MICROLENSING OF QUASAR ULTRAVIOLET IRON EMISSION

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ABSTRACT

We measure the differential microlensing of the UV Fe II and Fe III emission line blends between 14 quasar image pairs in 13 gravitational lenses. We find that the UV iron emission is strongly microlensed in four cases with amplitudes comparable to that of the continuum. Statistically modeling the magnifications, we infer a typical size of \( r_\ell \sim 4\sqrt{M/M_\odot} \) light-days for the Fe line-emitting regions, which is comparable to the size of the region generating the UV continuum (\( \sim 3–7 \) light-days). This may indicate that a significant part of the UV Fe II and Fe III emission originates in the quasar accretion disk.

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

Online-only material: color figures

1. INTRODUCTION

Iron, the stable end product of nucleosynthesis, has a large number of energy levels, generating thousands of emission-line transitions distributed throughout the UV and optical bands that likely make Fe II the main emission-line contributor to the overall spectra of quasars and active galactic nuclei (AGNs). Statistical studies of quasar spectra find that variations between them are dominated by the relative strength of the Fe II emission (Boroson & Green 1992). In spite of the relevance of the iron lines to understanding the physics of AGNs, both the mechanism generating the Fe II emission (Ferland et al. 2009) and the spatial scale of the region where it is emitted (Barth et al. 2013) are poorly understood. Two bands of Fe II emission are usually studied (see, e.g., Baldwin et al. 2004): the UV pseudo-continuum between C III \( \lambda 1909 \) and Mg II \( \lambda 2798 \), and the optical blends in the H\( \gamma \)-H\( \beta \) region. The few reverberation mapping studies of Fe II indicate that the region emitting the UV Fe II lines (Maoz et al. 1993) is considerably smaller than the region emitting the optical Fe II lines (Kuehn et al. 2008; Barth et al. 2013).

The size of the region generating the broad emission lines (BELs) in quasars can be also inferred from the impact of microlensing on the BELs. In a multiply imaged quasar, the UV iron emission is strongly microlensed in four cases (Sluse et al. 2013) and the non-thermal X-ray emission region (Pooley et al. 2007; Morgan et al. 2008, 2012; Chartas et al. 2009; Dai et al. 2010; Blackburne et al. 2011; Mosquera et al. 2013). In the particular case of the iron emission lines, Sluse et al. (2007) analyzed spectra of RXS J1131−1231 and found that a large fraction of the optical Fe II emission arises in the outer parts of the BLR, although they also found evidence of a very compact region associated with Fe II. Evidence of significant microlensing of the UV Fe II emission was also found in Q2237+0305 (Sluse et al. 2011).

Here we study the microlensing of the UV iron emission in a sample of 14 pairs of lensed quasar images, combining the spectra compiled by Mediavilla et al. (2009) with new observations. In Section 2, we describe the data and the procedure used to isolate the Fe II and Fe III line emission from the continuum and then to measure its microlensing. In Section 3, we use the measured microlensing amplitudes to derive constraints on the size of the UV iron emitting region, and we discuss and summarize the results in Section 4.

2. DATA ANALYSIS

We started with the sample compiled by Mediavilla et al. (2009) and then added unpublished archival spectra taken with the VLT or the MMT, as summarized in Table 1. We focus on the wavelength region between the C III \( \lambda 1909 \) and Mg II \( \lambda 2798 \) emission lines, and we will use these lines to define a flux ratio baseline that is only weakly affected by microlensing (Mediavilla et al. 2009, 2011b; Guerras et al. 2013). Table 2 defines the wavelength regions we consider. We loosely follow the definition of the Fe II wavelength windows by Francis et al. (1991). The primary modification is that we do not include the regions around C III \( \lambda 1909 \) to avoid modeling the blended emission. Iron emission is split into two windows designated Fe(1), dominated by Fe III, and Fe(2), dominated by Fe II (Vestergaard & Wilkes 2001), each bracketed by line-free continuum regions (Kuraszkiewicz et al. 2002; Francis et al. 1991; Brotherton et al. 2001). Fe(1) corresponds to 2050–2115 Å, and Fe(2) corresponds to three regions: 2250–2320 Å, 2333–2445 Å, and 2470–2625 Å.
We first fit four straight lines to the continuum regions bracketing the Fe emission windows (plus a continuum region blueward of the Ciii λ1909 line and another redward of the Mg ii λ2798 line) and subtract them from the spectrum. Then, for each image-pair we normalize the continuum-subtracted spectra to match the core of the Mg ii λ2798 emission lines defined by the total flux within ± FWHM/2 of the line center. Provided that these low-ionization lines are only weakly affected by microlensing, as we found in Guerras et al. (2013), the normalization constant (that is, the ratio between the Mg ii λ2798 emission lines) gives us the intrinsic macrolens magnification between the images. The flux ratio of the continuum as compared to that of the Mg ii λ2798 emission lines then gives us an estimate of the continuum microlensing magnification:

\[ \Delta m_{\text{cont}} = (m_1 - m_2)_{\text{cont}} - (m_1 - m_2)_{\text{Mg ii} \lambda 2798}. \]  

In Table 1, summary of data, we list the objects, redshifts, observation dates, rest wavelengths, and references for the spectra used in this study. The objects include SDSS J1353+1138, SDSS J0806+2006, QSO 0957+561, and HE 0435−1223, among others. The redshifts range from 1.6 to 2.3, and the observation dates range from 2000 to 2008.

Table 1  
Summary of Data

| Object (pair) | \(z\) | Observation Date | Rest Wavelength (Å) | Reference |
|---------------|------|-----------------|---------------------|-----------|
| HE 0047−1756 A, B | 1.67 | 2002 Sep 4 | (1461−2547) | Wisotzki et al. 2004 |
| HE 0435−1223 A, B | 1.689 | 2008 Jan 12 | (1210−3030) | Motta, V., unpublished data |
| HE 0435−1223 B, D | 1.689 | 2008 Oct 12 | (1638−2996) | Motta, V., unpublished data |
| SDSS 0806+2006 A, B | 1.54 | 2005 Apr 12 | (1575−3504) | Inada et al. 2006 |
| SDSS 0909+532 A, B | 1.38 | 2003 Mar 7 | (0750−5695) | Mediavilla et al. 2005 |
| SDSS J0924+0219 A, B | 1.524 | 2005 Jan 14 | (1783−3170) | Eigenbroad et al. 2006 |
| FBQ 0951+2635 A, B | 1.24 | 1997 Feb 14 | (1786−4018) | Schechter et al. 1998 |
| QSO 0957+561 A | 1.41 | 1999 Apr 15 | (0913−4149) | Goicoechea et al. 2005 |
| QSO 0957+561 B | 1.41 | 2000 Jun 2–3 | (0913−4149) | Goicoechea et al. 2005 |
| QSO 0957+561 A, B | 1.41 | 2008 Jan 13 | (1330−3380) | Motta et al. 2012 |
| SDSS J1001+5027 A, B | 1.838 | 2003 Nov 20 | (1409−3136) | Oguri et al. 2005 |
| HE 1104−1805 A, B | 2.32 | 2008 Apr 7 | (1310−2909) | Motta et al. 2012 |
| SDSS J1206+4332 A, B | 1.789 | 2004 Jun 21 | (1362−3048) | Oguri et al. 2005 |
| SDSS J1353+1138 A, B | 1.629 | 2005 Apr 12 | (1521−3385) | Inada et al. 2006 |
| WFI J2033−4723 B, C | 1.66 | 2008 Apr 14 | (1620−3625) | Motta, V., unpublished data |
| HE 2149−2745 A, B | 2.033 | 2000 Nov 19 | (1430−3174) | Motta, V., unpublished data |

Table 2  
Wavelength Regions

| Feature | Wavelength Intervals (Å) | Description |
|---------|--------------------------|-------------|
| Fe(1)   | (λ2050, λ2115)           |             |
| Fe(2)   | (λ2250, λ2320) ∪ (λ2333, λ2445) ∪ (λ2470, λ2625) | Blueward of Fe(1) |
| Continuum | (λ2000, λ2020) |             |
| Continuum | (λ2160, λ2180) | Redward of Fe(1) |
| Continuum | (λ2225, λ2250) | Blueward of Fe(2) |
| Continuum | (λ2640, λ2650) | Redward of Fe(2) |
| Mg ii λ2798 | (λ2776, λ2820) | Line core |
| Ciii λ1909 | (λ1893, λ1925) | Line core |

Notes.

- Originally taken at λ1942 in Vestergaard & Wilkes (2001).
- Contaminated with the wing of the Ciii λ1909 line (Kuraszkiewicz et al. 2002).
- Pure continuum window according to Kuraszkiewicz et al. (2002).
- As suggested in Francis et al. (1991). This continuum window is defined out of the Mg ii λ2798 wings (Brotherton et al. 2001) and of the iron blend Fe(2).
so these results should be treated with more caution. Using the C\textsc{iii} $\lambda$1909 line, we can then define estimates of the microlensing amplitudes $\Delta m_{\text{cont}}$, $\Delta m_{\text{Fe(1)}}$, and $\Delta m_{\text{Fe(2)}}$. All the resulting microlensing estimates are presented in Tables 3 and 4.

In Figure 2 we compare the microlensing magnification estimates for the continuum underlying each line or blend, C\textsc{iii} $\lambda$1909, Mg\textsc{ii} $\lambda$2798, Fe(1), and Fe(2), finding very good linear covariances. The Pearson correlation coefficients are above 0.92 in all cases, with one-tailed $p$-values well under 0.01.

In the same figures we also compare the microlensing measured in the Fe(1) and Fe(2) line regions with the microlensing of the continuum regions adjacent to the C\textsc{iii} $\lambda$1909 and Mg\textsc{ii} $\lambda$2798 emission lines. We find that the Fe(1) line region has a low degree of correlation with the continuum, while the Fe(2) line region is uncorrelated.

### 3. Constraining the Size of the UV Iron Emission Line Region

We follow the procedure we used in Guerras et al. (2013) to estimate the size of the emission regions corresponding to Fe(1), Fe(2), and the continuum regions adjacent to the Mg\textsc{ii} $\lambda$2798 and C\textsc{iii} $\lambda$1909 emission lines. We start by computing microlensing magnification maps using the inverse...
polygon mapping technique (Mediavilla et al. 2006, 2011a). We take the dimensionless surface density, \( \kappa \), and shear, \( \gamma \), for each image from the lens models by Mediavilla et al. (2009) and Mediavilla et al. (2011b). We assume a mass fraction in stars of 5\% (Abajas et al. 2007; Mediavilla et al. 2006; Pooley et al. 2009, 2012) and a stellar mass of \( M = 1 \ M_{\odot} \). We generate microlensing magnification maps with an outer scale of 1100 light-days and with a pixel scale of 0.04 Einstein radii (equal to 0.6 light-days in the worst case). Each magnification map is unit normalized and convolved with a Gaussian of size \( r_s \), \( I \propto \exp(-R^2/2r^2_s) \) to model the source. We consider a linear (logarithmic) grid of sizes from \( r_s = 1.5 \) to 13 light-days with steps \( \Delta r_s = 0.5 \) light-days (\( \Delta \log_{10} r_s = 0.0408 \)). The probability of observing a magnitude difference \( \Delta m_{\text{obs},k} \) for image pair \( k \) (\( k = 1, \ldots, 14 \)) given a source size \( r_s \) is then

\[
p_k(\Delta m_{\text{obs},k}|r_s) \propto \int f_{r_s,k,1}(m_1)f_{r_s,k,2}(m_1-\Delta m_{\text{obs},k})dm_1. \tag{3}
\]

where \( f_{r_s,k,1}(m) \) and \( f_{r_s,k,2}(m) \) are the frequency histograms obtained from the convolved magnification maps for images 1 and
then gives the likelihood distribution for the size $r_s$.

Normalizing the likelihood functions to unity gives the Bayesian posterior probabilities with either a uniform (linear grid) or logarithmic (log grid) prior on $r_s$. Figures 3 and 4 show, for linear and logarithmic grids, respectively, the resulting probability distributions for the Fe(1) and Fe(2) line regions, and the continuum under the Mg II $\lambda 2798$ (C II) $\lambda 1909$ line when using the Mg II $\lambda 2798$ (C II) $\lambda 1909$ line to estimate the flux ratios in the absence of microslensing. The most significant result is that the UV iron blends seem to originate in a region with a size comparable to that of the underlying UV continuum. From these posterior probability distributions we obtain size estimates, in $\sqrt{M_*/M}^\odot$ light-day units, for the uniform (logarithmic) prior of $r_s = 5.3 \pm 2.4$ ($r_s = 5.3 \pm 2.1$) and $r_s = 5.3 \pm 1.8$ ($r_s = 5.3 \pm 1.7$) for the Mg II $\lambda 2798$ and C II $\lambda 1909$ continua, respectively. This is in reasonable agreement with current expectations about the size of the region generating the continuum in quasars (e.g., Morgan et al. 2010; Jiménez-Vicente et al. 2012). We obtain similar sizes, in $\sqrt{M_*/M}^\odot$ light-day units, for the Fe(1) and Fe(2) line emission regions with $r_s = 4.6 \pm 1.8$ ($r_s = 4.8 \pm 1.7$) and $r_s = 5.1 \pm 1.8$ ($r_s = 5.1 \pm 1.7$), using the Mg II $\lambda 2798$ lines as the magnification reference, and $r_s = 2.7 \pm 1.1$ ($r_s = 2.9 \pm 0.9$) and $r_s = 3.3 \pm 1.2$ ($r_s = 3.4 \pm 1.1$), using the C II $\lambda 1909$. While the C II $\lambda 1909$ estimates are systematically smaller, the results are statistically consistent.

4. DISCUSSION AND CONCLUSIONS

We have found evidence that the UV iron line pseudo-continuum regions are microlensed, with amplitudes...
comparable to those of nearby continuum emission regions. When we formally estimate the size, we find $r_s \sim 4\sqrt{M/M_\odot}$ light-days, slightly smaller than the continuum regions ($r_s \sim 3-7\sqrt{M/M_\odot}$ light-days), and far smaller than either the high- or low-ionization line emission regions in the BLR, as estimated with either microlensing (Guerras et al. 2013) or reverberation mapping (see, e.g., Zu et al. 2011). These quantitative results should be regarded as preliminary since the sample is small and a single object (SDSS J1353+1138) has a disproportionate impact on the size estimates. In any case, our estimate for the size is in reasonable agreement with the results for the UV Fe\textsc{ii} emission region based on reverberation mapping by Maoz et al. (1993). Other reverberation mapping studies indicate that the Fe\textsc{ii} optical emission lines arise from a substantially larger region (Kuehn et al. 2008; Barth et al. 2013). However, Sluse et al. (2007) also found that a part of the optical Fe\textsc{ii} emission may originate in a more compact region.

It is also interesting to explore the shape of the spectra to know whether microlensing acts selectively over some components of the pseudo-continuum and may shed light on the structure and kinematics of the inner regions of quasars. The shape of the unmicrolensed spectra resembles the average SDSS quasar spectra well (see Figure 1). The microlensed spectra, however, seem to be selectively enhanced at some of the spectral features in the iron emission templates from Vestergaard & Wilkes (2001). This is particularly true for the Fe(1) blend that appears strongly magnified in three of the four microlensed objects. On the other hand, in the Fe(2) blend of SDSS J1353+1138 (see also the low signal-to-noise ratio (S/N) spectra from FBQS J0951+2635 and SDSS J0806+2006), the enhanced features look broader and more flat-topped. Notice, in particular, the relative weakness of the C\textsc{iii}$\lambda 2326$ emission line compared to the unmicrolensed spectra and the strong enhancement of the Fe\textsc{ii} emission at $\sim 2300$ Å that can be hardly identified in the average SDSS quasar spectrum. A similar relative enhancement of the Fe\textsc{ii} emission around the (tentatively identified) Fe\textsc{ii} $\lambda 2418$ (narrow) $+ [\text{Ne}\textsc{iv}] \lambda 2423$ blend is observed in SDSS J0806+2006. High-S/N spectra, combined with detailed modeling of the iron emission, could help to understand both the origin of the iron emission and the structure of the innermost regions of quasars (inner BLR or/and accretion disk).

In a series of papers, we used archival spectra of lensed quasars and microlensing to measure the fraction of matter in compact objects (Mediavilla et al. 2009), the size of a quasar’s accretion disk (Mediavilla et al. 2011b; Jiménez-Vicente et al. 2012), the size of the BLR (Guerras et al. 2013), and the temperature profile of the quasar’s accretion disk (J. Jiménez-Vicente et al., in preparation). It is clear that the next step is to revisit these objects to search for spectral changes, or even to begin systematic spectroscopic monitoring.

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