LENSED QUASARS: A MATTER OF RESOLUTION

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1 Lensed quasars

The interest in studying lensed quasars amongst the astronomical community has always been somewhat fluctuating. Periods of great enthusiasm and of profound disappointment have regularly followed one another.

Precisely described in the context of Einstein's Theory of Gerenal Relativity, the phenomenon of light deflection was first seen as a pure theoretical curiosity. It was however observed by Dyson et al. (1920), who measured, during a total solar eclipse, the angular displacement of a star by the sun's gravitational field. Gravitational lensing was thus established as an observed phenomenon, but the next important observational step was not made until 1979, with the discovery by Walsh et al. of the first lensed quasar, which had an angular separation of 6 arcsec between the two components. On the theoretical side, Refsdal (1964) proposed, well before Walsh's discovery, to use multiply imaged quasars to constrain cosmological parameters. As the travel times of photons along the light path to each quasar image are different, an intrinsic intensity variation of the quasar is seen at different moments in each lensed image. The so-called *time-delay* between the detection of the intensity variation in each image is directly related to the cosmological parameter, H_0 and to the position and shape of the deflecting mass. One can therefore infer an estimate of H_0 by measuring the time-delay, *provided the gravitational potential responsible for light splitting is well known.* Reasoning the other way around, one might as well want to assume a "preferred" value for H_0 and use the time-delay to constrain a lens model, i.e., to study the mass distribution in distant lens galaxies. Both issues are undoubtedly of capital importance. They both require high spatial resolution observations. With the Hubble Space Telescope (HST) or, better, with large ground based telescopes located in privileged sites, it is now possible to perform in a routine manner observations which were impossible only 10 years ago. As an illustration of this, we present in this report recent VLT FORS2 observations of HE 1104-1805, a doubly imaged quasar at z=2.319 discovered in the framework of the Hamburg-ESO survey for bright quasars (Wisotzki et al. 1993). The choice of HE 1104-1805 is not intended to be representative of the importance of this particular object, but rather reflects how old observationally intractable problems can be tackled in a new way. We also present more rencent results, obtained at the 1.54m Danish telescope for another Hamburg-ESO quasar: HE 2149-2745.

2 The first step: The lens geometry and the time delay

Resolving the blended images of multiple imaged quasars is one way to confirm or rule out their lensed nature. If each component of a system shows the same color, or even better the same spectral energy distribution, the quasar has good chance of being lensed. However, dust along the line of sight, microlensing, and even intrinsic variability of the quasar can affect the spectral energy distribution of the components. Finding the faint lensing galaxy between the quasar images is a much more reliable criterion. We show in Fig. 1 the discovery image of the lens in HE 1104-1805 (Courbin et al. 1998). The J-band image visible on the left panel was taken with at the ESO/MPI 2.2m with IRAC2b, which by today's standards had a relative small field of view, 1 arc minute on a side, with coarse sampling, 0.28 arc seconds per pixel. The lens is very difficult to see in this image. However, with deconvolution (Magain et al. 1998; MCS) one is able to detect it, located 1 arcsec away from the bright quasar image. The HST-NICMOS2 image obtained by Falco et al. in the H-band is also displayed. Comparison with the deconvolved image confirms not only the position of the lens, but also its ellipticity and orientation. The seeing at the time the data were taken were 0.8", which is average for La Silla. With the more modern facilities and larger telescopes, one will do better: seeing below 0.5 arcsec is relatively frequent at Paranal and detectors have now pixel size of the order of 0.1 arcsec, still keeping several arcmin field of view.

The measurement of the time delay itself remains challenging. Precise light curves with good temporal sampling have to be obtained for each component. It can take several years of continuous monitoring to obtain the time delay of a single lens. HE 1104-1805 has been spectrophotometrically monitored at ESO for fours years by Wizotski et al. (1998) and the time delay was estimated to be 0.73 years. We are currently using the Danish 1.54m and the 3.5m NTT to monitor on a weekly basis almost all multiply images quasars visible from the Southern Hemisphere (PI: P. Magain for ESO time, J. Hjorth for Danish time). The image quality is usually between 0.8 and 1.5 arcsec, which, with deconvolution, still allows accurate photometry of objects with angular separations of less than 1 arcsec, down to $R \sim 19-20$. One of the first results from this monitoring, the light curve for HE 2149-2745 (Lopez et al. 1998) is shown in

Fig. 2 (Burud et al. 2001). In this case, the two images of the quasar at z=2.03 are separated by 1.7 arcsec.

The monitoring data of HE 2149-2745 have been obtained during a wide variety of observing conditions, even during full moon or through thin cirrus, and very few epochs have been missed. Loosing too many data points due to instrument scheduling, or to excessively restrictive observing constraints would be fatal. One has use all the data available, even those taken under poor conditions.

We would like to point out that none of this would have been possible without the excellent collaboration of the 2.2m and NTT teams, and with the large number of visiting astronomers who not only performed the observations but also often took time to optimize their quality. We are extremely grateful to all these people.

3 A second, more challenging step: Spectroscopy of the lens

Imaging the lensing galaxy is difficult, but obtaining the spectrum is even more so. Accurate modelling was therefore often hampered by the lack of the lens redshift. Lens galaxies are heavily blended with the bright quasar images and are often too faint for the HST. The solution to the problem might be, here again, to use good quality ground based data. Using the spectroscopic version of the MCS deconvolution (Courbin et al. 2000a, Courbin et al. 1999) and VLT data, we have obtained a spectrum of the lensing galaxy in HE 1104-1805 (Lidman et al. 2000) and determined its redshift.

Apart from the many unpublished attempts to measure it, the redshift of the lens has been estimated from indirect means. From IR and optical photometry, Courbin et al. (2000b) estimated a redshift in the range $z = 0.8$ to $z = 1.2$. From the time delay measured at the ESO 3.6m and a model of the lens, Wisotzki et al. (1998) estimated a redshift of $z = 0.79$ and from the position of the lens on the fundamental plane, Kochanek et al. (2000) gave a redshift of $z = 0.73$.

Given these redshift estimates, a deep spectrum in the optical was likely to settle the issue. The VLT spectroscopic observations were taken with FORS2 on Kueyen at the Cerro Paranal Observatory on April 1st, 2000 as part of ESO program 65.O-0566(A). The observations 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, which is excellent for deconvolution purposes. The corresponding scale in the spectral direction is approximately 4Å per pixel. 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 the lens and aligned along the two components, three slits were placed on field stars that were used to determine the PSF for the deconvolution and to correct for telluric absorption, one slit was placed on a random object and the remaining slits were closed. Indeed, the final configuration looks very similar to the configuration presented in right hand side of Fig. 1 of Courbin et al. (1999).

The lensing galaxy is four to five magnitudes fainter than component A, which is located only one arc second away. Even with good seeing, the light of the galaxy is heavily blended with that of the quasar. To see the lensing galaxy, extract the spectrum and determine the redshift, deconvolution in the spatial direction was essential.

The 2-D spectrum of the lens is shown in Fig. 3. The lens is completely invisible in the raw data, shown in the top panel, while it is is obvious, including absorption features, in the bottom panel. The 1-D extraction of the deconvolved lens spectrum is displayed in Fig. 4. An unsmoothed version is shown in the lower half of the figure and a smoothed version, shifted by 0.03 units on the vertical scale, is shown in the upper half. Also shown, but reduced by a factor of 20, is the spectrum of component A. Note that the lens spectrum shows no trace of contamination by the QSO emission lines. The Calcium H and K absorption lines are clearly detected in the lens and the G-band is marginally detected. A template spectrum of an elliptical galaxy shifted to z=0.729 (Kinney et al. 1996) is overplotted in red. Cross correlation of the data with this template allows us to derive the redshift of the lens: $z = 0.729 \pm 0.001$.

The spectra of the two components of the quasar are shown in Fig. 5. We plot the spectra before and after the telluric features have been removed. The PSF stars are fainter than the quasar, so the later spectrum is noisier. The main emission features of the quasar and the telluric A and B bands are indicated in the figure.

4 On the future of quasar lensing.

Until recently, it was hard to resolve the lensed components of multiply imaged quasars. It is now relatively straightforward and it is becoming possible to extract the spectrum of the faint lensing galaxy. Measuring time delays is also becoming easier, since one can efficiently process data obtained with medium size telescopes under average or poor weather conditions.

The remaining problem in using gravitational lenses for measuring the Hubble constant is now model degeneracy; several models can reproduce the available constraints for any given system. Observing many different lenses, with very different image configurations is one approach to reduce the degeneracy. Another approach is of course to improve the accuracy of the observations for each individual system. Until now, one reconstructs the mass profile of the lens by probing the gravitational potential at only 2 or 4 positions, i.e., the position of the quasar images. Systems with more images are probably extremely rare, so the only way to use more constrains is to observe the distorted images of other objects behind the lensing galaxy. The host galaxy of the lensed quasar is an obvious candidate (e.g., Kochanek et al. 2000). With the very high angular resolution soon achievable with adaptive optics (AO) systems mounted on 8m class telescopes, it will be possible, in many objects, to see the quasar host galaxy as a lensed ring, hence providing new constrains for the mass modelling. Advanced multi-conjugate AO systems will allow for similar resolutions but on a wider field of view (about 1 arcmin) and with good PSF quality. Small arclets, as presently observed in lower resolution observations of rich galaxy clusters, should be seen in the immediate vicinity of the lens, providing us with measurements of the lensing potential at many positions.

It is very tempting to speculate further on what we may be doing in a few years from now. Although such an exercise is always somewhat dangerous, it not foolish to predict that a spectrograph mounted on a AO system will allow us to measure the rotation curve of lens galaxies, making it possible to compare, for the first time, the mass derived from direct velocity curve measurement, with the mass inferred from lensing. In the longer term, one may be using 2-D spectrographs on OWL to map the velocity field of lens galaxies, lensed quasar hosts, and lensed arclets in order to derive very precise lens models which will probably be fully non-parametric (e.g., like those described by Williams & Saha (2000).

In conclusion, leadership of ESO in the field of lensed quasars can be maintained, by using both the small telescopes to measure time delays, and the larger ones to conduct imaging/spectroscopic observations with unprecedented quality. It will be interesting to see how lensed quasars will be used in the future. Will we derive H_0 from quasar time delays, using the very detailed observations of lens galaxies, or will use the value of H_0 derived from other techniques to infer the mass profile for distant galaxies using lensing ? In either case, there is a great deal to be learnt from the study of lensed quasars.

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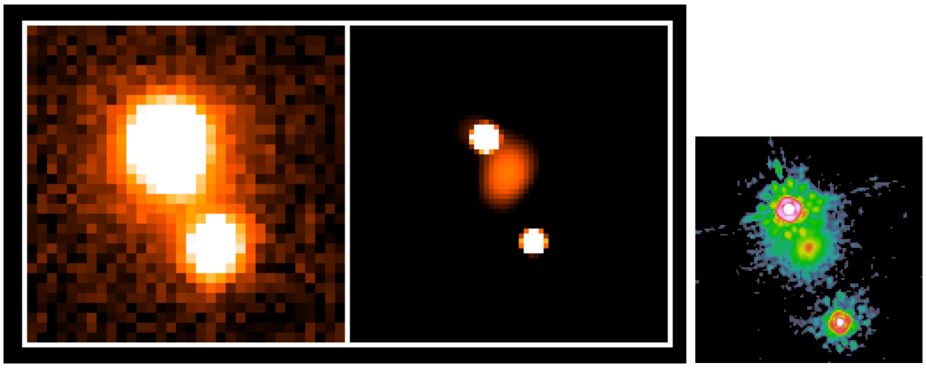

Figure 1: A J-band image of HE 1104-1805 obtained at the ESO/MPI 2.2m telescope with IRAC2b (Courbin et al, 1998). The seeing is about 0.8 arcsec and the pixel size is 0.28 arcsec. The middle panel shows a deconvolved version of the image, with a resolution (FWHM) of 0.28 arcsec and clearly revealing the lensing galaxy. An HST H-band image obtained later (PI: Emilio Falco) is displayed on the right panel and confirms the ground based observation.

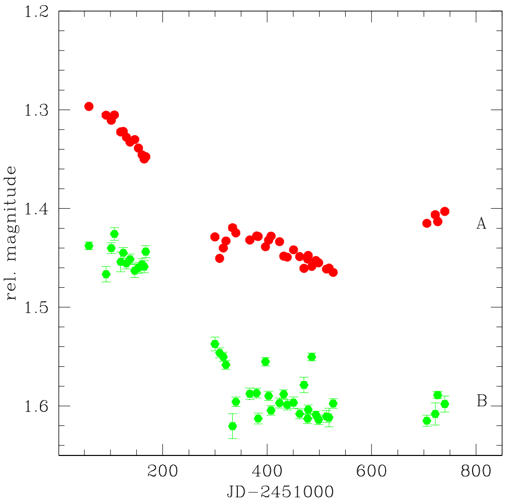

Figure 2: Example of light curve obtained at ESO in the framework of the lens monitoring program. These light curves, for the two quasar images of HE 2149-2745 (Burud et al, 2001) have been constructed from data obtained at the 1.54m Danish telescope under average weather conditions. The red curve shows the variation of the brightest quasar image while the green one corresponds to the fainter component, heavily blended with the lensing galaxy. The shift in time between the curves is the time-delay.

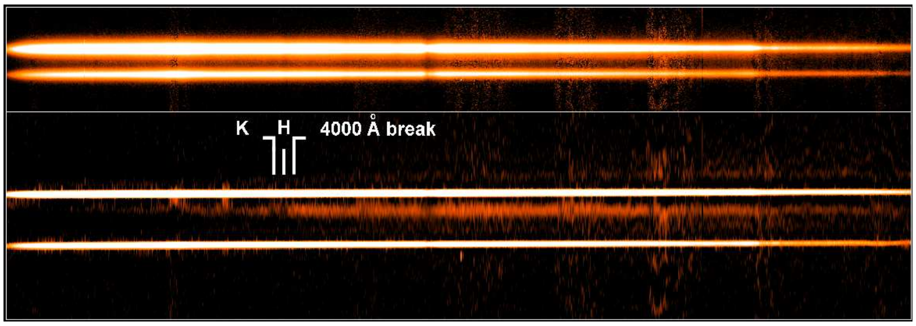

Figure 3: The two dimensional spectrum of HE 1104-1805 (Lidman et al, 2000). The image at the top is the spectrum of the lens after bias subtraction, flat fielding, and sky subtraction, with the 2 quasar spectra separated by 3.14 arcsec. The image at the bottom is the spatially deconvolved spectrum, with a (spatial) pixel size twice as small as in the original data (this is why the height of the deconvolved spectrum is twice that of the raw spectrum). The lens galaxy, including the H and K bands and the 4000Å break, is clearly visible. The spatial resolution in this spectrum is 0.2 arcsec.

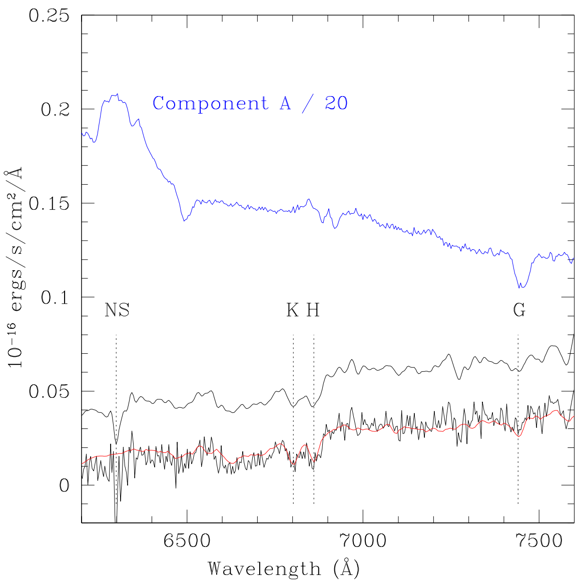

Figure 4: The spectrum of the lens in HE 1104-1805 (bottom). The major absorption lines are identified with the vertical dashed lines. Also plotted, but at 1/20th of the scale is component A of the quasar (top). The red line is a template of an elliptical galaxy shifted to $z = 0.729$ and not a smoothed version of the spectrum. The smoothed version of the spectrum has been shifted vertically by 0.03 units for clarity. The H and K Calcium bands and the G band are indicated. A strong sky line at about 6300 Å and introducing significant noise is also indicated.

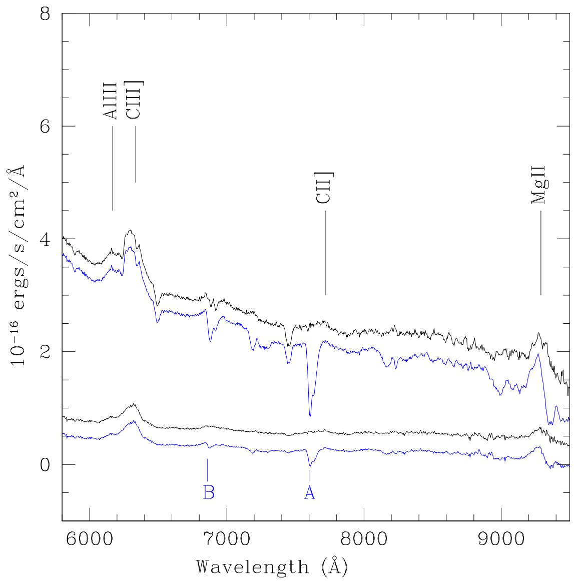

Figure 5: One dimensional spectra of components A and B of HE 1104-1805. The blue lines are the spectra before the correction for telluric features was applied and the black lines are the spectra after the correction. For clarity, the blue lines have been shifted down by 0.3 units.