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LETTER

Letter to the Editor

Imaging and spectroscopy with FORS1 in the field of Q 0307−0015⋆,⋆⋆

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Abstract. We present VLT–observations of a recently detected galaxy cluster candidate in the field of the radio–quiet quasar Q 0307−0015. R–band images and multi–object spectra (MOS) have been obtained during the commissioning phase II of FORS1 in December 1998. The presumed central cluster galaxy shows the typical spectrum and surface brightness profile of an early–type galaxy and has a redshift of z=0.396. We measured the redshift of 20 galaxies in the $6\farcm8 \times 6\farcm8$ field and found further 11 galaxies with similar redshift implying that we see a galaxy cluster at intermediate z. We estimate the cluster richness to be comparable with Abell class 0–1. The cluster is not physically associated with Q 0307−0015 having a redshift of z=0.770. This was to be expected considering the projected distance of $\approx 5'$on the sky.

A closer look at the immediate sourrounding of the QSO shows that Q 0307−0015 seems to reside in an unspectacular environment. Neither a definite close companion candidate nor any excess population of faint galaxies can be seen. This is consistent with the finding at low redshift that most radio–quiet QSOs reside in poorer environments than their radio–loud counterparts.

Key words: galaxies: active – galaxies: clusters: general – galaxies: quasars: individual: Q 0307−0015

1. Introduction

The region around the quasar Q 0307−0015 (z=0.770, Chaffee et al. 1991) discussed here has first been observed during our survey of fields around intermediate redshift QSOs (0.4<z<1.0) with the Calar Alto 2.2m telescope. Those observations were performed with CAFOS (**C**alar **A**lto **F**aint **O**bject **S**pectrograph) to investigate the QSO galaxy environment. CAFOS is a focal reducer which provides mainly spectroscopy and imaging within a $15'$ field. Preliminary results from this survey were presented in Jäger et al. (1999). The main aim of these observations was the search for galaxy companion candidates physically associated with the QSOs, the evolution of the QSO environments with redshift, and their relation to QSO activity and QSO properties. Since we intended to study quasar environments, only QSOs without known galaxy clusters in their line of sight have been selected from the Véron–Catalog (Véron–Cetty & Véron 1996) for the sample. However, due to the large field size of CAFOS and the deepness of our observations several new galaxy cluster candidates probably not associated with the survey–QSOs were detected. One of these cluster candidates $5'$ west of Q 0307−0015 was selected for test observations with FORS1 (**FO**cal **R**educer **S**pectrograph) at the ESO–VLT in imaging– and MOS–mode during commissioning to investigate some capabilities of the instrument. The cluster candidate is not found within the NASA Extragalactic Data Base (NED). Scientific goals of the observations presented here are: (i) the observation of faint galaxies around the QSO to detect possible close companion candidates; (ii) the determination of galaxy redshifts in the western part of the field to verify the cluster membership, and (iii) to assess the state of activity of these galaxies. FORS1 has a 2 K Tektronix CCD with 24μ pixels. In standard mode a resolution of $0\farcs2$/pixel with a total field of view of $6\farcm8 \times 6\farcm8$ can be used. A high resolution imaging mode provides $0\farcs1$/pixel and $3\farcm4 \times 3\farcm4$ field size. A mechanically complex unit with 19 individually moveable slitlets (each $22\farcs5$ wide) can be used for MOS. Furthermore, FORS1 allows long slit spectroscopy as well as polarimetric and spectropolarimetric work. An overview about FORS1 and its future twin FORS2 can be found in Moehler et al. (1995) while some general examples of first observational results obtained with FORS1 are presented in Appenzeller et al. (1999).

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⋆ Based on observations made with the VLT UT1, operated on Cerro Paranal (Chile) by the European Southern Observatory (ESO).

⋆⋆ Based on observations made with the 2.2m telescope of the German–Spanish Astronomical Centre at Calar Alto, operated by the Max–Planck–Institut für Astronomie (Heidelberg), jointly with the Spanish National Commission for Astronomy.

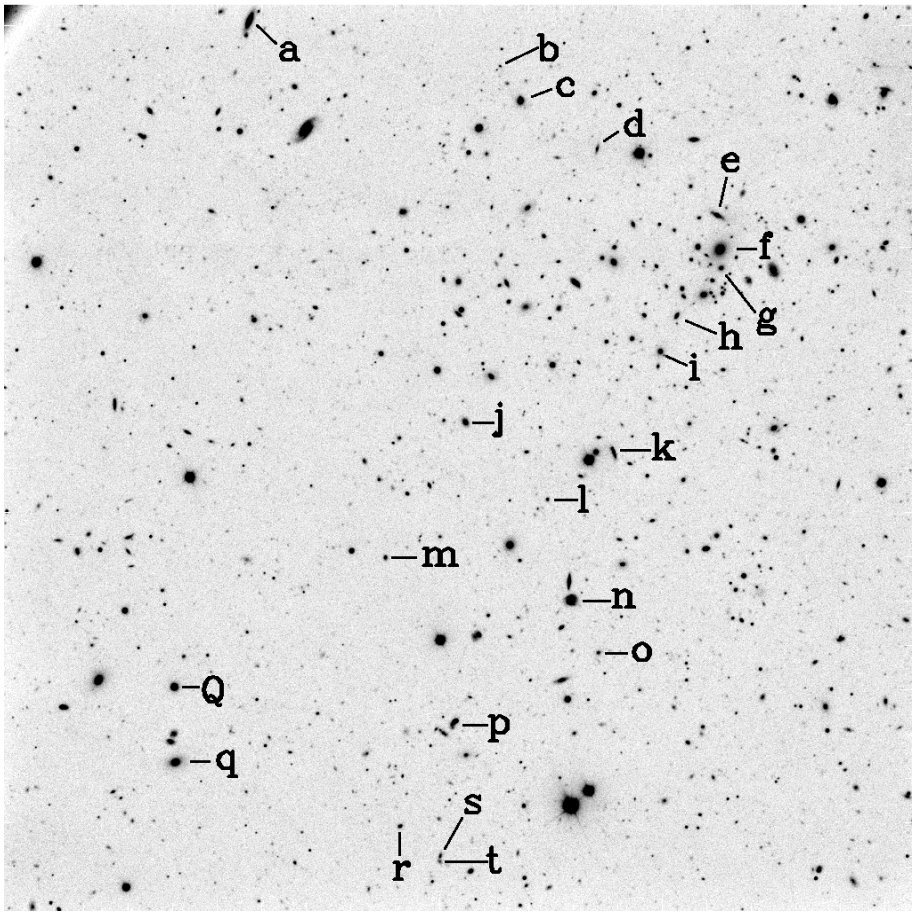

Fig. 1. The full FORS 6.′8 × 6.′8–field of view of the observed region near Q 0307−0015. The quasar is marked by a Q while the 20 objects from which we have useful spectra are labelled by a–t (north is up, east to the left).

2. Observations, data reduction and measurements

Observations were carried out with FORS1 at VLT UT1 on December 23 (Imaging) and December 26 (MOS) during the commissioning phase II. Three R–band images with five minutes integration time each were obtained of the field around Q0307−0015. The instrument has been used in standard mode. The telescope was pointed such that the QSO and the galaxy cluster candidate where located on the CCD. The individual frames were first bias substracted. Skyflats have been used to correct for the small scale pixel to pixel variations. For the correction of large scale gradients a normalized superflat was created by a medianed and smoothed stack of unregistered science frames (the Q 0307−0015 images were complemented by other frames from commissioning data). After removing the tracks of cosmic rays the individual frames have been aligned and coadded. The final coadded frame has an image quality of 0.″68 (FWHM). We used the Source Extractor package (SExtractor)(Bertin & Arnouts 1996) to carry out detection, classification and photometry of objects in the field. The photometric zeropoint was calculated from observations of Landolt fields (Landolt 1992). Based on differential number counts within the eastern part of the field (far from the central cluster region) and the comparison with other deep survey data (Metcalfe et al. 1995) we estimated completeness down to R=25. Within the MOS setup spectra of 23 objects in the range $18.6 < R < 23.7$ were obtained. The positioning of the slitlets was done on the basis of an aquisition frame of the field. A software allows a location of the slitlets on the targets with an accuracy of 0.″1. We used a slitwidth of 1″and grism GRIS150I+17 with a resolution of $\lambda/\Delta\lambda$ =185 (dispersion: 228 Å/mm, sampling: 5.5 Å/pixel) and a wavelength range of 3300–11000 Å. The integration time was 30 minutes. After the bias correction of the whole MOS frame, individual object spectra were extracted as well as the corresponding night sky spectra. Due to the slit length of 22″an appropriate sky spectrum for each object could be obtained from the same slitlet. For flatfielding two flatfield exposures taken with the same MOS setup – one with appropriate signal to noise for the red, one for the blue part of the spectral range – were normalized and combined. Wavelength calibration has been done with HgCd, He and two Ar lamps switched on at the same time for the subsequent focal field MOS-setup of the spectroscopic science observation. The curvature of the arc-lines and the dispersion solution was taken into account with a two-dimensional χ^2 fit of the positions and has been applied to the science observations later on. The crude instrument response was derived from the spectrophotometric standard star LTT 1788 observed during commissioning phase I at the end of September 1998 considering a standard atmospheric extinction law for an altitude of about 2500m (measured on La Silla). Slit losses were not considered for the spectra shown below and all science spec-

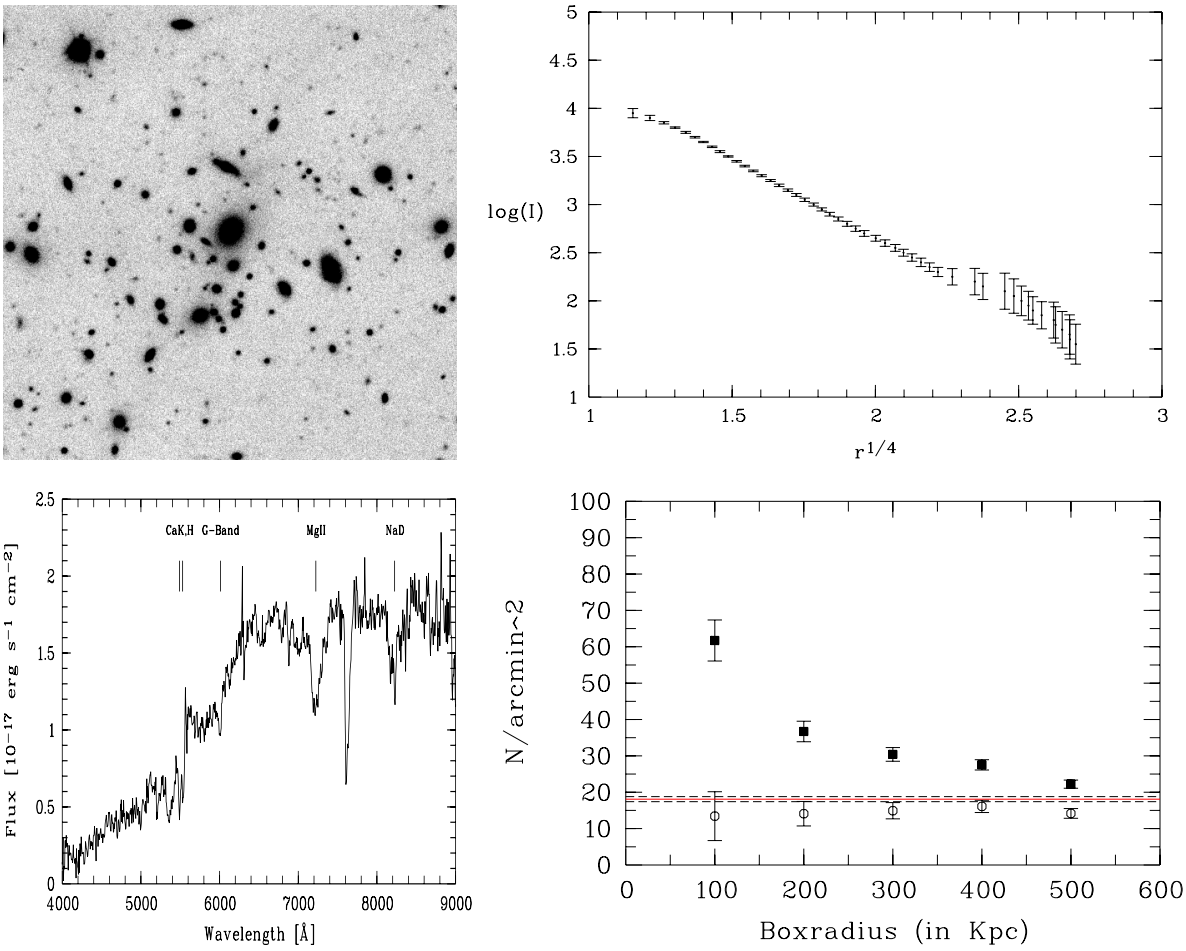

Fig. 2. Upper left: Central cluster region around galaxy f (100″field). Upper right: Surface brightness profile of galaxy f. Bottom left: FORS–spectrum of galaxy f showing typical features of an early–type galaxy at a redshift of z≈0.4. Major absorption lines are marked. Bottom right: The projected object density as function of distance to galaxy f (filled squares) and the QSO (open circles). See text for details.

tra have to be scaled individually to the flux derived from the photometry, according to the size of the objects.

3. Results and discussion

3.1. The galaxy cluster

We have obtained 23 spectra of faint objects in our FORS1 MOS–setup. Features characteristic for galaxies could be detected within 20 spectra and in most cases they were sufficient for redshift and galaxy type identification. Redshifts were derived using spectral analysis software from MIDAS. With starting guesses for the centers, maximum (minimum) values and widths (FWHM) and a simultaneous least-squares fit using the selected profile and a gradient search method, deblending of lines and a fit to the lines in a specified spectral region has been derived. The data points were continuum-subtracted before the fit was made. In Fig. 1 we show the coadded R–band image taken with FORS1 (north is up, east to the left) where the quasar and the 20 objects mentioned above are marked. In Table 1 we have listed these targets with their measured redshifts and their R magnitudes. The supposed cluster center with its dominant galaxy f is shown in Fig. 2 (u.l.). The luminosity profile of this brightest galaxy within that region is presented in Fig. 2 (u.r.). It follows clearly the de Vaucouleurs $r^{1/4}$ law for early–type galaxies. This is consistent with the obtained spectrum presented in Fig. 2 (b.l.). Both the shape of continuum as well as the absorption line features and the strength of the 4000 Å break are typical for an elliptical galaxy. From this spectrum we determine a redshift of z=0.396. Assuming $q_0 = 0.5$ and $H_0 = 75\,\mathrm{km\ s^{-1}\ Mpc^{-1}}$ (as throughout the paper) we calculate an absolute magnitude $M_R = -22.61$ (without K–correction) from the measured redshift and the apparent magnitude R=18.56. Thus it is a luminous ($M_R < M^\star$) elliptical galaxy typical for dominant central cluster galaxies. As Table 1 shows, 11 of the 20 observed galaxies reveal a similar redshift as galaxy f. The mean redshift is z=0.393±0.006. Therefore we conclude that we have detected a galaxy cluster at an intermediate redshift of z≈0.4. Although we have low resolution spectra, the scatter indicates a relatively high velocity dispersion ($> 1000\,\mathrm{km\ s^{-1}}$) of the cluster. Spectra of three cluster members are shown in Fig. 3. All of them are fainter than R=20. Several absorption line features identifies the objects as early type galaxies. In this galaxy cluster no remark-

Table 1. List of MOS–targets within the Q 0307–0015 field. The error of redshift determination is $\Delta z \approx 0.001$

Ident	z	R	M_R	Comment
a	0.108	18.82	-19.41	
b	0.493?	22.50	-19.18?	
c	0.389	19.39	-21.74	
d	0.392	21.20	-19.95	
e	0.402	19.63	-21.58	
f	0.396	18.56	-22.61	
g	0.404	20.43	-20.79	
h	0.388	20.26	-20.86	
i	0.390	20.10	-21.03	
j	0.392	20.02	-21.13	
k	0.393	20.07	-21.09	Em.lines
l	0.27?	21.79	-18.50	
m	0.184	21.13	-18.29	Em.lines
n	0.273	18.95	-21.36	Em.lines
o	0.4?	21.39	-19.80?	
p	0.129	19.41	-19.22	Em.lines
q	0.119?	18.94	-19.51?	
r	0.39?	21.25	-19.86?	
s	0.45?	21.65	-19.82?	
t	0.39?	22.06	-19.07?	

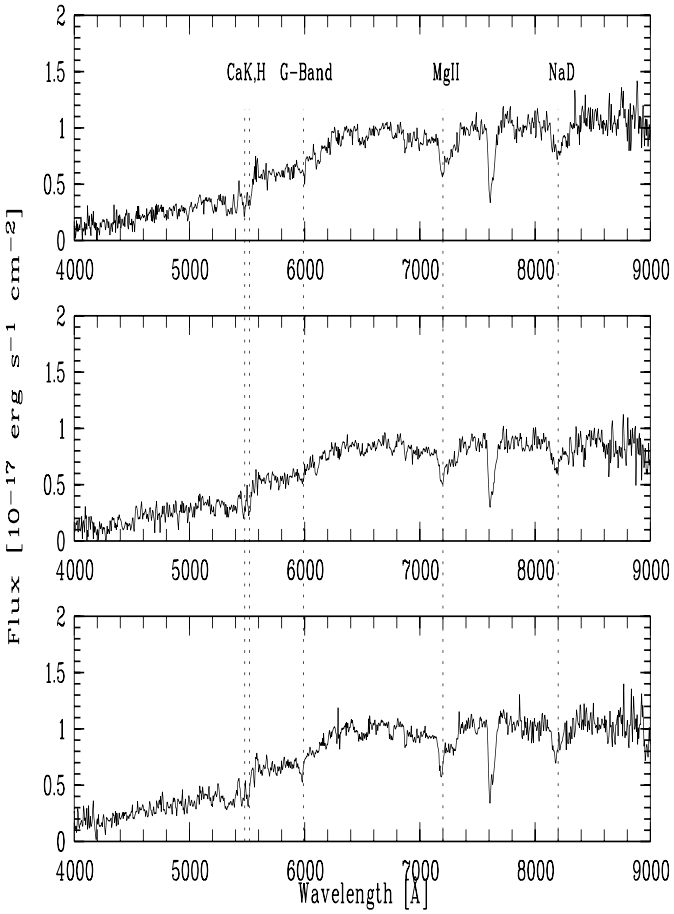

Fig. 3. FORS spectra of galaxies h (bottom), i (center) and j (top) (cf. Fig. 1). The main identified absorption lines are marked.

able signatures of gravitational interactions on larger scales are present. From the 12 identified galaxies with the clusters redshift only one shows emission lines (galaxy k) and this galaxy looks disturbed. Undergoing starbursts triggered by gravitational interaction seems not to be a common feature within the cluster. In Fig. 2 (b.r.) the projected field density of objects as a function of distance to galaxy f is shown by the filled squares. For this purpose we have counted the total number of detected objects within squares of increasing size (binsize=100kpc at z =0.4, maximum=500kpc) centered on galaxy f and have calculated the mean object density N/arcmin^2 in each box. For comparison we measured the counts of the rest of the field (outside the 500kpc box). We included all sources down to a limit of R=24 which corresponds roughly to M^*+4 at the cluster redshift. The continuous line in the x–direction shows the mean object density in the background while the dotted lines represent the 1σ–scatter derived from Poisson statistics. The filled squares are the measured densities within the boxes mentioned above. The 1σ–error bars are also from Poisson statistics. The density excess towards the assumed central cluster galaxy f can easily be seen. To estimate the richness of the cluster we counted all objects with $m_3 < m < m_3 + 2$ within 500kpc following mainly Abell (1958). m_3 corresponds to the third ranked cluster galaxy (regarding to their magnitudes) and $m_3 + 2$ to a galaxy two magnitudes fainter than m_3. There are three galaxies within the 500 kpc box which have the third brightest apparent magnitude compared to galaxy f. One of these galaxies has been observed within our MOS–setup and has the matching redshift of z≈0.4. According to our constraints mentioned above we have counted 61 objects which relate to an Abell richness class 0–1 for the galaxy cluster. On the one hand, we underestimate the richness since we counted galaxies in a smaller area than the often used Abell radius of 1.5Mpc. On the other hand, we overestimate the richness because some counted galaxies are certainly not cluster members but foreground or background objects.

3.2. Remarks on the close QSO environment

AGN environment studies provide information on the link between AGN activity and tidal interactions and on differences of the environments due to intrinsic AGN properties or an evolution with z. Following earlier studies at low z, radio–loud QSOs (RLQs) reside in early–type galaxies and tend to lie within clusters of Abell richness class 0–1 while radio–quiet QSOs (RQQs) reside in spiral hosts and within poor environments. Extensive work on environments of QSOs at z≈0.5 has been done in particular by Yee & Green (1987), Ellingson et al. (1991a,b) and Yee & Ellingson (1993). Now the picture has become more complex since some RQQs have recently been found also within elliptical hosts (e.g. Bahcall et al. 1997). Moreover, few observations at z>1 seem to show both, RLQs and RQQs, residing in comparable compact groups of possibly starbursting galaxies (e.g. Hutchings et al. 1995, Hutchings 1995). On the other hand, Fried (1997) took very deep (completeness down to R≈26) images of three RLQs at z=1 and did not find any galaxy density

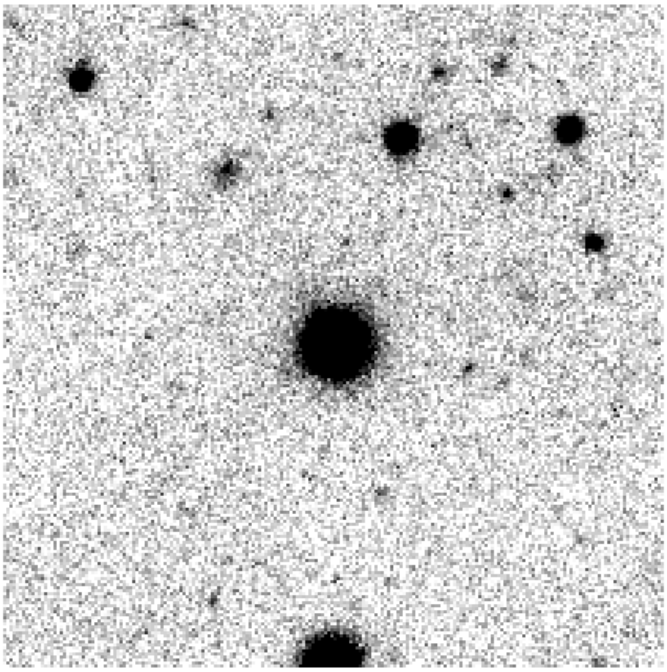

Fig. 4. Close environment of Q 0307−0015. A fieldsize of 45″diameter corresponding to ≈240 kpc at z=0.77 is displayed.

excess around these objects. Overall there are only few observations of QSO environments at intermediate z with sufficient limiting magnitudes to observe probable galaxy companion candidates and to calculate usable statistics for the detection of possible density enhancements. Fig. 4 shows the immediate region around Q 0307−0015 corresponding to a projected field of ≈240 kpc at the QSOs redshift z=0.770. Despite the subarcsecond resolution and the deepness of the image neither definite signs of a close companion galaxy candidate nor evidence for an enhancement of faint galaxies near the QSO seems to be present. For a quantitative measurement we counted all objects within a box of 300 kpc projected radius around the QSO and compared this number density D_Q with the mean object density of the field D_F outside this region. To avoid unrealistic high values of D_F due to contamination by the galaxy cluster in the western part of the observed field, only objects detected in the eastern half of the CCD frame have been used. Considering all detected sources down to R=25 we measured $D_Q = 27.45 \pm 3.05$ per arcmin^2 and $D_F = 31.23 \pm 1.49$ per arcmin^2. This is in good agreement with the assumption that Q 0307−0015 resides in an environment comparable to normal field galaxies. This also confirmed by Fig. 2(b.r.) which shows the projected object density as function of distance to the QSO (open circles) calculated in the same manner as for the galaxy cluster (cf. 3.1.). Thus, our result is in general agreement to observations of RQQs at low redshifts.

4. Summary

We have presented R–band imaging and MOS observations of the field around the z=0.770 radio–quiet quasar Q 0307−0015 obtained with FORS1 at VLT–UT1. A galaxy cluster candidate ≈5′ west of the QSO as well as the close QSO environment has been investigated. Since 12 out of 20 galaxies reveal a redshift of z≈0.4 we conclude that we have detected a new galaxy cluster at intermediate redshift. The brightest and assumed central cluster galaxy has an appropriate redshift and could be identified as an early type galaxy. From number count statistics we estimate an Abell richness of 0–1 for the cluster. Only one of the observed cluster members shows emission lines.

The QSO seems to reside in an unspectacular environment comparable to that of normal field galaxies. In particular no definite signs of a closeby galaxy in the vicinity of the QSO which may act as an absober, lensing candidate or even a real associated interacting companion have been detected.

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