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VARABILITY ALONG THE MAIN SEQUENCE OF QUASARS

EDI BON[1], PAOLA MARZIANI[2] and NATAŠA BON[1]
[1]*Astronomical Observatory, Volgina 7, Belgrade, Serbia*
E–mail ebon@aob.rs

[2]*INAF, Padova, Italy*
E–mail paola.marziani@inaf.it

Abstract. We explore the main sequence of quasars through the variability along the Eigenvector 1 (EV1), based on relationship between the relative strength of Fe II and Hβ (RFe) and the full width at half maximum (FWHM) of the Hβ emission line. We present some examples that show variability behaviour along EV1 diagrams and discuss physical properties.

1. INTRODUCTION

Active galactic nuclei (AGN) are among the most luminous and energetic objects in the universe. Understanding their properties and behaviors is crucial for astrophysical research. The Eigenvector 1 (EV1) parametrization, introduced by Boroson & Green (1992), provides a framework for studying the diversity of quasar properties by correlating the strength of Fe II emission and the FWHM of the Hβ emission line (Boroson, & Green 1992).

Differences between Type 1 and Type 2 spectra of AGNs, mainly described by the different viewing angle at the nuclear region of the galaxy, are already well known. On the other hand, there is a vast number of spectral characteristics, such as shift, width of the line, line ratios, Fe II blends, and many others that create diversity between different Type 1 spectra. One could expect that diversity also depends to some extent on the viewing angle.

There have been many efforts to systematize Type 1 spectral diversity in the EV1 parameter space, which represents the linear combination of several parameters, in order to introduce some order in spectral properties. The EV1 can be seen as an equivalent to the well-known Hertzsprung-Russell diagram for stars, and therefore capable of organizing Type 1 AGN into a "main sequence" of quasars. This kind of systematization allows setting observational constraints on the dynamics and physical properties of the broad line region. The principal component analysis of Boroson and Green (1992) showed that there is a hidden single parameter responsible for the vast majority of spectral differences – $R_{\rm Fe}$ – the ratio of the optical Fe II blend at λ 4570 to the Hβ flux. This idea was further developed by Sulentic et al. (2000), and Shen and Ho (2014) among others.

EV1 is a principal component that accounts for much of the observed variance in the properties of quasars. It is primarily driven by $R_{\rm Fe}$ and the FWHM of the Hβ emission line. This parametrization allows for a classification scheme that distinguishes between different quasar populations, often referred to as Population A and Population B (Sulentic 2000).

The relation between EV1 and some theoretically motivated parameters, such as Eddington ratio, black hole mass, chemical composition, black hole spin, orientation etc., is still not clear. The most favored parameter that drives EV1 is the Eddington ratio (Boroson & Green 1992, Sulentic et al. 2000, Marziani et al. 2001, Shen and Ho 2014). Shen and Ho (2014) argued that the viewing angle in Type 1 sources represents just a dispersion to the quasar "main sequence", although Marziani et al. (2018) showed progression of inclination effects along the main sequence.

Sulentic et al. (2000) measured the soft X-ray photon index and a measure of CIV λ1549 broad line profile velocity displacement at half maximum, to analyze an extended 4D Eigenvector 1 parameter space. They showed that the "main sequence" of quasars follows some physical trends involving dimensionless accretion rate and electron density, which increase down the sequence toward strong FeII emitters, while the ionization parameter decreases (Marziani et al. 2001). Pop B corresponds to high mass and low accreting quasars and is characterized by FWHM of Hβ higher than 4000 km/s and higher red asymmetry, while Pop A is characterised with mainly low mass and high accreting rates (Sulentic et al 2000, Zamfir et al. 2010).

Bon et al. 2018 explored the variability of NGC 5548 along the EV1 diagram implying that the accretion rate variations may be responsible for the changes in this parameter space. These effects were later-on explored and modeled by Panda et al. 2022 using the same object and Panda & Sniegowska 2024 using a sample of extremely variable AGN (so called "changing look" AGN).

In the optical band, variability of quasars shows distinct trends along the EV1 main sequence. Quasars with broad Hβ lines and low RFe values (Population B) exhibit more significant optical variability. These quasars generally have lower Eddington ratios, leading to more substantial fluctuations in both the optical continuum and broad emission lines. This pronounced variability makes them suitable for reverberation mapping studies, where time delays between variations in the continuum and line emissions are used to probe the structure of the broad-line region (see, for eg. Kaspi et al. 2000).

High Eddington ratio quasars, typically found in Population A with narrower Hβ lines and higher $R_{\rm Fe}$ values, display less optical variability. Their relatively stable accretion rates result in smaller amplitude changes in the optical continuum, with variability timescales that are longer and less noticeable over typical monitoring periods.

With very long term monitoring campaign data, we can analyze the variability patterns in Type 1 AGN using EV1 diagrams in different variability states. We focus our analysis on the nearby and frequently observed galaxies NGC 4151 NGC 5548 and PG0026, for which data from extensive monitoring campaigns are available.

2. SOME CASE STUDIES

A detailed study of the AGN NGC 5548 provides insights into the variability along the EV1 diagram (Bon et al. 2018). They found that variability could largely be attributed to changes in the accretion rate. Over several decades, NGC 5548 exhibited significant variability in both the optical continuum and Hβ line, while remaining within the characteristics of Population B sources. This study highlights that the relationship between variability and position on the EV1 diagram can differ when considering short-term versus long-term monitoring periods (Bon et al. 2018).

NGC 4151 is also very extensively studded AGN, belonging to Pop B, similarly as NGC 5548. We can see in Figures 1a and 2, both objects significantly vary along the EV1 diagram, but nevertheless, they keep their variability patterns within the same population (Pop B), without crossing into the area of Pop A. Changes of accretion rate (assuming that their mass and inclinations are being constant) seem to be the main drivers for their variability, and we can notice that when the accretion rate significantly decreases, the observations shifts from Pop B1 (from 4000 km/s to 8000 km/s) to Pop B1+ (from 8000 km/s to 12000 km/s) bin.

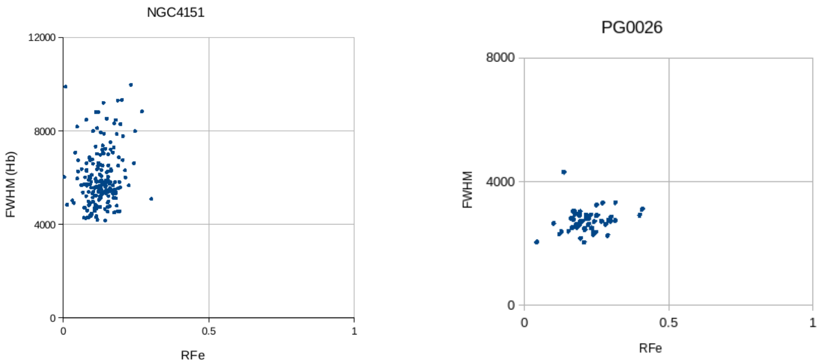

Figure 1: EV1 diagram of NGC 4151 variability (left panel) and PG0026 (right panel)
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In case of PG 0026, its variability changes the position along the EV1 diagram within the population Pop A1 (see Fig. 1b), slightly increasing the RFe with the accretion rate (for a constant mass and inclination the changes of luminosity will correspond to the changes of the accretion rate).

Single epoch observations are not allowing such a complex analysis, positioning the object on one place at the EV1 diagram. With long term monitoring programs we are able to study the the complex behaviour of emission lines over the EV1 diagram, in order to analyse the accretion rate changes. For that purpose, one may needs to make a correction for the anomaly produced by the effect of lagging of the broad emission line response to the continuum variations of an analysed object. Using the reverberation mapping results which measure the lag between the broad emission lines and the continuum one can correct the response of the broad emission lines for the measured lag, and analyse variability patterns along the EV1 diagram corrected for the lag. One such example is presented on Fig. 2 for the case of NGC 5548, where the FWHM of Hβ and equivalent widths of Hβ and the FeII equivalent widths are recalculated using the correction for measured reverberation lags (see Fig. 2b). These variability patterns before and after delagging show slightly different behaviour.

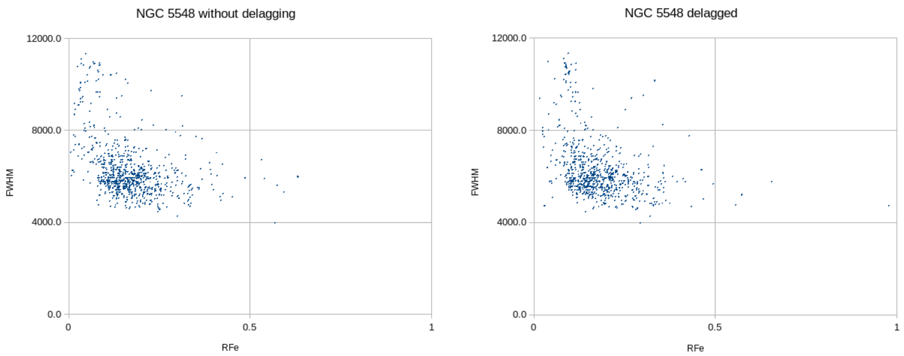

Figure 2: Variability of NGC 5548 before and after delagging correction for the reverberation lag of the Hβ broad line to the optical continuum emission.

3. Implications for AGN Research

Understanding the variability of quasars along the EV1 main sequence is crucial for interpreting their physical conditions and intrinsic properties. Variability studies, particularly in the optical band provide insights into the dynamics of the broad-line region, the accretion processes, and the interplay between the black hole and its surroundings. Properly accounting for variability is essential for accurate modeling and parameter estimation (see Marziani et al. 2001).

4. Conclusion

The EV1 parametrization, based on RFe and FWHM of Hβ, remains a fundamental tool in the study of quasar properties. Mapping quasars onto the EV1 main sequence reveals insights into the physical conditions and processes governing these objects. Variability, while adding complexity, also provides a deeper understanding when properly considered. Continued exploration of this framework promises to enhance our comprehension of the AGN phenomenon and its role in cosmic evolution.

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