Accretion discs in central regions of microlensed quasars

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ABSTRACT

The UC gravitational lensing group is collaborating with other national and foreign groups about the construction, analysis and interpretation of light curves of gravitationally lensed quasars. The collaboration mainly focuses on the microlensing variability of such objects, and in this contribution, we present results from long-term optical monitorings of the quadruply-imaged quasar QSO 2237+0305ABCD (the Einstein Cross) and the doubly-imaged quasar SDSS J1339+1310AB. The former is an iconic object for microlensing studies, while the latter is a recently-discovered microlensing factory. We detect significant microlensing-induced variations in the light curves of both quasars, which allow us to discuss the structure of the accretion flow around their central supermassive black holes

INTRODUCTION

► It is thought that UV continuum emission of radio-quiet quasars comes from hot gas in inner regions of accretion discs around their central supermassive black holes (e.g. Shakura & Sunyaev 1973, Rees 1978)

► The study of these UV sources offers a unique opportunity to test the physics under extreme conditions (in the vicinity of black holes) at remote epochs

► Although compact regions within quasar accretion discs cannot be resolved by direct imaging techniques, microlensed quasars can be used as Rosetta stones to resolve the inner accretion flow in distant active galactic nuclei (e.g. Wambsganss 1998)

► A multiply-imaged (gravitationally lensed) quasar suffers the gravitational effect of one or more massive galaxies near its sight line. Optical light curves of its multiple images may show phases of microlensing activity, which is due to microlenses (stars) that magnify/demagnify the UV emission (e.g. Schneider et al. 2006). These stars belong to the main lensing galaxy, and they gravitationally affect the UV light from the high-redshift quasar that is observed at optical wavelengths

► ***Two microlensed quasars***: QSO 2237+0305ABCD (the Einstein Cross; z_s = 1.695) consists of four quasar images (A–D) that are arranged like a cross around the nucleus of a nearly face-on spiral galaxy at z_l = 0.039 (Huchra et al. 1985, Yee 1988). SDSS J1339+1310AB (zs = 2.231) consists of two quasar images (A and B) located on two opposite sides of an early-type galaxy at z_l = 0.607 (Inada et al. 2009, Shalyapin & Goicoechea 2014, Goicoechea & Shalyapin 2016)

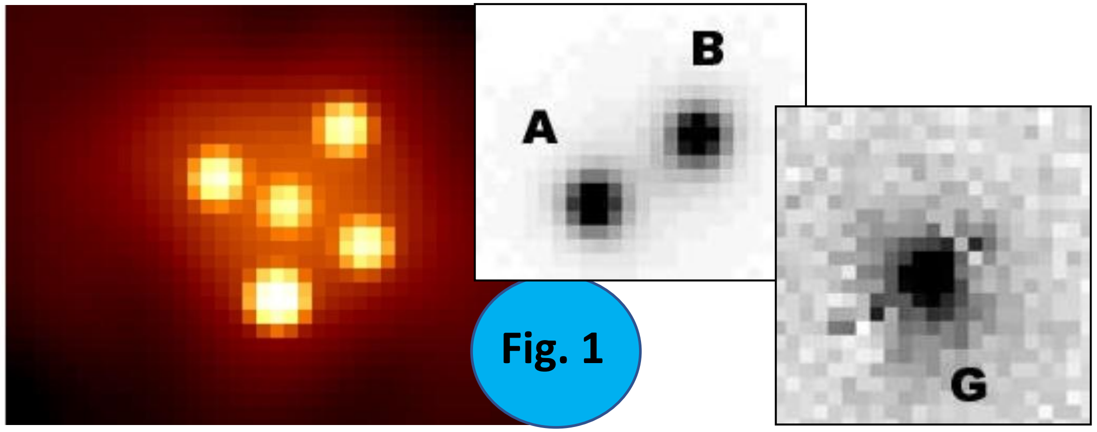


Fig. 1: The four images of the Einstein Cross around the nucleus of the lensing galaxy (*left*), the two images of SDSS J1339+1310AB (*middle*), and the faint lensing galaxy of SDSS J1339+1310AB after subtracting the two quasar images and the sky background (*right*). Typical separations between images are about 1–2″

Using the Liverpool Telescope (LT) and the main Maidanak Telescope, we obtained several thousands of frames of the Einstein Cross in the *gVrRI* bands over the 2006–2019 period. We also monitored SDSS J1339+1310AB with the LT in the *r* band from 2009 to 2019

We performed PSF-fitting photometry on the frames of both gravitationally lensed quasars using the 2D profile of a field star as empirical PSF. In the crowded region containing the four images of the Einstein Cross and the bulge of the lensing galaxy (see left panel of Fig. 1), the photometric model consisted of a constant background, four PSFs, and a de Vaucouleurs profile convolved with the PSF (Alcalde et al. 2002, Gil-Merino et al. 2018). For SDSS J1339+1310AB, the photometric model is simpler: two PSFs (images A and B), a de Vaucouleurs profile convolved with the PSF (early-type lensing galaxy G in the right panel of Fig. 1), and a constant background (Goicoechea & Shalyapin 2016)

MAIN RESULTS FOR QSO 2237+0305ABCD (THE EINSTEIN CROSS)

We built accurate 14-year multi-band light curves of the four quasar images, and then searched for microlensing-induced flux variations at recent epochs

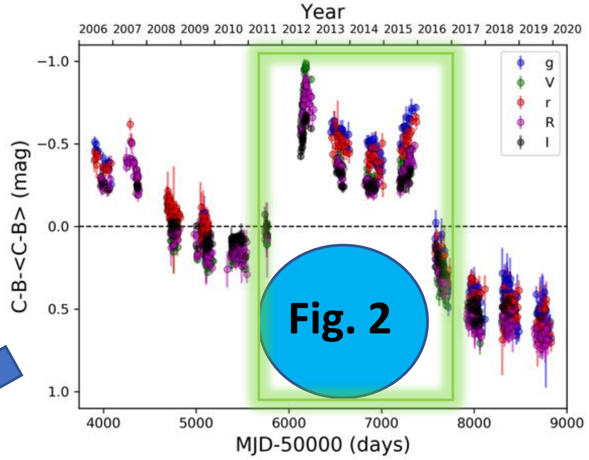


Fig. 2: The Liverpool-Maidanak light curves suggest that image C has been affected by a double caustic crossing between 2012 and 2016 (see rectangle highlighted in green)

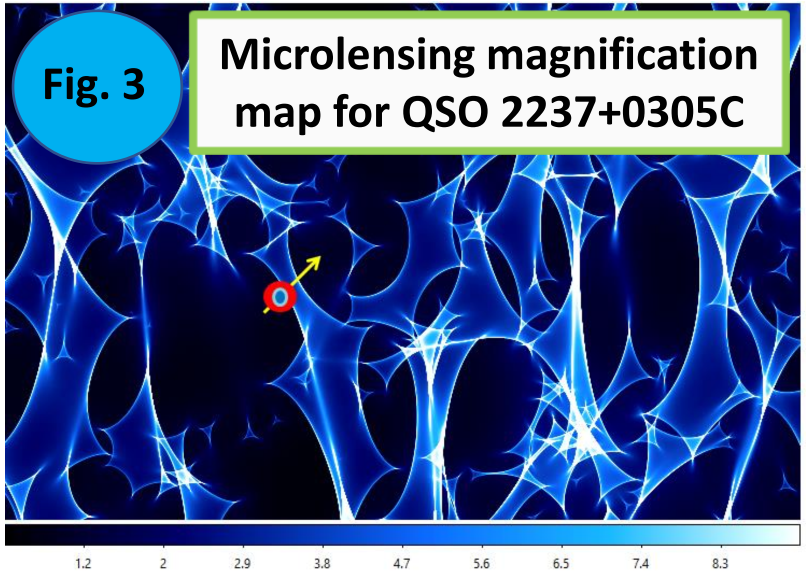


Fig. 3: Our data are consistent with a standard accretion disc entering a region interior to a caustic and then exiting from it. The standard gas disc accounts reasonably well for the growth in source radius as emission wavelength increases: $R_\lambda \propto \lambda^\alpha$, $\alpha = 1.33 \pm 0.09$ ($\lambda \approx$1780–3110 Å)

READ MORE AT

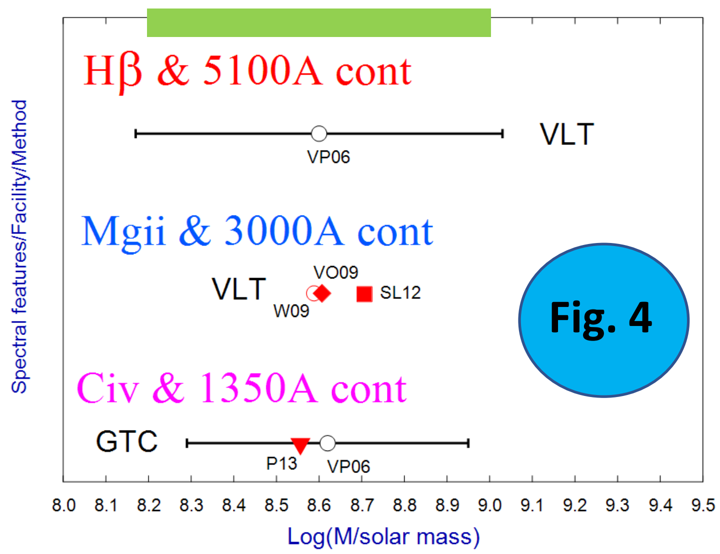
● [Liverpool-Maidanak monitoring of the Einstein Cross in 2006–2019. I. Light curves in the *gVrRI* optical bands and microlensing signatures]

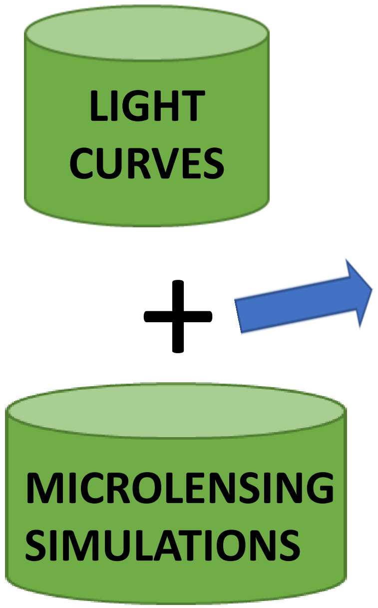
●● [First detection of a double caustic crossing in a microlensed quasar]

MAIN RESULTS FOR SDSS J1339+1310AB

To gain a more complete perspective of the inner accretion flow, we first measured the virial mass of the supermassive black hole at the quasar's centre using optical-NIR spectra of image A

Fig. 4: Black hole mass estimates from different facilities (GTC and VLT), emission lines and continuum luminosities (CIV & 1350 Å cont, MgII & 3000 Å cont, and Hβ & 5100 Å cont), and methods (VP06, VO09, W09, SL12, and P13). We adopt a **central dark mass of about four hundred million solar masses**: Log $(M/M_{sun}) = 8.6 \pm 0.4$ (see green rectangle)





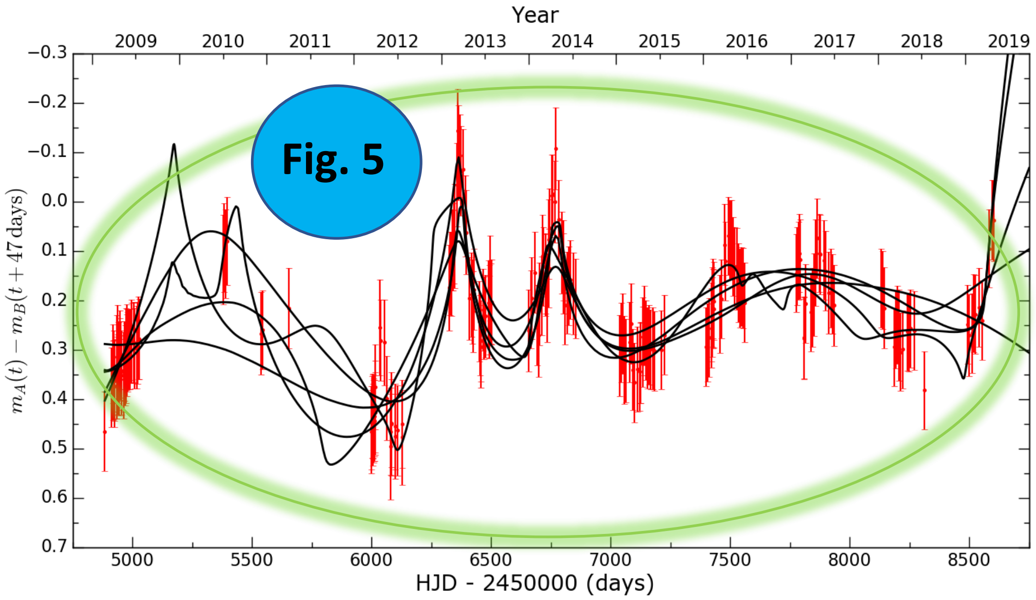


Fig. 5: The LT *r*-band light curves (red bars) are compared with USNA simulated microlensing curves. This comparison indicates that **the half-light radius of the 1930 Å continuum-emitting region is only about 10–20 Schwarzschild radii**

DISCUSSION AND PERSPECTIVES

► Despite the encouraging results on the Einstein Cross (Goicoechea et al. 2020), their final confirmation requires a detailed description of the observed microlensing variability through numerical simulations (e.g. Wambsganss 1998; Kochanek 2004). This detailed modelling will be carried out in a near future, and it will focus on discussing the brightness profile of UV continuum sources, and constraining the size and structure of the accretion disc

► For the Einstein Cross, assuming a relationship between source radius and emission wavelength: $R_\lambda \propto \lambda^\alpha$, the power-law index α is not well constrained yet. Our measurement $\alpha = 1.33 \pm 0.09$ confirms and improves a previous result ($\alpha = 1.2 \pm 0.3$; Eigenbrod et al. 2008). However, we also find some evidence of $\alpha \approx 1.0$ (see also Muñoz et al. 2016), suggesting that the source radius could grow more smoothly than the standard disc radius ($\alpha = 4/3$). In addition, new microlensing variability studies of other lensed quasars are leading to α values above 4/3 (e.g. Cornachione et al. 2020; submitted), and thus, more observational/interpretation efforts are required to firmly constrain the structure of quasar accretion discs

► Although UV observations are required to resolve the innermost stable circular orbit around the 4×10^8 M_{sun} black hole powering SDSS J1339+1310AB, our microlensing analysis resolves gas rings that are relatively close to the inner edge of the accretion disc (Shalyapin et al. 2020; submitted)

► Simultaneous measurements of black hole masses and accretion disc sizes are key tools to improve the precision of the physically relevant size–mass relation (Morgan et al. 2010) as updated by Morgan et al. (2018)