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Letter to the Editor

Exploring the gravitationally lensed system HE 1104−1805: VLT spectroscopy of the lens at z=0.729[⋆]

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Abstract. Using FORS2, mounted on Kueyen (UT2 of the VLT), we have obtained the redshift of the lensing galaxy in the gravitational lens system HE 1104−1805. We measure $z = 0.729 \pm 0.001$, in good agreement with previous estimates based on the time delay and the position of the lens on the fundamental plane. It also coincides with one of the metal line absorption systems that are seen in high resolution spectra of HE 1104−1805.

Key words: cosmology: gravitational lensing – galaxies: quasars: individual: – Magnetohydrodynamics (MHD)

1. Introduction

HE 1104−1805 was discovered as part of the Hamburg/ESO Quasar Survey and was first identified as a gravitational lens candidate by Wisotzki et al. (1993). It consists of two lensed images of a radio-quiet quasar at $z = 2.319$ that are separated by $\sim 3.2''$. The lensing galaxy was discovered from ground based near-IR (Courbin, Lidman & Magain, 1998) and HST optical observations (Remy et al. 1998; hereafter R98) and is $1''$ from the brighter quasar image (component A).

From a spectrophotometric monitoring program that lasted several years, Wisotzki et al. (1998; hereafter W98) measured a time delay of 0.73 years between the two components. To convert this into an estimate of the Hubble Constant, one needs to determine the geometry of the system (astrometry and lens and source redshifts) and to model the mass distribution of the lens. Several mass models for the lens have been published (W98; R98; Courbin et al. 2000; hereafter C2000; Lehar et al. 2000) and precise astrometry from HST images is available. Since the source redshift is known, the remaining unknown is the redshift of the lens.

In their discovery paper, Wisotzki et al. (1993) noted that the continuum of component A was considerably harder than that of component B, and that the broad emission lines of the two components were identical, only scaled by a factor of 2.8. This was still the case during the spectrophotometric monitoring carried out by Wisotzki et al. (1998) and in IR spectra covering the 1 to 2.5 μm range (C2000). This has been interpreted as microlensing of the continuum emitting region of the quasar in component A, which is twice as close to the lensing galaxy as component B. Presumably, the broad line region is too large to be affected. It may be possible to use this information to gain insight into the geometries and sizes of the continuum emitting and broad line regions; however, detailed predictions require the lens redshift.

From high resolution spectroscopic observations (Smette et al. 1995; Lopez et al. 1999), several metallic absorption line systems have been detected: $z = 0.517, 0.728, 1.280, 1.320, 1.662, 1.860, 2.220$ and $z = 2.300$. The systems at $z = 0.728$, $z = 1.320$ and $z = 1.662$ contain lines that are mostly detected in component A, the component that is closest to the lens. At one time or another, each system has been individually proposed to be the lens.

Despite its importance, the redshift of the lensing galaxy has proved elusive. Apart from the many unpublished attempts to measure it, the redshift of the lens has been estimated by indirect means. From IR and optical photometry, C2000 gave a redshift in the range $z = 0.8$ to $z = 1.2$ while from the time delay and a model of the lens, W98 estimated $z = 0.79$. From the position of the lens on the fundamental plane, Kochanek et al. (2000) derived $z = 0.77$. Although model dependent, the two latter estimates prove to be very close to the truth.

In this paper we describe the successful measurement of the lens redshift, $z = 0.729$, using the spectral deconvolution method described by Courbin et al. (2000).
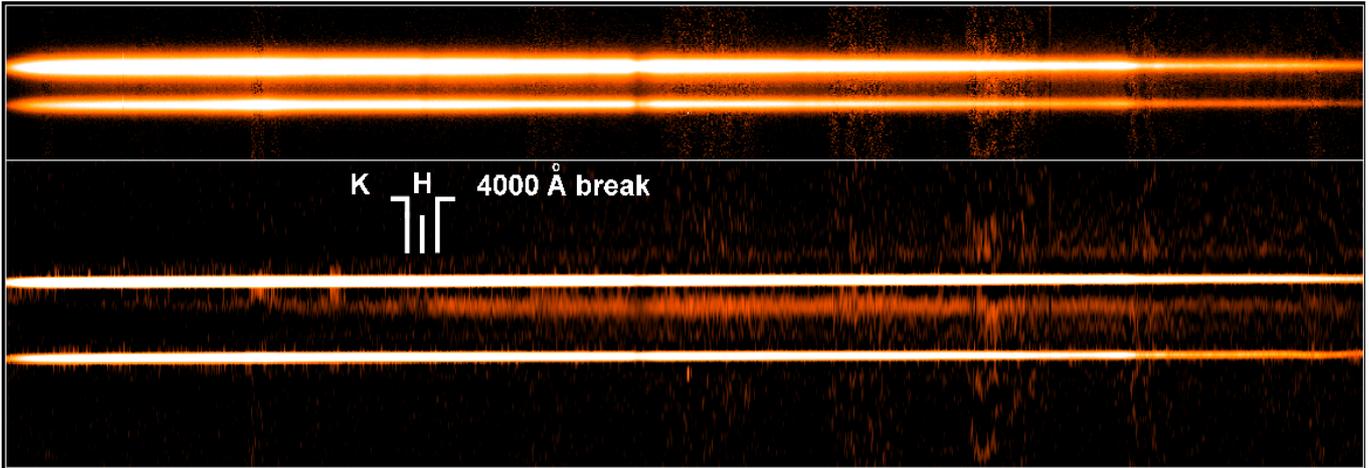
Fig. 1. *Top:* the 2D sky-subtracted spectrum of HE 1104−1805. This spectrum is the mean of the three 1080s exposures. *Bottom:* deconvolved spectrum. The spectra of the quasar images have a FWHM of $0.2''$. The pixel size is half that of the original data (hence, the height of this image is twice that of the original), i.e., $0.05''$. The main features of the lensing galaxy are marked. The scale in the spatial direction is given by the separation between the 2 quasar images, i.e., $3.14''$.

2. Observations-Reductions

The observations were taken with FORS2 on Kueyen (VLT/UT2) at the Cerro Paranal Observatory on April 1st, 2000, which also happened to be the first scheduled observing night for this telescope, and consisted of three 1080 second exposures with the G200I grism and the high resolution collimator. This gives a scale of $0.1''$ per pixel in the spatial direction and a scale of approximately 4Å per pixel in the spectral direction. The observing conditions were clear and the external seeing varied between $0.5''$ and $0.9''$.

We used the movable slits in the FORS2 focal plane to select targets and set the slit width. One slit was placed on HE 1104−1805 and aligned along the two quasar components, three slits were placed on field stars that were used to determine the PSF required for the deconvolution (see below) and to correct for telluric absorption. Used in this mode, the slits of FORS2 have a fixed length. This is less flexible than punched or laser designed masks, but it was adequate for our experiment.

The slit width was set to $1''$, which is larger than the FWHM of the images. For the deconvolution to work well, it is important that the targets are not too heavily occulted by the slit edges, since this can lead to differential occultation between the PSF stars and the quasar images and hence to a less accurate deconvolution. This can be minimized by carefully centroiding the stars in the slits and by having slits that are significantly wider than the PSF. Additionally, preparing the mask from an image that was taken with the same instrument, as was done in this case, also minimises differential alignment errors.

Instrumental signatures were removed in the standard manner using IRAF. The bias was removed by subtracting a constant from each frame and the pixel-to-pixel sensitivities were normalised with screen flats. The arc frames were used to correct for slit distortion and to set the wavelength scale. All spectra were rebinned to the same linear wavelength scale. The position of the night sky lines and the absorption features in component A were used to check the accuracy of the wavelength calibration, which was found to be around 3Å.

3. Spectral deconvolution: deblending the lens and source

The lensing galaxy is four to five magnitudes fainter than component A of HE 1104−1805 and only one arc second away. Even with excellent seeing, the spectrum of the lens is heavily contaminated by that of the quasar and needs to be extracted with sophisticated techniques.

The technique implemented by Courbin et al. (2000) spatially deconvolves spectra and decomposes them into point-sources and extended components. It is therefore very well suited to the present problem: extracting the spectrum of a faint extended lens galaxy close to a bright quasar spectrum. As is the case with image deconvolution, a reference PSF is necessary. Out of the three PSF stars that were available, two were unfortunately too faint. In order to build the PSF spectrum, we therefore used only one PSF star (which was slightly fainter than the quasar itself) in combination with the spectrum of the bright quasar image itself. Only half of the spatial profile of the quasar was actually used, the one unaffected by light contamination from the lensing galaxy. The deconvolved spectrum has a pixel size of $0.05''$ while the undeconvolved data have a pixel size of $0.1''$. The deconvolved spectrum is displayed in Fig. 1.

As the PSF stars were observed at exactly the same time and under the same conditions as the lensed quasar, they could also be used to remove telluric features. The spectra of the PSF stars were combined and then divided directly into the spectra of the lens and the two components of the quasar. Before division, the continuum of the PSF stars was normalised with a high-order function and obvious absorption features, such as $H\alpha$ and the Calcium triplet at 8600 Å, were removed. As we do not know the
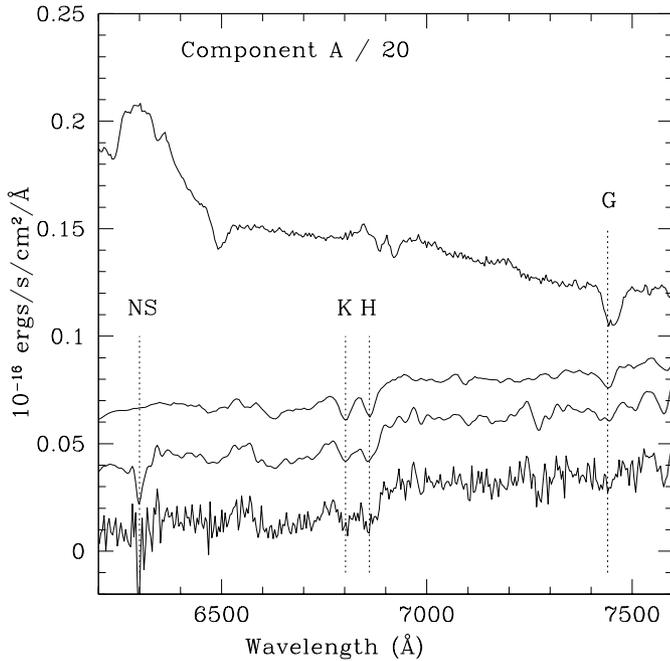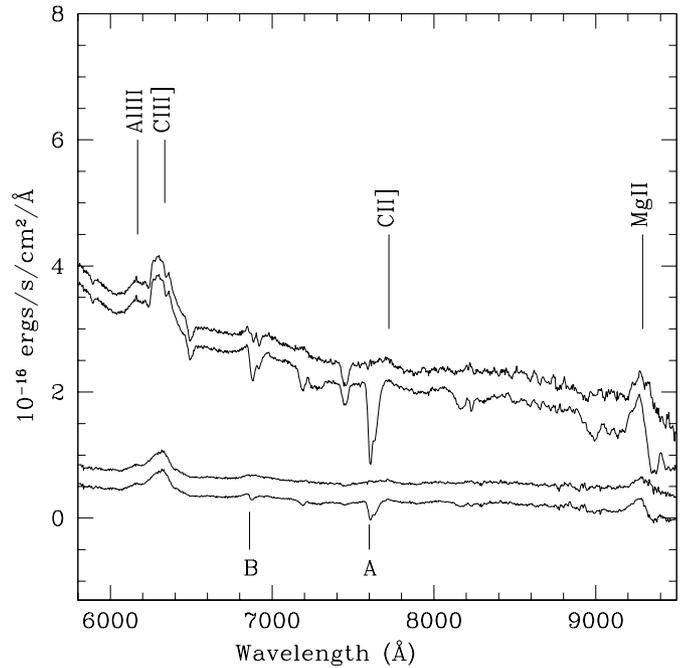
Fig. 2. From bottom to top the curves are: an unsmoothed spectrum of the lens in HE 1104−1805; a smoothed version with a vertical offset of 0.03 units; the spectrum of the template galaxy used in the cross correlation with a vertical offset of 0.05 units; and the spectrum of component A of the quasar divided by 20. The major absorption lines are identified with the dotted lines. A night sky feature at 6300 Å is also marked. The spectrum of the lens shows no trace of contamination by the quasar emission lines.

Fig. 3. One dimensional spectra of components A and B of HE 1104−1805. Both the spectra before and after the correction for telluric features was applied are shown. For clarity, the uncorrected spectra are shifted down by 0.3 units. The main quasar emission lines and the atmospheric A and B bands are marked.

spectral type of the PSF stars, weaker features may be present. Ideally, one should choose hot, featureless stars to make such a correction. Despite this, the correction works rather well.

The 1-D spectrum of the lens, extracted directly from the 2-D deconvolved image (extended component only), is shown in Fig. 2. An unsmoothed version and a smoothed version shifted by 0.03 units on the vertical scale are shown in the lower half of the figure. Also shown, but reduced by a factor of 20, is the spectrum of component A. The Calcium H and K absorption lines of the lensing galaxy are clearly detected and the G-band is marginally detected. The redshift was measured by cross correlating the lens spectrum with the elliptical template from the Kinney-Calzetti spectral atlas (Kinney et al. 1994), which has been plotted (third curve from the bottom) with a shift of 0.05 units in Fig. 2. For this we used the IRAF task RVSAO v2.0 (Kurtz and Mink 1998). The redshift is $z = 0.729 \pm 0.001$, where the error incorporates the internal error reported by the cross-correlation routine and the error in the wavelength calibration. An alternative measure of the accuracy is given by the r-statistic of Tonry and Davis (1979), which is the signal-to-noise ratio of the main peak in the cross correlation. We find that $r = 4.1$, which indicates that the redshift is reliable (Kurtz & Mink 2000).

The redshift is in good agreement with the redshift of the multiple absorption line system at a redshift of $z = 0.728$ (Smette et al. 1995; Lopez, 1999). This absorption line sys-

tem is made up of many sub-components spread over a range of redshifts ($\Delta z \approx 0.001$). Although it is not possible to say if the absorption line system and the lens are the same object, the two systems are probably dynamically associated.

As the quality of the PSF was not optimal, the quasar spectra from the deconvolved images are noisier than what one would calculate from the photon noise only. Therefore, the extraction of the quasar spectra was not done from the deconvolved spectrum but with narrow apertures from the undeconvolved spectrum. Since the galaxy is much fainter than either component of the quasar and since it is not spatially coincident, the contamination of the quasar spectra by the lensing galaxy is negligible.

The spectra of the two components of the quasar are shown in Fig. 3. In this figure we plot the data before and after the telluric features have been removed. The A and B atmospheric bands are removed very well and the FeII absorption lines at $z = 1.66$ become visible. Additionally, the MgII emission line, which is almost obscured by the strong telluric feature at 9300Å, is recovered.

As in W98 and C2000, we also plot the difference between the spectrum of component A and a scaled version of the spectrum of component B, that is $f_\lambda(A) - c.f_\lambda(B)$, where, c, is set to 2.8. The difference is plotted in Fig. 4, where we plot it before and after telluric correction. Apart from a slight excess at 6390Å and the metallic absorption lines in component A, the broad lines of the quasar disappear and only the excess continuum from component A remains. The strongest absorbers are now clear and are marked with the vertical dotted lines. The
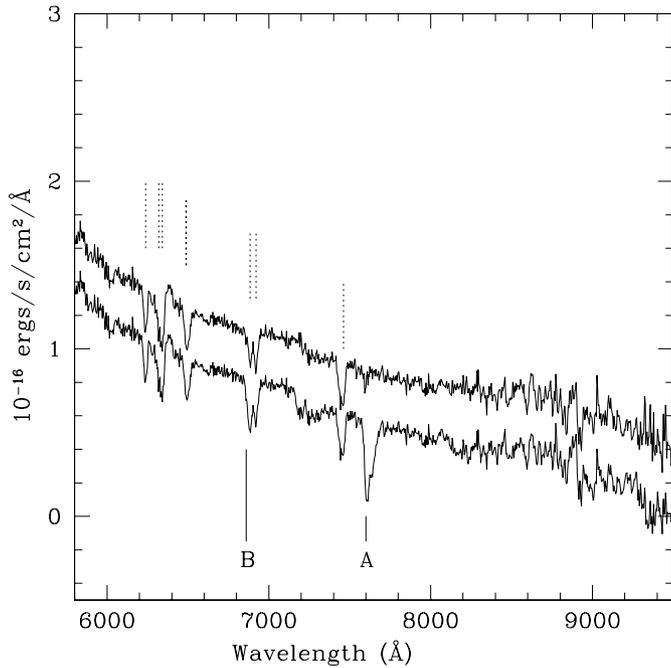
Fig. 4. The difference between the spectra of components A and B of HE 1104−1805. Both the spectra before and after the correction for telluric features was applied are shown. For clarity, the uncorrected spectra are shifted down by 0.3 units. The strongest absorbers are now clear and are marked with the vertical dotted lines. The atmospheric A and B bands are also marked.

wavelengths of the main absorption lines and the redshifts of the corresponding absorption line systems are given in Smette et al. (1995).

4. Discussion

The aim of our observations were modest: to measure the redshift of the lensing galaxy in HE 1104−1805, one of the ever growing list of lenses with known time delays. This was possible with only one hour of VLT time during average weather conditions. The prospects of measuring the lens redshifts in other systems are therefore very good, at least for double systems, where aligning the slit simultaneously on the quasar images and on the lens is straightforward.

With the time delay and the lens and source redshifts known and several mass models published, it is relatively straight forward to derive the Hubble constant. W98 present two models to describe the lens: a singular isothermal sphere with external shear and a singular isothermal ellipsoid without external shear. For the former (the model presented by R98 is very similar), one derives $H_0 = 52$ km/s/Mpc and for the latter, one derives $H_0 = 59$ km/s/Mpc. We have set $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$. C2000 also present two models: a singular ellipsoid without external shear and a two component model which consists of a singular isothermal ellipsoid to represent the lensing galaxy and a more extended component representing a galaxy cluster centered on the lensing galaxy. The first model leads to $H_0 = 62$

km/s/Mpc, but the second leads to values for the Hubble Constant which are a factor of 1.5 to 2 lower.

HE 1104−1805 is somewhat unusual in that the lensing galaxy is closest to the brighter component. It has been pointed out by several authors that the lens probably does not consist of a single galaxy (W98, R98, C2000; Lehar et al. 2000). Additional extended mass is required to match all the observational constraints: the position of the two images relative to the lens, the magnification ratio of the images, and the lens orientation and ellipticity. Deep images in the near-IR may be able to reveal the distribution of this additional mass.

As the lens appears to be associated with the absorption system seen in the quasar spectrum at $z = 0.728$, one could use the velocity spread in this system to constrain the lens velocity dispersion. However, this assumes that the absorption line system and the lens are the same object or, at the very least, in the same potential well. Without further supporting evidence that links the absorption line system to lens, it is premature to use the velocity spread as a constraint on the mass models.

The lens redshift estimates of W98 and Kochanek et al. (2000) have proven to be accurate, whereas the estimate of C2000 from IR and optical photometry is less so. The optical photometry is in good agreement with the VLT spectrum; however, if the lens is an elliptical galaxy, then the IR points are over-estimated by 0.3 magnitudes. The cause of this discrepancy requires further investigation.

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