RX J0911.4+0551: A Complex Quadruply Imaged Gravitationally Lensed QSO

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1. Introduction

Deriving cosmological parameters has long been the motivation for the development of many observational tests. These parameters, including the troublesome Hubble parameter, H_0, can be derived from different methods, e.g., monitoring of Cepheids in nearby galaxies, the use of the Tully-Fisher relation or, at higher redshifts, the photometric monitoring of supernovae. Another method to determine H_0, independently of these classical methods, is to measure the time delay between the gravitationally lensed images of QSOs. However, a good knowledge of the geometry of the lensed system is mandatory in order to make use of this information. Unfortunately, this is rarely the case, in many lensed QSOs the main deflecting mass is not even detected.

This was the background for a deep IR imaging project started at ESO in 1996 with the 2.2-m telescope, with the primary aim of detecting possible high-redshift galaxy clusters in the vicinity of known multiply imaged QSOs, as well as the main lensing galaxy. Observing in the IR optimises the contrast between low-z field galaxies and higher z cluster members, since the latter have their 4000-Å break, typical for galaxy spectra, redshifted into the IR for $z \geq 0.8$–1. Therefore, near-IR observations make easier the discrimination between field galaxies and high-redshift cluster members.

Near-IR (1 to 2.5 microns) observations have the further advantage that the relative brightness between the lensed QSO and any lensing galaxy decreases, making the galaxy easier to detect. The disadvantage is that the sky is considerably brighter in the IR than in the optical, and one is forced to take many short-exposure images to avoid detector saturation. Nevertheless, the image deconvolution technique developed by Magain, Courbin & Sohy (1997, 1998; hereafter MCS) allows one to take advantage of the numerous dithered frames obtained and to combine them into a single deep sharp image.

Successful results have already been obtained from this project, e.g., the detection of the deflector in the gravitational lens HE 1104-1805 (Courbin, Lidman & Magain, 1998), also confirmed by Remy, Claeskens, Surdej et al. (1998).

In this paper we report the detection of four QSO images in the recently discovered lensed QSO RX J0911.4+0551. With a maximum angular separation of 3.1″, it is the quadruply imaged QSO with the widest-known angular separation.

RX J0911.4+0551, was selected as an AGN candidate from the ROSAT All-Sky Survey (RASS) (Bade et al., 1995, Hagen et al., 1995), and was recently classified by Bade et al. (1997; hereafter B97) as a new multiply imaged QSO. The lensed source is a radio quiet QSO at $z = 2.8$. Since RASS detections of distant radio quiet QSOs are rare, B97 pointed out that the observed X-ray flux might originate from a galaxy cluster at $z \geq 0.5$ within the ROSAT error box.

We present here our first observations of RX J0911.4+0551 at the 2.2-m ESO/MPI IRAC 2b in K-band which made us suspect that the QSO might be quadruple. This was confirmed on our optical data from the 2.56-m Nordic Optical Telescope (NOT, La Palma, Canary Islands, Spain), and on the NTT/SOFI data of the object (Moorwood, Cuby & Lidman, 1998). Careful deconvolution of the data allows us to clearly resolve the object into four QSO components and a lensing galaxy. In addition, a candidate galaxy cluster has been detected in the vicinity of the four QSO images. We estimate its redshift from photometric analysis of its members.

2. Observations and Deconvolution

As a part of our near-IR imaging project of gravitational lenses, RX J0911.4+0551 was first observed in the K-band with IRAC 2b mounted on the ESO/MPI 2.2-m telescope on November 12, 1997. The data were processed as explained in Courbin, Lidman & Magain (1998), and they were deconvolved using the MCS algorithm. During the deconvolution process, the sampling of the images was improved, i.e., the adopted pixel size in the deconvolved image is half the pixel size of the original frames. The deconvolution procedure decomposes the images into a number of Gaussian point sources plus a deconvolved numerical background, and the quality of the results is checked from the residual maps, as explained in Courbin et al. (1998a,b). In spite of the poor seeing conditions (1.3″), preliminary deconvolution of the data made it possible to strongly suspect the quadruple nature of the object (see Fig. 1). From the observed image with a seeing of ~ 1.3″ only two separated components are resolved, one of them being elongated, suggesting that it is a blend of two or more images. The deconvolution programme was run once with three sources and then with four point sources (shown in the middle and bottom panel respectively in Figure 1). The residual maps, in units of the standard deviation in each pixel, indicate that the solution with four point sources gives a better χ^2-fit to the data. Note also that even on these poor seeing data the deconvolution algorithm allowed us to suspect not only a quadruply imaged QSO, but also the presence of a lensing galaxy.

Much better optical observations were obtained at the NOT. Three 300s exposures through the I filter, with a seeing of ~ 0.8″ were obtained with ALFOSC under photometric conditions on November 16, 1997. Under nonphotometric, but excellent seeing conditions (~ 0.5–0.6″), three 300s I-band exposures, three 300s V-band and five 600s U-band exposures were taken with HIRAC on the night of December 3, 1997.

These high-resolution data resolved the object into four components and clearly confirmed our preliminary IR-results from the ESO/MPI 2.2-m telescope.

RX J0911.4+0551 was also the first gravitational lens to be observed with the new wide-field near-IR instrument SOFI, mounted on the ESO 3.5-m NTT (Moor-

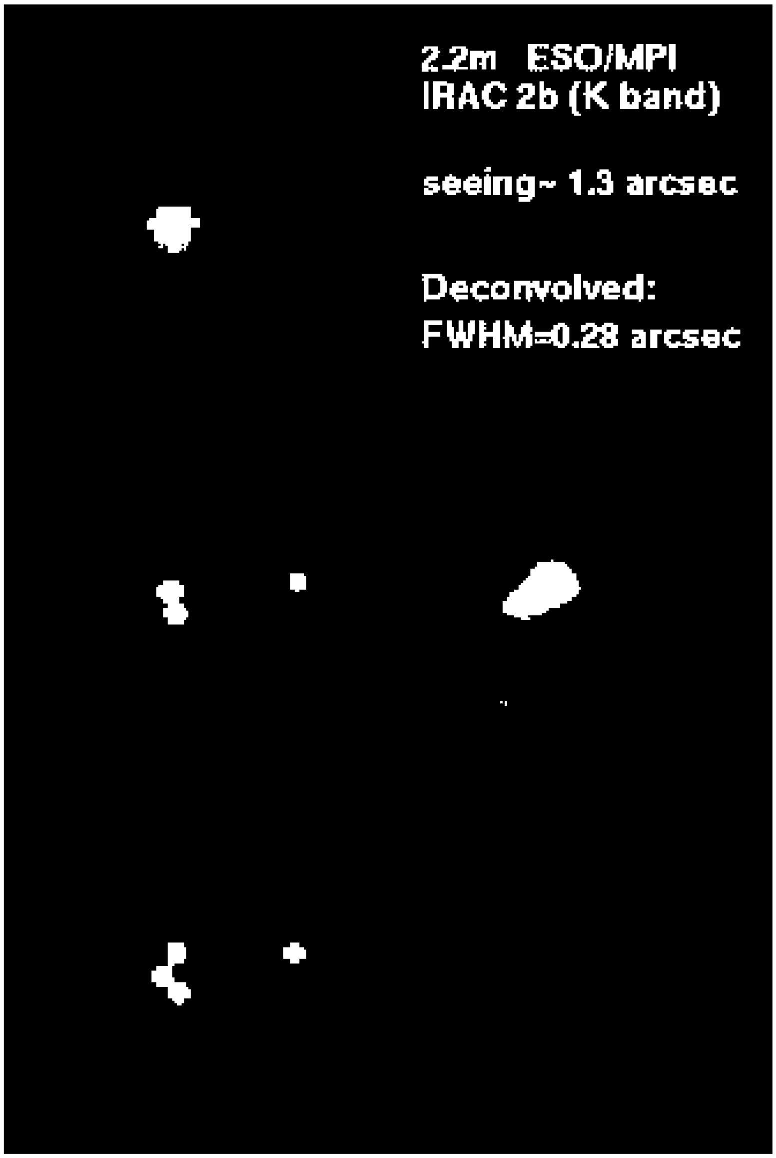

Figure 1: [Top:] Observed image from 2.2-m ESO/MPI IRAC 2b; [Middle:] Result from deconvolution with three point sources to the left and residual map to the right. The centre of the residual map has typical values of the order of $2\sigma_{sky}$ per pixel. [Bottom:] Same as above but with four point sources. All the values in the residual map are now close to σ_{sky}, showing that 4 point sources are needed to fit the data. The field is 9″ on a side, North is to the top and East is to the left in all the frames. This figure is to be compared with Figure 2. Note how well the lensing galaxy shows up in the deconvolution.

wood, Cuby & Lidman, 1998). Excellent *K* and *J* images were taken on December 15, 1997, and January 19, 1998 respectively. The 1024 × 1024 Rockwell detector was used with a pixel scale of 0.144″. These data were processed as the ones from the 2.2-m, but in a much more efficient way since the array used with SOFI is cosmetically superior to the array used with IRAC 2b.

All these images were also deconvolved and the final resolution adopted in each band was chosen according to the signal-to-noise (S/N) ratio of the data, the final resolution improving with the S/N. The deconvolution of NOT and SOFI frames are shown in Figure 2. Not only the quadruple configuration of the QSO is revealed but also the main lensing galaxy, as already suspected from our preliminary observations from the 2.2-m telescope, clearly confirming the lensing nature of this object.

3. Photometry

The flux ratios and positions of each QSO component relative to the brightest one (A1) as derived from the simultaneous deconvolutions are listed in Table 1. The position of the galaxy, also displayed in Table 1, was determined from the first-order moment of the light-distribution in the deconvolved numerical background. The galaxy is elongated in the *I*-band. In the near IR, it looks like an edge-on spiral, composed of a bright sharp nucleus plus a diffuse elongated disk. However, we can not exclude that the observed elongation is due to an unresolved blend of two or more intervening objects. Deeper observations will be required to perform precise surface photometry of the lens(es) and to draw a definite conclusion about its (their) morphology. The position angle of the major axis of the lensing galaxy is almost the same in the *I*, *J* and *K* bands: PA ≃ 140°± 5.

In order to detect any intervening galaxy cluster which might be involved in the overall lensing potential and contributing to the X-ray emission observed by ROSAT, we performed *I*, *J* and *K* band photometry on all the galaxies in a 2.5′ field around the lensed QSO. Aperture photometry was carried out using the SExtractor package (Bertin & Arnouts, 1996).

Table 1: Flux ratios and astrometric properties relative to component A1. Positions are defined positive to the North and West of A1. All measurements are given along with their 1σ errors.

	A1	A2	A3	B	G
F_K	1.000 ± 0.001	0.965 ± 0.013	0.544 ± 0.025	0.458 ± 0.004	–
F_J	1.000 ± 0.002	0.885 ± 0.003	0.496 ± 0.005	0.412 ± 0.005	–
F_I	1.000 ± 0.017	0.680 ± 0.013	0.398 ± 0.002	0.420 ± 0.003	–
F_V	1.000 ± 0.007	0.587 ± 0.009	0.334 ± 0.004	0.413 ± 0.006	–
F_U	1.000 ± 0.003	0.590 ± 0.013	0.285 ± 0.007	0.393 ± 0.004	–
x(″)	0.000	–0.259 ± 0.007	+0.013 ± 0.008	+2.935 ± 0.002	+0.709 ± 0.026
y(″)	0.000	+0.402 ± 0.006	+0.946 ± 0.008	+0.785 ± 0.003	+0.507 ± 0.046

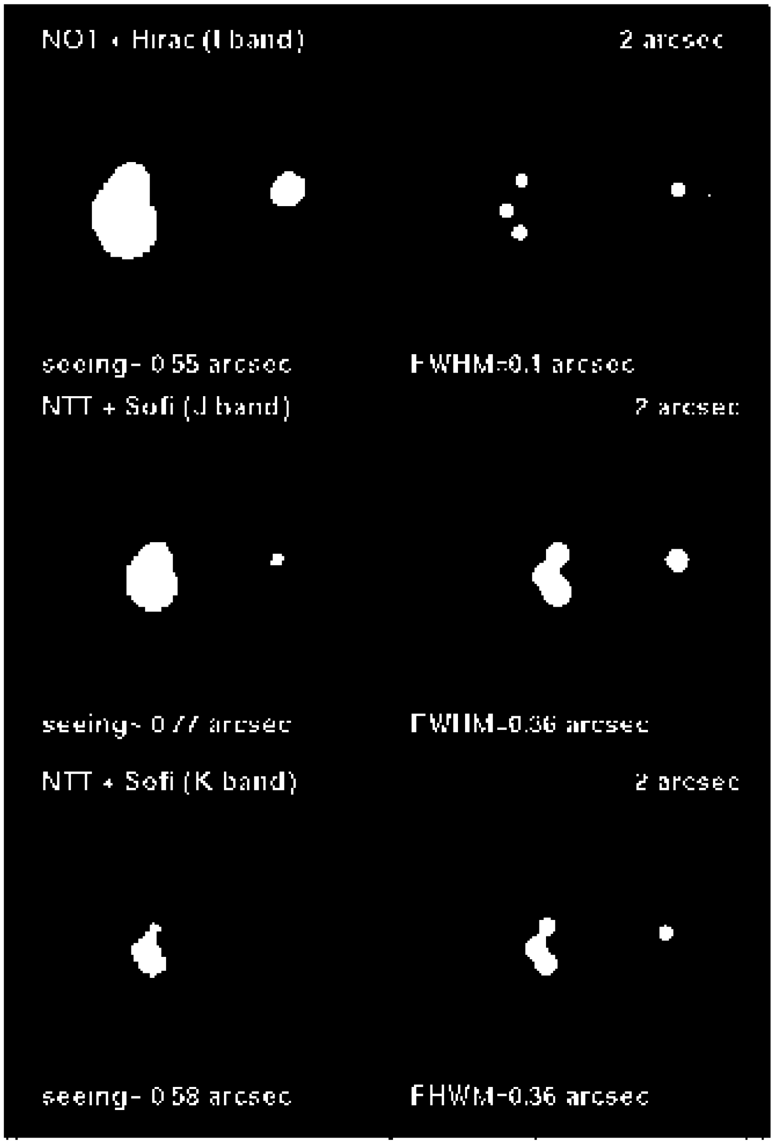

Figure 2: High-resolution images of RX J0911.4+0551 are displayed in the left panels together with their deconvolved versions with improved resolution and sampling in the right panels. In each band, the individual data frames are deconvolved simultaneously. [Top:] Stack of 3 NOT+HIRAC I-band image. The total exposure time is 900s. [Middle:] Stack of 9 NTT+SOFI J-band frames. The total exposure time is 1080s. [Bottom:] Stack of 19 NTT+SOFI K-band with a total exposure time of 2400s. For all three bands the object is clearly resolved into four QSO images plus the elongated lensing galaxy. The fields of the optical and near IR data are respectively 7″ and 9″ on a side. North is to the top and East is to the left in all the frames.

The faintest objects were selected to have at least 5 adjacent pixels above $1.2\sigma_{sky}$, leading to the limiting magnitudes 23.8, 21.6 and 20.0 *mag/arcsec*^{2} in the *I*, *J* and *K* bands respectively. The faintest extended object measured in the different bands have a magnitude of 23.0, 22.0 and 20.3 (*I*, *J* and *K).*

A composite colour image was also constructed from the frames taken through the 3 filters, in order to directly visualise any group of galaxies with similar colours, and therefore likely to be at the same redshift. The colour composite is presented in Figure 3. The marked circle indicates a candidate galaxy cluster centred on a double elliptical, with the same colour as the main lensing galaxy. In addition, a group of even redder galaxies is seen a few arcseconds to the left and to the right of the marked cross.

4. Discussion

Thanks to our first observations from the 2.2-m telescope and the MCS deconvolution algorithm, RX J0911.4+0551 was resolved into a quadruply imaged QSO, and a lensing galaxy. Furthermore, these preliminary results were confirmed by high-resolution optical data and new near-IR data from SOFI, thus clearly confirming the lensed nature of the system. The image deconvolution provides precise photometry and astrometry for this system.

Reddening in components A2 and A3 relative to A1 is observed from our *U*, *V* and *I* frames that were taken within three hours on the same night. The absence of reddening in component B and the difference in reddening between components A2 and A3 suggest extinction by the deflecting galaxy. Note that although the SOFI data were obtained from 15 days to 6 weeks after the optical images, they appear to be consistent with the optical fluxes measured for the QSO images, i.e. flux ratios increase continuously with wavelength, from *U* to *K,* indicating extinction by the lensing galaxy.

The observed orientation of the galaxy, together with the asymmetric image configuration, makes it difficult to model the lensing potential without including external shear from a nearby mass. If the lensing effect was only due to a symmetric galaxy, whose mass distribution is roughly aligned with the light, we should have observed a symmetric configuration of the QSO images about the axis through A2 and B.

A good galaxy cluster candidate has been detected in the vicinity of RX J0911.4+0551 from field photometry in the *I*, *J* and *K* bands. Comparison of our colours and magnitudes with that of a blank field (e.g., Moustakas et al., 1997) shows that the galaxies around RX J0911.4+0551 are redder than field-galaxies at an equivalent apparent magnitude. Furthermore, several of the galaxies are grouped in the region around a double elliptical at a distance of $\sim 38''$ and a position angle of $\sim 204°$ relative to A1 (see the circle in Fig. 3).

There is considerable evidence for at least one galaxy cluster in the field. The redshift of our best cluster candidate (the one circled in Fig. 3) can be estimated from the *I* and *K* band photometry. We have compared the *K*-band magnitudes of the brightest cluster galaxies with the empirical *K* magnitude vs. redshift relation found by (Aragon-Salamanca et al. 1998). We find that our cluster candidate, with a brightest *K* magnitude of ~ 17.0 should have a redshift of $z \sim 0.7$. A similar comparison has been done in the *I*-band without taking into account galaxy morphology. We compare the mean *I* magnitude of the cluster members with the mean magnitude found by Koo et al. (1996) for galaxies with known redshifts in the Hubble Deep Field and obtain a cluster redshift between 0.6 and 0.9. Finally, comparison of the $I - K$ colour of the cluster members with data and models from Kodama et al. (1998) confirm the redshift estimate of 0.6–0.8.

Some 10″ away from the lens, a group of even redder objects can be seen (close to the cross in Fig. 3). These galaxies

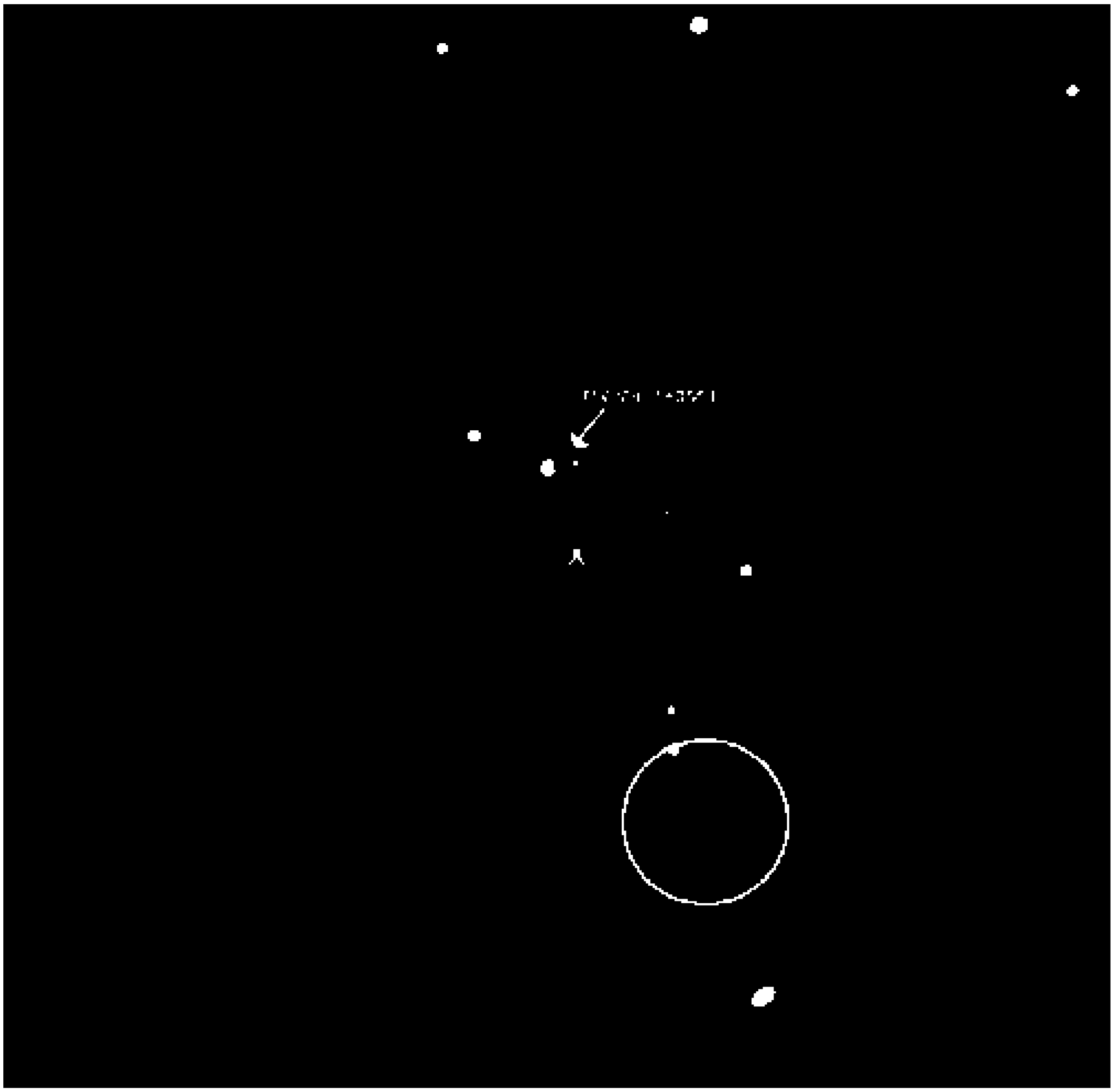

Figure 3: Composite image of a 2′ field around RX J0911.4+0551. The frame has been obtained by combining the ALFOSC I and the SOFI J and K-band data. North is up and East is to the left. Note the group of red galaxies with similar colours, about 38″ SW of the quadruple lens (circle) and the group of redder galaxies 10″ SW of the lens (cross).

might be a part of a second galaxy group at a higher redshift.

The colour of the main lensing galaxy is very similar to that of the cluster members, suggesting that it might be a member of the cluster. However, internal reddening and inclination effects, in case it is a spiral galaxy, might bias the colour interpretation. Given the brightness of the nucleus of the lens in *K*, we cannot rule out the possibility of a fifth central image of the source, as predicted from lens theory. Near-IR spectroscopy is needed to get a redshift determination of the lens and show whether it is blended or not with a fifth image of the source.

RX J0911.4+0551 is a new quadruply imaged QSO with an unusual image configuration. The lens configuration is complex, composed of one main lensing galaxy plus a plausible galaxy cluster at redshift between 0.6 and 0.8 and another possible group at $z > 0.7$. Multi-Object Spectroscopy is needed in order to confirm our cluster candidate(s) and derive its (their) redshift and velocity dispersion. In addition, weak lensing (shear) analysis of background galaxies will be useful to map the overall lensing potential involved in this complex system.

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