Astron. Astrophys. 326, 489–492 (1997)

ASTRONOMY AND ASTROPHYSICS

Research Note

Two X-ray clusters close to line of sight of the luminous QSO HS 1700+6416⋆

D. Reimers[1], **F. Toussaint**[1], **H.-J. Hagen**[1], **H. Hippelein**[2], **and K. Meisenheimer**[2]

[1] Hamburger Sternwarte, Universität Hamburg, Gojenbergsweg 112, D-21029 Hamburg, Germany
[2] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

Received 18 April 1996 / Accepted 27 March 1997

Abstract. We report the serendipitous discovery with ROSAT of two X-ray clusters close to the line of sight of the QSO HS 1700+6416 (z = 2.72) which is itself one of the most luminous QSOs known. Cluster A (1'40" northwest of the QSO) is Abell 2246, while cluster B (3' northeast) is a hitherto unknown distant cluster. We have determined the redshifts of clusters A and B as z = 0.25 and z = 0.44 respectively. Although both clusters appear barely resolved by ROSAT, the X-ray surface brightness distribution can be represented well by β-models $I(\theta) = I_o(1+(\theta/\theta_c)^2)^{-3\beta+0.5}$ where θ_c is the cluster core radius (cf. Henry et al. 1993) if the detector point spread function is taken into account. Assuming $\beta = \frac{2}{3}$ we find core radii θ_c (A) = 14" $\pm$ 2" and θ_c (B) = 18" $\pm$ 2". Gas temperatures are T (A) = 6 $\pm 3 \cdot 10^7 K$ and $T(B) = 3 \pm 1.5 \cdot 10^7 K$, X-ray luminosities are $L_x(0.4 - 2keV$ rest frame$) = 4.1 \cdot 10^{43} erg\, s^{-1}$ and $8.45 \cdot 10^{43} erg\, s^{-1}$ respectively ($Ho = 50, q_o = \frac{1}{2}$).

Cluster B shows a giant luminous arc located approximately 15" ($\simeq$ 1 core radius) NW of the cluster center. We show that magnification of HS 1700+6416 by cluster lensing by the two X ray clusters can be excluded as reason for the high apparent luminosity of the QSO.

Key words: galaxies: clusters: individual: A 2246, HS 1700 B – quasars: individual: HS 1700+6416 – cosmology: gravitational lensing

1. Introduction

The luminous QSO HS 1700+6416 (z = 2.72, V = 16.1) (Reimers et al. 1989, 1992) is one of the few high-redshift QSOs observed in the UV down to rest wavelengths $\lambda \simeq 330$ Å. Its flux f_λ increases to shorter wavelengths as $f_\lambda \sim \lambda^{-1}$, i.e. the "big blue bump" extends to at least 3 Rydbergs. In order to extend our knowledge of the energy distribution to shorter wavelengths, we observed HS 1700+6416 (not a ROSAT All Sky Survey source) with a deep pointed observation. The QSO was detected with a rate of $\sim 0.0115 cts\, s^{-1}$. It shows a rather typical behaviour in X-rays, flux and spectrum (Reimers et al. 1995). To our surprise the ROSAT image of the QSO appears to be framed by two bright X-ray clusters whose X-ray emission extends to the line of sight of the quasar. This unique constellation (Fig. 1) - we know of no other case - immediately raises the speculation whether the high apparent luminosity of HS 1700+6416 (one of the most luminous QSOs known) could be caused by the combined gravitational lens effect of the two clusters. Subsequently a deeper 27 ksec X-ray image has been taken in order to enable a more quantitative interpretation of the cluster X-ray data.

2. Observations

2.1. X-ray observations

Deep pointed ROSAT PSPC (for details cf. Trümper et al. 1991) observations have been performed on Nov. 13/14, 1992 (16.1 ksec) and July 21/22, 1993 (27.4 ksec). The X-ray image (cf. Fig. 1 in Reimers et al. 1995) shows a rather spectacular association of the QSO with two apparently distant clusters of galaxies. At a spatial resolution of $\sim$ 20" of the inner ROSAT PSPC detector, both clusters are barely resolved. In a first step, the X-ray photons of the QSO itself were removed from the image using an extraction radius of 60". This is too small for the soft ($Ep < 0.4keV$) X-ray photons so that for cluster A there is a small contamination with QSO photons at the lowest energies which, however, should be negligible at least for the analysis of the spatial structure of the clusters.

In the next step, we assume spherical symmetry for the intensity distribution of both clusters and determine the azimuthally averaged brightness distribution I(θ). The X-ray distribution of

Send offprint requests to: D. Reimers (dreimers@hs.uni-hamburg.de)
⋆ Based on observations by the ROSAT Observatory and the Calar Alto Observatory

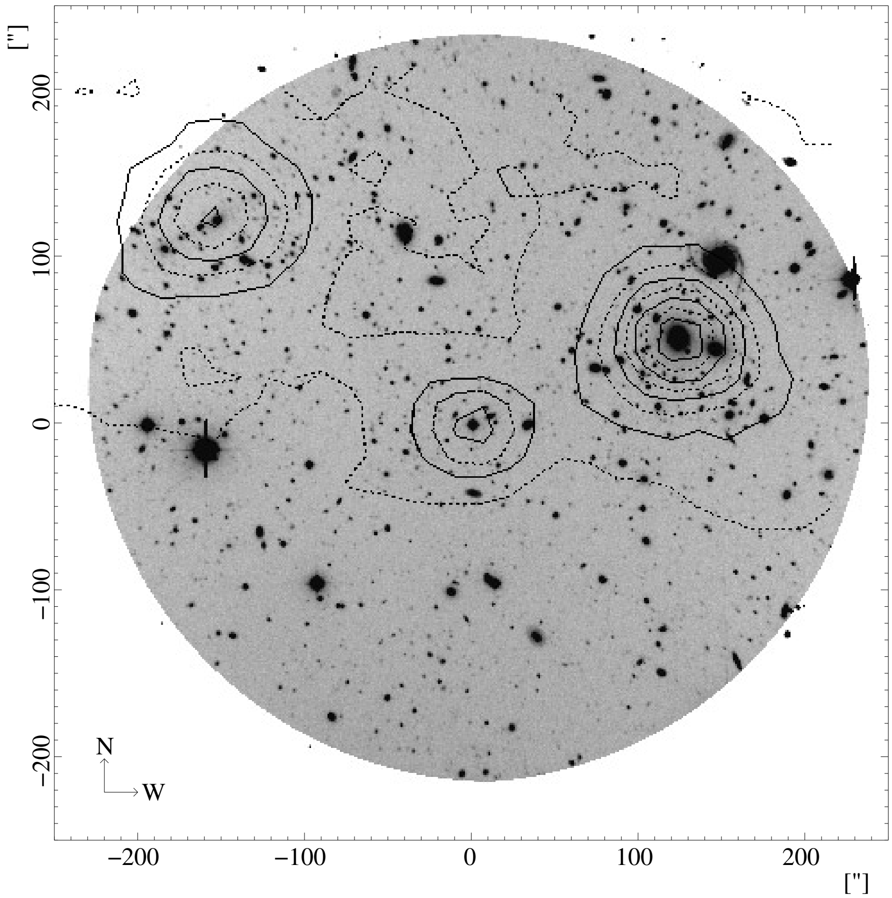

Fig. 1. Deep R image centered on HS 1700+6416 taken with the focal reducer at the prime focus of the Calar Alto 3.5 m telescope (total exposure time 4000 sec). The isointensity contours of the X-ray emission are superposed. Cluster A (A 2246) is NW, cluster B NE of the central QSO.

cluster B (3' northeast of the QSO, Fig. 1) is slightly elongated along the line connecting the two central CD galaxies (Fig. 2). Since both clusters are barely resolved, a defolding of their brightness distribution with the PSPC point spread function with subsequent fit to a β-model with both β and the core radius θ_c being free parameters

$$I(\theta) = I_o \left[1 + \left(\frac{\theta}{\theta_c}\right)^2\right]^{-3\beta+\frac{1}{2}}$$

does not give satisfactory results, while with a typical $\beta = \frac{2}{3}$ (Jones & Forman, 1984) we find stable results for the core radius θ_c. The theoretical intensity distribution is folded with the PSPC point spread function, represented by a Gaussian distribution

$$I \sim \text{const} \cdot \exp\,(-r^2/r_o^2) \text{ except for } I << I_{max}.$$

The width of the Gaussian curve has been determined from the QSO image as $r_o \approx$ 20". An optimal fit of the thus folded theoretical $\beta = \frac{2}{3}$ models to the observed radial intensity distributions yields $\theta_c(A)$ = 14" $\pm$ 2", $\theta_c(B)$ = 18" $\pm$ 2", $I_o(A) = 5.9 \cdot 10^4 cts/arcsec^2 \cdot s$ and $I_o(B) = 2.64 \cdot 10^{-4} cts/arcsec^2 \cdot s$.

2.2. Optical observations

While the position of cluster A coincides with A 2246 (Abell 1958), no corresponding cluster of galaxies is visible on the POSS red plate at the position of B.

In order to identify this X-ray source and possible other high redshift clusters in the field around HS 1700+6416 which might be responsible for the Lyman absorption systems at $z \simeq 1$ (Reimers et al. 1992), we carried out a deep multi-color survey at the prime focus of the 3.5m telescope on Calar Alto. Although the full data analysis is not completed, the presence of a distant cluster at the position of the X-ray source B was immediately obvious on our deep R and I band images. The deep R-band image, shown in Fig. 1 consists of a superposition of eight exposures á 500 sec. Its limiting magnitude is about R = 26. Since the field center was chosen near to the quasar position, the X-ray source B is placed near the field boundary of the focal reducer.

Nevertheless, the enhanced density of objects around two dominant galaxies (which we classify as cD on grounds of their extended halos) is conspicuous. The brighter, western cD is surrounded by an arc-like structure spanning position angles 270 to 340^o (Fig. 2).

Redshift measurements of A 2246 and the cluster B were made using the Calar Alto 2.2 m telescope. For the brightest member of A 2246 we find z = 0.25, consistent with the distance class in the Abell catalogue, corresponding to $z \approx 0.18$ (Abell 1958).

We further noticed that the UV spectrum of HS 1700+6416 taken with the GHRS of the Hubble Space Telescope shows a metal line system at z = 0.214 (Köhler et al. 1996) consistent

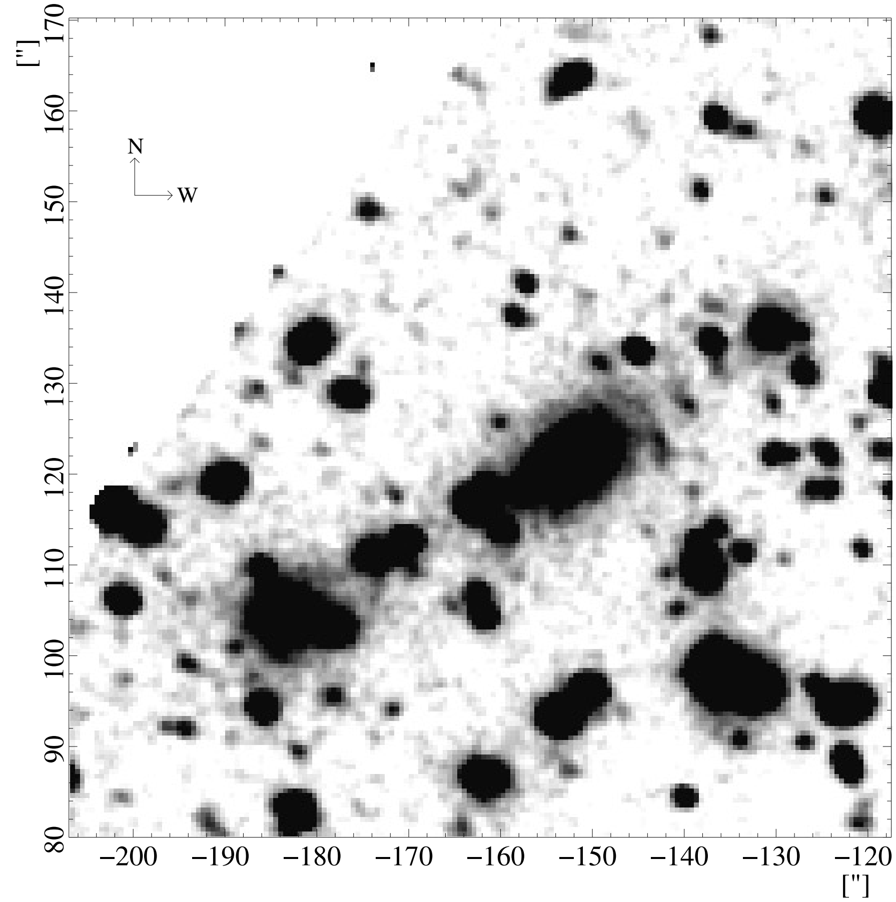

Fig. 2. Deep R image of the field around cluster B with its central two cD galaxies. Note the arc-like structure to the north-west of the brightest galaxy. The image is based on the same set of 8 exposures as Fig. 1. But they have been overlaid in such a way that the image distortion is at minimum around the cluster.

with its origin in matter (a galaxy) associated with cluster A. A faint galaxy 18”SE of the QSO has a redshift of z = 0.19 (Reimers et al. 1989). The two central cD galaxies of cluster B (see Fig. 2) have identical spectra which place them at $z = 0.44 \pm 0.01$ (Fig. 3). As a curiosity we mention the similarity between cluster B and A 370 which also contains two cD galaxies one of which is surrounded by an arc. Several more images elongated roughly perpendicular to the radius vector from cluster B are found in the region NW of the cluster. They may indicate that distortions due to gravitational lensing extend to several arcminutes from the cluster center.

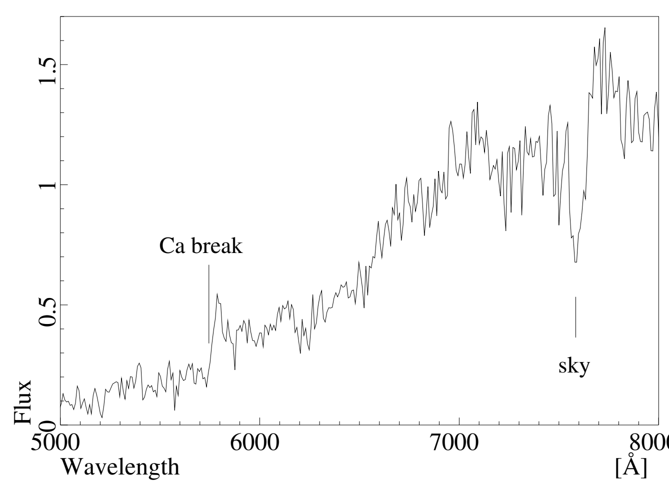

Fig. 3. Spectrum of one of the cD galaxies of cluster B (CAFOS, 2.2 m Calar Alto).

3. Interpretation and discussion

3.1. Gas temperatures and X-ray luminosities

Since both clusters are barely resolved we can determine only mean gas temperatures, and even these are fairly uncertain since, as has been shown by Henry et al. (1993), 30 % accuracy of the temperature requires 10^4 X-ray counts for hot clusters because the thermal X-ray spectra change very little in the ROSAT band for temperatures above 2 keV ($\cong 2 \cdot 10^7$ K).

For the gas temperature determination, we have adopted a hydrogen column density $N_H = 2.7 \cdot 10^{20}$ cm^{-2} as found from the interpretation of the X-ray spectrum of the QSO (Reimers et al. 1995). The galactic value is $N_H = 2.46 \cdot 10^{20}$ cm^{-2} (Stark et al. 1992).

After correction for absorption, a Raymond-Smith model with solar abundances was fitted to the 0.4 to 2 keV energy band shifted to the cluster rest frame. We found average temperatures of $(6 \pm 3) \cdot 10^7$ K and $(3 \pm 1.5) \cdot 10^7$ K for A and B, respectively,

Table 1. Properties of X ray clusters close to HS 1700+6416

Name	A (A2246)	B
Position RA	17:00:42	17:01:23
(2000) Dec	+64:12:54	+64:14:09
Projected distance to QSO	$1'40''$	$3'$
Redshift	0.25	0.44
X ray core radius Θ_o	$14'' \pm 2''$	$18'' \pm 2''$
Core radius ($q_o = \frac{1}{2}$)	$70 h_{50}^{-1} kpc$	$117 h_{50}^{-1} kpc$
$I_o [cts/arcsec^2 \cdot s]$	$5.9 \cdot 10^{-4}$	$2.64 \cdot 10^{-4}$
T	$(6 \pm 3) 10^7 K$	$(3 \pm 1.5) 10^7 K$
X Luminosity (0.4 - 2 keV observed frame)	$4.4 \cdot 10^{43} erg\, s^{-1}$	$7.3 \cdot 10^{43} ergs^{-1}$
X Luminosity (0.4 - 2 keV rest frame)	$4.1 \cdot 10^{43} erg\, s^{-1}$	$6.7 \cdot 10^{43} ergs^{-1}$

X-ray luminosities are L_x^A (0.4 - 2 keV) = 4.4 $\cdot 10^{43}$ erg s^{-1} and L_x^B = 7.3 $\cdot 10^{43}$ erg s^{-1}. For comparison with nearby clusters we give the corresponding 0.4 - 2 keV rest frame luminosities L_{xr}^A = 4.1 $\cdot 10^{43}$ erg s^{-1} and L_{xr}^B = 6.7 $\cdot 10^{43}$ erg s^{-1}.

With known central brightness I_o, core radius a_c, and an estimate of the gas temperature the central gas density n_o can be calculated according to Eq.(5) of Henry et al. (1993) (notice that there is a printing error in Eq.(5) of Henry et al.: the constant must be $1.2 \cdot 10^{+12}$ instead of $1.2 \cdot 10^{-12}$!). The gas density is insensitive to the gas temperature ($n_o \sim T^{-1/4}$). The dependence of surface brightness on redshift $n_o \sim$ (z + 1)$^{-4}$ has been taken into account. We find $n_o(A) = 3.5 \cdot 10^{-2} cm^{-3}$ and $n_o(B) = 1.5 \cdot 10^{-2} cm^{-3}$.

3.2. Cluster masses

A reliable determination of the cluster mass distribution *M*(r) requires knowledge of both the gas density and temperature gradients (cf. Henry et al. 1993). In particular the temperature gradients are not known so that we have no means to obtain reliable cluster masses. Following Henry et al. (1993) we can make a very rough estimate with the so called gamma model: under the assumption that the hot gas follows a polytropic equation of state $T(r)/T_o = (m_{gas}(r)/m_o)^{\gamma-1}$ where T_o is the central temperature and $m_{gas}(r)$ is the gas density model which corresponds to the $\beta = \frac{2}{3}$ model (see above) the mass model $M(r)$ is given by

$$M(r) = 3\beta\gamma a_c \cdot k \cdot T(r) \cdot (r/a_c)^3 / \left[G\mu m_p (1 + (r/a_c)^2)\right]$$

Without knowledge of the temperature gradient, we assume for a very rough estimate an isothermal model ($\gamma = 1$). With the numbers given in Table 1, the masses inside the core radii a_c are

$$M^A(a_c) = 5.7 \cdot 10^{13} M_\odot \text{ and } M^B(a_c) = 5.5 \cdot 10^{13} M_\odot$$

This is more than an order of magnitude less than for A 2256 or Coma (Briel et al. 1992, Henry et al. 1993) .

We conclude that according to cluster sizes, cluster X-ray luminosities and cluster masses both clusters are of intermediate size, consistent with both having not been detected in the ROSAT All Sky Survey.

3.3. The QSO-cluster association

Can the apparent high brightness of HS 1700+6416 be produced by magnification by cluster lensing? With projected distances of 1'40" for cluster A (490 kpc at z = 0.25) and 3' for cluster B (1170 kpc at z = 0.44), the line of sight of the QSO crosses the deflecting planes of A and B at 7 respectivly 10 core radii and any magnification effect can be excluded. Significant magnification can only be expected at projected separations of the order of or less than the core radii of the clusters (cf. Hammer et al. 1993). The estimated Einstein radii of clusters A and B are smaller than 30" and 15", respectively (cf. Eq. (2) of Böhringer (1995)).

Notice in Fig. 2 the giant luminous arc $\sim$ 15" NW of the northwestern cD. As reported by Hammer et al. (1993), 80% of clusters with giant luminous arcs have X-ray luminosities higher than 10^{44} erg/s. So cluster B is at the lower end of the X-ray luminosities of arc clusters. The question of possible lensing by a single cluster galaxy will be addressed in future work.

Acknowledgements. This work has been supported by the Verbundforschung of the BMBF under grant No. 50 OR 90 058. We thank Dr. H. Böhringer for discussions and Dr. U. Briel for critically reading the manuscript.

References

Abell G.O. 1958, ApJS 3, 211
Böhringer H., 1995, in "17th Texas Symp. on Relativistic Astrophysics and Cosmology", eds. H. Böhringer et al., New York Acad. Science, New York p. 67
Briel U.G., Henry J.P., Böhringer H. 1992, A&A 259, L 31
Hammer F., Angonin-Willaime M.C., Le Fèvre O. et al. 1993 in "Gravitational Lenses in the Universe", Proceed. 31st Liège International Colloquium, Liège p. 609
Henry J.P., Briel U.G., Nulsen P.E.J. 1993, A&A 271, 413
Jones C., Forman W. 1984, ApJ 276, 38
Köhler S., Wamsteker W., Reimers D. 1996, A&A 312, 33
Reimers D., Clavel J., Groote D. et al. 1989, A&A 218, 71
Reimers D., Vogel S., Hagen H.-J. et al. 1992, Nat 360, 561
Reimers D., Bade N., Schartel N. et al. 1995, A&A 296, L49
Stark A.A., Gammie C.F., Wilson R.W. et al. 1992, ApJS 79, 77
Trümper J., Hasinger G., Aschenbach B. et al. 1991, Nat. 349, 579

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.