

RX J0911+05: A MASSIVE CLUSTER LENS AT $Z = 0.769$

JEAN-PAUL KNEIB¹

Observatoire Midi-Pyrénées, 14 Avenue Edouard Belin, 31400 Toulouse, France; kneib@ast.obs-mip.fr

JUDITH G. COHEN

Palomar Observatory, Mail Stop 105-24, California Institute of Technology, Pasadena, CA 91125; jlc@astro.caltech.edu

AND

JENS HJORTH

Astronomical Observatory, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark; jens@astro.ku.dk

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ABSTRACT

We report the detection of a massive high-redshift cluster of galaxies near the quadruple quasar RX J0911+05, using the Low-Resolution Imaging Spectrograph instrument on the Keck II telescope. The cluster is found to have a mean redshift of $\bar{z} = 0.7689 \pm 0.002$ and a velocity dispersion of $\sigma = 836^{+180}_{-200}$ km s⁻¹, based on redshift measurements for 24 member galaxies. This massive high-redshift cluster is the origin of the unusually large external shear required by lensing models of the quadruple quasar system. We predict the expected time delay depending on the exact contribution of the cluster. A measurement of the time delay and further deep lensing and X-ray observations will unravel useful properties of this serendipitously discovered high-redshift cluster and may put interesting cosmological constraints on H_0 .

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (RX J0911.4+0551) — gravitational lensing

1. INTRODUCTION

Multiply imaged quasars are among the most promising objects for measuring distances and hence cosmological parameters (Refsdal 1964; Blandford & Narayan 1992). That promise is finally starting to be realized after time delays have been measured in several systems in recent years (e.g., Schechter et al. 1997; Kundić et al. 1997c; Hjorth et al. 2000). Contrary to local estimates of the Hubble parameter, multiply imaged quasars with time delays can be used to measure the Hubble parameter on a *cosmological* scale and hence are insensitive to local bulk flows.

Until recently, simple mass distributions have been used to model multiply imaged quasi-stellar objects (QSOs). However, the rapid development of observing techniques and the availability of powerful observatories like the *Hubble Space Telescope* (*HST*) and the 8–10 m class telescopes have shown that most of the image configurations are more complex than allowed by simple models. As an example, the double quasar 0957+561, first thought to be produced by a single galaxy, is now known to be a complex system involving a massive lens plus one or more galaxy clusters (Bernstein & Fisher 1999 and references therein). In parallel to the surge in observational efforts, the modeling of galaxies and their surroundings has greatly improved and is starting to provide very important insights into the distribution of dark matter in galaxies (e.g., Hjorth & Kneib 2000; Maller et al. 2000; Kochanek et al. 1999).

A major uncertainty in the mass models comes from the surroundings of the lens, in the form of “external shear,” e.g., due to either nearby galaxies, a galaxy group, or a cluster close to the line of sight to the QSO (Keeton, Kochanek, & Seljak 1997; Kundić et al. 1997b). It is important to underline that a

reliable mass model requires not only γ , the gravitational external shear, but also the external surface mass density κ producing γ . Therefore, a measurement of the mass distribution in the vicinity of the lensed quasar is *mandatory* in putting stringent constraints on cosmological parameters.

The quadruple lens system RX J0911+05, was identified by Bade et al. (1997) as a multiply imaged radio-quiet QSO at $z = 2.80$, selected as an active galactic nucleus (AGN) candidate from the *ROSAT* all-sky survey. In high-resolution Nordic Optical Telescope and New Technology Telescope images (Burud et al. 1998), RX J0911+05 was soon found to consist of four QSO components and an elongated lensing galaxy, confirmed by subsequent *HST* imaging. Regular monitoring of RX J0911+05 is expected to give a time delay to about 10% (J. Hjorth et al. 2000, in preparation). Moreover, recently, the redshift of the main lens was measured at $z = 0.769$ with the Keck telescope (E. E. Falco, M. Davis, & C. Stern 1999, private communication). The unusual image configuration of RX J0911+05 requires a large external shear ($\gamma \sim 0.15$) in order to reproduce the complex geometry observed in RX J0911+05. The probable source of this shear is a galaxy cluster located about 38'' from RX J0911+05, as suggested by Burud et al. (1998). Such a cluster may contribute to the X-ray emission observed by *ROSAT*. The color of the presumed cluster galaxies indicates a redshift in the range 0.6–0.8, consistent with the determined spectroscopic redshift of the main lens galaxy.

In this Letter we present the results of spectroscopic observations of RX J0911+05 conducted at the Keck Observatory using the Low-Resolution Imaging Spectrograph (LRIS) instrument. Section 2 summarizes the photometric and spectroscopic observations. Section 3 presents the constraints on the mass model of the high-redshift cluster of galaxies detected near the quadruple lens. A discussion of the results is presented in § 4. Throughout this Letter we use a Hubble parameter $H_0 = 50 h_{50}^{-1}$ km s⁻¹ Mpc⁻¹, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$, which gives a physical scale of $10.37 h_{50}^{-1}$ kpc arcsec⁻¹ at the cluster redshift ($z = 0.769$).

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FIG. 1.—Keck/LRIS *BRI* color composite image ($4'.75 \times 6'.15$ field) showing the central region of the RX J0911+05 cluster. Circled objects were observed in MOS mode; the redshift identification is noted on the side of the circle. The zoomed image corresponds to the *HST*/NICMOS observation of RX J0911+05 multiple QSOs.

2. OBSERVATIONS

We observed RX J0911+05 during the 1999 December 7/8 and 2000 March 6/7 nights with the LRIS instrument (Oke et al. 1995) mounted on Keck II. Imaging was done in *B*, *R*, and *I* (under $1''.1$ seeing conditions) and calibrated using photometric standards PG 2213–006 and other stars in the SA 92 field (Landolt 1992). Spectroscopic observations were conducted with the 400/8500 grating blazed at 7200 \AA , which gives a dispersion of $1.84 \text{ \AA pixel}^{-1}$ covering $5000\text{--}9000 \text{ \AA}$. Standard FIGARO and IRAF pipeline reduction packages were used to reduce the photometric and spectroscopic data. A color image made of the *B*, *R*, and *I* images is presented in Figure 1.

We exposed two multiobject spectrometer (MOS) masks, with 24 and 30 slitlets, respectively, using three to four stars for

alignment. Object selection was limited in magnitude to $I_{AB} < 22.5$ and generally followed the color selection of Burud et al. (1998). Redshifts were estimated independently by J.-P. K. and J. G. C. by simple line-fitting techniques as well as by using the cross-correlation package RVSAO V2.0 in IRAF (Kurtz & Mink 1998). Redshift identifications are displayed on Figure 1. Table 1 summarizes the photometry and the redshift of the cluster members. Figure 2 shows the redshift histogram of the entire sample and the cluster sample. The majority of the cluster member spectra are typical of an old stellar population. Only three out of 23 spectra show a strong [O II] emission line (one of them being an AGN), and four others show a weak [O II] line. Although our target selection was clearly biased to have a large number of early-type galaxies, it clearly shows that these galaxies

TABLE 1
CATALOG OF THE CLUSTER GALAXIES IN THE FIELD OF RX J0911+05

| Identification | α (J2000) | δ (J2000) | I_{AB} | z | Δz | Line Identification | Cross-Correlation Template R^a | Object Type and Quality ^b |
|-----------------|---------------------|---------------------|----------|--------|------------|---------------------|-------------------------------------|-----------------------------------------|
| G1 | 09 11 26.46 | +05 50 14.5 | 19.99 | 0.7682 | 0.0002 | H/K/br/G | g6V-3.03 | A-1 |
| G2 | 09 11 27.29 | +05 50 25.4 | 20.82 | 0.7738 | 0.0003 | [O II]/H/K/G | spec-em-3.92 | C-1 |
| G3 | 09 11 27.92 | +05 50 49.5 | 20.90 | 0.7618 | 0.0003 | H/K/br/G | g6V-3.43 | A-1 |
| G4 | 09 11 21.17 | +05 49 39.8 | 20.94 | 0.7693 | 0.0004 | H/K/br/G | gell-5.40 | A-1 |
| G5 | 09 11 21.40 | +05 48 03.8 | 21.24 | 0.7697 | 0.0003 | H/K/br/G | gell-7.50 | A-1 |
| G6 | 09 11 28.36 | +05 51 07.9 | 21.30 | 0.7650 | 0.001 | wk[O II]/K/H/G | ... | C-1 |
| G7 | 09 11 26.43 | +05 50 07.7 | 21.65 | 0.7754 | 0.0005 | H/K/br/G | gell-4.49 | A-1 |
| G8 | 09 11 26.45 | +05 50 52.0 | 21.71 | 0.776 | 0.001 | wk[O II]/H/K/br | ... | C-1 |
| G9 | 09 11 26.39 | +05 49 52.7 | 21.72 | 0.7674 | 0.0003 | H/K/br/G | f6V-3.73 | A-1 |
| G10 | 09 11 22.93 | +05 52 40.3 | 21.87 | 0.7628 | 0.0004 | Mg II/[O II]/H/K | ... | C-1 |
| G11 | 09 11 22.76 | +05 48 29.9 | 21.89 | 0.7692 | 0.0002 | H/K/br/G | gell-5.90 | A-1 |
| G12 | 09 11 30.61 | +05 50 17.1 | 21.94 | 0.766 | 0.001 | H/K/br/G | ... | A-2 |
| G13 | 09 11 31.59 | +05 50 37.6 | 21.98 | 0.769 | 0.001 | H/K/G | ... | A-3 |
| G14 | 09 11 27.79 | +05 50 45.5 | 22.04 | 0.760 | 0.001 | H/K/br | ... | A-3 |
| G15 | 09 11 31.22 | +05 51 26.6 | 22.05 | 0.7745 | 0.0005 | wk[O II]/H δ | ... | E-3 |
| G16 | 09 11 27.82 | +05 50 41.2 | 22.05 | 0.7758 | 0.001 | wk[O II]/K/H/G | ... | C-3 |
| G17 | 09 11 27.55 | +05 51 03.4 | 22.10 | 0.7767 | 0.0003 | H/K/br/G | g6III-4.01 | A-1 |
| G18 | 09 11 24.17 | +05 49 35.2 | 22.16 | 0.760 | 0.001 | [O II]/H/K/br | ... | E-3 |
| G19 | 09 11 26.78 | +05 50 19.0 | 22.25 | 0.7640 | 0.0002 | H/K/br/G | g6III-6.17 | A-1 |
| G20 | 09 11 26.72 | +05 50 17.6 | 22.25 | 0.7694 | 0.0006 | H/K/br/G | gell-3.65 | A-1 |
| G21 | 09 11 26.74 | +05 50 34.1 | 22.30 | 0.7705 | 0.0005 | H/K/br/G | ... | A-3 |
| G22 | 09 11 27.98 | +05 49 18.9 | 22.35 | 0.770 | 0.002 | H/K/br/G | ... | A-3 |
| G23 | 09 11 30.57 | +05 51 13.4 | 22.42 | 0.770 | 0.002 | H/K/br/G | ... | A-3 |
| L1 ^c | 09 11 27.56 | +05 50 54.2 | 22.4 | 0.769 | ... | ... | ... | ... |

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a R is the cross-correlation parameter. See Kurtz & Mink 1998 for more details.

^b Type and quality classification is similar to the one used by Cohen et al. 1999.

^c Main galaxy lens.

belong to an evolved cluster. Note that the small group of slightly redder objects detected some $10''$ southwest from the lens (Burd et al. 1998) is found at the same redshift as the cluster; further multicolor analysis needs to be done to explain the significance of this difference in color.

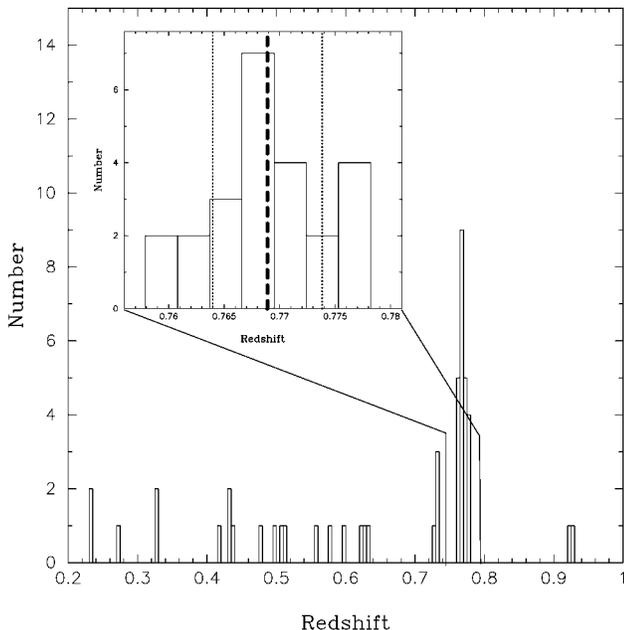


FIG. 2.—Redshift histogram of the redshift survey. *Inset:* Redshift histogram of the galaxy distribution at the cluster redshift. The dashed lined corresponds to the mean redshift of the cluster distribution, the dotted line to the standard deviation of 836_{-200}^{+180} km s⁻¹.

3. CLUSTER DYNAMICS AND MASS MODEL

Including the redshift of the lensing galaxy (E. E. Falco, M. Davis, & C. Stern 1999, private communication), we have redshift measurements of 24 cluster members with a mean redshift $\bar{z} = 0.7689 \pm 0.002$. The velocity dispersion of the 24 galaxies is $\sigma = 836_{-200}^{+180}$ km s⁻¹. If one keeps only the 14 high-quality spectra, we estimate the mean redshift of $\bar{z} = 0.7692 \pm 0.004$ and a velocity dispersion of $\sigma = 832_{-250}^{+175}$ km s⁻¹. The two estimates are in good agreement, so we will retain the first one in the following discussion. We used the biweight estimator to measure the cluster redshift and its dispersion. The errors were estimated by using the bootstrap algorithm for the mean redshift and the jackknife algorithm for the velocity dispersion (Beers, Flynn, & Gebhardt 1990).

We computed the harmonic radius R_h (e.g., Nolthenius & White 1987) from our spectroscopic cluster members as

$$R_h = D_A(\bar{z}) \frac{\pi N_m(N_m - 1)}{2} (\sum_i \sum_{j>i} \theta_{ij}^{-1})^{-1}, \quad (1)$$

where θ_{ij} is the angular distance between galaxies i and j , N_m is the number of cluster members, and $D_A(\bar{z})$ is the angular diameter distance at the mean cluster redshift \bar{z} . The cluster virial mass can then be estimated as $M_V = 6\sigma^2 R_h / G$. We found a harmonic radius of $R_h = 632 h_{50}^{-1}$ kpc and a mass $M_V = 6.2_{-2.6}^{+2.9} \times 10^{14} M_\odot$. Assuming that the cluster follows the σ - T_X relation (e.g., Girardi et al. 1996), we expect an X-ray temperature of $T_X = 4.5 \pm 1.2$ keV.

We have thus identified a new massive cluster at high redshift. This cluster is not as massive as the cluster MS 1054-03 (Tran et al. 1999; Hoekstra, Franx, & Kuijken 2000), but it has a similar velocity dispersion as MS 1137.5+6625 ($\sigma = 884$ km s⁻¹ as measured by Donahue et al. 1999). Finally, its

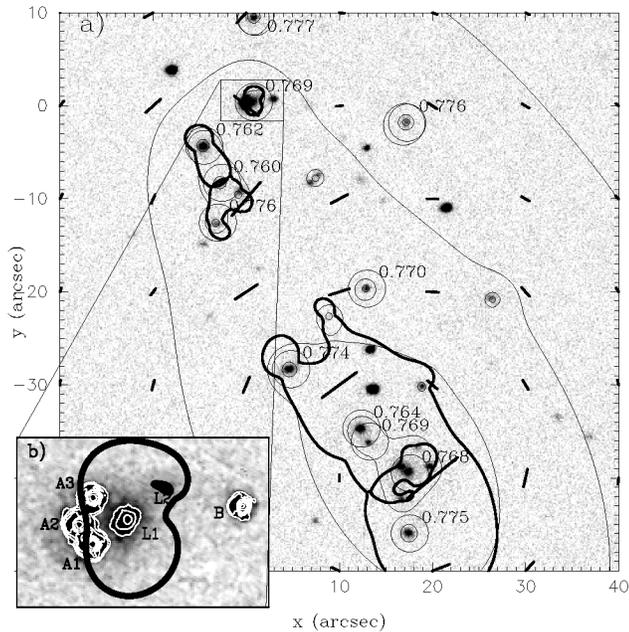


FIG. 3.—(a) Mass distribution of the cluster (*thin lines*) overlaid on the K-band image (F. Courbin 2000, private communication). The thick lines are the critical lines at redshift $z = 2.80$ of the QSO. (b) *HST*/NICMOS2 F160W archival image of the quadruple QSO RX J0911+05 (PI: E. E. Falco). The main lens is composed of two galaxies, L1 and L2. The critical lines (*thick lines*) correspond to the redshift $z = 2.80$ of the QSO. The shear field predicted for faint galaxies with mean redshift $z_s = 1$ is indicated by dashes; the smaller dashes correspond to a distortion of 10%, which should be easily measured with deep *HST* WFPC2 observations. Image A1 is the reference coordinates (0, 0). North is up, and east is to the left.

appearance is relatively elongated, and thus it resembles more that of MS 1054–03 or RX J1716+67.

Assuming a singular isothermal sphere centered on the brightest galaxy of the cluster, the computed velocity dispersion translates to a gravitational shear of $\gamma = \kappa = 0.11^{+0.04}_{-0.03}$ for $(\Omega, \lambda) = (1, 0)$ and $\gamma = \kappa = 0.13^{+0.04}_{-0.03}$ for $(\Omega, \lambda) = (0.3, 0.7)$ at the location of the multiple QSO. This quick estimate of the external shear is close to the value found in the modeling of the lens plus an external shear (Burud et al. 1998).

Having identified the cluster redshift and derived an estimate of the galaxy velocity dispersion, we can go a step further and try to model the mass distribution of the cluster and its galaxies in a similar way as for Abell 2218 (Kneib et al. 1996). The cluster galaxies are modeled as truncated isothermal spheres, with a velocity dispersion and truncation radius scaled with the galaxy luminosity. The center position of the cluster is set to the position of the brightest galaxy, and the velocity dispersion as given by our spectroscopic survey. The constraints are the quasar positions and flux ratios (although we only give a relatively small weight to the flux ratio constraints because of possible microlensing; Burud et al. 1998), the position, orientation, and ellipticity of the main lens system as measured on the *HST*/near-infrared camera and multiobject spectrograph 2 (NICMOS2) image (PI: E. E. Falco). The fiducial best-fitting model found is displayed in Figure 3, where we show the surface mass density of the model. Note that the lens model favors an elongated mass distribution of the cluster aligned with the cluster light distribution. We found a total mass-to-light ratio of $\sim 150\text{--}250 h_{50} M_{\odot} / L_{\odot}^V$ depending on the exact contribution of the cluster, which is a typical value for galaxy

clusters. The time delay expected between images A and B is strongly dependent on the exact morphology and mass distribution of the cluster; we found that $190 h_{50}^{-1} < \Delta t(\text{days}) < 260 h_{50}^{-1}$. The lower time delay value corresponds to a more massive cluster. Clearly, it would be very important to further constrain the mass distribution of the cluster before trying to get a constraint on the Hubble parameter.

4. DISCUSSION

We have identified a massive high-redshift cluster of galaxies at $\bar{z} = 0.769 \pm 0.002$ responsible for the very large external shear ($\gamma \sim 0.15$), affecting the lens potential of the quadrupole quasar RX J0911+05. The measured velocity dispersion based on 24 members leads to a velocity dispersion of $\sigma = 836^{+180}_{-200} \text{ km s}^{-1}$. Using these results we present a new mass model for this lens that predicts a time delay of $190 h_{50}^{-1} < \Delta t(\text{days}) < 260 h_{50}^{-1}$, depending on the exact mass distribution of the cluster.

Further observations using the Wide Field Planetary Camera 2 (WFPC2) on board *HST* will allow direct measurement of the predicted cluster weak shear from the distortions of faint background galaxies; X-ray observations conducted with the new X-ray satellites (*Chandra* or *XMM-Newton*) will permit the study of gas properties of this distant cluster in detail. Such complementary data will be essential in producing a more reliable mass model which, in combination with the foreseen measurement of the time delay, may provide an accurate cosmological estimate of the Hubble parameter.

This serendipitous cluster discovery is very interesting because it demonstrates that multiple QSOs with large separation are efficient in revealing high-redshift collapsed structure. Indeed, there is a growing number of such multiple QSOs where a cluster or group has been detected (e.g., Q0957: Bernstein & Fischer 1999; the Cloverleaf: Kneib et al. 1998a, 1998b; MG 2016+116: Hattori et al. 1997; Benitez et al. 1999; Soucail et al. 2000; PG 1115+080: Schechter et al. 1997; Kundić et al. 1997a). Therefore, multiple QSO systems constitute a useful way to discover and study high-redshift groups and clusters along their line of sight.

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