Sulentic, J. W., et al. 2003, ApJ, 597, L17
Wang, T., Brinkmann, W., & Bergeron, J. 1996, A&AS, 309, 81
Yuan, W., Siebert, J., & Brinkmann, W. 1998, A&AS, 334, 498