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The Canarias Einstein ring: a newly discovered optical Einstein ring

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ABSTRACT

We report the discovery of an optical Einstein ring in the Sculptor constellation, IAC J010127-334319, in the vicinity of the Sculptor dwarf spheroidal galaxy. It is an almost complete ring ($\sim 300^{\circ}$) with a diameter of ~ 4.5 arcsec. The discovery was made serendipitously from inspecting Dark Energy Camera (DECam) archive imaging data. Confirmation of the object nature has been obtained by deriving spectroscopic redshifts for both components, lens and source, from observations at the 10.4 m Gran Telescopio CANARIAS (GTC) with the spectrograph OSIRIS. The lens, a massive early-type galaxy, has a redshift of $z = 0.581$, while the source is a starburst galaxy with redshift of $z = 1.165$. The total enclosed mass that produces the lensing effect has been estimated to be $M_{\rm tot} = (1.86 \pm 0.23) \times 10^{12}\,{\rm M}_{\odot}$.

Key words: gravitational lensing: strong – galaxies: distances and redshifts – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: starburst.

1 INTRODUCTION

Strongly lensed galaxies are very important in the study of galaxy formation and evolution because they permit derivation of important physical parameters such as the total mass of the lensing object, without any assumption on the dynamics. Cases in which the Einstein ring (ER) is almost complete and the central lensing galaxy isolated are rare; these permit constraining with great accuracy the enclosed mass within the projected Einstein radius $\Theta_{\rm E}$ (Kochanek, Keeton & McLeod 2001). Miralda-Escudé & Lehár (1992) predicted several 10^6 optical ER to be detectable over the whole sky, down to a magnitude limit of $B = 26$ and a lower limit for the enclosed mass of $M \sim 5 \times 10^{11}\,{\rm M}_{\odot}$. This notwithstanding, despite extensive surveys (see for example Bolton et al. 2008; Stark et al. 2013) only a few tens of complete or nearly complete optical ERs have been identified so far, and among these objects, only a few show a close similarity, in morphology and elongation of the ring, to the one we discuss in this present work.

The first ER to be discovered is the radio source MG1131+0456 (Hewitt et al. 1988). Warren et al. (1996) report the discovery of a partial ER ($\sim 170^{\circ}$) with $\Theta_{\rm E} \sim 1.35$ arcsec; the background O II emitting galaxy at $z = 3.595$ is lensed by an elliptical massive galaxy at $z = 0.485$. This is the first known case in the literature of an ER discovered at optical wavelengths. Cabanac et al. (2005) discovered an almost complete ER ($\sim 260^{\circ}$) with $\Theta_{\rm E} \sim 1.48$ arcsec produced by a massive and isolated elliptical galaxy at $z = 0.986$. The source galaxy is a starburst at $z = 3.773$. Then, a similar ER to the one we report in this Letter, in morphology, but not in the physics of the source galaxy, a BX galaxy, is the so called Cosmic Horseshoe (Belokurov et al. 2007); the ring extension is similar to the one we report here, ($\sim 300^{\circ}$), but the Einstein radius is double, $\Theta_{\rm E} \sim 5$ arcsec; the lensing galaxy has a huge mass of $\sim M = 5.4 \times 10^{12}\,{\rm M}_{\odot}$. Other partial ER discovered recently are: the 'Cosmic Eye' (Smail et al. 2007), the '8 o'clock arc' (Allam et al. 2007) and the 'Clone' (Lin et al. 2009).

Here, we report the discovery of IAC J010127-334319, an optical, almost complete ER, that we refer to as the 'Canarias Einstein Ring', noticed as a peculiar object in DECam images. No previous reference to the object has been found in the literature. Subsequently, we observed it with OSIRIS@GTC for a spectroscopic confirmation of its nature. In this Letter, we provide the first physical parameters of this system. In the following discussion, we assume that a flat cosmology with $\Omega_{\rm m} = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70\,{\rm km\,s^{-1}\,Mpc^{-1}}$.

2 DISCOVERY

The serendipitous discovery of IAC J010127-334319 was made, while performing photometry on stacked images, in g and r

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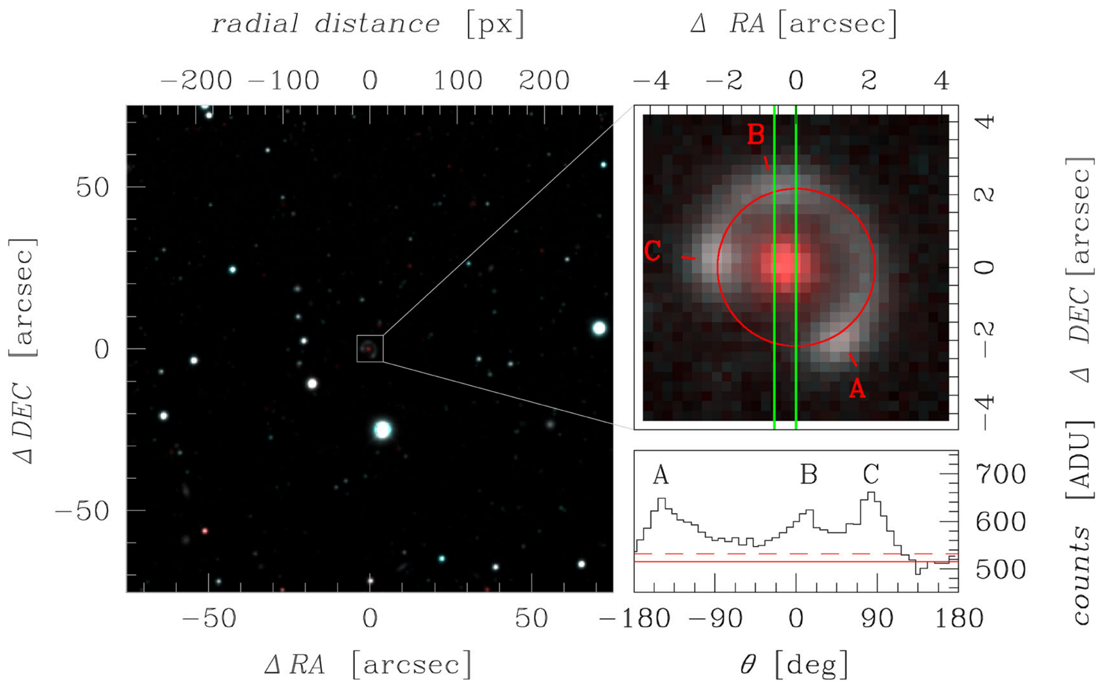

Figure 1. Composite *g*, *r* field of view of 2.5 arcmin × 2.5 arcmin centred on the object (on the left), North is up, while East points left; a zoom of the object with overplotted the best-fitting circle, the slit position and width are also plotted as green lines (right upper panel); counts from photometry along the best-fitting circle of the ring (lower right panel): the measured sky value is indicated by the red solid line, and the 1σ value is indicated by the red dashed one.

Table 1. List of parameters.

Lens	
Right ascension(J2000):	$01^h01^m27\overset{s}{.}83$
Dec.(J2000):	$-33°43'19\overset{''}{.}68$
Redshift:	0.581 ± 0.001
Surface brightness lens (*g*,*r*) (mag arcsec^{-2}):	25.2, 22.2
Apparent magnitude (*g*,*r*)	23.61, 21.48
Absolute magnitude (*g*,*r*)	−21.05, −23.18
Ring	
Redshift:	1.165 ± 0.001
Einstein radius:	2.16 arcsec $\pm$ 0.13
Enclosed mass (10^{12} $M_{\odot}$):	1.86 ± 0.23
Surface brightness A (*g*,*r*) (mag arcsec^{-2}):	23.7, 22.9
Surface brightness B (*g*,*r*) (mag arcsec^{-2}):	23.9, 23.2
Surface brightness C (*g*,*r*) (mag arcsec^{-2}):	23.7, 23.0
Apparent magnitude (*g*,*r*)	20.94, 20.12

filters, taken with DECam (Flaugher et al. 2015) at the Blanco 4 m telescope at the Cerro Tololo Inter-American Observatory (CTIO), reduced with the NOAO Community Pipeline (Valdes et al. 2014) and obtained from the NOAO Science Archive (Seaman et al. 2002). The total exposure time is 7680 s in the *g* filter and 5700 s in the *r* filter. Fig. 1 shows the resulting colour composite image: it is evident that two components with different colours are present. In particular, the central one (the lens) appears redder than the second component (the lensed image of the source), which in turn appears as elongated all around the first. The ring is almost perfectly circular with an apparent radius of 8 px which translates to 2.16 arcsec. Three peaks, A, B and C, are clearly visible (bottom-right panel of Fig. 1); they are located respectively at −150°, 14° and 83° from North counterclockwise. In Table 1, all the derived parameters for the object are listed. From the DECam photometry, we estimated an apparent magnitude for the lens in both *g* and *r* bands of $g = 23.61$ and $r = 21.40$. The colour $(g - r) > 2$ indicates that this galaxy is probably a luminous red galaxy (Eisenstein et al. 2001). All the details about the photometric calibration will be given in a forthcoming paper (Bettinelli et al., in preparation).

3 FOLLOW-UP SPECTROSCOPY

In order to confirm the lensing nature of this system, we performed a spectroscopic follow-up at the 10.4 m Gran Telescopio CANARIAS (GTC) on Roque de los Muchachos Observatory (La Palma, Spain) using the Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy (OSIRIS) spectrograph (Cepa 1998). OSIRIS has a mosaic of two E2V CCD42-82 (2048 × 4096 px). All the obtained spectra were registered on the second detector, which is the default for long-slit spectroscopy. We used a binning of 2 × 2 providing a pixel size of 0.254 arcsec px^{-1}, and the grism R300B, which provides a spectral coverage of 4000–9000 Å and a nominal dispersion of 4.96 Å px^{-1}. The slit width was 0.6 arcsec. Long-slit spectral observations were performed on 2015 December 2 in good seeing conditions of ∼0.8 arcsec. The slit was placed along the N–S direction, in order to minimize the effects of atmospheric differential refraction at culmination. The total exposure time was 3600 s divided into six exposures of 600 s each. In each of the six exposures, the two components, ring and lensing galaxy, have been detected and in particular their spectra were not overlapping. The position of the slit was such that the spectra obtained for the ring refers to peak B.

For the pre-reduction, we have used the OSIRIS Offline Pipeline Software (OOPS); sky subtraction and flux calibration were

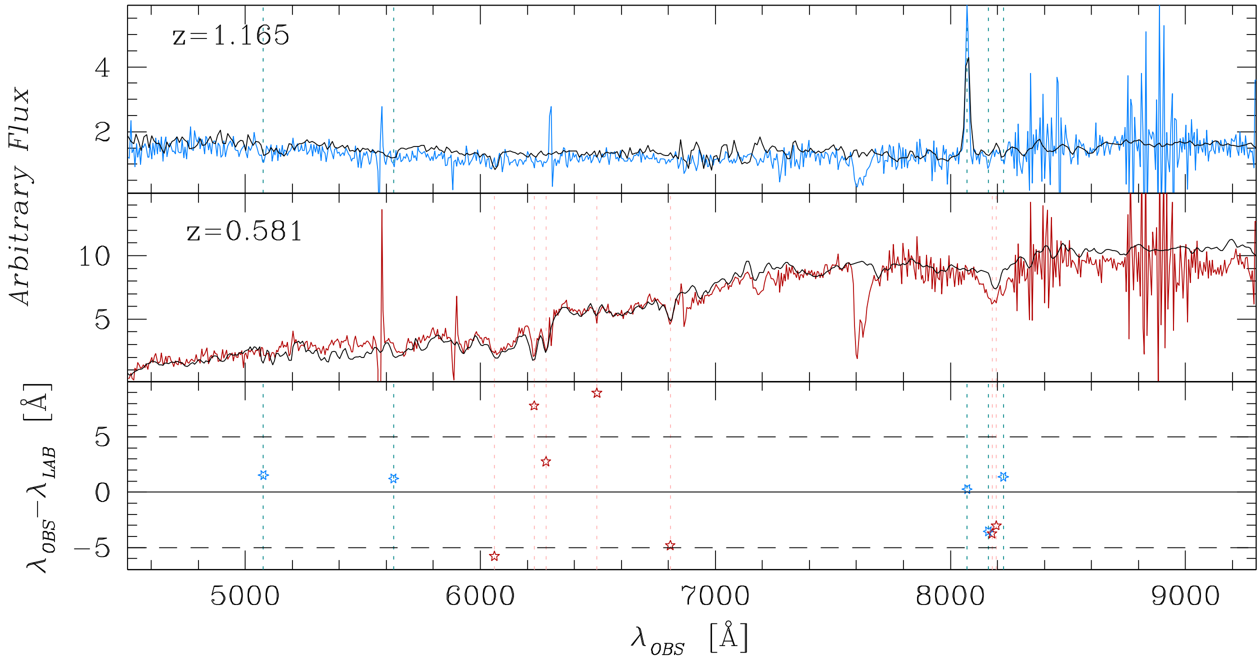

Figure 2. Top panel: source galaxy spectrum (in blue) with overplotted a starburst template spectrum by Calzetti, Kinney & Storchi-Bergmann (1994). Middle panel: lens galaxy spectrum (in red) with overplotted an early-type galaxy template by Kinney et al. (1996). Bottom panel: measured wavelength displacement between observed and laboratory line position for the selected features (see text for details).

performed using IRAF.[1] We performed wavelength calibration using standard HgAr+Ne+Xe arc lamps; the resulting error on wavelength determination has been measured to be consistent with the above spectral resolution. We corrected the extracted spectra for instrumental response using observations of the spectrophotometric standard star GD140, a white dwarf, obtained the same night. The fluxes of this standard star are available in Massey et al. (1988).

4 ANALYSIS AND DISCUSSION

In order to derive the redshifts for the two components, we noted the strong emission line in the source spectrum and the 4000 Å Balmer discontinuity in the lens spectrum. This led us to choose template models for a starburst galaxy and an early-type galaxy, respectively, as specified below. Following line identification, we determined redshifts.

4.1 Lens

Using the template spectra by Kinney et al. (1996) results that the spectrum of the lens galaxy fits well the spectrum of a S0 galaxy (see Fig. 2), a typical early-type galaxy characterized by a large increase in flux from the UV part of the spectrum to the optical. The 4000 Å Balmer discontinuity at ∼6330 Å is noticeable. The redshift of the lens galaxy is $z = 0.581 \pm 0.001$, and it has been determined from the measurements of: Hη λ3835.4, Ca K λ3933.7, Ca H λ3968.5, Hδ λ4141.8, *G*-band λ4307.7, Mg-b2 λ5172.7, Mg-b1 λ5183.6 (marked red features from left to right in Fig. 2 middle panel).

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

4.2 Source

For the source galaxy, we used the template spectra by Calzetti et al. (1994), and we found that the spectrum best fitting our observed spectrum corresponds to a starburst galaxy in the case of clumpy scattering slab, where it is assumed that clumped dust is located close to the source of radiation. In such circumstances, Calzetti et al. (1994) show that scattering into the line of sight dominates over absorption by the dust, providing a significant positive contribution to the emerging radiation. This template spectrum fits well the strong O II λ3727 emission line. We also identified the following lines: Fe II λ2344.0, Fe II λ2600.0, H I 11 λ3770.6, O II λ3727.3, H I 10 λ3797.9 (marked blue features from left to right in Fig. 2 upper panel). According to these features, we derived for the source galaxy a redshift of $z = 1.165 \pm 0.001$. We note that the selected slit position enable us to extract only the portion of the spectrum corresponding to peak B (see Fig. 1); this notwithstanding, the O II emission coming from the opposite side of the ring can be easily noted in our spectra.

4.3 Enclosed mass derivation

The strong circular symmetry, of our object (see Fig. 1), suggests that it can be approximated to the case of a circularly symmetric lens, with source and lens in the line of sight. Under these assumptions, for an arbitrary mass profile M(Θ) (i.e. without assuming any particular model for the potential), we can apply the following relation (Narayan & Bartelmann 1996) and solve it for the mass.

$$\Theta_{\mathrm{E}}^2 = \frac{4\mathrm{G}}{\mathrm{c}^2}\,\mathrm{M}(\Theta)\,\frac{\mathrm{d_{LS}}}{\mathrm{d_L}\,d_{\mathrm{S}}} \tag{1}$$

Here, Θ_{E} is the Einstein radius in radians; M(Θ) is the mass enclosed within the Einstein radius; d_{LS}, d_{L}, d_{S} are the angular diameter distances, respectively, of source-lens, lens-observer and source-observer. These last quantities are related to the relative

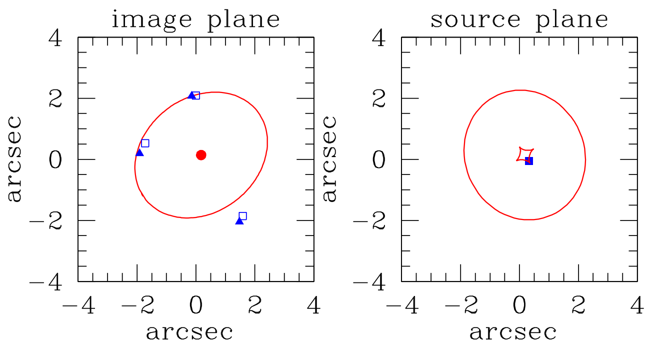

Figure 3. Best-fitting SIE model obtained with the GRAVLENS/LENSMODEL software. On the left (image plane): the source images positions are plotted as blue triangles, the fitted position recovered by the software as blue squares, the red central dot represents the position of the lensing galaxy and the red curve is the critical curve. On the right (source plane): the blue square represents the calculated position of the source; the caustics are shown in red.

comoving distances and, in general, this relation depends on the assumed curvature of the Universe (Hogg 1999). In our case, $\Omega_K = 0$ has been assumed, and the resulting angular diameter distances are $d_L = 951\,h^{-1}$ Mpc, $d_S = 1192\,h^{-1}$ Mpc and $d_{LS} = 498\,h^{-1}$ Mpc. We calculated a total mass $M_{tot} = (1.86 \pm 0.23) \times 10^{12}\,M_\odot$ where the error on the mass (12 per cent) is overwhelmingly due to the measurement error in the determination of the Einstein radius, which we have estimated to be 0.5 px which corresponds to 0.135 arcsec. The error on the redshift derives from the error estimated on the wavelength calibration, which is ∼5 Å. This value is consistent with the spectral resolution (4.96 Å px^{-1}) of the grating R300B that we used.

Under the assumption of a singular isothermal sphere (SIS), it is possible to give an estimate of the magnification of the ring: $\mu = 4\Theta_E/\delta\Theta_s$, where $\delta\Theta_s$ is the source size. From Nagy et al. (2011), the average size of a starburst galaxy in our redshift range is ∼2 Kpc, which corresponds to 0.24 arcsec. The derived magnification is ∼36.

We determined also the mass-to-light ratio of the lens in the g band; a *K*-correction of 2.1 has been derived for the lens using the NED calculator (Chilingarian & Zolotukhin 2012). The resulting ratio is $M_{tot}/L \sim 58\,M_\odot/L_\odot$.

The former mass estimate can be improved by applying to the system a singular isothermal ellipsoid (SIE) model using the GRAVLENS/LENSMODEL software (Keeton 2001). This software allows to fit a SIE model using only the image positions and fluxes. The obtained best-fitting model is plotted in Fig. 3. The solutions have been derived for point-like sources; the ring shape is due to the fact that the source should actually be more extended with respect to the caustics than is shown here. The best fit ellipticity is 0.2 calculated as $1 - q$, where q is the axis ratio; the associated position angle is $-57°$, angle measured from North to East. The best-fitting χ^2 value is 6.12, calculated setting to 0 the weights relative to image fluxes. The derived Einstein radius is $\Theta_E = 2.38$ arcsec, which translates in an enclosed mass of $\sim 2.26 \times 10^{12}\,M_\odot$, hence, in excellent agreement with our previous estimate.

5 CONCLUSIONS

We report the discovery of an almost complete (∼300°) circular optical ER in the constellation of Sculptor. The gravitational lens is a massive luminous red galaxy at $z = 0.581$. The source galaxy is a starburst at redshift $z = 1.165$; its spectrum is dominated by a strong O II emission line. Using these redshift determinations and the Einstein radius $\Theta_E = 2.16$ arcsec, we calculated the total enclosed mass that produced the lensing effect: $M_{tot} = (1.86 \pm 0.23) \times 10^{12}\,M_\odot$.

All the parameters, we determined for IAC J010127-334319, are listed in Table 1.

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