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The redshift of the Einstein ring in MG 1549+305

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ABSTRACT
A deep spectrum taken with the Echelle Spectrograph and Imager (ESI) at the Keck II Telescope as part of the Lenses Structure and Dynamics (LSD) Survey reveals the redshifts of the extremely red source of the radio Einstein ring in the gravitational lens system MG 1549+305 ($z_s = 1.170 \pm 0.001$) and an intermediate-redshift lensed spiral galaxy ($z_G = 0.604 \pm 0.001$). The source redshift allows us to determine the mass of the SB0 lens galaxy enclosed by the Einstein radius ($R_E = 1.15 \pm 0.05$ arcsec): $M_E \equiv M(<R_E) = 8.4 \pm 0.7 \times 10^{10} \, h_{65}^{-1} M_{\odot}$. This corresponds to a singular isothermal ellipsoid (SIE) velocity dispersion $\sigma_{SIE} = 214 \pm 5$ km s$^{-1}$, in good agreement with the measured stellar velocity dispersion $\sigma = 227 \pm 18$ km s$^{-1}$. The mass-to-light ratio within the Einstein radius ($\sim 1.4$ effective radii) is $10 \pm 1 \, h_{65} M_{\odot}/L_{B,\odot}$. This is only marginally larger than typical stellar mass-to-light ratios of local early-type galaxies, indicating that dark matter is not likely to be dominant inside the Einstein radius.

Key words: gravitational lensing – galaxies: elliptical and lenticular, cD – galaxies: fundamental parameters – galaxies: kinematics and dynamics – distance scale.

1 INTRODUCTION
The number of known gravitational lens systems has grown steadily since their initial discovery (Walsh, Carswell & Weymann 1979), amounting now to nearly a hundred systems.1

In addition to the pure theoretical interest in certain properties of gravitational lensing (e.g. scaling relations, image multiplicities, catastrophe theory, etc.), gravitational lenses have proven extremely valuable for a variety of applications: (i) the determination of cosmological parameters via lens statistics of well-defined samples (e.g. Turner, Ostriker & Gott 1984; Fukugita et al. 1992; Kochanek 1996; Falco, Kochanek & Munoz 1998; Helbig et al. 2000; Sarbu, Rusin & Ma 2001; Chae et al. 2002); (ii) the study of the evolution of the stellar populations of early-type galaxies (Keeton, Kochanek & Falco 1998; Kochanek et al. 2000; Treu & Koopmans 2002a; Rusin et al. 2003; Koopmans & Treu 2003; van de Ven, van Dokkum & Franx 2003); and (iii) the determination of the Hubble constant ($H_0$) from gravitational time-delays (e.g. Kundic et al. 1997; Schechter et al. 1997; Koopmans & Fassnacht 1999; Fassnacht et al. 1999; Koopmans et al. 2000; Burud et al. 2002a,b; Hjorth et al. 2002).

Unfortunately, the sample of known lenses is still plagued by incomplete information on the redshift of the lens ($z_s$) or of the source ($z_G$), which sets the physical scale2 of the system and is therefore vital for most astrophysical applications of gravitational lens systems. This has motivated dedicated efforts on large telescopes to complete the determination of redshifts of the sample of known lenses (e.g. Fassnacht & Cohen 1998; Lubin et al. 2000; Tonry & Kochanek 2000; Cohen, Blandford & Lawrence 2003).

Here, we present the redshift of the Einstein ring in MG 1549+305. The redshift $z_s = 1.170 \pm 0.001$ of the extremely red object (ERO) source of the radio ring was obtained at the Keck II Telescope as part of the Lenses Structure and Dynamics (LSD) Survey (Koopmans & Treu 2002, 2003; Treu & Koopmans 2002a, hereafter KT02, KT03, TK02a). The currently ongoing LSD Survey aims to study the mass distribution of intermediate-redshift ($0.1 < z < 1$) E/S0 galaxies by combining lensing and dynamical analysis. The joint analysis – based on Hubble Space Telescope (HST) images and deep Keck spectroscopy – allows us to remove degeneracies inherent to each method alone and therefore to probe the mass distribution with greater accuracy than is possible with either method individually (e.g. Treu & Koopmans 2002b).

The gravitational lens system MG 1549+305 is potentially very useful for studying the structure of early-type galaxies: the radio ring (Lehár et al. 1993) – one of the handful of rings known – provides

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1 See e.g. http://cfa-www.harvard.edu/glensdata/ (CASTLES).
2 The by now well-established cosmological parameters (e.g. Spergel et al. 2003) affect the physical scale at a negligible level for a given value of the Hubble constant.
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a wealth of information on the inner mass distribution of the lens. Furthermore, the lens is relatively nearby \( (z_l = 0.111; \text{Lehár et al. 1993}) \) and extended, and is therefore ideally suited to study in great detail the structure of the lens galaxy. Unfortunately, the redshift of the extremely red source has proven hard to measure, preventing the use of this system in detailed analyses of early-type lens galaxies. To allow for a prompt scientific exploitation of this lens system, we publish the redshift before our full lensing and dynamical analyses of this system.

Throughout the paper, we use \( H_0 = 65 \text{ \text{km s}^{-1} \text{Mpc}^{-1}} \), and we assume \( \Omega_m = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \).

2 OBSERVATIONS

Spectroscopy of MG 1549+305 (Fig. 1) was performed on 2001 July 21–22, using the Echelle Spectrograph and Imager (ESI: Sheinis et al. 2002) at the Keck II Telescope in echelle mode. The slit \( (1.25 \times 20 \text{ arcsec}^2) \) was centred on the lens galaxy G1 [the notation of Lehár et al. (1993) is adopted throughout this paper], at position angle PA = 110°, i.e. aligned with the bar. This choice of PA yielded at the same time spectra of galaxy G2 – an intervening late-type galaxy – and of the source of the radio ring, galaxy G3. Five exposures totalling 7800 s were obtained, dithering along the slit by 5 arcsec after each exposure. The seeing was 0.6–0.7 arcsec and the nights were photometric. The spectra were reduced using the ESI two-dimensional reduction IRAF package EASI2D developed by D. J. Sand and T. Treu (Sand, Treu & Ellis 2002; Sand et al., in preparation). Relevant parts of the spectra of galaxies G2 and G3 are shown in Figs 2 and 3.

Several features yield unambiguously the redshift of G2 \( (z_{G2} = 0.604 \pm 0.001; \text{also [O III] and H\beta emission lines are detected at the appropriate wavelengths}) \). In contrast, only one feature is detected for G3 in the entire spectral range 3900–10 500 Å. Since the line is a doublet with the correct separation, we identify it as \([O\text{ II}]3726,3729 \) Å at \( z = 1.170 \pm 0.001 \).

To cross-check the redshift of G3 we measured the photometric properties of galaxy G3. To this end, HST images of MG 1549+305 were taken from the HST archive and reduced as described in TK02a. The Near Infrared Camera and Multiple Object Spectrograph (NICMOS; Camera 2) image through filter F160W (hereafter \( H_{16} \)) total exposure time 1111.58 s; GO7495; PI: Falco) is shown in Fig. 1. Photometry on the NICMOS image was measured using SEXTRACTOR (Bertin & Arnouts 1996), yielding a total magnitude \( (\text{mag}_{\text{auto}}) \) of the source of the radio ring (galaxy G3) of \( H_{16} = 19.6 \pm 0.1 \pm 0.1 \) (random plus systematic errors). Unfortunately, the Wide Field and Planetary Camera 2 (WFPC2) images through filters F555W

![Figure 1. NICMOS image of MG 1549+305 through filter F160W. North is up, east is left. The image is ≈19 arcsec on a side. The galaxies are labelled following Lehár et al. (1993): G1 is the lens, G2 is an intervening late-type galaxy and G3 is the source of the radio ring. The spectroscopic slit used in the observations is overplotted. At ground-based resolution (seeing FWHM 0.6 arcsec) a non-negligible fraction of the light from G3 falls in the slit, yielding the spectrum shown in Fig. 3.](https://academic.oup.com/mnras/article-abstract/343/2/L29/1043278/)

![Figure 2. Part of the spectrum of galaxy G2. The lower curve represents the noise. The hatched region is affected by sky residuals.](https://academic.oup.com/mnras/article-abstract/343/2/L29/1043278/)

![Figure 3. Part of the spectrum of the lensed source G3. The error bars represent the noise. Note that the spectral resolving power of ESI is sufficient to resolve the doublet, with correct wavelength ratio, which we identify as [O II]3726,3729.](https://academic.oup.com/mnras/article-abstract/343/2/L29/1043278/)
and F814W (total exposure time 640 s on the Planetary Camera; GO7495; PI: Falco) are rather shallow and galaxy G3 is undetected.

We obtained deeper V- and I-band images using ESI in imaging mode on 2001 July 26. The seeing was 0.6 arcsec FWHM, conditions were photometric, and the exposure time totalled 300 s per filter. Photometric calibration, accurate to 0.05 mag, was obtained by imaging photometric standards (Landolt 1992). The images were reduced in a standard manner. After matching the resolution of the NICMOS image to the resolution of the ground-based images, we measured the colours of G3 to be $V - H = 4.8 \pm 0.2$ and $I - H = 3.1 \pm 0.1$ (±0.1 systematic uncertainty on the zero-point calibration of NICMOS and ESI). The luminosity and colours of G3 are typical of radio galaxies at $z \approx 1$ (e.g. Best, Longair & Röttgering 1998; de Breuck et al. 2002), supporting the redshift identification.

3 DISCUSSION

With the redshift of the source ($z_s = 1.170 \pm 0.001$), we can derive some basic physical properties of the lens galaxy G1 (redshifts and positions of G1, G2 and G3 are listed in Table 1). Adopting the Einstein radius by Lehár et al. (1993, $R_E = 1.15 \pm 0.05$ arcsec; see also Rusin et al. 2003), the projected mass enclosed by the Einstein radius is $M_E = (8.4 \pm 0.7) \times 10^{10} h^{-1}$ $M_\odot$ and a singular isothermal ellipsoid (SIE) velocity dispersion of $\sigma_{\text{SIE}} = 214 \pm 5$ km s$^{-1}$ is derived (Kormann, Schneider & Bartelmann 1994). Note that G2 is at an intermediate redshift between the lens and the source, and a detailed lens model should therefore be done with at least two lens planes. However, G2 is a relatively faint late-type galaxy ~4 $R_E$ away from G1 and can, for modelling purposes, be regarded as a minor perturber at the redshift of G1 (Kochanek & Apostolakis 1988).

Using the effective radius ($0.81 \pm 0.08$ arcsec), total magnitude and colours tabulated by Rusin et al. (2003), we derive the magnitudes of the lens galaxy within the Einstein radius, $F814W = 17.25 \pm 0.05$ and $F555W = 18.74 \pm 0.05$, assuming an $R^{1/4}$ surface brightness profile. Correcting to rest frame (Treu et al. 2001) and for foreground extinction (Schlegel, Finkbeiner & Davis 1998), the luminosity within the Einstein radius is $L_{F814W} = (8.5 \pm 0.8) \times 10^9 h_7^2 L_\odot$.

The mass-to-light ratio enclosed by the Einstein radius is then $M_*/L_B = (10 \pm 1) h_7 M_\odot/L_\odot$, in the upper range of the typical stellar values for local early-type galaxies (7.3 $\pm 2.2 h_7 M_\odot/L_\odot$; TK02a and references therein), but not dramatically larger. This suggests that dark matter is not dominant within the Einstein radius, as expected given that it is similar to the effective radius (e.g. TK02b). To show the presence of dark matter inside the Einstein radius, more sophisticated dynamical and lens models are required. Nevertheless, it is already remarkable that, despite the complex morphological inner structure of the barred lens galaxy G1, the stellar velocity dispersion measured by Lehár et al. (1996) ($\sigma = 227 \pm 18$ km s$^{-1}$) is in such good agreement with the equivalent SIE velocity dispersion $\sigma_{\text{SIE}} = 214 \pm 5$ km s$^{-1}$.

The system MG 1549+305 – with its detailed multi-colour HST images, a radio Einstein ring and extended kinematic profiles along major and minor axes – is an ideal case to explore how this ‘coincidence’ arises. The structure of the radio Einstein ring provides unique information on the projected mass distribution, while its relatively large angular size and luminosity make it possible to derive accurate and spatially extended kinematic information along more than one axis. The combination of these constraints should allow us to measure its internal mass distribution and orbital structure accurately. A more detailed model of this system is being developed as part of the LSD Survey.

Table 1. Coordinates and redshifts of the galaxies in the MG 1549+305 system. Offsets are relative to the position of G3, RA = $15^h49^m12^s$ 877, Dec. = $30^\circ47'12''$ (J2000). Uncertainties are 0.02 arcsec on offsets and 0.001 on redshifts.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>ΔRA(J2000) (arcsec)</th>
<th>ΔDec.(J2000) (arcsec)</th>
<th>$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>−6.64</td>
<td>3.40</td>
<td>0.111</td>
</tr>
<tr>
<td>G2</td>
<td>−2.26</td>
<td>1.91</td>
<td>0.604</td>
</tr>
<tr>
<td>G3</td>
<td>≡0</td>
<td>≡0</td>
<td>1.170</td>
</tr>
</tbody>
</table>

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