

# SPECTROSCOPY OF LENSING GALAXIES IN THE GTC ERA

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## RESUMEN

Estamos usando OSIRIS para obtener espectros de galaxias débiles y próximas a cuásares múltiples, e inicialmente nos hemos concentrado en los campos de HE 1413+117 (Hoja de Trébol) y SDSS 1116+4118. En esta contribución, presentamos observaciones de dos galaxias cercanas a la Hoja de Trébol, mostrando que una de ellas no contribuye a la cizalla externa del sistema lente gravitatoria. También analizamos y discutimos espectros de la galaxia candidata a lente principal en SDSS 1116+4118. Si SDSS 1116+4118 es un sistema lente, nuestros espectros indican que la lente principal no puede estar formada por una única galaxia dominante.

## ABSTRACT

We are using OSIRIS to obtain spectra of faint galaxies close to multiply imaged quasars. We initially focused on the fields of HE 1413+117 (Cloverleaf quasar) and SDSS 1116+4118. In this contribution, we present long-slit spectroscopy of two galaxies in the southwest of the Cloverleaf, and show that one of them makes a negligible contribution to the external shear of the gravitational lens system. Spectra of the main lensing galaxy candidate in SDSS 1116+4118 are also analysed and discussed. If gravitational lensing is causing the quasar image splitting, our spectra reveal that the main lens can not consist of only one dominant galaxy.

*Key Words:* galaxies: general — gravitational lensing: strong — techniques: spectroscopic

## 1. FIRST TARGETS AND GOALS

Time delays between multiple images of lensed quasars can be used in lensing mass reconstructions and the determination of cosmological parameters (e.g., Oguri 2007). However, a spectroscopic follow-up of lensing galaxies is essential to use time delays to constraint lensing mass distributions or cosmology (for a recent review see Schneider et al. 2006). Here, we present the first observations of our spectroscopic programme with OSIRIS on the GTC, which are part of an ambitious project with the new 10.4 m telescope (Ullán & Goicoechea 2003). These 2011 data of faint galaxies at relatively large angular separations from lensed quasars have been obtained in average seeing conditions or even worse.

We have recently measured the three time delays of the quadruple quasar HE 1413+117 (Cloverleaf quasar; Goicoechea & Shalyapin 2010). The external shear strength in this lens system is  $\gamma \sim 0.1$ , and the shear direction points towards the three field galaxies 1, 2, and H2 (MacLeod et al. 2009; Goicoechea & Shalyapin 2010). Thus, we have obtained OSIRIS/GTC spectra of the galaxies 1 and 2, which allow us to discuss the contribution of these

targets to the external shear on the Cloverleaf. We have also taken long-slit spectra of the galaxy between the pair of quasars SDSS 1116+4118 at redshift  $z \sim 3$ . Both quasars are separated by  $13''.7$ , so we want to check if the galaxy produces an image splitting  $\Delta\theta \sim 14''$  for a source at  $z \sim 3$  (Sánchez Alvaró & Rodríguez Calonge 2007; Ellison et al. 2007).

## 2. RESULTS AND DISCUSSION

### 2.1. HE 1413+117 (Cloverleaf quasar)

This year we have performed seven 2 ksec spectroscopic observations of the galaxies 1 and 2 in the southwest of the Cloverleaf quasar, using the low-resolution grism R300R ( $\lambda/\Delta\lambda = 348$ ) and placing the slit along the line joining both galaxies (e.g., MacLeod et al. 2009). From the first five datasets of each galaxy corresponding to March 31 and June 6 (mean seeing of  $\sim 1''.5$ ), we infer the combined spectra that appear in Figure 1. The galaxy No. 2 ( $R \sim 24$  mag) has a noisy spectrum that only includes one strong emission line in the 5000–8000 Å region. Fortunately, the spectrum of the galaxy No. 1 ( $R \sim 23$  mag) shows two strong emission lines that we identify with the O II( $\lambda 3727$ ) and O III( $\lambda 4959$ , 5007), leading to  $z = 0.57 \pm 0.01$ .

Emission line galaxies at  $z \sim 0.5 - 0.6$  have an average rotation velocity of  $175 \text{ km s}^{-1}$ . This  $V_{\text{rot}}$  is also measured in some relatively bright ( $R \sim 21$  mag) galaxies at  $z \sim 0.5 - 0.6$  (e.g., Bamford

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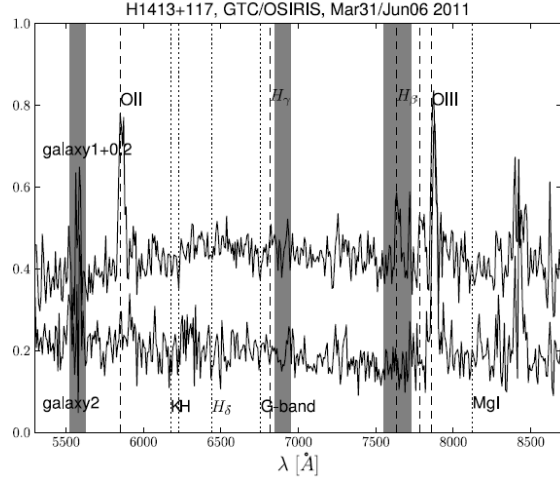


Fig. 1. Spectra of the galaxies 1 and 2 around the Cloverleaf quasar. Vertical dashed and dotted lines correspond to emission and absorption lines at  $z = 0.57$ , respectively. The three gray highlighted regions are associated with prominent atmospheric and night sky features.

et al. 2005). Therefore, we consider a singular isothermal sphere (SIS) model and an upper limit  $V_{\text{rot}} \leq 175 \text{ km s}^{-1}$  to describe the halo mass of the galaxy No. 1. If the main lens redshift was  $z = 0.57$ , then the shear from this galaxy would be less than 0.02. However, the main lens redshift is likely about 2 (Goicoechea & Shalyapin 2010), and thus, the effective shear should be less than 0.002 (Momcheva et al. 2006). This shear strength is significantly lower than the external shear in the system ( $\gamma \sim 0.1$ ).

## 2.2. SDSS 1116+4118

We have observed the lens system candidate on March 31 and April 7, 2011. The low-resolution spectra along the major and minor axes of the galaxy between the pair of quasars at  $z \sim 3$  are displayed in Figure 2. The exposure times/seeing values are 2.0 ksec/2''00 (major axis) and 1.2 ksec/2''35 (minor axis), and both spectra are consistent with each other. From the Kinney-Calzetti templates, we conclude that the candidate for main lensing galaxy ( $R \sim 19 \text{ mag}$ ; Sánchez Alvaro & Rodríguez Calonge 2007) is a spiral (Sb?) at  $z = 0.195 \pm 0.002$ .

Assuming a SIS model and a standard rotation velocity ( $V_{\text{rot}} \leq 300 \text{ km s}^{-1}$ ), the lensing galaxy candidate can only generate an image splitting  $\Delta\theta \leq 2''$  for a source at  $z \sim 3$ . This is well below the observed separation between the pair of quasars. Even for an extremely massive spiral with  $V_{\text{rot}} \sim 500 \text{ km s}^{-1}$ , e.g., UGC 12591 (Giovannelli et al. 1986) or ISO-HDFS 27 (Rigopoulou et al. 2002), the predicted image splitting is  $\Delta\theta \sim 6''$ . This extreme value is

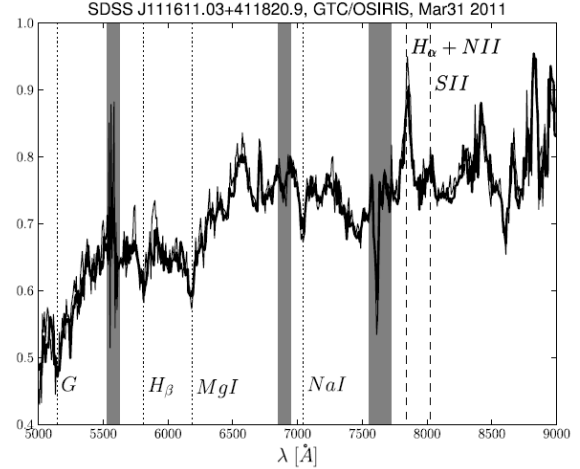


Fig. 2. Spectra of the candidate for main lensing galaxy of SDSS 1116+4118. The darkest line represents the spectrum along the major axis of the galaxy, while the other line describes the spectrum along its minor axis. The gray highlighted regions have the same meaning as in Figure 1, and the vertical marks correspond to emission and absorption lines at  $z = 0.195$ .

less than half of the angular separation between the two distant quasars.

Based on observations made with the Gran Telescopio Canarias (GTC), installed in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias, in the island of La Palma.

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