

Letter to the Editor

Identification of a complete sample of northern ROSAT All-Sky Survey X-ray sources

V. Discovery of a $z = 4.28$ QSO near the RASS source RX J1028.6–0844

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Received 10 January 1997 / Accepted 22 April 1997

Abstract. We report on the discovery of the first $z > 4$ QSO in the ROSAT All Sky Survey (RASS) near the X-ray source RX J1028.6–0844. From the Ly α emission line found in an optical spectrum we measured $z = 4.276 \pm 0.005$. This is so far the highest redshift for a QSO in the RASS. The RASS X-ray count rate of 0.035 cts s^{-1} leads to an X-ray flux of $f_x = 8.33 \cdot 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ and a luminosity of $L_x \approx 6 \cdot 10^{46} \text{ erg s}^{-1}$ in the 2–10 keV rest frame energy band of the QSO if galactic column density of neutral hydrogen and a photon index $\Gamma = -2$ is assumed. The spectral energy distribution as inferred from the observed hardness ratios indicates the presence of considerable intrinsic absorption in the QSO around 2–2.5 keV.

Key words: Surveys – X-rays: general – X-rays: galaxies – (*Galaxies:*) quasars: general – Galaxies: active – (*Galaxies:*) quasars: emission lines

1. Introduction

The optical identification of large and complete subsamples of X-ray sources from the ROSAT All Sky Survey (RASS) showed about 40% of the sources detected at high galactic latitude to have AGN as optical counterparts (e.g. Zickgraf et al. 1997 (Paper II), Thiering et al. 1997 (Paper III), Bade et al. 1996). The bulk of these AGN is at low to intermediate redshifts. Zickgraf et al. (1997), e.g., found median redshifts of typically 0.2 to 0.3 for AGN in three study areas with nearly complete identification and X-ray flux limits on the order of a few times 10^{-13}

$\text{erg s}^{-1} \text{ cm}^{-2}$. At high redshifts the frequency distribution has a tail up to $z \approx 1.5 - 2$ (Krautter et al. 1997, Paper IV).

At very high redshifts, i.e. $z > 4$, only a few quasars have been detected so far at X-ray energies. One of these, RX J1759.4+6638, is the first X-ray-selected $z > 4$ quasar ($z = 4.32$) (Henry et al. 1994). It was found in a deep pointed ROSAT PSPC observation with a flux of $\approx 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-1}$ in the 0.5–2.0 keV energy range, well below the flux limits of the above mentioned RASS samples. The radio-selected quasar GB 1508+5714 ($z = 4.30$) was detected with the EINSTEIN IPC (Mathur & Elvis 1995), and the optically selected quasar 0000-263 ($z = 4.11$) (Bechtold et al. 1994) was detected in deep pointed ROSAT PSPC exposures. However, no quasar at $z > 4$ was found until now in the RASS.

In this paper we report on the first discovery of a QSO at $z > 4$ in the RASS. The quasar was found among the RASS sources studied by us within a project for optical identification of a complete sample of RASS X-ray sources at high galactic latitude in the northern hemisphere ($\delta \geq -9^\circ$). The project has been described in detail by Zickgraf et al. (1997). The full catalog of identifications and a statistical evaluation of the results can be found in Paper III and Paper IV, respectively.

In Sect. 2 the observations are presented. The results are discussed in Sect 3. Throughout this paper we use the cosmological parameters $H_0 = 50 \text{ km s}^{-1}$ and $q_0 = 0.5$, an energy index α as $S_\nu \propto \nu^\alpha$ and likewise the photon index $\Gamma = \alpha - 1$ with photon flux density $f(E) \propto E^\Gamma$ in photons $\text{cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$.

2. Observational results

2.1. RASS observations

RX J1028.6–0844 is one of the 674 RASS X-ray sources studied by us. Position, X-ray flux, etc. as derived from the RASS

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Table 1. X-ray properties of the RASS source RXJ1028.6–0844. For the conversion of count rate to flux f_x a photon index of $\Gamma = -2$ and galactic N_H was assumed (Dickey & Lockman 1990). The hardness ratios are defined as $HR1 = ([B] - [A])/([B] + [A])$ and $HR2 = ([D] - [C])/([D] + [C])$, where $[A]$, etc. are the count rates in the respective energy bands $A = 0.11 - 0.41$ keV, $B = 0.52 - 2.01$ keV, $C = 0.52 - 0.90$ keV, and $D = 0.91 - 2.01$ keV (cf. Zimmermann et al. 1994).

α_{2000}	$10^{\text{h}}28^{\text{m}}37.7$
δ_{2000}	$-08^{\circ}44'23''.6$
count rate	$0.0353 \pm 0.011 \text{ cts s}^{-1}$
t_{exposure}	424 s
$f_x(0.1-2.4 \text{ keV})$	$8.33 \cdot 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$
N_H	$4.59 \cdot 10^{20} \text{ cm}^{-2}$
$HR1$	$+0.73 \pm 0.32$
$HR2$	$+0.72 \pm 0.26$
$L_x(0.1-2.4 \text{ keV})$	$1.3 \cdot 10^{47} \text{ erg s}^{-1}$
$L_x(2-10 \text{ keV})$	$6.4 \cdot 10^{46} \text{ erg s}^{-1}$
optical counterpart:	
α_{2000}	$10^{\text{h}}28^{\text{m}}38''.7$
δ_{2000}	$-08^{\circ}44'38''.8$

data base (Voges et al. 1997a (Paper I), Paper III) are summarized in Tab. 1. In the re-processed SASS II data base (Voges et al. 1997b) the position shifted slightly by about $22''$ towards the SE ($\Delta\alpha = +20''$, $\Delta\delta = -7''$) relative to the position given in Tab. 1.

2.2. Optical observations

We obtained direct images in the Cousins R and Johnson B bands of the field around RXJ1028.6–0844 in May 1992 and December 1996 with the 2.15 m telescope at the Guillermo Haro Observatory near Cananea, Sonora, Mexico. The telescope was equipped with a focal reducer camera (*LFOSC*) which has a field of view of $10' \times 6'$ and an image scale of $1'' \text{ px}^{-1}$. A detailed description of the instrumentation is given in Paper II. In March 1996 we obtained a further R image and spectra of 3 possible optical counterparts of RXJ1028.6–0844 at the ESO/MPIA 2.2 m telescope at La Silla, Chile. The observations were obtained with the *EFOSC2* spectrometer (cf. ESO Users Manual) equipped with a Thomson 1024×1024 CCD chip (ESO CCD #19). *EFOSC2* gave a higher spatial resolution than *LFOSC*. The image scale of $0.336'' \text{ px}^{-1}$ resulted in a field of view of $5.7' \times 5.7'$.

Fig. 1 shows the R band image obtained with *EFOSC2* in March 1996. The position of the RASS X-ray source as given in Tab 1 is at the center of the 90% error circle for which a radius of $27''$ has been determined by Zickgraf et al. (1997) for sources with low X-ray count rates. The revised SASS-II position (see above) is indicated in Fig. 1 by a small circle. For the objects labelled A to C spectra were obtained with *EFOSC2* using grism #1 and a $1''$ slit yielding a spectral resolution of $\sim 24 \text{ \AA}$. A spectrum of object “d” was obtained with *LFOSC* in December 1996. The spectral resolution was about 18 \AA .

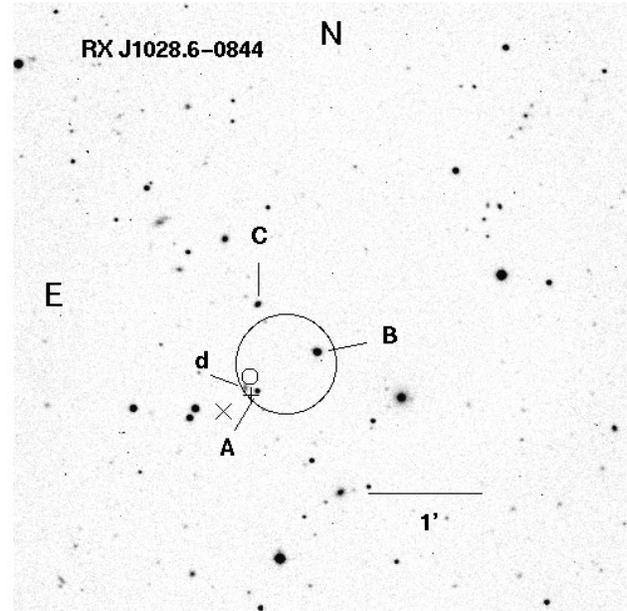


Fig. 1. R image of the field of RXJ1028.6–0844. The 90% error circle of the RASS position from Paper III is indicated. The revised SASS-II position is given by the small circle. The position of the radio source PKS B1026–084 is marked by +. The PMN 4.85 GHz source is indicated by \times .

The spectrum of the object marked “A” in Fig. 1 is displayed in Fig. 2. This object is a QSO for which $\text{Ly}\alpha$ gives a redshift of $z = 4.276 \pm 0.005$. From the emission line of C IV $\lambda 1548/1551$ we measured $z = 4.17 \pm 0.01$. However, this line appears to be affected on the red side by the broad atmospheric absorption feature around 8200 \AA . We therefore adopt the redshift from $\text{Ly}\alpha$ in the following. The $\text{Ly}\alpha$ forest is clearly visible. Also the Ly -continuum absorption edge at $\lambda_{\text{rest}} = 912 \text{ \AA}$ is indicated at $\lambda_{\text{obs}} = 4700 \text{ \AA}$.

Object B in Fig. 1 is a late F to early G-type star, and object C is an elliptical galaxy at redshift $z = 0.16$. Object “d” (see Fig. 3) is a galaxy without emission lines in the spectrum. Due to the very low S/N-ratio of the spectrum the redshift cannot be determined.

We estimated the brightnesses of the objects visible near the X-ray position from our CCD images. Unfortunately, the B and R image obtained at the Guillermo Haro Observatory were observed during non-photometric conditions and our programme for photometric calibration of the deep images is not yet finished. In order to obtain an approximate calibration for the B image we therefore made use of the COSMOS UK Schmidt (UKST) plate scan data base of the Royal Observatory Edinburgh which is available at the Max-Planck-Institut für extraterrestrische Physik. Object A was barely visible on our B image. The estimated statistical error of the B magnitude measured from this image is of the order of 0.5^{m} . This does not include a systematic error due to the calibration of the COSMOS data which is probably also of the order of 0.5^{m} , yielding an approximate total error of 0.7^{m} . For the calibration of the R

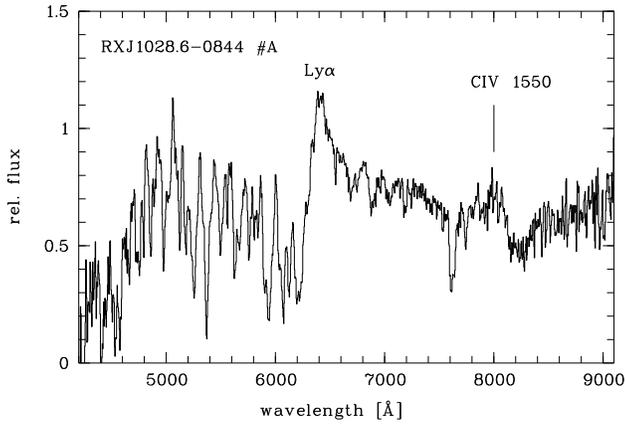


Fig. 2. Spectrum of object #A in Fig. 1. It is a quasar with redshift of $z = 4.276 \pm 0.005$ as measured from Ly α .

Table 2. *B* and *R* magnitudes of the objects #A to #d near the X-ray position of RXJ1028.6–0844.

object #	<i>B</i>	<i>R</i>
A	21.5 ± 0.7	18.9 ± 0.1
B	17.1 ± 0.5	16.7 ± 0.1
C	20.4 ± 0.5	18.6 ± 0.1
d	20.2 ± 0.5	20:

image observed at ESO under good conditions we determined the instrumental zero point from a photometrically calibrated *R* image of the field around the RASS source RXJ0720–3125 (Haberl et al. 1996). We estimated the resulting error to about 0.1^m . The *B* and *R* magnitudes for the four marked objects in Fig. 1 derived in this way are summarized in Tab. 2. Because object #d is quite faint and diffuse on our *R* image its brightness is rather uncertain.

3. Discussion

The probable optical counterpart of RXJ1028.6–0844 is the QSO. The star #B is too faint to be a likely counterpart. For F to G type stars the expected $\log f_x/f_V$ is of the order of -4.6 to -2.5 (Stocke et al. 1991, Maccacaro et al. 1988). With the *B* and *R* magnitudes given in Tab. 2 and the spectral type the estimated *V* magnitude is about 17^m . With an energy conversion factor *ECF* from count rate to flux of $6 \cdot 10^{-12}$ cts $\text{cm}^2 \text{erg}^{-1}$ (Paper II) we obtained $\log f_x/f_V \approx -0.5$. Taking the correction for the ROSAT energy band into account (cf. Paper II) this is about 2 dex above the limit for late F to early G-type stars. Likewise, the elliptical galaxy, object #C, is optically too faint to be a plausible counterpart. The estimated *V* magnitude is of the order of 19^m . As discussed in Paper II, elliptical galaxies are expected to be brighter than 17^m in order to have detectable X-ray emission in the RASS. The diffuse object #d to the East of #A also is a galaxy. A BL Lac object as bright as object #d would lead to a plausible f_x/f_V ratio. Spectroscopically we cannot rule out that #d is a BL Lac object. However, based upon

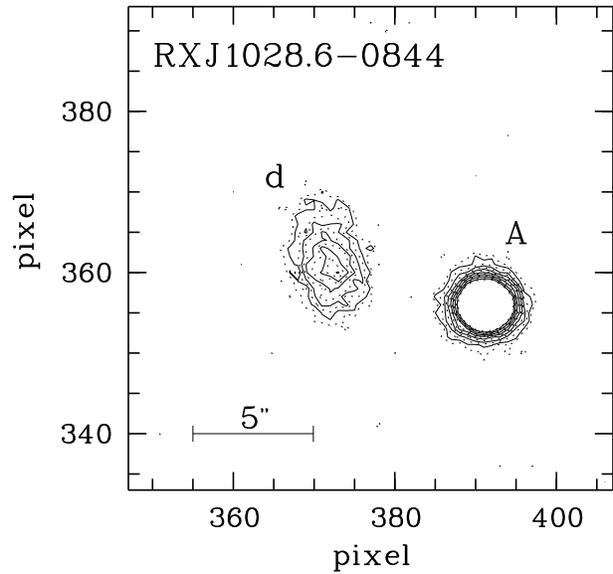


Fig. 3. Iso-contour plot (on a logarithmic intensity scale, step size is 0.01 between contour lines) of the region around the QSO #A shown in Fig. 1. The seeing was $\sim 1.5''$. Object #d is clearly extended.

its morphology in our direct images (cf. Fig. 3) we consider this possibility very unlikely. It is more probably a spiral galaxy which is optically by far too faint to be the counterpart of the X-ray source. Hence, the most likely optical counterpart for the X-ray source RXJ1028.6–0844 is the QSO whose optical position from the COSMOS UKST data base (plate epoch 2000.0) is given in Tab. 1. The positional uncertainty is $\approx 1''$ in right ascension and declination, respectively.

Assuming a photon index of $\Gamma = -2$ (-1.5) and a galactic absorption $N_H = 4.59 \cdot 10^{20} \text{ cm}^{-2}$ (Dickey & Lockman 1990) the observed count rate of 0.0353 ± 0.011 cts s^{-1} yields an unabsorbed flux in the $0.1 - 2.4$ keV energy band of $f_x = 8.33 \cdot 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ ($7.0 \cdot 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$). Due to the high redshift the observed energy range corresponds to $0.53 - 12.66$ keV in the quasar rest frame. The given flux yields a luminosity in the standard $2 - 10$ keV rest frame energy range of $L_x = 6.4 \cdot 10^{46} \text{ erg s}^{-1}$ ($6.6 \cdot 10^{46} \text{ erg s}^{-1}$). Likewise, the luminosity in the $0.1 - 2.4$ keV energy range is $L_x = 1.3 \cdot 10^{47} \text{ erg s}^{-1}$ ($4.6 \cdot 10^{46} \text{ erg s}^{-1}$).

By cross-correlation with the NED and SIMBAD data bases we found a radio source, PKS B1026–084, at a distance of $23''$ from the RASS X-ray position. The distance of the radio source to the QSO which very likely is its optical counterpart, is only $5''$. The radio source was also detected at 4.85 GHz in the Parkes-MIT-NRAO (PMN) Survey (Griffith et al. 1995) at about $22''$ distance to the QSO. The radio fluxes at 2.7 GHz and 5 GHz in the Parkes catalog of radio sources (Parkes Catalogue 1990, cf. Otrupcek & Wright 1991) are 270 mJy and 220 mJy, respectively, implying a spectral energy index of $\alpha_r = -0.3$. In the PMN survey a 4.85 GHz flux of 159 ± 13 mJy was measured. The positions of the radio sources are indicated in Fig. 1. The continuum coefficients α_{r0} and α_{ox} (Tananbaum et al.

1979) were calculated using S_{2500} (in $\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$) derived from the Cousins R magnitude assuming an energy index $\alpha_0 = -0.7$ and the absolute flux calibration for Cousins R given in Lamla (1982):

$$\log S_{2500} = -0.4 R - 19.8 - 0.3 \log(1 + z). \quad (1)$$

The 4.85GHz radio flux $S_{4.85}$ was k-corrected using $\alpha_r = -0.3$. We obtained $\alpha_{r0} = 0.61$ and $\alpha_{ox} = 1.03$ which places RX J1028.6–0844 among the radio-loud QSOs in the $\alpha_{ox} - \alpha_{r0}$ diagram (e.g. Stocke et al. 1991).

An important finding of pointed ROSAT observations of high redshift QSOs at $z \gtrsim 3$ was that radio-loud QSOs show a low energy cut-off in the X-ray spectra which cannot be explained by absorption due to intervening gas in our galaxy but rather seems to be due to intrinsic absorption in these QSOs (Elvis 1996). The fraction of absorbed quasars seems to increase with redshift. Interestingly, RX J1028.6–0844 exhibits a very hard X-ray spectrum indicating strong absorption of the soft X-ray photons. Although the number of detected photons is too small to directly fit a model spectrum, we can make use of the observed hardness ratios $HR1$ and $HR2$ to study the spectral energy distribution. Fitting a power law energy distribution to the observed hardness ratios with the galactic value of N_H formally yields a photon index of $\Gamma \approx +0.7$, i.e. an increasing flux distribution with increasing energy, however, with a poor fit only. (This Γ value would lead to practically the same flux f_x as given above.) This result can be understood in terms of intrinsic absorption in the QSO leading to the hard observed spectrum. In order to investigate this qualitatively we assumed a warm absorber model. Fixing the photon index at $\Gamma = -2$ and N_H at the galactic value, we additionally assumed the presence of absorption edges at rest energies E_0^i with an optical depth τ_i . The absorption was assumed to be proportional to $\exp(-\tau / (E - E_0)^3)$ for $E \geq E_0$ with E being the energy, and $\tau = \tau_{1+z}$ given in units of keV^3 (cf. Zimmermann et al. 1994). Due to the high redshift of RX J1028.6–0844 the oxygen absorption edge at 0.8 keV has an effect on the observed spectrum at low energies. $HR1$ is, however, mainly affected by the galactic absorption. For the galactic N_H a $\tau \approx 0.1 - 0.2$ at the oxygen absorption edge energy is sufficient to reproduce the observed $HR1$. In order to reproduce the observed hardness ratio $HR2$ a second absorption edge at $E_0 \approx 2 - 2.5 \text{ keV}$ is needed with a rather large optical depth of the order of $\tau \gtrsim 20$. This absorption edge is probably due to silicon and sulfur. It indicates the presence of gas with a very high column density on the order of $N_H \approx 10^{24} \text{ cm}^{-2}$ at a temperature around 10^6 K (assuming an incident power law energy distribution with an energy index of 1, Krolik & Kallman 1984). RX J1028.6–0844 thus appears to be a further example of an absorbed high-redshift quasar.

Based on their deep pointed ROSAT survey Henry et al. (1994) estimated a surface density for $z > 4$ QSOs of $\sim 3.7 \text{ deg}^{-2}$. We found one such object in our complete X-ray flux-limited sample covering an area of 685 deg^2 . The average flux limit of our survey is on the order of 50 (20 to 100) higher than in the survey of Henry et al. (cf. Paper II). Assuming a logarithmic slope of 1.6 for the $\log N - \log S$ distribution

(cf. Boyle et al. 1993) we hence would expect on the order of $\sim 10^3$ times less $z > 4$ QSOs, i.e. $\sim 4 \cdot 10^{-3} \text{ deg}^{-2}$. Actually we found $\sim 7 \cdot 10^{-3} \text{ deg}^{-2}$ which is in agreement with Henry et al.. It is, however, clear that a considerably larger data base than presently available is needed in order to enable statistically significant conclusions on the number density of X-ray selected high-redshift QSOs.

Acknowledgements. The ROSAT project is supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) and the Max-Planck-Gesellschaft. We would like to thank the ROSAT team for observing and processing the ROSAT All-Sky Survey data. We thank the Max-Planck-Institut für Astronomie, Heidelberg, for granting observing time at the ESO/MPIA 2.2 m telescope. We also would like to thank the staff at ESO, La Silla, and of the Guillermo Haro Observatory for the support during the observations.

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