Micro lensing and Intrinsic Variability of the Broad Emission Lines of Lensed Quasars

C. Fian1,2, Eduardo Guerras3, E. Mediavilla1,2, J. Jiménez-Vicente4,5, J. A. Muñoz6,7, E. E. Falco8, V. Motta9, and A. Hansmeier10

1 Instituto de Astrofísica de Canarias, Vía Láctea S/N, La Laguna E-38200, Tenerife, Spain
2 Departamento de Astronomía, Universidad de la Laguna, La Laguna E-38200, Tenerife, Spain
3 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA
4 Departamento de Física Teórica y del Cosmos, Universidad de Granada, Campus de Fuentenueva, E-18071 Granada, Spain
5 Instituto Carlos I de Física Teórica y Computacional, Universidad de Granada, E-18071 Granada, Spain
6 Departamento de Astronomía y Astrofísica, Universidad de Valencia, E-46100 Burjassot, Valencia, Spain
7 Observatorio Astronómico, Universidad de Valencia, E-46980 Paterna, Valencia, Spain
8 Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA
9 Instituto de Física y Astronomía, Universidad de Valparaíso, Avda. Gran Bretaña 1111, Playa Ancha, Valparaíso 2360102, Chile
10 Institute of Physics (IGAM), University of Graz, Universitätsplatz 5, A-8010, Graz, Austria

Received 2018 January 9; revised 2018 March 27; accepted 2018 March 28; published 2018 May 23

Abstract

We study the broad emission lines in a sample of 11 gravitationally lensed quasars with at least two epochs of observation to identify intrinsic variability and to disentangle it from microlensing. To improve our statistical significance and emphasize trends, we also include 15 lens systems with single-epoch spectra. Mg II and C III−emission lines are only weakly affected by microlensing, but C IV shows strong microlensing in some cases, even for regions of the line core, presumably associated with small projected velocities. However, excluding the strongly microlensed cases, there is a strikingly good match, on average, between the red wings of the C IV and C III−profiles. Analysis of these results supports the existence of two regions in the broad-line region (BLR), one that is insensitive to microlensing (of size $\lesssim 50$ lt-day and kinematics not confined to a plane) and another that shows up only when it is magnified by microlensing (of size of a few light-days, comparable to the accretion disk). Both regions can contribute in different proportions to the emission lines of different species and, within each line profile, to different velocity bins, all of which complicates detailed studies of the BLR based on microlensing size estimates. The strength of the microlensing indicates that some spectral features that make up the pseudo-continuum, such as the shelf-like feature at $\lambda 1610$ or several Fe III blends, may in part arise from an inner region of the accretion disk. In the case of Fe II, microlensing is strong in some blends but not in others. This opens up interesting possibilities to study quasar accretion disk kinematics. Intrinsic variability seems to affect the same features prone to microlensing, with similar frequency and amplitude, but does not induce outstanding profile asymmetries. We measure intrinsic variability ($\lesssim 20\%$) of the wings with respect to the cores in the C IV, C III−, and Mg II lines consistent with reverberation mapping studies.

Key words: gravitational lensing: micro – quasars: emission lines – quasars: general

1. Introduction

To date, the primary probe of the geometry and kinematics of the broad-line regions (BLRs) of active galactic nuclei (AGNs) has been reverberation mapping (RM; Blandford & McKee 1982; see also Peterson 2006, and references therein) based on the measurement of the lag between the intrinsic variability of the continuum and that of the broad emission lines (BELs). This technique has shown that the global structure of the BLR is consistent with photoionization models (Bentz et al. 2009). RM results also suggest that there is no common kinematic structure, with differing sources showing signs of inward, outward, and rotating disk-like velocity structures (e.g., Bentz et al. 2010; Grier et al. 2017a, and references therein). Until now, RM studies have been largely limited to relatively nearby, lower-luminosity AGNs. Very recently, new results for individual (Shen et al. 2016; Grier et al. 2017b) or composite (Li et al. 2017) sources ($z \lesssim 1.1$) of intermediate luminosity based on the first year of the Sloan Digital Sky Survey (SDSS) RM project have been presented, mainly for Hα, Hβ, and Mg II. However, there are few RM measurements for C IV (Kaspi et al. 2007), which is the most easily studied line in quasars with $1.5 \lesssim z \lesssim 2.5$.

An alternative means of studying the structure of the BLR is to examine how it is microlensed in gravitationally lensed quasars. Microlensing, the stars in the lens galaxy differentially magnify components of the quasar emission regions, leading to time- and wavelength-dependent changes in the spectra of the images (Abajas et al. 2002; Wambsganss 2006). The amplitude of the magnification is controlled by the size of the emission region, with smaller source regions showing larger magnifications. Microlensing is now a well-established tool for studying quasar structure, for both individual objects and larger statistical samples (Motta et al. 2012; Sluse et al. 2012; Guerras et al. 2013a, 2013b).

In Guerras et al. (2013a; see also Motta et al. 2012) we compared the emission-line profiles of pairs of images from a sample of 13 lensed quasars for which archival single-epoch spectroscopy is available. For single-epoch data some method is needed to separate the effects of microlensing from those of extinction and uncertainties in the magnification produced by the lens galaxy (macro-magnification). In principle, the cores of the emission lines can be used as a reference that is little affected by microlensing. Specifically, the ratio of the line core fluxes of two images to their line wing fluxes gives an estimate of the size of the wing emission
| Object       | Image | Epoch | Date          | C IV | C III | Mg II | Region 1 | Region 2 | Facilities   | References     |
|--------------|-------|-------|---------------|------|-------|--------|----------|----------|--------------|----------------|
| HE 0047−1756 | A, B  | I     | 2002 Sep 04   | x    | x     | …      | x        | …        | Magellan     | Wisotzki et al. (2004) |
|              |       | II    | 2005 Jul 18   | …    | x     | x      | …        | x        | VLT          | Sluse et al. (2012)     |
|              |       | III   | 2008 Jan 13   | …    | x     | x      | …        | x        | Magellan     | Rojas et al. (2014)     |
| Q0142−100    | A, B  | I     | 2006 Aug 15   | x    | x     | …      | x        | …        | VLT          | Sluse et al. (2012)     |
|              |       | II    | 2008 Jan 12   | x    | …     | x      | x        | …        | MMT          | V. Motta (2018, private communication) |
| SDSS J0246−0825 | A, B | I     | 2006 Aug 22   | …    | …     | …      | …        | x        | VLT          | Sluse et al. (2012)     |
| HE 0435−1223 | A, B  | I     | 2002 Sep 05   | x    | x     | x      | x        | …        | CAO          | Wisotzki et al. (2003)  |
|              |       | II    | 2004 Oct–Nov  | …    | x     | x      | x        | x        | VLT          | Eigenbrod et al. (2007) |
|              | B, D  | III   | 2008 Jan 12   | x    | x     | x      | x        | …        | VLT          | Sluse et al. (2012)     |
|              | A, B, C, D | IV | 2007 Dec 10   | x    | x     | …      | x        | …        | Magellan     | V. Motta (2018, private communication) |
| SDSS J0512−3329 | A, B | I     | 2001 Aug 13   | …    | …     | …      | …        | x        | HST          | Wucknitz et al. (2003)  |
| SDSS J0806+2006 | A, B | I     | 2005 Apr 12   | …    | x     | x      | …        | x        | APO          | Inada et al. (2006)     |
|              |       | II    | 2006 Apr 22   | …    | x     | x      | …        | x        | VLT          | Sluse et al. (2012)     |
| HS 0818−1227 | A, B  | I     | 2008 Jan 12   | …    | …     | …      | …        | x        | MMT          | Motta et al. (2012)     |
| SBS 0909+532 | A, B  | I     | 2003 Mar 07   | …    | …     | …      | x        | x        | HST          | Mediavilla et al. (2005) |
| SDSS J0924+0219 | A, B | I     | 2005 Jan 14   | …    | …     | …      | …        | x        | VLT          | Eigenbrod et al. (2006) |
| FBQ 0951+2635 | A, B  | I     | 1997 Feb 14   | …    | …     | x      | …        | x        | Keck         | Schechter et al. (1998) |
|              |       | II    | 2006 Mar 31   | …    | …     | x      | …        | x        | VLT          | Sluse et al. (2012)     |
| Q0957+561    | A     | I     | 1999 Apr 15   | x    | x     | x      | x        | x        | HST          | Goicoechea et al. (2005) |
|              |       | B     | 2000 Jun 2    | x    | x     | x      | x        | x        | HST          | Goicoechea et al. (2005) |
|              | A, B  | II    | 2008 Jan 12   | x    | x     | x      | x        | …        | MMT          | Motta et al. (2012)     |
| SDSS J1001+5027 | A, B | I     | 2003 Nov 20   | …    | …     | …      | …        | x        | APO          | Oguri et al. (2005)     |
| SDSS 1004+4112 | A, B, C, D | I | 2003 May 31   | x    | x     | x      | x        | x        | APO          | Richards et al. (2004)  |
|              | A, B  | II    | 2004 Jan 19   | x    | x     | …      | x        | …        | WHT          | Gómez-Alvarez et al. (2006) |
|              |       | III   | 2008 Jan 12   | x    | x     | …      | x        | x        | MMT          | Motta et al. (2012)     |
| Q1017−207    | A, B  | I     | 1996 Oct 28   | …    | …     | …      | x        | …        | HST          | Surdej et al. (1997)    |
| SDSS J1029+2623 | A, B | I     | 2008 Jan 12   | …    | …     | …      | x        | …        | MMT          | Motta et al. (2012)     |
| HE 1104−1805 | A, B  | I     | 2008 Jan 11   | x    | …     | …      | x        | …        | MMT          | Motta et al. (2012)     |
|              |       | II    | 2008 Apr 07   | x    | x     | x      | x        | …        | VLT          | Motta et al. (2012)     |
|              |       | III   | 1993 May 11   | x    | x     | …      | x        | …        | NTT          | Wisotzki et al. (1993)  |
|              |       | IV    | 1994 Nov 29   | x    | …     | …      | x        | …        | ESO 3.6 m    | Wisotzki et al. (1995)  |
| SDSS J1138+0314 | B, C | I     | 2005 May 10   | …    | …     | …      | x        | …        | VLT          | Sluse et al. (2012)     |
| Object          | Image | Epoch | Date       | C IV | C III] | Mg II | Region 1<sup>a</sup> | Region 2<sup>b</sup> | Facilities | References                     |
|-----------------|-------|-------|------------|------|--------|-------|----------------------|----------------------|------------|--------------------------------|
| SDSS J1155+6346 | A, B  | I     | 2010 Sept 20 | ...  | ...    | x     | ...                  | ...                  | HST        | Rojas et al. (2014)            |
| SDSS J1206+4332 | A, B  | I     | 2004 Jun 21  | ...  | ...    | x     | x                    | x                    | APO        | Oguri et al. (2005)           |
| SDSS J1335+0118 | A, B  | I     | 2005 Feb 17  | ...  | ...    | ...   | ...                  | x                    | VLT        | Sluse et al. (2012)           |
| SDSS J1339+1310 | A, B  | I     | 2013 Apr 13  | ...  | x      | x     | ...                  | x                    | GTC        | Shalyapin & Goicoechea (2014) |
|                 |       | II    | 2014 Mar 27  | ...  | x      | x     | x                    | x                    | GTC        | Goicoechea & Shalyapin (2016) |
|                 |       | III   | 2014 May 20  | x    | x      | ...   | ...                  | ...                  | GTC        | Goicoechea & Shalyapin (2016) |
| SDSS J1353+1138 | A, B  | I     | 2005 Apr 12  | ...  | ...    | ...   | ...                  | x                    | Keck       | Inada et al. (2006)          |
| Q1355−2257      | A, B  | I     | 2005 Mar 13  | ...  | ...    | ...   | ...                  | x                    | VLT        | Sluse et al. (2012)          |
| SBS 1520+530     | A, B  | I     | 1996 Jun 12  | ...  | ...    | x     | ...                  | ...                  | SAO        | Chavushyan et al. (1997)     |
| WFI 2033−4723    | A1, A2, B, C | I  | 2003 Sep 15  | x    | x      | x     | x                    | ...                  | Magellan   | Morgan et al. (2004)         |
|                 | B, C  | II    | 2005 May 13  | ...  | x      | x     | ...                  | x                    | VLT        | Sluse et al. (2012)          |
|                 |       | III   | 2008 Apr 14  | ...  | x      | x     | ...                  | x                    | VLT        | Motta et al. (2017)          |
| HE 2149−2745     | A, B  | I     | 2000 Nov 19  | x    | x      | x     | x                    | x                    | VLT        | Burud et al. (2002)          |
|                 |       | II    | 2006 Aug 04  | x    | x      | ...   | x                    | x                    | VLT        | Sluse et al. (2012)          |
|                 |       | III   | 2008 May 07  | x    | x      | x     | x                    | x                    | VLT        | Motta et al. (2017)          |

Notes.

<sup>a</sup> Region between C IV and C III].

<sup>b</sup> Region between C III] and Mg II.
Guerras et al. (2013a) were able to measure wing microlensing magnifications of \( \sim 0.1 \) mag, which, under the above hypothesis, led to estimates for the BLR size of 

\[
\begin{align*}
\text{high-ionization lines:} & \quad r_s = 24^{+22}_{-15} \text{ lt-day} \\
\text{low-ionization lines:} & \quad r_s = 55^{+150}_{-35} \text{ lt-day} 
\end{align*}
\]

(90\% confidence) for the high- and low-ionization lines, respectively. As expected from ionization stratification, high-ionization lines come from a smaller region than low-ionization lines, and higher-luminosity quasars have larger emission regions. The sizes were somewhat smaller than those found for existing (full-line) reverberation studies, as expected from measuring the size of the line wings. Using similar techniques, Guerras et al. (2013b) have found a strong microlensing signal (up to \( \sim 0.6 \) mag) in the UV pseudo-continuum emission from Fe II and Fe III, indicating that the region emitting this pseudo-continuum is quite small, with a size comparable to that of the accretion disk determined from microlensing of the continuum.

As a qualitative leap forward from the static single-epoch analysis, here we study the variability of the emission lines by comparing spectroscopy from at least two different epochs. The response to microlensing over time of different kinematic regions (corresponding to emission lines of different origin or to different wavelength regions in a given emission line) contains a large amount of information that can improve our understanding of the BLR structure and kinematics. The analysis may be complex, for in a microlensing event the source structure and the pattern of microlensing magnification are convolved, but the expectations are promising.

On the other hand, the comparison of two epochs of spectroscopic observations is necessary to study intrinsic quasar variability that may be of great interest by itself and in comparison with microlensing. In particular, we would like to compare the frequency and amplitude of both sources of variability and determine whether they affect the same kinematic regions or not. This last question may be very interesting when cross-checking the results obtained from reverberation mapping and microlensing.

Spectroscopic monitoring of at least two epochs is also useful to separate intrinsic variability and microlensing. In principle, at a given epoch, intrinsic variability should affect all the images of a lensed quasar in the same way, whereas microlensing may induce differences between the spectra of different images. However, the time delay in the arrival of the light from two lensed images can complicate this simple scheme by inducing differences between images that may arise from intrinsic variability. Although there are reasons to suppose that the contamination by intrinsic variability modulated by the time delay is weak (Guerras et al. 2013b), a second epoch of spectroscopic observations can allow us to untangle the causes of variability. If the different images change in the same way, the origin of the variability must be intrinsic, but if one of the images exhibits differences with respect to the others, we may expect that it is affected by microlensing.

Figure 1. C IV, C III], and Mg II emission line profiles from different epochs superimposed after subtracting the continuum and matching the line core. Different colors correspond to different epochs, and different color shadings stand for different images in the corresponding epoch. Blue/red shaded regions show the integration windows used for the magnitude difference calculations. The ordinate is in arbitrary units of flux. Note: due to the lack of wavelength coverage toward the blue, the definition of the continuum window on this side slightly overlaps with the blue wing in the case of SDSS J1339+1310 (epochs I and II).
Finally, the changes in the spectra of an image between two epochs are completely unaffected by extinction and uncertainties in the lens model and hence potentially provide independent estimates of the microlensing of the core and wings. This enables us to make independent estimates of the sizes of the two regions rather than (to be precise) of the differences in the sizes of the two regions measured when only a single epoch is available.

Obviously, all these positive prospects for the study of BEL variability are affected by the quality of the data, which, in our case, include several old spectra available in the literature, as described in Section 2. Section 2 also includes the data analysis. Section 3 is devoted to the discussion of the results in the context of BLR structure and kinematics. Finally, the main conclusions are summarized in Section 4.

2. Data Analysis and Results

2.1. Data

We collected from the literature rest-frame UV spectra of lensed quasars obtaining a sample of 26 lensed quasars, of which 11 are observed in (at least) two different epochs. Information about the observations and references is summarized in Table 1.

As mentioned in Section 1, one of the motivations to consider a second-epoch spectroscopy is the possibility of comparing the intensity of a given spectral feature (the wing of the C III line, for instance) of the same image (A) in two epochs (I and II), to study differences of the type (A\textsuperscript{I}–A\textsuperscript{II})\textsubscript{wing(C III)}. This difference is free from extinction or inaccurate macro-modeling effects. However, it is not free from instrumental problems such as slit misalignment or errors in the calibration of the instrumental response with wavelength, which, unfortunately, are likely present in the available data. Thus, we need a nonchanging reference spectral feature to scale the spectra. As a first step (Section 2.2) we consider the usual assumption of single-epoch-based studies that the cores of C IV, C III, and Mg II (defined by the flux within a narrow interval of ±6 Å centered on the peak of the line) arise from a substantially larger area than the wings (∼30 Å wavelength intervals on either side of the emission-line peak) and are consequently little affected by microlensing (see Guerras et al. 2013a, and references therein). Specifically, we start using the cores of the C IV, C III, and Mg II lines as references to study the wings of these lines and other weaker emission lines and blends in the C IV-to-Mg II wavelength range. Next (Section 2.3), we discuss the hypothesis of unchanging cores by studying the variability of the cores of C IV and C III, taking Mg II as reference.

2.2. Variability Taking as Reference the Cores of the C IV, C III, and Mg II Emission Lines

Figure 1 shows, for 11 lens systems with at least two epochs of observation (Table 1), the core-matched spectra in the wavelength regions around the C IV, C III, and Mg II lines (see Appendix A for details about the core-matching analysis). The spectra of 26 lens systems (11 with at least two epochs of observation and 15 with single-epoch spectra), split into two wavelength regions from C IV to C III and from C III to Mg II,
are shown in Figure 2. Under the assumption that the line core arises from a significantly larger region than the wings, the \((F_{1\text{core}}/F_{2\text{core}})/(F_{1\text{wings}}/F_{2\text{wings}})\) ratio of the line core fluxes of two images, \(F_{1\text{core}}/F_{2\text{core}}\), to the line wing fluxes of these two images, \(F_{1\text{wings}}/F_{2\text{wings}}\), yields a measurement of the size of the high-velocity wing emission regions. The computed magnitude differences between images with signal-to-noise ratio \((S/N)\) greater than 1.5 (see Appendix A for the details of the computation) are given for each epoch in Tables 2 (C IV, C III], and Mg II) and 4 (other considered emission-line features). Similarly, the magnitude differences between epochs for each image are presented in Tables 3 (C IV, C III], and Mg II) and 5 (other emission-line features). To qualify the magnitude differences between epochs or images as candidates for intrinsic variability or microlensing, we have used the following criteria: (i) the \(S/N\) should be greater than 2, (ii) any difference between images is considered a candidate for microlensing, (iii) we consider as a candidate for intrinsic variability a difference between two epochs when it is present in at least two images, and (iv) when neither criterion (ii) nor criterion (iii) applies, we consider that we have insufficient information to qualify the difference, although intrinsic variability may be more likely (partial evidence of intrinsic variability). The resulting classification of the differences between spectra corresponding to several emission-line features in the C IV-to-Mg II wavelength range is included in Tables 2, 3, 4, and 5.

The first result that can be inferred from Figures 1–3 as shown in Tables 2–5 is that the Mg II line is weakly affected by either microlensing or intrinsic variability with no significant changes \((S/N \gtrsim 2)\) in the selected windows.\(^{11}\) A similar result can be derived for the C III] line.\(^{12}\)

In the case of C IV the presence of microlensing or intrinsic variability is more the rule than the exception, particularly in the extreme red wing. In Figure 3 we show the mean\(\pm\)\(\sigma\) spectra of the C IV emission line for each system to emphasize the variability in the wings. There is evidence, at the \(2\sigma\) level, of intrinsic variability within the defined integration windows in one image of Q0142–100 and in HE 1104–1805. There is also evidence of intrinsic variability in the extreme red wing of C IV, specifically in the shelf-like feature blueward of He II, around \(\lambda 1610.1\).\(^{13}\) Microlensing is detected in C IV, at the \(2\sigma\) level, in the integration windows\(^{14}\) as defined in Figure 1 and in the shelf-like feature at \(\sim 1610.1\).\(^{15}\) The origin of this feature is uncertain (e.g., Fine et al. 2010, and references therein). It has been interpreted as an (extreme) C IV red wing or another species. In most of our objects\(^{16}\) microlensing or intrinsic variability seems to affect, in a more or less smooth way, the whole red wing. However,

\(^{11}\) Except for a difference between images D and B in the blue wing of HE 0435–1223 at epoch II.

\(^{12}\) With only two exceptions: B–A at epoch I in HE 0435–1223 and C–B at epoch I in WFI J2033–4723.

\(^{13}\) In Q0142–100, QSO 0957+561, HE 1104–1805, and HE 2149–2745.

\(^{14}\) In SDSS J1004+4112, HE 0435–1223, and SDSS J1339+1310.

\(^{15}\) It may be strongly microlensed \((\gtrsim 2\sigma)\) in HE 0435–1223, SDSS J1004+4112, and SDSS J1339+1310.

\(^{16}\) Q0142–100, HE 0435–1223, QSO 0957+561, HE 1104–1805, and SDSS J1339+1310.
the absence of a blue counterpart of this feature would need further explanation. On the other hand, in SDSS J1004+4112 (and perhaps HE 2149–2745), a feature at \( \sim \lambda 1610 \) shows up very distinctly, which supports the hypothesis of an unidentified species. Apart from this feature, in the pseudo-continua between C IV and C III and between C III and Mg II, there are several lines and blends showing evidence of intrinsic variability and microlensing at the 2\( \sigma \) level (see Appendix B), which very noticeably affect the complex formed by the He II emission line, the O III/Al II blend, and the underlying pseudo-continuum in the C IV–C III wavelength range\(^{17} \) and the Fe II and Fe III blends in the C III–Mg II range.

According to the criteria explained in Appendix A (see Tables 2–5), we can consistently separate most of the observed systems in terms of intrinsic variability or microlensing. There are four objects clearly dominated by microlensing (SDSS J0806+2006, FBQS J0951+2635, SDSS J1004+4112, and SDSS J1339+1310) and five objects in which intrinsic variability prevails (Q0142–100, HE 1104–1805, WFI J2033–4723, HE 2149–2745, and HE 0047–1756; in the last object there is evidence of microlensing in epoch I). The differences observed in QSO 0957+561 may be explained by intrinsic variability combined with the large time delay between the images of this double, plus a possible contribution from microlensing. Finally, HE 0435–1223 shows both intrinsic variability\(^{18} \) and microlensing of relatively lower amplitude.\(^{19} \)

In Figures 4 and 5 we present, for the different species, histograms of microlensing magnification and intrinsic variability. We have overlaid the corresponding Gaussian kernel density estimates of the probability density functions (pdf’s) to show the impact of errors in the individual measurements. According to these figures, within the limitations of the size of the sample of lens systems and of the data quality, intrinsic variability and microlensing seem to affect the same spectral features with similar strength. The impact of microlensing (and of intrinsic variability) looks similar for the shelf-like feature at \( \sim \lambda 1610 \), Fe II and III, and significantly smaller for C IV. Comparing with microlensing data of the continuum, we can say that the former features exhibit microlensing values similar to those typical of the optical continuum (\( |\Delta m_{\text{opt}}| \sim 0.3 \text{ mag} \); see Jiménez-Vicente et al. 2015) and that, in extreme cases, some spectral features (Fe III \( \lambda \lambda 2039–2113 \), for instance) can undergo microlensing magnifications close to those typical of the X-ray continuum (\( |\Delta m_{\text{X-ray}}| \sim 1 \text{ mag} \); see Jiménez-Vicente et al. 2015).

Moreover, we obtain rms intrinsic variabilities of the wings with respect to the cores of 18%, 12%, and 15% for the C IV, C III, and Mg II lines, respectively. This implies that the intrinsic variability affects the wings and core with different intensity, and/or that there is a delay between both. This difference is

---

\(^{17}\) Other lines in this wavelength range, such as Al III and Si III, are also affected by microlensing, but their study is hampered because they are strongly blended with C III.

\(^{18}\) Strong in the shelf-like feature at \( \sim \lambda 1610 \), He II, Fe II, and Fe III, and weaker in C IV.

\(^{19}\) Mainly in B–A (epoch IV in C IV, shelf-like feature at \( \lambda 1610 \) and Fe III).
observed in RM studies with resolution in velocity and is the basis for studying the kinematic structure of the BLR (e.g., Bentz et al. 2010; Grier et al. 2017a, and references therein). Typical rms variabilities for C IV and C III] of about 13% ± 9% have been found by Kaspi et al. (2007). For the Mg II line, an rms variability of about 19% ± 3% can be inferred from the reduced sample of sources of Shen et al. (2016). In spite of the reasonable agreement between these quantities and our results, the extent of the comparison is limited by the heterogeneity of the samples (in luminosity, redshift, and timescales) and by the fact that Kaspi et al. (2007) and Shen et al. (2016) are measuring the variability of the whole line.

2.3. Variability of the Cores of the C IV and C III] Emission Lines Taking Mg II as Reference

One important consequence of the previous section is that there is little differential microlensing between the core and wings of Mg II (the same result also applies to the red wing of C III]). This result looks, in principle, consistent with the relatively small range of velocities corresponding to the wings of Mg II (as compared with C IV). However, this conclusion should be regarded with caution, as we shall see later, the correspondence between velocity channel and microlensing impact is not simple. On the other hand, there are several systems (SDSS J1004+4112 and SDSS J1339+1310, in particular) in which microlensing is strongly affecting the wings of C IV (with respect to the core) without traces of this microlensing in the wings of Mg II. Consequently, it seems very unlikely that microlensing is present in Mg II but does affect the core and the wings with the same strength. Thus, it is reasonable to assume that the entire Mg II line is weakly sensitive to microlensing and to use this line as a reference to match the spectra of an image at different epochs. Therefore, we circumvent the problems originating from inaccuracies in the alignment of the slit and in the calibration of the spectra, and thus we obtain a measurement of intrinsic variability unaffected by extinction or macro-magnification modeling.

2.3.1. Core Microlensing

Let us start the core microlensing study (taking Mg II as reference) by computing, for each available epoch, differences of the type (B–A)core(C III]) – (B–A)core(Mg II), which we expect to be less affected by instrumental and calibration problems. In principle, this difference is sensitive to the differential microlensing between the cores of both emission lines, to differential extinction, and to differences in intrinsic variability between both lines during the time delay between A and B. If we assume that the Mg II line is fairly insensitive to

| Emission Line | Wing | Object | Image Pair | Epoch | $d^a \pm \sigma^b$ | $d/\sigma$ | Classification |
|--------------|------|-------|------------|-------|-----------------|----------|---------------|
| C IV Blue wing | SDSS 1004+4112 | B–A | I | $0.56 \pm 0.16$ | 3.4 | Microlensing |
| | | III | | $0.39 \pm 0.07$ | 5.8 | Microlensing |
| | | C–A | I | $0.69 \pm 0.14$ | 4.8 | Microlensing |
| | | D–A | I | $0.90 \pm 0.36$ | 2.5 | Microlensing |
| | | C–B | I | $0.13 \pm 0.06$ | 2.2 | Microlensing |
| Red wing | HE 0435–1223 | B–A | IV | $0.20 \pm 0.07$ | 2.8 | Microlensing |
| | | D–B | | $-0.12 \pm 0.08$ | 1.5 | |
| | | D–C | I | $-0.39 \pm 0.27$ | 1.5 | |
| | SDSS 1004+4112 | B–A | I | $0.30 \pm 0.06$ | 5.1 | Microlensing |
| | | II | | $-0.53 \pm 0.31$ | 1.7 | |
| | | III | | $-0.52 \pm 0.15$ | 3.6 | |
| | C–B | I | $0.35 \pm 0.10$ | 3.5 | Microlensing |
| | | D–B | I | $0.40 \pm 0.26$ | 1.6 | |
| SDSS J1339+1310 | B–A | III | | $-0.62 \pm 0.15$ | 4.2 | Microlensing |
| C III] Blue wing | SDSS 1004+4112 | C–A | I | $0.33 \pm 0.18$ | 1.9 | |
| | WFI 2033–4723 | C–B | II | $0.12 \pm 0.06$ | 2.1 | Microlensing |
| Red wing | HE 0435–1223 | B–A | I | $0.29 \pm 0.14$ | 2.0 | Microlensing |
| | | C–A | I | $0.29 \pm 0.15$ | 1.9 | |
| | HE 1104–1805 | B–A | II | $0.21 \pm 0.14$ | 1.5 | |
| Mg II Blue wing | HE 0435–1223 | D–B | II | $0.11 \pm 0.04$ | 3.0 | Microlensing |
| Red wing | HE 0435–1223 | D–B | II | $-0.27 \pm 0.16$ | 1.7 | |

Notes.

$^a$ Magnitude difference.

$^b$ Standard deviation of magnitude difference.
microslensing, this difference basically measures extinction and the impact of microlensing in the C III] core. The average of the absolute value of these differences is $0.09 \pm 0.08$ mag (68% confidence interval), indicating that there is little differential microlensing between C III] and Mg II (as shown in Table 6).

We repeat the same calculation for the C IV core but now using the core of C III] as reference, $(B-A)_{\text{core}(\text{C IV})} - (B-A)_{\text{core}(\text{C III})}$, in order to prevent the larger extinction impact of a direct comparison with Mg II, obtaining a mean value for the absolute differences of $0.12 \pm 0.11$ mag (68% confidence interval; see Table 6). Taking into account that the typical rms uncertainty in the determination of a single B–A difference is around 0.05 mag and other possible sources of uncertainty of the matching process, we can conclude that microlensing should have, on average, little impact in the cores of Mg II, C III], and C IV lines. However, it is important to notice that in the two strongest cases of microlensing in the C IV line, if we match the C III] lines, the core of C IV is affected by microlensing with maximum amplitudes of $0.23 \pm 0.07$ mag (SDSS J1004+4112) and $0.16 \pm 0.03$ mag (SDSS J1339+1310).

2.3.2. Core Intrinsic Variability

We can now try to compare a given image in two different epochs by computing the differences $(A^f-A^b)_{\text{core}(\text{C III})} - (A^f-A^b)_{\text{core}(\text{Mg II})}$ or $(A^f-A^b)_{\text{core}(\text{C IV})} - (A^f-A^b)_{\text{core}(\text{Mg II})}$. These types of quantities are supposed to be free from extinction and are affected by intrinsic variability and microlensing. After our previous conclusion about the low impact of microlensing in the cores of C IV, C III], and Mg II, we can reasonably think that they will mainly measure intrinsic variability. These quantities can nevertheless be strongly affected by uncertainties in the calibration of the spectral response at two different epochs. We have computed the absolute values of the differences between the cores of C III] (with respect to Mg II) and C IV (with respect to C III]) to obtain averages of $0.24 \pm 0.21$ mag and $0.29 \pm 0.25$ mag for the C III] and C IV cores, respectively (see Table 7). The scatter is

---

**Table 3**

Differences between Epochs—C IV, C III], and Mg II Lines

| Emission Line | Wing | Object | Image | Epoch | $d^a \pm \sigma^b$ | $d/\sigma$ | Classification |
|---------------|------|--------|-------|-------|---------------------|-----------|----------------|
| C IV          | Blue wing | Q0142–100 | A | II–I | $-0.07 \pm 0.05$ | 1.5 |                  |
|               |       | SDSS 1004+4112 | A | II–I | $0.28 \pm 0.07$ | 4.1 | Microlensing Variability |
|               |       |            | III–I | $0.18 \pm 0.04$ | 4.2 | Microlensing Variability |
|               |       |            | III–II| $-0.10 \pm 0.06$ | 1.5 |                  |
|               |       | HE 1104–1805 | A | II–I | $0.14 \pm 0.08$ | 1.7 |                  |
|               |       |            | III–I | $0.26 \pm 0.14$ | 1.9 |                  |
|               |       |            | IV–I | $0.28 \pm 0.15$ | 1.9 |                  |
|               |       |            | IV–II| $0.19 \pm 0.10$ | 1.9 |                  |
|               |       | B | II–I | $0.18 \pm 0.11$ | 1.6 |                  |
|               |       |            | III–I | $0.36 \pm 0.21$ | 1.8 |                  |
|               |       |            | IV–I | $0.22 \pm 0.15$ | 1.5 |                  |
|               |       |            | III–II| $0.19 \pm 0.11$ | 1.7 |                  |
| Red wing      |       | Q0142–100 | A | II–I | $-0.20 \pm 0.08$ | 2.5 | Intrinsic Variability? |
|               |       | HE 0435–1223 | C | III–I | $-0.49 \pm 0.34$ | 1.5 |                  |
|               |       | SDSS 1004+4112 | A | III–I | $0.26 \pm 0.08$ | 3.1 | Microlensing Variability |
|               |       | HE 1104–1805 | A | II–I | $0.14 \pm 0.06$ | 2.1 | Intrinsic Variability |
|               |       |            | IV–II| $0.11 \pm 0.04$ | 2.7 | Intrinsic Variability? |
|               |       | B | IV–I | $0.43 \pm 0.20$ | 2.2 | Intrinsic Variability |
|               |       |            | IV–II| $0.35 \pm 0.19$ | 1.8 |                  |
|               |       |            | IV–III| $0.26 \pm 0.16$ | 1.7 |                  |
| C III]        | Red wing | HE 0047–1756 | A | III–II| $-0.30 \pm 0.20$ | 1.5 |                  |
| Mg II         | Blue wing | HE 0435–1223 | A | IV–III| $-0.12 \pm 0.08$ | 1.5 |                  |
|               |       | D | III–II| $-0.21 \pm 0.11$ | 1.9 |                  |
|               |       |            | IV–III| $-0.20 \pm 0.12$ | 1.6 |                  |
|               |       | FBQ 0951+2635 | A | II–I | $-0.11 \pm 0.07$ | 1.5 |                  |
|               |       | WFI 2033–4723 | C | III–II| $0.12 \pm 0.07$ | 1.6 |                  |
| Red wing      |       | HE 0435–1223 | D | IV–III| $-0.37 \pm 0.23$ | 1.6 |                  |

Notes.

$^a$ Magnitude difference.

$^b$ Standard deviation of magnitude difference.

---

For the same reason, differential extinction may have on average only a marginal impact between Mg II and C III] and between C III] and C IV, although it is clear that extinction can play an important role in some of the outliers in the histograms of core microlensing (not shown here).
### Table 4
**Differences between Images—Other Emission-line Features**

| Emission Line | Object | Image Pair | Epoch | $\Delta* \pm \sigma^\circ$ | $d/\sigma$ | Classification |
|---------------|--------|------------|-------|---------------------------|-----------|----------------|
| Red shelf $\lambda\lambda 1580–1620$ | HE 0435–1223 | B–A | IV | 0.25 ± 0.08 | 3.3 | Microlensing |
| | | C–A | IV | 0.14 ± 0.08 | 1.7 | Microlensing |
| | | D–B | IV | $-0.17 \pm 0.06$ | 2.9 | Microlensing |
| | QSO 0957+561 | B–A | I | $-0.37 \pm 0.24$ | 1.6 | Microlensing |
| | SDSS J1004+4112 | C–A | I | 0.68 ± 0.34 | 2.0 | Microlensing |
| | | D–A | I | 0.58 ± 0.23 | 2.5 | Microlensing |
| | | C–B | I | 0.51 ± 0.11 | 4.6 | Microlensing |
| | HE 1104–1805 | B–A | I | 0.15 ± 0.10 | 1.5 | Microlensing |
| | SDSS 1339+1310 | B–A | I | $-0.89 \pm 0.48$ | 1.9 | Microlensing |
| | | II | | 1.53 ± 0.29 | 5.2 | Microlensing |
| | | III | | $-0.77 \pm 0.09$ | 8.8 | Microlensing |
| Fe $\text{III} \lambda \lambda 1978–2018$ | FBQS J0951+2635 | B–A | I | $-1.11 \pm 0.43$ | 2.6 | Microlensing |
| | QSO 0957+561 | B–A | II | $-0.43 \pm 0.11$ | 3.9 | Microlensing or intrinsic variability + $\Delta \tau$ |
| | SDSS 1339+1310 | B–A | I | $-1.05 \pm 0.71$ | 1.5 | Microlensing |
| | | II | | $-0.97 \pm 0.56$ | 1.7 | Microlensing |
| Fe $\text{III} \lambda \lambda 2039–2113$ | QSO 0957+561 | B–A | II | 0.40 ± 0.10 | 3.2 | Microlensing or intrinsic variability + $\Delta \tau$ |
| | SDSS J1004+4112 | C–A | I | 1.29 ± 0.85 | 1.5 | Microlensing |
| | SDSS 1339+1310 | B–A | I | $-0.96 \pm 0.29$ | 3.3 | Microlensing |
| | | II | | $-0.74 \pm 0.37$ | 2.0 | Microlensing |
| Fe $\text{III} \lambda \lambda 2386–2449$ | HE 0047–1756 | B–A | II | $-0.11 \pm 0.07$ | 1.6 | Microlensing |
| | HE 0435–1223 | B–A | IV | $-0.27 \pm 0.13$ | 2.1 | Microlensing |
| | | C–A | III | $-0.25 \pm 0.16$ | 1.6 | Microlensing |
| | | D–A | III | 0.19 ± 0.12 | 1.5 | Microlensing |
| | | C–B | IV | 0.29 ± 0.16 | 1.8 | Microlensing |
| | | D–B | IV | 0.28 ± 0.14 | 1.9 | Microlensing |
| | | D–C | III | 0.43 ± 0.23 | 1.9 | Microlensing |
| | SDSS J0806+2006 | B–A | I | $-0.68 \pm 0.24$ | 2.8 | Microlensing |
| | FBQS J0951+2635 | B–A | II | $-0.19 \pm 0.12$ | 1.6 | Microlensing |
| | SDSS 1339+1310 | B–A | I | $-0.42 \pm 0.24$ | 1.7 | Microlensing |
| | | II | | $-0.30 \pm 0.12$ | 2.5 | Microlensing |
| Fe $\text{II} \lambda \lambda 2158–2197$ | FBQS J0951+2635 | B–A | II | $-0.70 \pm 0.27$ | 2.6 | Microlensing |
| | QSO 0957+561 | B–A | II | 0.37 ± 0.18 | 2.0 | Microlensing or intrinsic variability + $\Delta \tau$ |
| | SDSS 1339+1310 | B–A | I | $-1.24 \pm 0.27$ | 4.6 | Microlensing |
| | | II | | $-1.13 \pm 0.72$ | 1.6 | Microlensing |
| Fe $\text{II} \lambda \lambda 2209–2239$ | SDSS 1339+1310 | B–A | I | $-1.62 \pm 0.81$ | 2.0 | Microlensing |
| Fe $\text{II} \lambda \lambda 2261–2364$ | HE 0435–1223 | D–C | III | $-0.23 \pm 0.15$ | 1.5 | Microlensing |
| | FBQS J0951+2635 | B–A | I | $-0.66 \pm 0.37$ | 1.8 | Microlensing |
| | SDSS 1339+1310 | B–A | I | $-0.86 \pm 0.30$ | 2.9 | Microlensing |
| | | II | | $-0.46 \pm 0.20$ | 2.3 | Microlensing |
| Fe $\text{II} \lambda \lambda 2460–2564$ | HE 0047–1756 | B–A | I | $-0.12 \pm 0.08$ | 1.6 | Microlensing |
| | HE 0435–1223 | B–A | IV | $-0.33 \pm 0.29$ | 1.6 | Microlensing |
| | | C–A | III | $-0.29 \pm 0.12$ | 2.5 | Microlensing |
too high to establish any reasonable comparison with other measurements. Nevertheless, we should take into account that, owing to the heterogeneity of the instrumentation used to obtain the data, errors of 20% in the spectral response in the observed wavelength range cannot be discarded. Therefore, we cannot be sure about the real impact of intrinsic variability on the cores, and the above values should be interpreted as upper bounds.

As a consequence of the analysis of this section, the microlensing results of Section 2.2 based on the hypothesis of core matching in a given epoch are reliable, whereas it cannot be excluded that the results concerning intrinsic variability of the wings might be somewhat affected by core intrinsic variability.

### 2.4. Microlensing Variability

We have identified differences in a given image between two epochs that can be consistently attributed to microlensing variability in the four systems dominated by microlensing (SDSS J0806+2006, FBQS J0951+2635, SDSS J1004+4112, SDSS J1339+1310) and, at a lower amplitude, in HE 0435–1223. In all these systems, microlensing variability is clearly noticeable in several FeIII and FeII blends. The well-studied case of SDSS J1004+4112 (Richards et al. 2004; Gómez-Alvarez et al. 2006; Motta et al. 2012; Fian et al. 2016, and references therein) presents outstanding examples of variability induced by microlensing in all the high-ionization lines. Note the high asymmetry of the effect, dominant in the blue part of the lines (see Figure 2). In contrast, in SDSS J1339+1310 the enhancement of CIV is clearly asymmetrical toward the red. From Mosquera & Kochanek (2011), we derived the effective transverse velocity for SDSS J1004+4112 and SDSS J1339+1310 and made two rough estimates of the distance moved by the accretion disk relative to the magnification pattern during the time elapsed between epochs of observation (∼1 yr in SDSS J1339+1310 and ∼5 yr in SDSS J1004+4112). For SDSS J1339+1310 the distance traveled in the source plane is too small (less than 0.6 lt-day) to see variability in both wings. In SDSS J1004+4112 we have obtained more interesting results, owing to a larger displacement of the source (∼4 lt-day), leading to variations in both wings. If we compare epochs I and II, we can see that the magnified blue wing fades while the red wing enhances. This supports that the separation between the approaching and receding parts of the microlensed region of the BLR is of about a few light-days.

In several cases, mainly affecting the shelf-like feature at ∼λ1610 and several blends of FeII and FeIII, the impact of microlensing and microlensing variability (see Tables 2–5) is |Δm| ≫ 1 mag, comparable to the typical microlensing magnification amplitudes observed in the X-ray continuum.

It is important to notice that the spectral features mainly affected by intrinsic variability are also the CIV wings, some blends of FeII and FeIII, and the shelf-like feature at ∼λ1610. In contrast with microlensing, we have not observed marked asymmetries induced by intrinsic variability in the line profiles. This result supports (within the statistical significance of our relatively limited sample) the hypothesis that the small region sensitive to microlensing is not systematically affected by extinction, beaming, or any other mechanism that may selectively enhance one part of it. Consequently, the asymmetric enhancements observed, in either the blue or red parts of microlensed line profiles, likely originate from an anisotropic distribution of microlensing magnification in the source plane.

### 3. Discussion

#### 3.1. Microlensing and Kinematics

The main result of the previous sections is that the cores of CIV, CIII], and MgII and the wings of the last two lines are only weakly affected by microlensing. However, the wings of CIV can be strongly affected. In other high-ionization emission-line features, such as the FeIII λ2039–2113 blend and the shelf-like feature at ∼λ1610, the whole feature may be globally affected by high-magnification microlensing.

To discuss these results with more detailed kinematic information than the separation between core and wings, in Figure 6 we have overlapped the averaged line profiles corresponding to CIV, CIII], MgII, and FeIII λ2039–2113.

---

**Table 4 (Continued)**

| Emission Line | Object | Image Pair | Epoch | d′ ± σ † | d/σ | Classification |
|---------------|--------|------------|-------|-----------|-----|----------------|
|               |        |            |       |           |     |                |
| D–A           | III    |            | 0.17 ± 0.11 | 1.5 |
| C–B           | IV     |            | 0.33 ± 0.22 | 1.5 |
| D–C           | III    |            | 0.47 ± 0.13 | 3.6 |
| SDSS J0806+2006 | B–A | I   | –0.72 ± 0.21 | 3.4 |
| FBQS J0951+2635 | B–A | II  | –0.20 ± 0.09 | 2.2 |
| SDSS 1339+1310 | B–A | I   | –0.16 ± 0.10 | 1.6 |
| Fe II λ2596–2645 | HE 0435–1223 | B–A | I   | 1.28 ± 0.80 | 1.6 |
|                 | C–B | I   | –1.04 ± 0.68 | 1.5 |
| FBQS J0951+2635 | B–A | II  | –0.27 ± 0.17 | 1.6 |
| SDSS J1004+4112 | B–A | I   | –0.70 ± 0.38 | 1.9 |

**Notes.**

† Magnitude difference.

‡ Standard deviation of magnitude difference.
### Table 5
Differences between Epochs—Other Emission-line Features

| Emission Line | Object | Image | Epoch | $d^a \pm \sigma^b$ | $d/\sigma$ | Classification    |
|---------------|--------|-------|-------|-----------------|-----------|------------------|
| Red shelf $\lambda\lambda 1580$–1620 | Q0142–100 | A | II–I | $-0.36 \pm 0.08$ | 4.5 | Intrinsic variability? |
|                | HE 0435–1223 | A | III–I | $-0.99 \pm 0.52$ | 1.9 | Microvariability |
|                |                | IV–III | $-0.32 \pm 0.12$ | 2.6 | Microvariability |
|                |                | B | IV–I | $-0.48 \pm 0.32$ | 1.5 | Microvariability |
|                |                | C | IV–I | $-0.90 \pm 0.60$ | 1.5 | Microvariability |
|                |                | D | IV–I | $-0.50 \pm 0.30$ | 1.6 | Microvariability |
|                | QSO 0957+561 | A | II–I | $0.50 \pm 0.21$ | 2.4 | Intrinsic variability? |
|                |                | B | II–I | $0.93 \pm 0.55$ | 1.7 | Microvariability |
|                | SDSS J1004+4112 | A | II–I | $0.33 \pm 0.18$ | 1.9 | Microvariability |
|                |                | III–I | $0.44 \pm 0.08$ | 5.4 | Microvariability |
|                | HE 1104–1805 | A | III–I | $1.19 \pm 0.67$ | 1.8 | Intrinsic variability? |
|                |                | IV–I | $0.33 \pm 0.08$ | 4.3 | Intrinsic variability? |
|                |                | III–II | $1.24 \pm 0.81$ | 1.5 | Intrinsic variability? |
|                |                | IV–II | $0.24 \pm 0.08$ | 2.9 | Intrinsic variability? |
|                | SDSS 1339+1310 | A | III–II | $0.68 \pm 0.24$ | 2.8 | Microvariability |
|                | HE 2149–2745 | A | II–I | $0.52 \pm 0.18$ | 2.9 | Intrinsic variability? |
|                |                | III–II | $-0.51 \pm 0.16$ | 3.2 | Intrinsic variability? |
|                |                | B | II–I | $0.28 \pm 0.19$ | 1.5 | Microvariability |
| Fe $\lambda\lambda 1705$–1730 | HE 1104–1805 | B | IV–III | $-0.70 \pm 0.53$ | 1.5 | Microvariability |
|                | SDSS 1339+1310 | A | III–I | $1.24 \pm 0.85$ | 1.5 | Microvariability |
|                |                | B | III–I | $1.28 \pm 0.74$ | 1.7 | Microvariability |
| Fe $\lambda\lambda 1760$–1800 | Q0142–100 | A | II–I | $-1.17 \pm 0.62$ | 1.9 | Microvariability |
| Fe $\lambda\lambda 1978$–2018 | QSO 0957+561 | A | II–I | $0.97 \pm 0.55$ | 1.8 | Microvariability |
|                | HE 1104–1805 | A | III–II | $-0.73 \pm 0.40$ | 1.8 | Microvariability |
|                | SDSS 1339+1310 | B | II–I | $1.02 \pm 0.67$ | 1.5 | Microvariability |
| Fe $\lambda\lambda 2039$–2113 | QSO 0957+561 | A | II–I | $1.30 \pm 0.67$ | 1.9 | Microvariability |
|                |                | B | II–I | $1.70 \pm 0.89$ | 1.9 | Microvariability |
| Fe $\lambda\lambda 2386$–2449 | HE 0047–1756 | A | II–I | $-0.82 \pm 0.08$ | 10.4 | Intrinsic variability |
|                |                | B | II–I | $-0.97 \pm 0.12$ | 8.4 | Intrinsic variability |
|                | HE 0435–1223 | A | IV–III | $0.43 \pm 0.17$ | 2.6 | Intrinsic variability |
|                |                | B | IV–I | $-0.39 \pm 0.17$ | 2.4 | Microvariability |
|                |                | C | III–I | $-0.58 \pm 0.28$ | 2.1 | Intrinsic variability? |
|                |                | IV–III | $0.70 \pm 0.16$ | 4.4 | Intrinsic variability |
|                | SDSS J0806+2006 | B | II–I | $0.78 \pm 0.40$ | 2.0 | Microvariability |
|                | SDSS J1004+4112 | A | III–I | $-0.43 \pm 0.20$ | 2.2 | Microvariability |
|                | WFI J2033–4723 | B | II–I | $-0.25 \pm 0.13$ | 2.0 | Intrinsic variability |
|                |                | C | II–I | $-0.31 \pm 0.11$ | 2.7 | Intrinsic variability |
|                | HE 2149–2745 | B | II–I | $0.26 \pm 0.13$ | 2.0 | Intrinsic variability? |
|                |                | III–II | $-0.28 \pm 0.12$ | 2.4 | Intrinsic variability? |
| Fe $\lambda\lambda 2158$–2197 | QSO 0957+561 | B | II–I | $1.13 \pm 0.73$ | 1.6 | Intrinsic variability |
| Fe $\lambda\lambda 2209$–2239 | HE 0435–1223 | C | IV–I | $0.69 \pm 0.42$ | 1.7 | Intrinsic variability |
|                |                | IV–III | $1.34 \pm 0.86$ | 1.6 | Intrinsic variability |
|                | D | III–II | $-1.14 \pm 0.53$ | 2.1 | Intrinsic variability? |
The wings of Mg II correspond to relatively low velocities as compared with other lines. This is consistent with the weak impact of microlensing on this line. Regarding C III] and C IV, the red parts of these lines match very well, except at the lowest intensity level, where the shelf-like feature at \( \sim \lambda 1610 \) is present in C IV (the blue side of C III] is blended with Al III, Si III, and Fe II, and no reasonable comparison can be made). In spite of this remarkable kinematic coincidence, the C IV line can be strongly affected by microlensing, whereas C III] seems to be rather insensitive to this effect (see, e.g., the cases of SDSS J1004+4112 and SDSS J1339+1310). In addition, they have a different degree of ionization (C IV is of high ionization and C III] of low ionization). These results suggest that both lines are mostly generated in the same region, but that there is also a contribution, exclusive to the C IV line, from emitters located in a region small enough to be strongly affected by microlensing. As far as a zero-velocity contribution from the core of the C IV line may also undergo some microlensing at a lower level of amplitude, compatible with our results in Section 2.3.2 (about 20% of microlensing magnification in the cores of SDSS J1004+4112 and SDSS J1339+1310).

| Emission Line | Object | Image | Epoch | \( d^a \pm \sigma^b \) | \( d/\sigma \) | Classification |
|---------------|--------|-------|-------|----------------|-----------|---------------|
| Fe II \( \lambda \lambda 2261\text{–}2364 \) | HE 0047–1756 | A | II–I | \(-0.46 \pm 0.13\) | 3.5 | Intrinsic variability? |
| | | B | II–I | \(-0.71 \pm 0.46\) | 1.5 | |
| | HE 0435–1223 | A | IV–I | \(0.75 \pm 0.46\) | 1.6 | |
| | | | IV–III | \(0.88 \pm 0.41\) | 2.1 | Intrinsic variability |
| | | | C | IV–III | \(0.84 \pm 0.34\) | 2.5 | Intrinsic variability |
| | | D | III–II | \(-0.60 \pm 0.22\) | 2.8 | Intrinsic variability? |
| | | | | IV–III | \(1.09 \pm 0.54\) | 2.0 | Intrinsic variability |
| | FBQS J0951+2635 | B | II–I | \(0.52 \pm 0.24\) | 2.2 | Microlensing variability |
| Fe II \( \lambda \lambda 2460\text{–}2564 \) | HE 0047–1756 | A | II–I | \(-0.74 \pm 0.07\) | 11.3 | Intrinsic variability |
| | | B | II–I | \(-0.87 \pm 0.08\) | 10.5 | Intrinsic variability |
| | HE 0435–1223 | A | IV–I | \(0.49 \pm 0.32\) | 1.5 | |
| | | | IV–III | \(0.65 \pm 0.21\) | 3.1 | Intrinsic variability |
| | | | C | III–II | \(-0.57 \pm 0.24\) | 2.4 | Microlensing variability |
| | | | | IV–III | \(0.95 \pm 0.20\) | 4.7 | Intrinsic variability |
| | | D | IV–II | \(0.44 \pm 0.28\) | 1.6 | |
| | SDSS J0806+2006 | A | II–I | \(0.61 \pm 0.31\) | 1.9 | |
| | FBQS J0951+2635 | A | II–I | \(-0.19 \pm 0.12\) | 1.5 | |
| | | B | II–I | \(-0.27 \pm 0.18\) | 1.5 | |
| | SDSS 1339+1310 | A | II–I | \(-0.30 \pm 0.19\) | 1.6 | |
| | WFI J2033–4723 | C | II–I | \(-0.24 \pm 0.10\) | 2.5 | Intrinsic variability? |
| | HE 2149–2745 | A | II–I | \(0.28 \pm 0.09\) | 3.0 | Intrinsic variability |
| | | | III–II | \(-0.29 \pm 0.09\) | 3.3 | Intrinsic variability |
| | | B | II–I | \(0.37 \pm 0.15\) | 2.5 | Intrinsic variability |
| | | | III–II | \(-0.38 \pm 0.16\) | 2.4 | Intrinsic variability |
| | HE 0435–1223 | A | IV–I | \(1.40 \pm 0.77\) | 1.8 | |
| | | | IV–III | \(1.34 \pm 0.78\) | 1.7 | |
| | | B | IV–II | \(0.98 \pm 0.47\) | 2.1 | Intrinsic variability |
| | | | C | IV–III | \(1.28 \pm 0.71\) | 1.8 | |
| | | D | IV–II | \(1.16 \pm 0.43\) | 2.7 | Intrinsic variability |
| | | | | IV–III | \(0.97 \pm 0.57\) | 1.7 | |

Notes.

* Magnitude difference.

* Standard deviation of magnitude difference.
Table 6
Core Differences between Images

| Object        | Image Pair | Epoch | C IV   | C III  |
|---------------|------------|-------|--------|--------|
|               |            |       | $d^b$ ± $\sigma^b$ | $d/\sigma$ | $d^b$ ± $\sigma^b$ | $d/\sigma$ |
| HE 0047−1756  | B−A        | I     | −0.08 ± 0.03 | 1.1 | −0.01 ± 0.01 | 1.2 |
|               |            | II    | ... | ... | ... | ... |
|               |            | III   | ... | ... | 0.01 ± 0.04 | 0.4 |
| Q0142−100     | B−A        | I     | 0.03 ± 0.03 | 1.1 | ... | ... |
|               |            | II    | 0.05 ± 0.02 | 2.2 | ... | ... |
| HE 0435−1223  | B−A        | I     | −0.07 ± 0.04 | 1.7 | ... | ... |
|               |            | IV    | −0.34 ± 0.03 | 12.3 | 0.09 ± 0.02 | 4.1 |
|               | C−A        | I     | 0.02 ± 0.07 | 0.3 | ... | ... |
|               |            | II    | ... | ... | ... | ... |
|               |            | III   | −0.08 ± 0.04 | 2.0 | 0.08 ± 0.04 | 2.1 |
|               |            | IV    | 0.05 ± 0.04 | 1.2 | 0.14 ± 0.02 | 7.2 |
|               | D−A        | I     | −0.09 ± 0.03 | 2.7 | ... | ... |
|               |            | II    | ... | ... | 0.03 ± 0.03 | 1.2 |
|               |            | III   | 0.08 ± 0.07 | 1.2 | −0.19 ± 0.07 | 2.9 |
|               |            | IV    | −0.39 ± 0.03 | 13.2 | 0.07 ± 0.05 | 1.4 |
|               | C−B        | I     | 0.08 ± 0.08 | 1.0 | ... | ... |
|               |            | IV    | 0.38 ± 0.04 | 10.8 | 0.06 ± 0.02 | 3.3 |
|               | D−B        | I     | −0.03 ± 0.05 | 0.6 | ... | ... |
|               |            | II    | ... | ... | 0.03 ± 0.03 | 1.2 |
|               |            | IV    | −0.05 ± 0.03 | 1.5 | −0.01 ± 0.03 | 0.3 |
|               | D−C        | I     | −0.11 ± 0.03 | 3.2 | ... | ... |
|               |            | II    | ... | ... | 0.16 ± 0.09 | 1.8 |
|               |            | III   | 0.08 ± 0.04 | 2.3 | −0.26 ± 0.08 | 3.5 |
|               |            | IV    | −0.44 ± 0.02 | 19.6 | −0.07 ± 0.04 | 1.8 |
| SDSS J0806+2006 | B−A    | I     | ... | ... | ... | ... |
| QSO 0957+561  | B−A        | I     | −0.09 ± 0.05 | 2.0 | 0.10 ± 0.02 | 5.3 |
|               |            | II    | 0.08 ± 0.07 | 1.1 | 0.14 ± 0.04 | 3.3 |
| SDSS J1004+4112 | B−A   | I     | 0.06 ± 0.02 | 2.5 | 0.11 ± 0.03 | 3.4 |
|               |            | II    | 0.17 ± 0.06 | 2.6 | ... | ... |
|               |            | III   | 0.10 ± 0.04 | 2.3 | 0.00 ± 0.03 | 0.1 |
|               | C−A        | I     | 0.05 ± 0.04 | 1.1 | 0.18 ± 0.13 | 1.4 |
|               | D−A        | I     | 0.13 ± 0.03 | 4.8 | 0.19 ± 0.04 | 4.6 |
|               | C−B        | I     | −0.01 ± 0.05 | 0.3 | 0.07 ± 0.13 | 0.5 |
|               | D−B        | I     | 0.08 ± 0.03 | 2.5 | 0.07 ± 0.05 | 1.4 |
|               | D−C        | I     | 0.10 ± 0.03 | 3.5 | 0.00 ± 0.12 | 0.0 |
| HE 1104−1805  | B−A        | I     | 0.06 ± 0.02 | 3.0 | ... | ... |
|               |            | II    | 0.01 ± 0.02 | 0.07 | −0.13 ± 0.14 | 1.0 |
|               |            | III   | −0.08 ± 0.03 | 2.6 | ... | ... |
|               |            | IV    | −0.14 ± 0.02 | 7.7 | ... | ... |
| SDSS 1339+1310 | B−A   | I     | −0.35 ± 0.04 | 9.9 | −0.06 ± 0.07 | 0.9 |
|               |            | II    | −0.33 ± 0.06 | 5.2 | −0.13 ± 0.02 | 5.5 |
|               |            | III   | −0.20 ± 0.03 | 8.1 | ... | ... |
| WFI J2033−4723 | A2−A1   | I     | −0.10 ± 0.16 | 0.6 | ... | ... |
|               |            | B−A1  | ... | ... | ... | ... |
|               | B−A2      | I     | −0.21 ± 0.11 | 1.9 | ... | ... |
|               | C−A1      | I     | −0.16 ± 0.10 | 1.7 | ... | ... |
|               | C−A2      | I     | −0.11 ± 0.12 | 1.0 | ... | ... |
|               | C−B       | I     | 0.08 ± 0.14 | 0.5 | ... | ... |
|               |            | II    | ... | ... | 0.03 ± 0.02 | 1.1 |
|               |            | III   | ... | ... | 0.03 ± 0.02 | 1.4 |
| HE 2149−2745  | B−A        | I     | 0.04 ± 0.04 | 0.9 | −0.01 ± 0.03 | 0.3 |
|               |            | II    | −0.03 ± 0.04 | 0.8 | 0.03 ± 0.03 | 0.9 |
|               |            | III   | 0.03 ± 0.05 | 0.6 | 0.00 ± 0.04 | 0.0 |

Notes.
* Magnitude difference.
* Standard deviation of magnitude difference.
Even if Fe III λλ2039–2113 is the iron spectral feature least contaminated by other species, it is still a blend of many Fe III single emission lines (Vestergaard & Wilkes 2001), and its kinematic interpretation is not straightforward. A simple fit to the blend of the average spectrum based on the sum of Gaussians of the same FWHM (considering the nominal wavelengths and strengths of the single Fe III lines of this blend; Vestergaard & Wilkes 2001) results in a kinematic FWHM of about 9400 km s$^{-1}$, significantly greater than that corresponding to C IV. In addition, the strength of microlensing in the Fe III λλ2039–2113 blend can, in some cases, be greater than in the optical continuum, comparable even to that of the X-ray regions.

In Figure 7 we represent the average amplitude of microlensing with respect to the line broadening for Fe III, C IV, C III], and Mg II. There is a global trend relating high microlensing with line broadening. Notice the high differential microlensing of C IV with respect to C III], even when both lines have close FWHMs, revealing the existence of the small region prone to microlensing not contributing to C III].
3.2. Microlensing and Size

Single-epoch microlensing measurements can be used to estimate (or constrain) the size of the emitting regions (e.g., Guerras et al. 2013a). For the size calculations we will treat each event as a single-epoch event. From the microlensing magnification corresponding to all the lens image pairs with more than one epoch of observation we compute the joint microlensing probability, $P(r_s)$, of obtaining an average estimate of the size, following the steps described in Guerras et al. (2013a),

$$P(r_s) = \prod_i P_i(r_s),$$  \hspace{1cm} (1)

$$P_i(r_s) \propto e^{-\frac{\chi_i^2(r_o)}{2}},$$  \hspace{1cm} (2)

$$\chi_i^2(r_o) = \sum_{\alpha_i} \sum_{\beta_i} \left( \frac{\Delta m_{\beta_i,\alpha_i}^{\text{obs}} - \Delta m_{\beta_i,\alpha_i}(r_o)}{\sigma_{\beta_i,\alpha_i}} \right)^2,$$  \hspace{1cm} (3)

where $\Delta m_{\beta_i,\alpha_i}^{\text{obs}}$ is the observed differential microlensing magnification between images $\alpha$ and $\beta$ of system $i$ and $\Delta m_{\beta_i,\alpha_i}(r_o)$ is the differential microlensing magnification predicted by the simulations for a given value of $r_o$. The simulations are based on $3000 \times 3000$ pixel magnification maps, spanning $600 \times 600$ lt-day$^2$ on the source plane, obtained using the Inverse
Polygon Mapping method (Mediavilla et al. 2006, 2011). The general characteristics of the magnification maps are determined (for each quasar image) by the local convergence $\kappa$ and the local shear $\gamma$, which were obtained by fitting a singular isothermal sphere with an external shear (SIS+$\gamma_e$) that reproduce the coordinates of the images (Mediavilla et al. 2006). We have assumed a mean stellar mass of $0.3 M_\odot$. To simulate the effect of the finite source, we have convolved the magnification maps with 2D Gaussian profiles of sigma $r_e$, logarithmically spanning an interval between 0.2 and 120 lt-day. Sizes are converted to half-light radius multiplying by 1.18, $R_{1/2} = 1.18 r_e$.

The resulting joint likelihood function can be seen in Figure 8. From Figure 8 we can estimate a size for the region emitting the low-ionization emission of $50.3^{+30.4}_{-14.0} \sqrt{M/0.3 M_\odot}$ lt-day. This result is in good agreement with the estimates by Guerras et al. (2013a). It is also in agreement, within the uncertainties, with the RM size estimates for Mg II of the two SDSS-RM sources of highest luminosity in the comparatively low luminosity sample of Shen et al. (2016) (object 101, $\tau = 36.7^{+10.4}_{-4.8}$ days; object 589, $\tau = 34.0^{+6.0}_{-12.2}$ days). Finally, our measurement matches very well the Bentz et al. (2013) size–luminosity relation based on H$\beta$ RM.
In principle, we could now repeat the same procedure with the high-ionization lines, starting with C IV. However, from our previous kinematic analysis, we know that the C IV microlensed line profile is likely a combination of emission coming from the large region weakly sensitive to microlensing, where C III] and Mg II originate, and from another small region that shows up in the line profile only when microlensing is present. Moreover, we can suspect that the proportion of the contributions from the two regions to the line profile changes with wavelength. Thus, we should refine the previous approach taken in Guerras et al. (2013a, 2013b), in which the core and wings were supposed to come exclusively from one of the regions. Instead of this approach, which is complex and needs some modeling (we defer it to future work), we are going to suppose that the spectral features with the highest microlensing magnification arise exclusively from the small region susceptible of microlensing. From the likelihood function corresponding to the observed microlensing (see Figure 9) we infer (using a logarithmic prior for the size) a size of $4.1^{+0.3}_{-0.8} / M_\odot$ It-day for the $\sim \lambda 1640$ feature at the red shelf of C IV, comparable to the optical continuum. In Figure 10 we show the pdf’s corresponding to three different blends of Fe III ($\lambda\lambda 1978–2018$, $\lambda\lambda 2039–2113$, and $\lambda\lambda 2386–2449$).
estimated average size, $11.3^{+5.0}_{-4.8}\sqrt{M/0.3}\,M_\odot$ lt-day, is consistent within the errors with the sizes measured for the red shelf feature at $\sim\lambda 1610$. Actually, the highest microlensing values are measured in Fe III, but the presence of several systems with low microlensing amplitudes in the subsample of systems with more than one epoch of observation (used to compute the pdf’s) has made slightly larger the size of Fe III. We obtain slightly larger sizes for the emission regions if we take into account the rescaling of the radii by the luminosity of the systems ($r_i = r_0(1/L_i/L_0)$).

In Figure 11 we finally present the pdf’s corresponding to several blends of Fe II (\$\lambda\lambda 1705–1730, \lambda\lambda 1760–1800, \lambda\lambda 2158–2197, \lambda\lambda 2209–2239, \lambda\lambda 2261–2364, \lambda\lambda 2460–2564, and \lambda\lambda 2596–2645). The main result that can be inferred from this figure is the different sensitivity to microlensing, which implies different sizes. The microlensing-based size of the \$\lambda\lambda 2158–2197 blend is $5.2^{+1.8}_{-2.3}\sqrt{M/0.3}\,M_\odot$ lt-day, comparable to the sizes of the Fe III emitting regions. In contrast, the other blends seem to arise from regions of significantly larger size.

### 3.3. Structure and Kinematics of the BLR

From the impact of microlensing, which we have separately studied in the core and wings of the CIV, CIII, and Mg II emission lines, we can attempt to broadly outline a basic relationship between kinematics and structure in the BLR. In the first place, both kinematic regions, core and wings, seem to be little affected by microlensing in C III and Mg II, indicating that these low-ionization lines (as has been usually assumed) arise from a large region, with a lower limit in size of about 50 lt-day according to microlensing estimates. The absence of a central dip in any of the cores of the line profiles (as in most quasars and AGNs; see Popović et al. 2004) very likely indicates that the motion of the emitters contributing to the core is not confined to a plane (Mathews 1982). The average line profiles of C III and C IV match very well (at least in the unblended red part), thereby indicating that both arise mainly from the same region. However, the resemblance between the line profiles is broken by the changes induced by microlensing that reveal the existence of a second region that only shows up in the presence of microlensing. This region contributes to the C IV line (with high strength to the wings and a lower amplitude to the core) but not to C III or Mg II. According to the high impact of microlensing in other high-ionization lines and blends studied, these features also arise from this region, whose size, according to microlensing estimates, would be a few light-days. This and the high velocities involved make it natural to identify the relatively small region with part of the accretion disk. In some cases (Fe III \$\lambda\lambda 2039–2113, for instance) the large microlensing magnifications and the high velocities involved support the hypothesis that the emitters may arise from an inner region of the accretion disk.

Microlensing provides estimates of the emitting region sizes, which, combined with the Doppler broadening of the emission lines, should help us to study the kinematics of the BLR and the mass of the central black hole, $M_{BH}$, in a similar way as with RM. It is common in RM studies to suppose that the broadening of the lines (FWHM or $\sigma$) is related to the mass of the central BH through the virial theorem according to

$$M_{BH} \approx 9.8 \times 10^7 \,M_\odot \left( \frac{R_{BLR}}{5\,\text{lt-days}} \right) \left( \frac{\Delta v_{\text{FWHM}}}{10,000\,\text{km}\,\text{s}^{-1}} \right)^2.$$  

\[ (4) \]
Table 7
Core Differences between Epochs

| Object      | Image Pair | Epoch | C IV   | d' ± σb | d/σ | C III  | d' ± σb | d/σ |
|-------------|------------|-------|--------|---------|-----|--------|---------|-----|
| HE 0047–1756| A          | III–II| ...    | ...     | −0.01 ± 0.05 | 0.2   |
|             | B          | III–II| ...    | ...     | 0.02 ± 0.04  | 0.5   |
| Q0142–100   | A          | II–I  | −0.55 ± 0.03 | 18.1   | ... |        | ...     |     |
|             | B          | II–I  | −0.53 ± 0.03 | 16.2   | ... | ...    | ...     |     |
| HE 0435–1223| A          | III–I | 0.85 ± 0.05 | 16.0   | ... |        | ...     |     |
|             |            | IV–I  | 0.64 ± 0.03 | 21.4   | ... | ...    | ...     |     |
|             |            | IV–III| −0.21 ± 0.06 | 3.4    | −0.73 ± 0.06 | 11.6  |
|             | B          | IV–I  | 0.35 ± 0.05 | 7.7    | ... |        | ...     |     |
|             |            | IV–II | ...    | ...     | −0.39 ± 0.02 | 24.6  |
| C           | III–I      | 0.74 ± 0.04 | 20.9   | ... | ...    | ...     |     |
|             | IV–I       | 0.67 ± 0.08 | 8.3    | ... | ...    | ...     |     |
|             | IV–III     | −0.09 ± 0.08 | 1.1    | −0.67 ± 0.05 | 13.7  |
| D           | III–I      | 1.02 ± 0.08 | 13.5   | ... | ...    | ...     |     |
|             | IV–I       | 0.33 ± 0.08 | 4.1    | ... | ...    | ...     |     |
|             | III–II     | ...    | ...    | ...     | 0.03 ± 0.06 | 0.5   |
|             | IV–II      | ...    | ...    | ...     | −0.44 ± 0.06 | 7.1   |
|             | IV–III     | −0.69 ± 0.12 | 5.9    | −0.47 ± 0.08 | 6.1   |
| SDSS J0806+2006| A        | II–I  | −0.49 ± 0.09 | 5.2    | 0.12 ± 0.03 | 3.8   |
|             | B          | II–I  | −0.33 ± 0.04 | 8.8    | 0.17 ± 0.07 | 2.4   |
| QSO 0957+561| A          | II–I  | −0.08 ± 0.02 | 3.5    | ... | ...    | ...     |     |
|             | B          | II–I  | −0.33 ± 0.04 | 8.8    | 0.17 ± 0.07 | 2.4   |
| SDSS J1004+4112| A        | II–I  | −0.08 ± 0.02 | 3.5    | ... | ...    | ...     |     |
|             | III–I      | 0.14 ± 0.05 | 3.1    | −0.04 ± 0.04 | 1.2   |
|             | III–II     | 0.24 ± 0.07 | 3.3    | ... | ...    | ...     |     |
|             | B          | II–I  | 0.02 ± 0.05 | 0.3    | ... | ...    | ...     |     |
|             | III–I      | 0.20 ± 0.04 | 4.6    | −0.15 ± 0.02 | 7.8   |
|             | III–II     | 0.18 ± 0.07 | 2.4    | ... | ...    | ...     |     |
| HE 1104–1805| A          | II–I  | 0.37 ± 0.01 | 27.2   | ... | ...    | ...     |     |
|             | III–I      | 0.44 ± 0.05 | 9.2    | ... | ...    | ...     |     |
|             | IV–I       | 0.51 ± 0.03 | 15.5   | ... | ...    | ...     |     |
|             | III–II     | 0.06 ± 0.03 | 1.9    | ... | ...    | ...     |     |
|             | IV–II      | 0.27 ± 0.01 | 21.4   | ... | ...    | ...     |     |
|             | IV–III     | 0.21 ± 0.04 | 5.2    | ... | ...    | ...     |     |
|             | B          | II–I  | 0.33 ± 0.02 | 18.0   | ... | ...    | ...     |     |
|             | III–I      | −0.04 ± 0.03 | 1.3   | ... | ...    | ...     |     |
|             | IV–I       | 0.45 ± 0.04 | 10.6   | ... | ...    | ...     |     |
|             | III–II     | −0.04 ± 0.03 | 1.3   | ... | ...    | ...     |     |
|             | IV–II      | 0.12 ± 0.05 | 2.7    | ... | ...    | ...     |     |
|             | IV–III     | 0.17 ± 0.04 | 4.7    | ... | ...    | ...     |     |
| SDSS 1339+1310| A        | II–I  | 0.11 ± 0.04 | 2.9    | −0.32 ± 0.07 | 22.5  |
|             | III–I      | 0.03 ± 0.04 | 0.7    | ... | ...    | ...     |     |
|             | III–II     | −0.09 ± 0.02 | 4.0    | ... | ...    | ...     |     |
|             | B          | II–I  | 0.13 ± 0.06 | 2.0    | −0.38 ± 0.05 | 7.3   |
|             | III–I      | 0.16 ± 0.03 | 5.2    | ... | ...    | ...     |     |
|             | III–II     | 0.03 ± 0.06 | 0.5    | ... | ...    | ...     |     |
| WFI J2033–4723| B         | III–II| ...    | ...     | −0.03 ± 0.06 | 0.6   |
|             | C          | III–II| ...    | ...     | −0.03 ± 0.04 | 0.9   |
| HE 2149–2745| A          | II–I  | −0.17 ± 0.03 | 5.1    | −0.31 ± 0.03 | 10.2  |
|             | III–I      | −0.02 ± 0.01 | 1.4    | −0.04 ± 0.01 | 4.3   |
When we apply this relationship to C IV emission lines with $\Delta v_{\text{FWHM}} \sim 4700 \, \text{km} \, \text{s}^{-1}$ (corresponding to the average C IV line obtained from our sample) and $R_{\text{BLR}} \sim 50.3^{+30.4}_{-14.0}$ lt-day (corresponding to the large BLR region little affected by microlensing), we obtain $M_{\text{BH}} \sim 4^{+2.4}_{-2.2} \times 10^8 \, M_\odot$ for $f = 2$, which is a reasonable result for the bright quasars of our sample (Mosquera et al. 2013). A consistent result, $M_{\text{BH}} \sim 3.9^{+1.8}_{-1.4} \times 10^8 \, M_\odot$ (for $f = 2$), is obtained by considering the Fe III $\lambda\lambda 2039-2113$ blend of size $R_{\text{BLR}} \sim 11.3^{+5.3}_{-4.4}$ lt-day and velocity $\Delta v_{\text{FWHM}} \sim 9400 \, \text{km} \, \text{s}^{-1}$. The coincidence between both estimates indicates that microlensing-based sizes are in agreement with the hypothesis of virialized kinematics.

Microlensing may, in addition, give more precise information relating velocity and size by considering not the mean properties of the line as a whole but discrete velocity bins in the emission line. However, Equation (4) cannot be directly applied to a velocity bin. Its direct application, considering Gaussian sources, to velocity bins in the range $1000-10,000 \, \text{km} \, \text{s}^{-1}$ (in the cases of SDSS J1339+1310 and SDSS J1004+4112) leads to microlensing sizes so small, as compared with those inferred from RM, that the obtained central black hole masses would be unexpectedly low. Consequently, a kinematic model that describes the geometry of the region contributing to each velocity interval is needed, to simulate the impact of microlensing in this region. On the other hand, as discussed above, we should

Table 7

| Object    | Image Pair | Epoch  | C IV | C III |
|-----------|------------|--------|------|-------|
|           | III–II     | 0.13 ± 0.05 | 2.5  | 0.26 ± 0.03 | 9.6 |
| B         | II–I       | –0.23 ± 0.04 | 6.0  | –0.28 ± 0.05 | 5.3 |
|           | III–II     | –0.02 ± 0.02 | 1.2  | –0.04 ± 0.03 | 1.1 |
| III–II    | 0.21 ± 0.05 | 4.5    | 0.24 ± 0.06 | 4.2 |

Notes.

a Magnitude difference.
b Standard deviation of magnitude difference.
also take into account that the C IV line profile has contributions from two different regions, but that one of them is much more sensible to microlensing than the other.

There are other high-ionization lines that seem to arise exclusively from the small region sensitive to microlensing that, owing to the high microlensing magnifications observed, we have identified with the accretion disk, even with its inner regions. A study based on these lines is not straightforward, as they usually form blends and the S/N of the available observations is not sufficient. In any case, an interesting conclusion is that the BEL of these species may be used to study the kinematics of quasar accretion disks.

4. Conclusions

We have analyzed the BEL of a sample of 11 gravitationally lensed quasars with at least two epochs of observation. We have studied, in most cases, up to 11 different spectral features (emission lines or blends) between the C IV and Mg II lines. Although it is limited, the temporal sampling available has allowed us to identify intrinsic variability and to classify the differences between pairs of spectra as candidates for intrinsic variability or microlensing. The main conclusions are the following:

1. We can consistently separate a group of four systems dominated by microlensing (SDSS J0806+2006, FBQS J0951+2635, SDSS J1004+4112, and SDSS J1339+1310) and another group of five objects in which intrinsic variability prevails (Q0142−100, HE 1104−1805, WFI J2033−4723, HE 2149−2745, and HE 0047−1756). The case of QSO 0957+561 may be explained by intrinsic variability combined with the time delay between the images plus a possible contribution from microlensing. Finally, HE 0435−1223 seems to be a hybrid case with both microlensing and intrinsic variability present.

2. We study the effects of microlensing and intrinsic variability in the core of the lines (which have been considered unchanging in single-epoch-based studies). On average, we measure a weak microlensing effect in the cores of C III] (≤0.09 ± 0.08 mag with respect to Mg II) and C IV (≤0.12 ± 0.11 mag with respect to C III]). Although in the two strongest cases of microlensing, the core of C IV is significantly affected (0.23 ± 0.07 mag in
Figure 5. Histograms of the difference between epochs for different emission-line features. Black curves show the corresponding Gaussian kernel density estimates of the PDFs. For the BELs, C\textsc{iv}, C\textsc{iii}, and Mg\textsc{ii} (top row) histograms of the blue and red wings are shown. The blue (red) curve illustrates the Gaussian density estimate for the blue (red) wing.

Figure 6. Average line profiles of C\textsc{iv}, C\textsc{iii}, Mg\textsc{ii}, and Fe\textsc{ii} λλ2040–2100 as a function of velocity.
Taking the cores as reference, we find that the wings of MgII and CIII are not significantly affected (at the 2σ level) by either intrinsic variability or microlensing. On the other hand, the wings of CIV and the other spectral features analyzed (λ1610 shelf-like feature, He II, the O III/Al II blend, Al III, Si III, Fe II, and Fe III) show strong changes. These results basically confirm the existence of two distinct regions suggested in single-epoch-based studies,21 one large and insensitive to microlensing and another small and prone to microlensing, but with a significant nuance: the small region also contributes to the core of the high-ionization lines, although it shows up only in the presence of strong microlensing. We have also analyzed core intrinsic variability and obtained estimates of $\Delta m \approx 0.24 \pm 0.21$ mag for CIII (with respect to MgII) and $\Delta m \approx 0.29 \pm 0.25$ mag for CIV (with respect to CIII). Owing to the presence of systematic instrumental effects, these

---

21 Which could neither remove intrinsic variability nor be used to study the impact of microlensing on the cores.
values should be regarded as upper limits on the intrinsic variability of the cores.

3. There is evidence of microlensing variability in the four systems dominated by microlensing and in the hybrid case, HE 0435−1223. Owing to the changes in some spectral features (C IV wings mainly), strong microlensing variability can induce very noticeable asymmetries in the line profile shape. Intrinsic variability affects the same spectral features with similar strength, although no outstanding evidence of asymmetry associated with intrinsic variability has been detected. These results support the hypothesis that the small region susceptible to both intrinsic variability and microlensing is intrinsically symmetrical (i.e., not differentially obscured by dust or magnified by relativistic beaming) and that the asymmetry induced by microlensing in the line profile is related to the anisotropic spatial distribution of microlensing magnification at the source plane.

4. The relative impact of microlensing indicates that the Mg II and C III] emission lines arise from a region ~50 lt-day in size, in good agreement with RM studies. The kinematic coincidence, in the absence of microlensing, between C III] and C IV supports the hypothesis that a large part of the C IV line also arises from this large region. As the cores of the lines show no central dip, the hypothesis of motion not confined to a plane is supported. The small regions (a few light-days in size) inferred for several high-ionization lines suggest that these lines arise from the accretion disk. In the Fe III λ2039–2113 blend, a spectral feature relatively uncontaminated by other species, we measure very large microlensing variability (comparable in some extreme cases to that typical of X-ray) and the largest kinematic broadening. These results suggest that Fe III (and likely other high-ionization species present in strongly microlensed complexes) may arise in part from an inner region of the accretion disk. RM studies of the strongly microlensed iron spectral features could be of great interest in probing the accretion disk of quasars.

We thank Burud, Chavushyan, Eigenbrod, Goicoechea, Gómez-Álvarez, Inada, Morgan, Oguri, Richards, Rojas, Schechter, Shalyapin, Sluse, Surdej, Wisotzki, and Wucknitz for kindly making the spectroscopic data listed in Table 1 available. We thank the anonymous referee for valuable suggestions. C.F. gratefully acknowledges the financial support of a La Caixa PhD fellowship. E.M. is supported by the Spanish MINECO with grants AYA2013-47744-C3-3-P and AYA2013-47744-C3-1-P. I.A.M. is supported by the Generalitat Valenciana with grant PROMETEO/2014/60. J.J.-V. is supported by the Spanish Ministerio de Economía y Competitividad and the Fondo Europeo de Desarrollo Regional (FEDER) through grant AYA2014-53506-P and by the Junta de Andalucía through project FQM-108.

Appendix A
Data Analysis Methods

For each of the brightest emission lines (C IV, C III], and Mg II) we fit a straight line \( y = a \lambda + b \) to the continuum on either side of the emission line and subtract it from the spectrum. For all images and all epochs we normalize the continuum-subtracted spectra to match the core of the emission line defined by the flux within a narrow interval (±6 Å) centered on the peak of the line. The magnitude differences of the wings are then constructed from the fluxes found after subtracting the linear model for the continuum emission underneath the line profile. We estimate the average wing emission in different wavelength intervals (~25 Å for C IV, ~35 Å for C III] and Mg II) on either side of the emission-line peak, corresponding to velocity intervals of ~4500 km s\(^{-1}\) for C IV, ~5300 km s\(^{-1}\) for C III], and ~3600 km s\(^{-1}\) for Mg II. We have separated the line core from the wings by a buffer of ±9 Å to prevent underestimation of the microlensing in the wings. In those cases in which the emission line is affected by absorption lines an integration window avoiding absorption features was chosen. See the core-matched spectra corresponding to C IV, C III], and Mg II in Figure 1. We use the following statistics to calculate the magnitude difference between two different images/epochs (\( x, y \)):

\[
d_i = w_i \ast (y_i - x_i),
\]

with weights \( w_i = \sqrt{(y_i + x_i)/(y_i - x_i)} \), selected to equalize the typical deviations of the differences. From the mean value in a given wavelength interval, \( \langle d_i \rangle \), we compute the magnitude difference between images/epochs, \( d = \langle d_i \rangle \), and its standard deviation \( \sigma \) (see Tables 2–5).

We have also analyzed the wavelength regions between C IV, C III], and Mg II to measure the changes in the UV Fe II and Fe III emission line blends, the complex formed by the He II line, the O III]/Al II blend and the subjacent pseudo-continuum, and the red shelf of C IV. We follow the definition of the wavelength regions of Guerras et al. (2013a, 2013b), Vestergaard & Wilkes (2001), and Vanden Berk et al. (2001) and use the cores of the C IV, C III], and Mg II emission lines as a baseline for no microlensing. We fit various straight lines to the continuum regions bracketing the emission-line windows and subtract them from the spectra. Then, for each image pair and each epoch, we normalize the continuum-subtracted spectra to match the core of the Mg II (C III]) emission line. In many cases, the Mg II (C III]) based normalization does not match the C III] (C IV) emission line. We assume that this mismatch of the line cores arises from differential extinction in the lens galaxy. This is corrected by applying a linear extinction correction to match both emission lines simultaneously (obviously, this correction is applied to the data in Section 2.2 but not in Section 2.3). Finally, for each pair of images (and each epoch) we compare the flux ratios in the defined emission-line windows of the continuum-subtracted and extinction-corrected spectra using the same statistics as described above. See the resulting core-matched spectra and chosen integration windows in Figure 2.

Appendix B
Intrinsic Variability and Microlensing in the C IV-to-Mg II Wavelength Region

In the wavelength region between C IV and C III], there is evidence of variability at the 2σ level that very noticeably affects the complex formed by the He II line, the O III]/Al II blend, and the subjacent pseudo-continuum. We find microlensing in HE 0047−1756, HE 0435−1223, SDSS J1004+4112, and SDSS J1339+1310 and intrinsic variability in Q0142−100, HE 0435−1223, and HE 2149−2745 (with partial evidence in QSO 0957+561 and HE 1104−1805). In the Al III lines there is microlensing in SDSS J1004+4112 and partial evidence of
intrinsic variability in HE 0435−1223. In the Si III lines there is evidence of microlensing in HE 0435−1223, SDSS J1004+4112, HE 1104−1805, and WFI J2033−4723 and partial evidence of intrinsic variability in HE 0435−1223. Finally, the Fe II blends included in this spectral range show no evidence of intrinsic variability or microlensing.

In the wavelength region between C III and Mg II there is also evidence of intrinsic variability and microlensing affecting several lines and complexes, particularly the Fe II and Fe III iron lines. In Fe II we detect (2σ level) microlensing in HE 0435−1223, SDSS J0806+2006, FBQS J0951+2635, QSO 0957+561 (this can be also interpreted as intrinsic variability plus a time delay), and SDSS J1339+1310 and intrinsic variability in HE 0047−1756, HE 0435−1223, WFI J2033−4723 (partial evidence), and HE 2149−2745. In the Fe III λ2040−2100 blend, we obtain basically the same results, microlensing in HE 0435−1223, SDSS J0806+2006, FBQS J0951+2635, QSO 0957+561 (this can be also interpreted as intrinsic variability plus a time delay), and SDSS J1339+1310 and intrinsic variability in HE 0047−1756, HE 0435−1223, SDSS J1339+1310, WFI J2033−4723, and HE 2149−2745 (partial evidence).

ORCID iDs
E. E. Falco @ https://orcid.org/0000-0002-7061-6519
V. Motta @ https://orcid.org/0000-0003-4446-7465

References
Abajas, C., Mediavilla, E., Muñoz, J. A., Popović, L. Ć, & Oscoz, A. 2002, ApJ, 576, 640
Bentz, M. C., Denney, K. D., Grier, C. J., et al. 2013, ApJ, 767, 149
Bentz, M. C., Peterson, B. M., Netzer, H., Popge, R. W., & Vestergaard, M. 2009, ApJ, 697, 160
Bentz, M. C., Walsh, J. L., Barth, A. J., et al. 2010, ApJ, 716, 993
Blandford, R. D., & McKee, C. F. 1982, ApJ, 255, 419
Burud, I., Courbin, F., Magain, P., et al. 2002, A&A, 383, 71
Chavushyan, V. H., Vlasyuk, V. V., Stepanian, J. A., & Erastova, L. K. 1997, A&A, 318, L67
Eigenbrod, A., Courbin, F., Dye, S., et al. 2006, A&A, 451, 747
Eigenbrod, A., Courbin, F., & Meylan, G. 2007, A&A, 465, 51
Fian, C., Mediavilla, E., Hansmeier, A., et al. 2016, ApJ, 830, 149
Fine, S., Croom, S. M., Bland-Hawthorn, J., et al. 2010, MNRAS, 409, 591
Goicoechea, L. J., Gil-Merino, R., & Ullán, A. 2005, MNRAS, 360, L60
Goicoechea, L. J., & Shalyapin, V. N. 2016, A&A, 596, A77
Gómez-Álvarez, P., Mediavilla, E., Muñoz, J. A., et al. 2006, ApJL, 645, L5
Grier, C. J., Pancoast, A., Barth, A. J., et al. 2017a, ApJ, 849, 146
Grier, C. J., Trump, J. R., Shen, Y., et al. 2017b, ApJ, 851, 21
Guerras, E., Mediavilla, E., Jimenez-Vicente, J., et al. 2013a, ApJ, 764, 160
Guerras, E., Mediavilla, E., Jimenez-Vicente, J., et al. 2013b, ApJ, 764, 160
Inada, N., Oguri, M., Becker, R. H., et al. 2006, AJ, 131, 1934
Jiménez-Vicente, J., Mediavilla, E., Kochanek, C. S., & Muñoz, J. A. 2015, ApJ, 806, 251
Kaspi, S., Brandt, W. N., Maoz, D., et al. 2007, ApJ, 659, 997
Li, J., Shen, Y., Horne, K., et al. 2017, ApJ, 846, 79
Mathews, W. G. 1982, ApJ, 258, 425
Mediavilla, E., Mediavilla, T., Muñoz, J. A., et al. 2011, ApJ, 741, 42
Mediavilla, E., Muñoz, J. A., Kochanek, C. S., et al. 2005, ApJ, 619, 749
Mediavilla, E., Muñoz, J. A., Lopez, P., et al. 2006, ApJ, 653, 942
Morgan, N. D., Caldwell, J. A. R., Schechter, P. L., et al. 2004, AJ, 127, 2617
Mosquera, A. M., & Kochanek, C. S. 2011, ApJ, 738, 96
Mosquera, A. M., Kochanek, C. S., Chen, B., et al. 2013, ApJ, 769, 53
Motta, V., Mediavilla, E., Falco, E., & Muñoz, J. A. 2012, ApJ, 755, 82
Motta, V., Mediavilla, E., Rojas, K., et al. 2017, ApJ, 835, 132
Oguri, M., Inada, N., Hennawi, J. F., et al. 2005, ApJ, 622, 106
Peterson, B. M. 2006, in ASP Conf. Ser. 360, AGN Variability from X-Rays to Radio Waves, ed. C. M. Gaskell et al. (San Francisco, CA: ASP), 191
Popović, L. Ć., Mediavilla, E., Bon, E., & Ilíc, D. 2004, A&A, 423, 909
Richards, G. T., Keeton, C. R., Pindor, B., et al. 2004, ApJ, 610, 679
Rojas, K., Motta, V., Mediavilla, E., et al. 2014, ApJ, 797, 61
Schechter, P. L., Gregg, M. D., Becker, R. H., Helfand, D. J., & White, R. L. 1998, AJ, 115, 1371
Shalyapin, V. N., & Goicoechea, L. J. 2014, A&A, 568, A116
Shen, Y., Horne, K., Grier, C. J., et al. 2016, ApJ, 818, 30
Sluse, D., Hutsemékers, D., Courbin, F., Meylan, G., & Wambsganss, J. 2012, A&A, 544, A62
Surdej, J., Claeskens, J.-F., Remy, M., et al. 1997, A&A, 327, L1
Vanden Berk, D. E., Richards, G. T., Bauer, A., et al. 2001, AJ, 122, 549
Vestergaard, M., & Wilkes, B. J. 2001, ApJS, 134, 1
Wambsganss, J. 2006, in Saas-Fee Advanced Course 33, Gravitational Lensing: Strong, Weak and Micro, ed. G. Meylan et al. (Berlin: Springer), 453
Wisotzki, L., Becker, T., Christensen, L., et al. 2003, A&A, 408, 455
Wisotzki, L., Koehler, T., Ikonomou, M., & Reimers, D. 1995, A&A, 297, L59
Wisotzki, L., Koehler, T., Kayser, R., & Reimers, D. 1993, A&A, 278, L15
Wisotzki, L., Schechter, P. L., Chen, H.-W., et al. 2004, A&A, 419, L31
Wucknitz, O., Wisotzki, L., Lopez, S., & Gregg, M. D. 2003, A&A, 405, 445