Observations of the Einstein Cross with CanariCam

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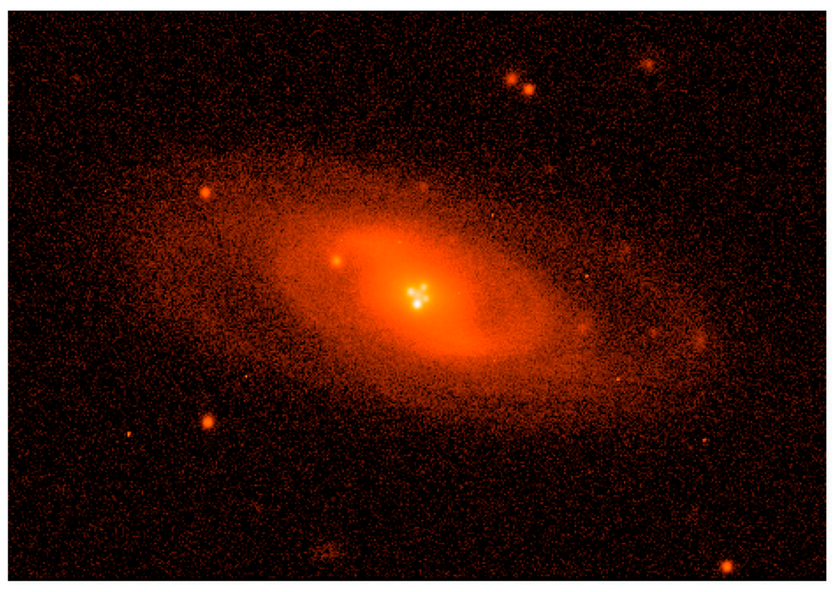
Abstract

We present mid-IR observations taken with CanariCam at Gran Telescopio Canarias of the quadruply lensed quasar QSO2237+0305. We have obtained flux ratios between the four images that, unlike optical, near-IR and, to a lesser extent, radio emission, are unaffected by the ISM (extinction/scattering) or stellar microlensing. We have used these flux ratios to obtain a mass model for the lensing galaxy and test for the presence of CDM substructure. We also compare these "true" ratios to the (stellar) microlensed flux ratios observed in the optical/near-IR to constrain the structure of the quasar accretion disk and the fraction of the lens mass in stars as compared to dark matter.

The Einstein Cross

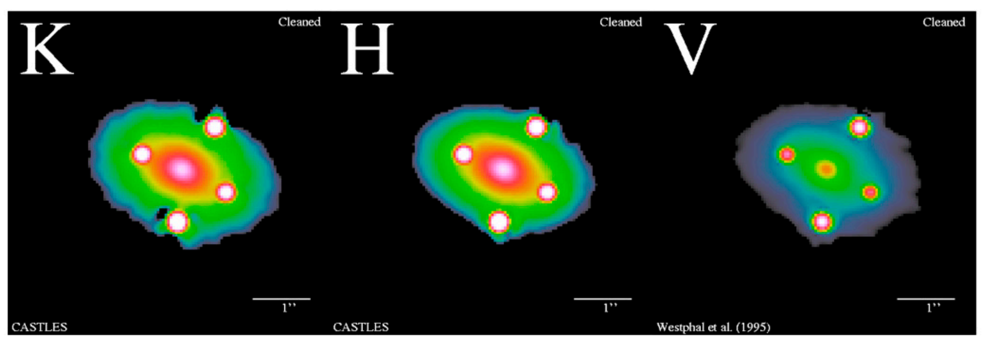
The object QSO2237+0305 is a gravitational lens system consisting of a relatively nearby spiral galaxy (z_L=0.039) bending the light of a quasar located much further away (z_S=1.695) but along the same line of sight. The ellipticity of the mass distribution in the lens galaxy combined with the precise alignment of the quasar with the center of the lens create four distinct images of it. Since the lens is so close to us, the paths of the light from the quadruply lensed quasar images go through the bulge of the spiral galaxy. This creates a much higher probability of the individual stars in it producing further lensing effects in each of the quasar images, and in fact this was the first system where gravitational microlensing was detected.



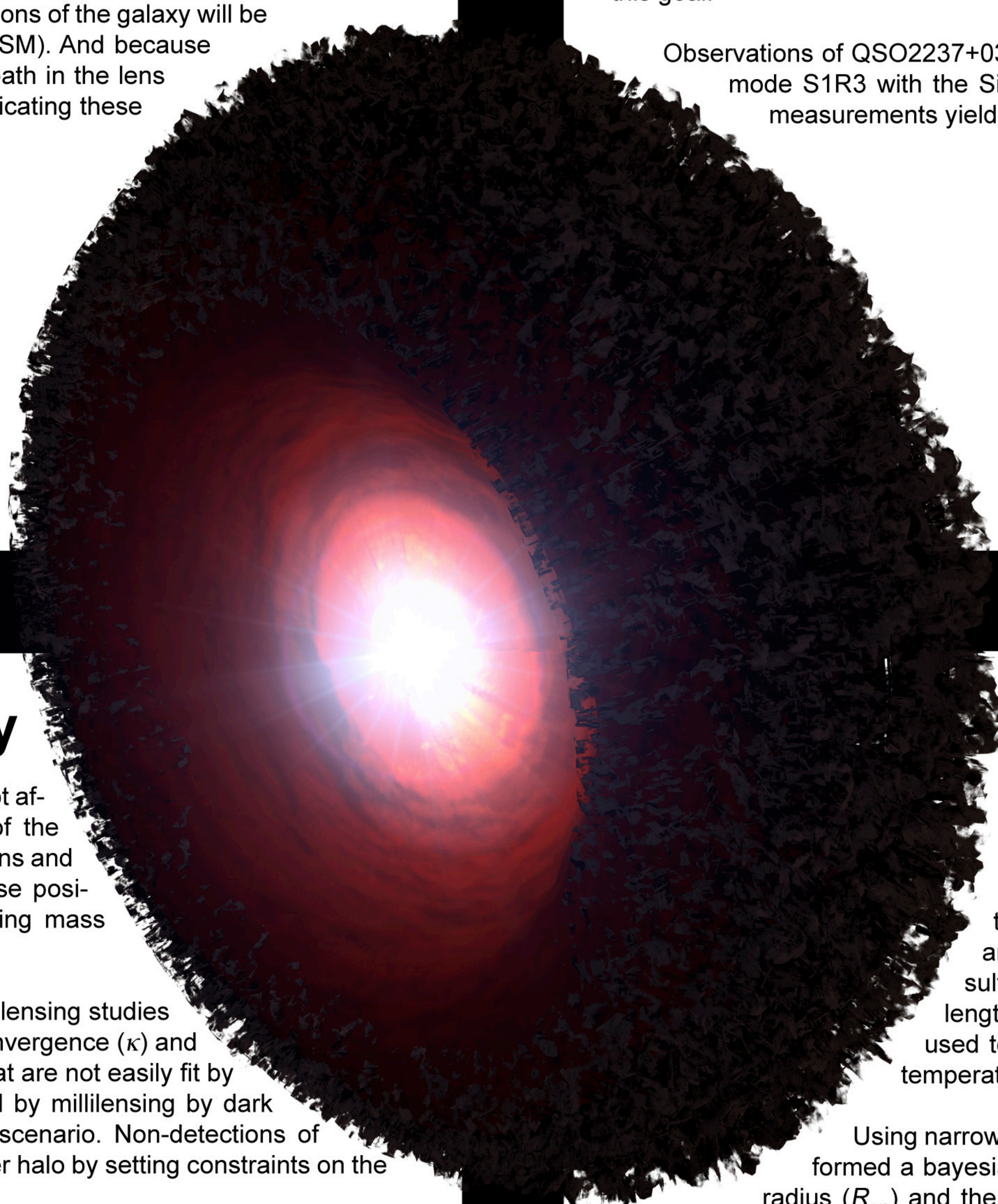
The Einstein Cross observed with the Nordic Optical Telescope (NOT)

The high density of stars in the bulge, coupled with the relatively high transverse velocity between lenses, source and observer due to the low galaxy redshift causes microlensing due to the stars to happen continuously, making the Einstein Cross a very interesting system for studying it. Furthermore, because the light paths for the different images are not so different, the time delays between intrinsic brightness variations on the quasar are less than 1 day between image pairs. Since these are short timescales compared to the microlensing variability (~1 month), there's no need to correct for this effect in this system when performing microlensing studies.

As a downside, the light passing through such high-density regions of the galaxy will be importantly affected by extinction in the interstellar medium (ISM). And because the light of each of the four images goes through a different path in the lens galaxy, the extinction will affect each of them differently, complicating these studies.



Optical and near-infrared observations of QSO2237+0305 with the Hubble Space Telescope



Mid-IR observations with CanariCam

In order to study microlensing effects from the variation of the quasar brightness, we must know the true flux ratios due only to the global mass distribution in the lens galaxy (called the *macromodel*), so a baseline for zero microlensing is needed. The light we get from the quasar when observing it in optical wavelengths comes mainly from its accretion disk, a structure of a smaller size than the Einstein radius of the stars of the lens galaxy when both are projected along the line of sight. If the projected size of a source is bigger than this, the changes in brightness due to microlensing become attenuated because only part of the object is being affected by high magnification.

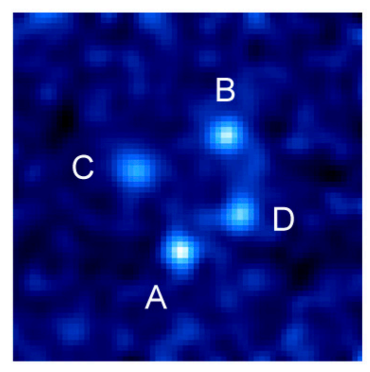
It follows, then, that getting light from regions of the quasar that are much bigger than the accretion disk would allow to get fluxes unaffected by microlensing. This can be done by measuring the fluxes of the emission lines in the Narrow Line Region of the quasar in each of the images, but optical wavelengths are affected by extinction by the interstellar medium, which can have different properties in each region of the lens galaxy. The dusty tori that surround the accretion disks of quasars has an appropriate size (~100 light-days) and glows in the mid-infrared due to its relatively low temperature. These wavelengths are unaffected by the ISM, making the torus a very good candidate for these observations.

However, observing in the mid-IR through the Earth's atmosphere proves hard, because water vapor absorbs a big fraction and also emits on its own, making the sky more than a thousand times brighter than the object of interest. The CanariCam detector circumvents this problem by repeatedly subtracting sky from a nearby position during the observation, and since it is limited by diffraction in the 10.4 meter wide Gran Telescopio Canarias, it provides a good resolution for this goal.

Gran Telescopio Canarias

Observations of QSO2237+0305 along with several PSFs were performed using the readout mode S1R3 with the Si-5 filter (λ = 11.6μm, $\Delta\lambda$ = 0.9μm). The combined photometry measurements yielded the flux ratios between images of the quasar shown below.

Flux ratios:
B/A = 0.99 ± 0.10
C/A = 0.69 ± 0.10
D/A = 0.84 ± 0.10



CanariCam mid-infrared observations of QSO2237+0305 and flux ratios derived from photometric measurements

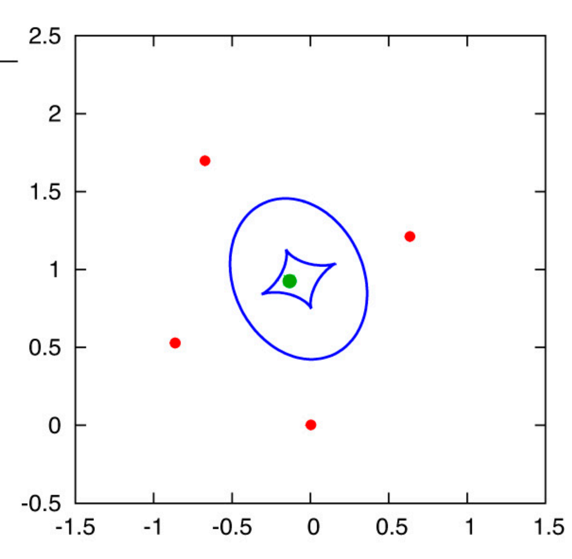
Mass model for the galaxy

The positions and relative fluxes of the quasar images, when not affected by microlensing, are determined by the distribution of the mass in the lens galaxy and the distances between observer, lens and source. Once measured from mid-IR observations, then, these positions and fluxes can serve as constraints to apply when fitting mass models to the lens galaxy.

Obtaining an accurate mass model is important because microlensing studies depend on the distortion of the quasar images given by the convergence (κ) and shear (γ) of the projected gravitational potential. Also, fluxes that are not easily fit by simple, physically reasonable mass models could be affected by millilensing by dark matter subhaloes predicted in the Cold Dark Matter (CDM) scenario. Non-detections of these anomalies, however, still allow us to probe the dark matter halo by setting constraints on the amount of substructure that may be present.

The flux ratios measured with CanariCam show a small discrepancy in image C when compared to the predictions given by a singular isothermal ellipsoid plus external shear (SIE + γ) model. Although the mass profile describes most lens galaxies properly, it might not account for the significant role the galactic bulge and bar would play in the lensing properties of this system accurately enough, so we are developing a more realistic model including these components. The parameters and critical lines for one of the best iterations are shown below, and correspond to a fit with χ^2_{red}= 0.694.

	NFW	de Vaucouleurs
κ_s (NFW), b (Vauc)	$0.0071^{+0.0010}_{-0.002}$	$1.375^{+0.004}_{-0.05}$
x_0 (")	-0.075±0.003	-0.076±0.002
y_0 (")	0.939±0.003	$0.9396^{+0.0017}_{-0.0016}$
e	$0.17^{+0.10}_{-0.17}$	$0.300^{+0.010}_{-0.002}$
θ_e (°)	-53^{+30}_{-25}	$-64.5^{+0.6}_{-0.7}$
γ	$0.014^{+0.008}_{-0.004}$	
θ_γ (°)	-81^{+4}_{-5}	
r_s (NFW), R_e (Vauc) (")	32^{+5}_{-7}	$6.9^{+2.5}_{-1.0}$



Parameters (above) and critical lines (right) of a mass model with two density profiles fit to the CanariCam observations

Quasar accretion disk

Since the magnitude of the microlensing effect on the quasar images depends on the projected size of the source compared to the average Einstein radius of the microlenses, this can be used to determine the size of the accretion disk. The temperature of the disk increases radially towards the center, however, and observations in different optical bands will give different results, because the emission peak corresponds to shorter wavelengths for higher temperatures. These chromaticity effects can be used to determine the scaling slope of the radial dependence for the temperature, assuming it follows a power law.

Using narrow filter observations of QSO2237+0305 at several epochs we performed a bayesian analysis to estimate two parameters of the disk, its half-light radius ($R_{1/2}$) and the logarithmic scaling slope (p). This estimate uses microlensing probabilities derived from magnification maps generated with the κ and γ parameters of the potential from the literature. These maps were convolved with different sizes of the source instead of fitting individual microlensing light curves, and the estimate is therefore not affected by the degeneracy between the source size and the peculiar velocity of the galaxy. The results of the latest analysis using this method are (Muñoz et al. 2014, in preparation):

$$R_{1/2} = 8.7^{+10.6}_{-4.8}\sqrt{0.3M/M_\odot}\ \text{lt-days}$$

$$p = 0.6 \pm 0.5, (T \propto R^{1/p})$$

This value of the half-light radius is very large compared to the predictions of the thin disk model by Shakura and Sunyaev, (~1 light-day), but is reasonable according to the scaling of the size with the BH mass, that predicts sizes of ~5 light-days when adopting a mass of 1.2 x 10^9 M_{Sun} for the central black hole.

We are now recalculating $R_{1/2}$ and p of the quasar accretion disk using these new CanariCam flux ratios to build a realistic mass model for the lens galaxy (Vives-Arias et al. 2014, in preparation).