A&A 531, L15 (2011)
DOI: 10.1051/0004-6361/201117190

Astronomy & Astrophysics

Letter to the Editor

Discovery of a massive X-ray luminous galaxy cluster at $z = 1.579$ ⋆

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Received 4 May 2011 / Accepted 30 May 2011

ABSTRACT

We report on the discovery of a very distant galaxy cluster serendipitously detected in the archive of the *XMM-Newton* mission, within the scope of the *XMM-Newton* Distant Cluster Project (XDCP). XMMUJ0044.0-2033 was detected at a high significance level (5σ) as a compact, but significantly extended source in the X-ray data, with a soft-band flux $f(r < 40'') = (1.5 \pm 0.3) \times 10^{-14}$ erg s^{-1} cm^2. Optical/NIR follow-up observations confirmed the presence of an overdensity of red galaxies matching the X-ray emission. The cluster was spectroscopically confirmed to be at $z = 1.579$ using ground-based VLT/FORS2 spectroscopy. The analysis of the $I-H$ colour−magnitude diagram shows a sequence of red galaxies with a colour range $[3.7 < I-H < 4.6]$ within 1′ from the cluster X-ray emission peak. However, the three spectroscopic members (all with complex morphology) have significantly bluer colours relative to the observed red-sequence. In addition, two of the three cluster members have [OII] emission, indicative of on-going star formation. Using the spectroscopic redshift we estimated the X-ray bolometric luminosity, $L_{\mathrm{bol},40''} \sim 5.8 \times 10^{44}$ erg s^{-1}, implying a massive galaxy cluster. This places XMMU J0044.0-2033 at the forefront of massive distant clusters, closing the gap between lower redshift systems and recently discovered proto- and low-mass clusters at $z > 1.6$.

Key words. galaxies: clusters: individual: XMMUJ0044.0-2033 – galaxies: high-redshift – X-rays: galaxies: clusters

1. Introduction

In the hierarchical clustering scenario for structure formation, galaxy clusters result from the gravitational collapse of the densest peaks in the primordial fluctuations, and grow through accretion and mergers with neighboring poor clusters or groups (e.g. Colberg et al. 1999). The most massive galaxy clusters are therefore the last structures to form and virialize.

Fully assembled clusters strongly emit thermal X-rays arising from the intracluster medium (ICM), a hot, diffuse plasma that contains most of the cluster baryons. X-ray data is therefore essential to assess the dynamical state of a high-redshift overdensity of galaxies, allowing us to discriminate between a cluster and a proto-cluster. During the last decade, we have witnessed a tremendous improvement on the detection and study of massive clusters up to $z = 1$ and beyond, thanks to the *Chandra* and *XMM-Newton* observatories. While clear X-ray emission has been detected in several massive $z > 1.4$ clusters (Stanford et al. 2006; Fassbender et al. 2011a; Nastasi et al., subm.), the IR selected clusters at $z = 1.6$ (Papovich et al. 2010) and 2.1 (Gobat et al. 2011) show no prominent X-ray diffuse emission, which prevents the assessment of their dynamical status from an X-ray analysis.

The discovery and study of very distant massive clusters is essential to trace the epoch of cluster formation and has important consequences for cosmology. Recent observational (e.g. Jee et al. 2009) and theoretical studies (e.g. Baldi & Pettorino 2011) have shown that high-z clusters are important probes to test the standard ΛCDM model, either by detecting departures from the standard model (e.g. as a test for dynamical coupled dark energy) or as an indication that the initial conditions are not completely Gaussian (Jimenez & Verde 2009; Sartoris et al. 2010).

Serendipitous searches of the *XMM-Newton* archive provide one of the most efficient ways to find massive distant clusters, due to the large area and photon collecting power of this mission. In particular, the *XMM-Newton* Distant Cluster Project (XDCP) with a survey area of ∼80 deg^2 and an average soft band sensitivity of 0.8×10^{-14} erg s^{-1} cm^{-2}, has proven to be a successful high-z cluster survey, with about 30 clusters confirmed to be at $0.8 < z < 1.6$ (e.g. Mullis et al. 2005; Santos et al. 2009; Fassbender et al. 2011a). The technical details of this program can be found in Fassbender et al. (in prep.).

In this Letter we present the properties of a newly discovered galaxy cluster at $z = 1.58$, using a multi-wavelength dataset covering X-rays, optical/NIR imaging, and optical

⋆ This work is based on observations obtained with *XMM-Newton*, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA); and on observations carried out using the New Technology Telescope and the Very Large Telescope at the La Silla Paranal Observatory, under Program IDs 079.A-0634(B), 081.A-0312(A) and 084.A-0844(A).
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spectroscopy. The adopted cosmological parameters are H_0 = 70 km s^{-1} Mpc^{-1}, Ω_m = 0.3, Ω_Λ = 0.7. In this cosmology, 1′ on the sky corresponds to 508 kpc at z = 1.58. Filter magnitudes are presented in the Vega system unless stated otherwise.

2. Observations and data analysis

2.1. X-ray properties

XMMUJ0044.0-2033[1] (hereafter XMMUJ0044, RA: 00^{h}44^{m}05.2^s, Dec: −20^{d}33^{m}59.7^s) was serendipitously detected in the *XMM-Newton* field with OBSID = 0042340201, at an off-axis angle of 10.8 arcmin. The nominal exposure time of this observation is 15 ks, with a clean effective time of 8.5 ks. The data reduction and source extraction were performed with `SAS v6.5`. The cluster candidate was detected as a strong extended source, with an extent significance of 5σ. The X-ray emission is compact, however, it is significantly extended compared to the local PSF.

Based on the X-ray contours and lack of an optical counterpart on DSS, XMMUJ0044 was classified as a strong distant cluster candidate. Using the growth curve method we measured the cluster unabsorbed soft-band flux (Galactic $N_H = 1.9 \times 10^{20}$ cm^{-2}) within a circular region of 40″ radius, $f_x[0.5-2.0] = (1.5 \pm 0.3) \times 10^{-14}$ erg/s/cm^2, and within the estimated R_{500}, $f_x[0.5-2.0] = (1.6 \pm 0.3) \times 10^{-14}$ erg/s/cm^2. The scaled radius R_{500} (519 kpc) was obtained using the scaling relations in Pratt et al. (2009). Using the cluster redshift (see Sect. 2.3) we measure the cluster soft-band luminosity $L_{X,40''}[0.5-2.0] = (1.8 \pm 0.4) \times 10^{44}$ erg/s and bolometric luminosity, $L_{bol,40''} = 5.8 \times 10^{44}$ erg/s ($L_{bol,R_{500}} = 6.1 \times 10^{44}$ erg/s).

We followed two approaches to estimate the cluster temperature and mass, in order to evaluate statistical and systematic errors associated with these measurements. In an initial, more empirical approach, we scaled the X-ray properties of another XDCP distant cluster, XMMUJ2235.3-2557 at z = 1.393 (Mullis et al. 2005), which were accurately measured using high-quality *Chandra* data: $T = 8.6^{+1.3}_{-1.2}$ keV and $L_{bol,40''} = 8.5 \times 10^{44}$ erg/s (Rosati et al. 2009). The cluster total mass, obtained from weak lensing measurements, is equal to $7.3 \pm 1.3 \times 10^{14}$ $M_\odot$ (Jee et al. 2009). Applying the empirical scaling relation, $L \propto T^{2.88}$ (Arnaud & Evrard 1999), and the self similar relation $M \propto T^{3/2}$ (Rosati et al. 2002), we obtain estimates of the temperature and total mass of XMMUJ0044: $T_{est} \approx 6.9$ keV, $M_{tot} \approx 5 \times 10^{14}$ $M_\odot$.

Following the assumption of a non-evolving $L_X - T$ scaling relation and the related slower evolution of the $L_X - M$ relation (Fassbender et al. 2011b), we estimate an ICM temperature of $T_{est} = 4.8 \pm 1.2$ keV, and a mass $M_{500} = (2.3 \pm 0.5) \times 10^{14}$ $M_\odot$, corresponding to a total mass $M_{200} \sim 3.5 \times 10^{14}$ $M_\odot$.

2.2. Optical/NIR photometry

The initial follow-up procedure of the XDCP candidates is to perform 2-band imaging in the NIR and optical, using SOFI (Moorwood et al. 1998) and EMMI (Dekker et al. 1986) mounted on the 3.5 m ESO/NTT telescope. In 2007 (Prog ID 079.A-0634(B), PI H. Quintana) we acquired 1 h of H-band imaging with SOFI using the *large field* mode, corresponding to a 5′ × 5′ FoV, and a pixel scale of 0.288″/pixel. I-band imaging (30 min) was taken with EMMI in the RILD (Red Imaging and Low Dispersion spectroscopy) mode, which is suitable for observations redder than 400 nm, using the I#610 filter. In this mode the FoV is 9.1′ × 9.9′, the pixel scale is 0.335″/pix, and we used a binning of 2 × 2. The H-band data was reduced with the package ESO/MVM (Vandame 2004) and the I-band imaging was processed with IRAF routines. The seeing of the images is on average 0.8″ in the H-band image, and 1.0″ in the I-band. The photometric zero points are 22.52 ± 0.02 mag and 25.61 ± 0.01 mag in the H- and I-band, respectively, based on 5 standard stars taken in the nights of the science observations.

Pre-imaging in the z-band (10 min) was obtained in 2008 for the upcoming spectroscopic observations, using VLT/FORS2 (Prog ID 081.A-0312(A)), PI H. Quintana). In Fig. 1 we show the colour composite (IzH), where we clearly identify an overdensity of red galaxies coincident with the X-ray emission.

2.3. Spectroscopic data

In 2009 we acquired medium-deep observations (2.2 h) with VLT/FORS2 (Prog ID 084.A-0844(B), PI H. Quintana), to obtain spectroscopic redshifts for the galaxies associated with the cluster We observed one MXU-mode slit-mask using the 300I grism that covers the wavelength range 5800−10500 Å, with a resolution of R = 660. The data reduction was performed with an adapted version of the VIMOS Interactive Pipeline and Graphical Interface (VIPGI, Scodeggio et al. 2005).

The target selection for the spectroscopic mask was based primarily on the initial $I-H$ colour–magnitude diagram (CMD). Technical constraints concerning the positioning of the slits in the candidate cluster center limited the number of targets to five slits in the region encompassing the X-ray emission, and a total of seven slits within a cluster-centric distance of 1′. Three out of seven targeted galaxies within 46″ from the X-ray centroid have a redshift of $z \sim 1.58$. The cluster redshift is thus $z = 1.579 \pm 0.003$. The redshift measurements were based on the detection of the [OII] (λ 3727) emission line and the FeII absorption series (see Table 1 and Fig. 2), and by cross-correlating the spectra with a set of spectral templates. Two of the three confirmed members have [OII] emission, indicating ongoing star formation, with equivalent widths of (−32 ± 6) Å and (−88 ± 8) Å for galaxies ID 2 and ID 3 respectively.

2.4. Colour–magnitude diagram

In order to identify a sequence of red elliptical galaxies that typically characterize relaxed galaxy clusters (Gladders & Yee 2000), we investigated the $I-H$ colour−magnitude diagram using the cluster redshift obtained in the previous section.

We applied the IRAF task GAUSS to perform the PSF matching of the two bands and used SExtractor (Bertin & Arnouts 1996) in *dual image mode* to produce the photometric catalogs. The CMD is presented in Fig. 2-left panel, showing only objects within a cluster-centric distance of 1′. To limit intrinsic galaxy colour gradients, the $I-H$ colour was measured in small apertures of 1.3″ diameter, which is slightly larger than the PSF. Errors on the colours are derived from the SExtractor I- and H-band uncertainties, ranging from 0.06 to 0.49 mag (for the faint, red galaxies). Total H-band magnitudes were obtained with the SExtractor parameter `MAGAUTO`. The galactic extinction was accounted for using dust extinction maps from Schlegel et al. (1998) available at the Nasa Extragalactic Database. We retrieved $E(B-V)$ = 0.018 mag, corresponding to corrections in the I- and H-bands of 0.034 mag and 0.010 mag, respectively.

[1] Also listed as extended in the 2XMM catalogue as 2XMM J004405.2-203359 (Watson et al. 2009).

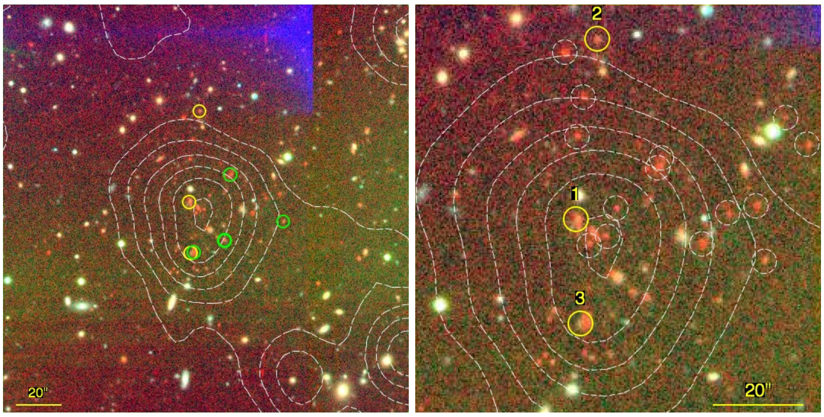

Fig. 1. *IzH* colour image of XMMUJ0044 with X-ray contours overlayed in white and the 3 spectroscopically confirmed cluster members shown with yellow circles (ID numbers refer to Table 1). *Left*: cluster field image ($3' \times 3'$) showing the 4 interlopers (green circles) within $1'$. *Right*: blow-up of the core region ($1.5' \times 1.5'$) showing the red-sequence galaxies (white circles) – see Fig. 2. North is up and East is to the left. The *XMM-Newton* PSF at the cluster off-axis angle is $\sim 10''$ (*FWHM*).

Table 1. Spectroscopic redshifts of 7 galaxies located within $1'$ of the X-ray centroid, including the three cluster members of XMMU J0044 (ID 1, 2, 3).

ID	RA J2000	Dec J2000	H mag	$I-H$ mag	d_c $''$	z_{spec}	Features
1	00:44:05.63	–20:33:53.99	18.6	3.07	8	1.5790 ± 0.0003	FeII, MgII
2	00:44:05.33	–20:33:13.72	19.8	3.23	46	1.5788 ± 0.0003	[OII], FeII
3	00:44:05.57	–20:34:16.10	19.3	2.27	17	1.5721 ± 0.0008	[OII]
4	00:44:04.57	–20:34:10.76	19.7	3.17	14	0.5924 ± 0.0002	[OII], H_β, [OIII]
5	00:44:04.40	–20:33:42.05	18.9	4.29	21	1.0709 ± 0.0009	CaH/K
6	00:44:02.73	–20:34:02.19	20.1	3.79	35	1.3271 ± 0.0008	CaH/K
7	00:44:02.41	–20:33:46.67	22.1	2.02	41	1.0178 ± 0.0007	[OII]

Notes. We list total Vega H-band magnitudes, $I-H$ colours, projected distances in arcseconds relative to the X-ray center, spectroscopic redshift and spectral features.

We estimate m^* to be at $H = 20.1$ mag (vertical dotted line in Fig. 2) using the evolution of m^*_H predicted by Kodama & Arimoto (1997) models with $z_f = 3$. We note that these expectations are confirmed up to $z = 1.4$, with the study of the H-band luminosity function of XMMUJ2235 (Strazzullo et al. 2010). We identify a sequence of 14 red galaxies located within a radius of $1'$ from the X-ray center (Fig. 1, left-panel), by applying a reasonable colour-cut of $3.7 < I-H < 4.6$, and considering only galaxies up to the 50% completeness limit in the H-band.

In addition to the three cluster members and the four interlopers, we also indicate the colour of the large, central galaxy. The three cluster members have $I-H$ colours that are bluer than what one would naively expect using Simple Stellar Population (SSP) models considering a Salpeter IMF (Salpeter 1955) with solar metallicity of passively evolving ellipticals with formation redshift $z_f = 3$ and 5, that predict $I-H$ equal to 3.75 and 4.0, respectively, at the cluster redshift. In particular, galaxy ID 3 has a very prominent [OII] line, which is reflected in its $I-H$ colour, 1 mag bluer than the other two spectroscopic members. This rather blue galaxy is located in the core, which is unusual in the X-ray clusters studied so far out to $z \sim 1.4$, since star forming galaxies in clusters are typically located in the outskirts of the cluster. The confirmed members and the large central galaxy show signs of distorted morphology and resemble late-type galaxies. Sill, only with the *Hubble* Space Telescope it will be possible to accurately assess the structure of these galaxies.

3. Discussion

The X-ray analysis, based on 110 cluster counts in the [0.35–2.4] keV band, allowed us to estimate a bolometric luminosity of $\sim 6 \times 10^{44}$ erg/s. This value is typical of low-z massive galaxy clusters and corresponds to about three times the luminosity of another cluster at a very similar redshift, XMMUJ1007.4+1237 at $z = 1.56$, which has $L_{bol}(r < R_{500}) \sim 2.1 \times 10^{44}$ erg/s (Fassbender et al. 2011a). Furthermore, XMMUJ0044 is also significantly more luminous than the more distant poor cluster/groups discovered at $z = 1.62$, CIG2018.3-0510 with $L_{[0.1-0.24]} \sim 0.3 \times 10^{44}$ erg/s ($T_{est} = 1.7$ keV, Tanaka et al. 2010) and CLJ1449+0856 at $z = 2.07$ with $L_{[0.1-0.24]} \sim 0.7 \times 10^{44}$ erg/s ($T_{est} = 2.0$ keV, Gobat et al. 2011). We note that recent work using shallow *Chandra* data of *Spitzer*/IRAC cluster ISCS J1438.1+3414 at $z = 1.49$, shows this to be a massive cluster, with $L_{[0.5-2.0]} = 1.0 \times 10^{44}$ erg/s and luminosity derived $M_{200} \sim 2.2 \times 10^{14}\ M_\odot$ (Brodwin et al. 2010).

The optical/NIR data depicts a population of red galaxies centered on the X-ray contours. In addition to the SSP models, we also compared the sequence of 14 red galaxies with what we would expect from a de-evolved CMD of XMMUJ2235 at $z = 1.58$ (solid blue line in Fig. 2). This empirical expectation is in excellent agreement with predictions from Kodama & Arimoto (1997) models for $z_f = 5$, therefore the observed red-sequence (RS) of XMMUJ0044 appears fainter and redder than expected. A possible explanation is that this sequence is not entirely formed by normal passive galaxies, but instead it is populated by dusty star-forming galaxies (Pierini et al. 2005). On the other hand, the large uncertainty in the colours of the faint, red galaxies prevents a more accurate assessment of the locus of the red-sequence. The bright population in the cluster core (including ID 1 and ID 3) is not dominated by passive galaxies as observed at lower redshifts, instead we observe bright blue star forming galaxies in the center of the cluster that might dominate the bright end of the colour–magnitude diagram. Similar findings have been reported at $z = 1.45$ (Hilton et al. 2010) and $z = 1.6$ (Tran et al. 2010).

The central group of three red galaxies for which we have no spectroscopic information is of particular interest. The $I-H$ colour of the largest and brightest galaxy (magenta star in Fig. 2) is redder (by 0.26 mag) than the brightest spectroscopic member (ID 1, only $2''$ away). The other two smaller central galaxies are about 1 mag fainter relative to the former and are significantly redder ($I-H = 4.13$ and 4.17 mag). We may argue that

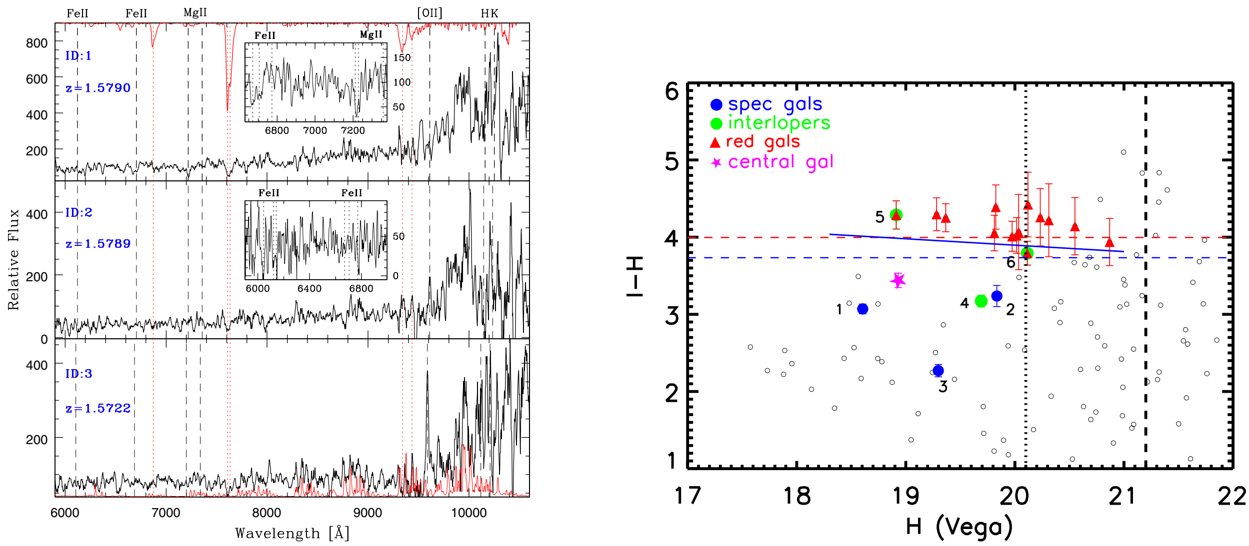

Fig. 2. *Left*: FORS2 spectra of the three confirmed cluster members, smoothed with a 7 pixel boxcar filter. In the *first panel* we overlay the telluric absorption spectrum in red. Sky emission lines are shown in red in the *bottom panel*. The *inset* shows the FeII and MgII lines. *Right*: $I-H$ colour−magnitude diagram of XMMUJ0044. Only objects within 1′ radial distance from the cluster X-ray center are shown. The three confirmed members are shown in blue circles and the interlopers are marked in green. The ID numbers refer to Table 1. The large, central galaxy is identified by a magenta star. We also flag the red ($3.7 < I-H < 4.6$) galaxies that are likely associated with the cluster (red triangles). The horizontal dashed lines refer to SSP model galaxies with different stellar formation epochs at the cluster redshift (red line: $z_f = 5$, blue line: $z_f = 3$). The solid blue line refers to the de-evolved CMD of XMMUJ2235 at $z = 1.58$. The 50% completeness limit in the H-band is shown by a vertical dashed line.

this group is in the process of merging that will eventually lead to the formation of the brightest cluster galaxy.

4. Conclusions

In this Letter we present a multi-wavelength analysis of an X-ray luminous galaxy cluster at $z = 1.579$, XMMUJ0044.0-2033, that was serendipitously discovered in the archive of the *XMM-Newton* observatory. Here we summarize our main results:

– XMMUJ0044 was detected as a bright, compact but significantly extended source in the *XMM-Newton* data.
– In dedicated observations in the H- and I-bands we found an overdensity of red galaxies coincident with the X-ray peak.
– Using FORS2 spectroscopy we secured three cluster members within $r = 46''$ from the cluster X-ray peak, with $z \sim 1.58$.
– The $I-H$ colour−magnitude diagram shows that the three confirmed members have bluer colours with respect to the sequence of 14 galaxies with $[3.7 < I-H < 4.6]$. The cluster members show a distorted morphology and two of them exhibit [OII] line emission.
– We identified an interesting central group of 3 galaxies located at $\sim 2''$ from the cluster X-ray centroid. The brightest galaxy is redder than the confirmed members, but bluer than the two smaller companions, which sit on the observed RS.
– Knowing the cluster redshift, we measured a luminosity, $L_{\mathrm{bol},40''} = 5.8 \times 10^{44}$ erg/s or $L_{\mathrm{bol},R_{500}} = 6.1 \times 10^{44}$ erg/s, and estimated a range of the cluster mass, $M_{\mathrm{tot}} \sim 3.5$–$5.0 \times 10^{14}\ M_{\odot}$, depending on the methods used to scale the luminosity.

The analysis presented here confirms XMMUJ0044 as one of the most massive, distant clusters known to date, characterized by a high X-ray luminosity. Deeper, high-resolution X-ray data will allow us to measure the ICM temperature, which is crucial to better assess the dynamical state of this cluster, as well as the gas metal content. Additional spectroscopy and already awarded HAWK-I J/Ks imaging data will enable a more complete characterization of the galaxy cluster population.

Acknowledgements. J.S.S. thanks Simona Mei for fruitful discussions and advice on the CMD and Gabriel Pratt for comments on the X-ray analysis. This work was supported by the DFG under grants Schw 536/24-2, BO 702/16-3, and the DLR under grant 50 QR 0802. This research has made use of the NASA/IPAC Extragalactic Data base (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology.

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