X-ray luminous radio-quiet high redshift QSOs in the ROSAT All-Sky Survey

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Abstract. X-ray luminous radio-quiet high redshift QSOs are rare and can be used for the investigation of several important astronomical questions. We have conducted a large area survey for radio-quiet high redshift QSOs in the ROSAT All-Sky Survey, from which QSO candidates are selected using the digitized objective prism spectra from the Hamburg Quasar Survey. The 22 candidates with Galactic latitudes larger than 35° were observed with the 2.16m telescope at Xinglong station of Beijing Astronomical Observatory. Among the 19 new QSOs in our sample, six are radio-quiet QSOs with redshifts larger than 1.3 and three of them have redshifts larger than 2. Thus we have doubled the number of known X-ray luminous, radio-quiet high redshift QSOs in the surveyed sky area. The distribution of $f_{1.4\,GHz}/f_{1keV}$ of radio-loud and radio-quiet QSOs in this area shows two well separated peaks. This can be taken as an evidence for different emission mechanisms of the observed X-rays in the two subgroups.

Key words: galaxies: active – galaxies: quasars: general – X-rays: galaxies

1. Introduction

High redshift (z > 1.8) QSOs, especially radio-quiet objects, are rare in the ROSAT All-Sky Survey (RASS, Voges et al., 1996). A comparison of the radio-loud and radio-quiet QSOs detected in the RASS indicated that the X-ray detection rate of radio-quiet QSOs drops much faster towards higher redshift than that of radio-loud QSOs (Yuan et al. 1998). The catalogue of Yuan et al. (1998) (see Table 1 in that paper) contains 18 radio-quiet QSOs with z > 2 detected in the RASS. In the northern sky with galactic latitude b > 35°, only 20 QSOs with z > 1.3 and four QSOs with z > 2 have been known in the literature so far.

At high redshifts the rest frame energy range is shifted to higher energies, e.g., for z = 2.5 the ROSAT/PSPC (sensitive between 0.1 and 2.4 keV) receives photons emitted between 0.35 and 8.4 keV. Only upper limits exist for radio-quiet QSOs above

100 keV whereas several radio-loud objects with blazar properties have been detected above 100 keV (e.g. von Montigny et al. 1995). From several high redshift QSOs low energy cutoffs have been found, which are interpreted as due to the strong low energy absorption probably caused by the material near the QSO itself (Elvis et al. 1998). Higher resolution spectroscopy with future X-ray telescopes, e.g., AXAF, XMM, and Astro-E, will be able to quantify the contribution of metals to this proposed strong absorption. Low energy cut-offs have mainly been discovered in radio-loud objects, only some tentative evidence for low energy cutoffs are known in several radio-quiet QSOs. However, the statistics above z > 2.5 is poor; only three radio-quiet objects are included in a previous study (Fiore et al. 1998).

In addition, high redshift QSOs found in the RASS belong to the most luminous members of this class, making the upper end of the luminosity function. It is known from the magnification bias (Borgeest et al. 1991) that such objects have high probability to be gravitationally magnified. This is particularly true for radio-quiet objects, which seem to be the more common but intrinsically X-ray faint population. Among the radio-quiet z > 2 QSOs in the RASS, two are known gravitationally lensed objects. HE1104–1805 (z = 2.4) is a double QSO detected in Hamburg (Wisotzki et al. 1993). The other object is RX J0911.4+0551 (z = 2.8, Bade et al. 1997), a gravitationally lensed system with at least four QSO images.

The full sky coverage and the sensitivity of the RASS make it the most appropriate for finding these rare objects. Radio-loud QSOs have been selected mainly during the identifications of bright radio sources. Projects which may be able to select radio-quiet QSOs down to B = 18 mag on large sky areas are under way (e.g. SDSS, see Kent 1994; Hamburg/ESO Survey, see Wisotzki et al. 1996); but up to now results are only available for comparatively small and patchy areas of the sky. Therefore studies using correlations between existing AGN catalogues and the RASS to determine the relation between radio bright and quiet QSOs in the X-rays are probably affected by selection effects.

In order to enlarge the current sample of X-ray luminous radio-quiet high redshift QSOs, we start this survey project to select this kind of QSOs in the RASS using optical observations.

Table 1. Spectroscopic observation results of high redshift QSO candidates

ROSAT names	X-ray coordinates R.A. (2000.0) Decl.	Opt. coordinates R.A. (2000.0) Decl.	Offset ($''$)	f_x^*	B	$f_{1.4G}$ (mJy)	Date	Exp. (s)	Type	z	L_x^{**}
RX J0923.2+4602	09 23 12.6 46 02 42	09 23 12.7 46 02 42	2	4.9	18.4	11.7	97/12/07	4200	QSO	0.729	1.87
RX J0959.8+0049	09 59 48.9 00 49 27	09 59 46.9 00 49 16	33	3.5	19		97/12/07	3600	QSO	2.243	26.9
RX J0959.8+5942	09 59 49.3 59 42 53	09 59 48.5 59 42 50	8	4.8	17.5		97/12/07	1800	Seyfert	0.168	0.07
RX J1059.8+0909	10 59 51.5 09 09 15	10 59 51.0 09 09 05	13	4.0	17.1		98/03/05	3000	QSO	1.683	13.6
RX J1112.4+1101	11 12 25.5 11 01 03	11 12 25.4 11 01 03	2	5.0	18		98/05/24	900	QSO	0.636	1.37
RX J1144.9+5434	11 44 55.8 54 34 58	11 44 54.9 54 34 51	11	12.7	18.4		98/03/05	1800	QSO	0.437	1.44
RX J1208.3+5240	12 08 22.3 52 40 40	12 08 22.3 52 40 12	29	13.0	17.1	41.1	98/03/05	1800	QSO	0.435	1.46
RX J1243.8+0828	12 43 52..3 08 28 25	12 43 52.5 08 28 26	3	3.3	17.6		98/05/24	900	QSO	0.384	0.28
RX J1259.8+3423[a]	12 59 48.7 34 23 25	12 59 48.9 34 23 19	4	6.0	16.9	11.8	98/05/24	600	QSO	1.376	11.7
RX J1353.0+2947	13 53 00.0 29 47 42	13 52 59.1 29 47 39	14	23.3	18		98/05/24	1100	QSO	0.436	2.63
RX J1404.1+0937	14 04 10.4 09 37 45	14 04 10.7 09 37 45	3	9.1	17.3	20.1	98/05/24	600	QSO	0.437	1.03
RX J1410.2+0811	14 10 13.6 08 11 29	14 10 13.7 08 11 28	1	5.2	19		98/05/24	800	Seyfert	0.088	0.02
RX J1425.0+2749	14 25 03.0 27 49 21	14 25 02.6 27 49 10	12	2.6	18.8		98/03/05	1800	QSO	2.346	22.8
RX J1428.9+2710	14 28 54.0 27 10 44	14 28 53.0 27 10 39	17	4.7	17.8	7.2	98/05/24	900	QSO	0.443	0.55
RX J1441.2+3450	14 41 17.3 34 50 53	14 41 17.6 34 50 52	2	20.0	16.8		98/05/24	800	QSO	0.352	1.34
RX J1451.9+7214	14 51 53.6 72 14 41	14 51 54.1 72 14 44	6	4.1	18		98/03/05	600	QSO	0.749	1.67
RX J1514.3+4244	15 14 20.4 42 44 39	15 14 20.4 42 44 44	5	15.9	18.0	6.6	98/05/24	600	Seyfert	0.152	0.18
RX J1541.2+7126	15 41 16.3 71 26 06	15 41 15.2 71 25 58	9	3.9	18		98/03/05	900	QSO	1.418	8.26
RX J1548.3+6949	15 48 18.7 69 49 30	15 48 16.7 69 49 33	11	8.3	18.2	33.6	98/05/24	900	QSO	0.375	0.66
RX J1604.6+5714	16 04 38.6 57 14 37	16 04 37.3 57 14 36	11	7.3	17.3	496.8	98/05/24	800	QSO	0.725	2.75
RX J1616.9+3621	16 16 55.3 36 21 33	16 16 55.5 36 21 34	2	0.7	16.9	330.9	98/03/05	1200	QSO	2.259	5.50
RX J1701.4+3511	17 01 25.3 35 11 50	17 01 24.6 35 11 56	19	4.7	18		98/03/05	900	QSO	2.115	30.5

[*] f_x is in unit of $10^{-13}\, erg\, cm^{-2}\, s^{-1}$;
[**] L_x is the luminosity between 0.1–2.4 keV in units of $10^{45}\, erg\, s^{-1}$;
[a] A radio detected object but is formally radio quiet

Our study will also verify whether some selection effects are serious in the above mentioned correlation studies.

2. High redshift QSO candidates selection

We used the digitized objective prism spectra from the Hamburg Quasar Survey (HQS, Hagen et al. 1995) for the selection of QSOs with high redshifts. Currently the Hamburg identification project of RASS sources (Bade et al. 1998) covers about $10,200\, deg^2$ of the northern high galactic latitude sky ($|b| > 20°$). This survey uses photo plates which are sensitive between $5400\, \text{Å}$ and the atmospheric limit at $\sim 3400\, \text{Å}$. Thus the Ly-α line can be detected between $1.8 < z < 3.2$. If the CIV 1549 emission line is discernible in the objective prism spectrum, too, the reliability of the classification is very high ($> 90\%$). If only one strong emission line is visible, other strong emission lines can be source of the line (e.g.. CIII 1909, MgII 2798, [OIII]5007) and smaller redshifts are possible. Follow-up observations of the QSO candidates are thus necessary.

The classification of AGN candidates in the Hamburg identification project of RASS sources is based mainly on their blue continuum which can be well described by a power law. For the selection of QSOs with higher redshifts we inspected the objective prism spectra by eye, looking for strong emission lines. If the magnitude of the AGN candidate is near the plate limit, it is difficult to distinguish emission lines from noise. Another problem for number counts is the varying detection limit of the

objective prism plates. Taking all effects into account, B = 18 is a good approximation of the detection limit for strong emission lines. Following these procedures we finally selected 22 QSO candidates in the northern sky with galactic latitude b > 35°.

In the 1st to 7th columns of Table 1, we list their ROSAT names, coordinates of the X-ray sources and their optical counterparts, offsets between the X-ray and optical positions, X-ray fluxes, B-band magnitudes and 1.4 GHz radio fluxes from NVSS (Condon et al. 1998). The X-ray fluxes between 0.1 and 2.4 keV are calculated by assuming a power law with photon index -1.8 and only galactic neutral hydrogen absorption.

The follow-up observations were split into two observing campaigns in the spring of 1998 when the area of 300 HQS plates covering $6500\, deg^2$ was observable. Because varying weather conditions prevented us from observing the high redshift QSO candidates uniformly, the surveyed area is only a rough estimate.

3. Spectroscopic observations of high redshift QSO candidates

We have performed the spectroscopic observations on the 22 selected high redshift QSO candidates using the 2.16m telescope at Xinglong station of Beijing Astronomical Observatory. The exposure time varied from 10 to 70 minutes for each object depending on weather conditions and object brightness. The spectra of these high redshift QSO candidates were obtained after the standard sky subtraction and relative flux calibration using the
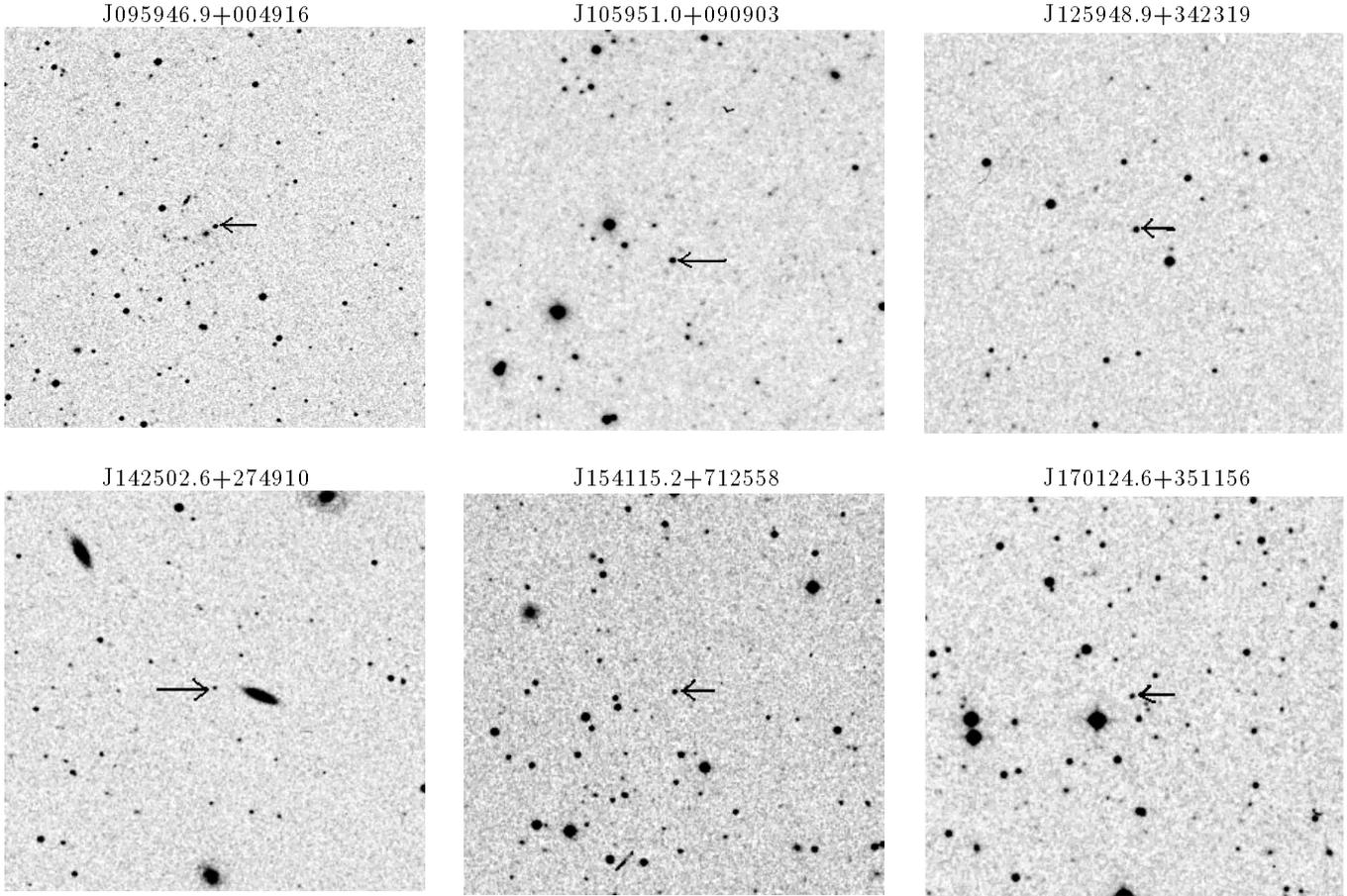
Fig. 1. The $8' \times 8'$ POSS-I images of six new radio-quiet, X-ray luminous quasars with redshift larger than 1.3. The arrow points to the new quasar in each image.

MIDAS software package developed at the European Southern Observatory (Banse et al. 1983). The observation dates, exposure times, types and redshifts of these high redshift candidates are given in the 8th to 11th columns of Table 1. The 12th column gives the rest frame luminosity L_X between 0.1–2.4 keV. For the determination of the luminosity $H_0 = 50 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$ and $q_0 = 0$ are assumed.

Table 1 shows that seven objects are QSOs with redshift larger than 1, and four of them have redshift larger than 2. 12 candidates are QSOs with redshifts between 0.3 and 1. Three candidates are low redshift Seyfert galaxies. If the strongest emission line in the objective prism spectrum is Ly α, redshift of the object is larger than 2. If the strongest line is CIV or MgII in the prism spectrum, the redshift is larger than 1 or between 0.3 and 1, respectively. However, in several cases the emission line in the prism spectrum is produced by a strong forbidden emission line of Seyfert galaxies, such as [OII] or [NeV]. This is the reason why we also identified three Seyfert galaxies.

We checked the radio fluxes of our high redshift candidates with three main radio catalogues, namely GB 5 GHz catalogue (Gregory et al. 1996), NVSS 1.4 GHz catalogue (Condon et al. 1998) and FIRST 1.4 GHz catalogue (White et al. 1997).

According to the definition of radio-loud AGNs, namely $R > 10$ with R being the ratio of 5 GHz radio flux and the B-band optical flux (Kellermann et al. 1989), we found that eight objects in our sample are radio-loud (see Table 1). Among them six objects are weak radio sources and only two new quasars have strong radio emission. RX J1616.9+3621 with z = 2.259, was found to be positionally coincident with a radio-loud object FIRST J161655.5+362134. Another new QSO, RX J1604.6+5714 with z = 0.725, is coincident with 87GB 160335.3+572233. One weak radio source (RX J1259.8+3423), which does not match the definition of radio-loud AGNs, and other 13 sources with no previous radio detection are most probably radio-quiet objects. Table 1 shows that five new QSOs have $L_x(0.1$–$2.4 \, \mathrm{keV}) > 10^{46} \, \mathrm{erg \, s^{-1}}$, and all of them are radio-quiet QSOs with z > 1.3. Another radio-quiet QSO with z > 1.3, RX J1541.2+7126, also has $L_x = 8.26 \times 10^{45} \, \mathrm{erg \, s^{-1}}$. Therefore, these six new radio-quiet QSOs are really X-ray luminous objects. In Figs. 1 and 2, we give the finding charts and spectra of these six new QSOs. The finding charts were extracted from the Palomar (POSS-I) Digitized Sky-Survey.

Table 1 lists 18 sources having offsets less than $15''$ between X-ray and optical positions. They are all the most nearby
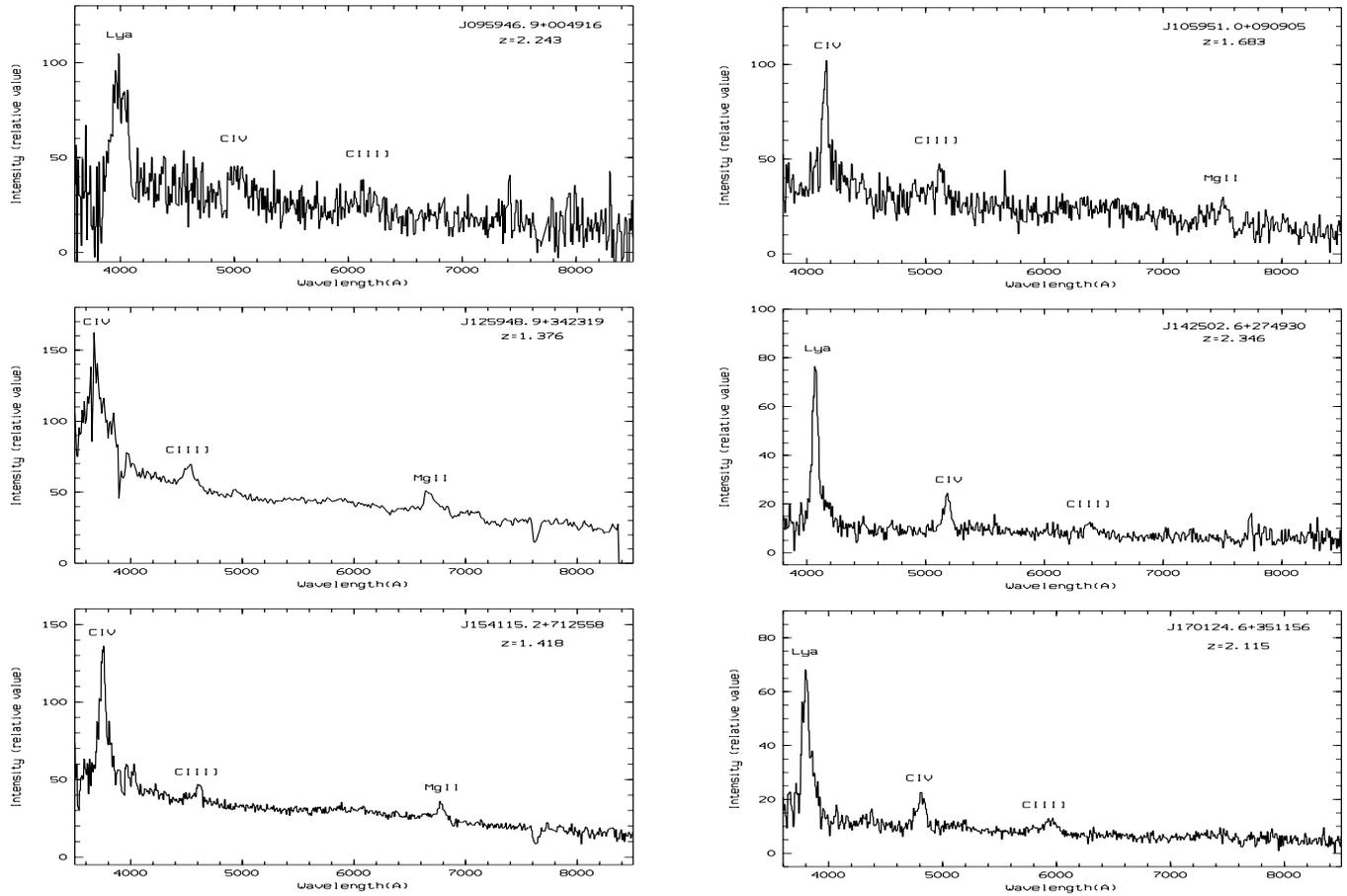
Fig. 2. Spectra of 6 new high redshift radio-quiet, X-ray luminous quasars. Three most significant emission lines in each spectrum are labeled.

optical sources to the X-ray positions, so that we suggest that they are the most likely true identifications of the X-ray sources. Four candidates have X-ray to optical offsets larger than $15''$, which are not uncommon for ROSAT detection at the detection limit. Here we discuss briefly each of these cases. For *RX J0959.8+0049*, the optical counterpart we selected is $33''$ away from the X-ray position and is identified as a quasar with z = 2.243. Three other optical sources (fainter than $O = 19.5$) are found to be closer to the X-ray position, but all of them are red objects with $O - E > 2$. Although such colors are compatible with a M-type dwarf, the optical weakness makes this identification unplausible. Therefore, our identification of this X-ray source with a z = 2.243 QSO is highly likely, though a future high resolution X-ray image of this source is required to confirm this identification. For *RX J1208.3+5240*, it is identified with a QSO with $z = 0.345$, which is $29''$ away from the X-ray position. Another nearby optical source is fainter than our candidate and is $38''$ far away from the X-ray source. Thus we regard our identification as most likely correct. For *RX J1428.9+2710*, its X-ray position is $17''$ away from a QSO with $z = 0.443$. We note that another optical source, is only $8''$ away from the X-ray position. This source, with $O = 19.2$ and $O - E = 1.1$, is fainter than our candidate QSO and is also point-like. Again
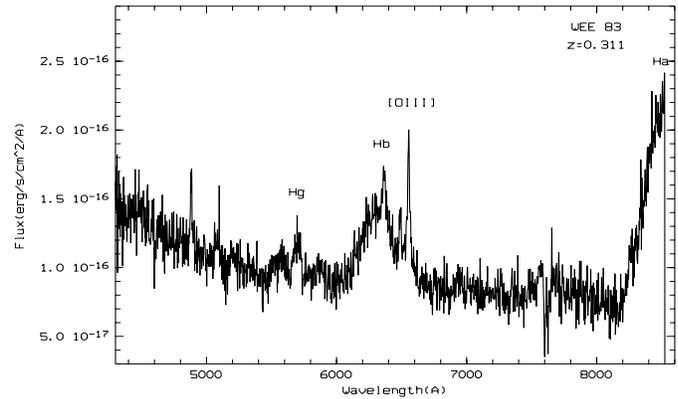

Fig. 3. The slit spectrum of WEE 83. The emission lines of H_γ, H_β and [OIII] are evident and the left wing of H_α is clearly shown,

future high quality X-ray observations are needed to confirm our identification. Finally for *RX J1701.4+3511*, the optical source we selected is $19''$ away from the X-ray position and was found to be a new QSO with $z = 2.115$. Other four nearby optical sources, with angular distances from $25''$ to $39''$ to the X-ray position, are faint and red objects with $O - E > 2$. Therefore, we believe that our identification is reliable.
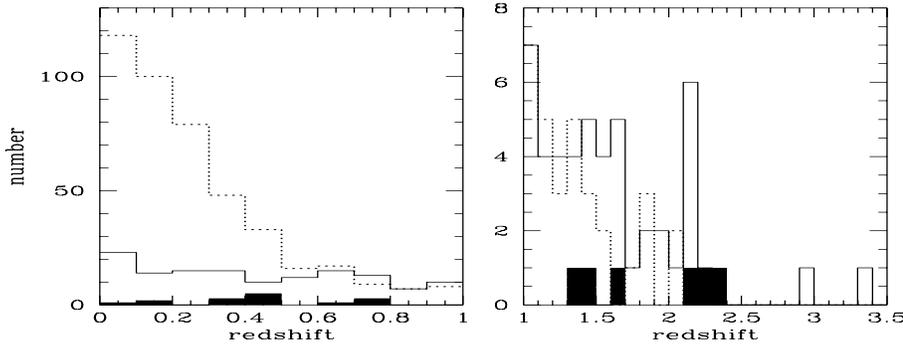
Fig. 4. The histogram of redshift distributions of previously known QSOs detected by the RASS in the sky area with b $> 35°$, and that of the newly discovered AGNs in our sample. The redshift bin is 0.1. The solid and dotted lines correspond to the previously known AGNs with 5 GHz radio fluxes larger than 20 mJy and those with 5 GHz radio fluxes less than 20 mJy, respectively. The shaded areas present the newly discovered radio-quiet AGNs in our sample.

4. Discussion

Among the new radio-quiet QSOs discovered by us, six have redshifts larger than 1.3 and three of them have redshifts larger than 2. These identifications substantially increase the number of such objects detected in the RASS. In the sky area of high galactic latitudes (b $> 35°$), we have made a correlation between the catalogue of identifications of RASS sources from the HQS Schmidt plates and the catalogue of QSOs and AGNs (Véron-Cetty & Véron 1996). This area contains only 18 previously known QSOs with 5 GHz radio fluxes less than 20 mJy and redshifts larger than 1.3, and only four of them have redshifts larger than 2. These four QSOs are RX J09190+3502, KUV 12461+2710, PG 1247+268 and WEE 83. The QSO identified with RX J09190+3502 was discovered at Hamburg (Bade et al. 1995), but a confident identification was not made previously because an AGN with low redshift was detected closer to the X-ray position. WEE 83 was selected by Weedman (1985) on objective prism plates, because it showed a strong emission line, which was regarded as Ly α. In Fig. 3 we show the slit spectrum of WEE 83 which we took in February 1998. Clearly we can see at least four emission lines and the average redshift of this object is 0.311 rather than 2.04. Therefore, actually only two X-ray luminous and radio-quiet QSOs with z > 2 in the sky area of b $> 35°$ were known previously. In Fig. 4 we show the redshift distributions of the previously known radio-loud and radio-quiet AGNs in the area with b $> 35°$, and the redshift distribution of the new radio-quiet AGNs in our sample. It is clear that the radio-quiet QSOs are more numerous than the radio-loud QSOs at lower redshift (z < 0.7); most of the QSOs with higher redshift have high radio fluxes, and radio-quiet QSOs with higher redshifts are relatively rare. The new QSOs discovered by us represent a substantial contribution to the number of radio-quiet, X-ray luminous QSOs with z > 1.6.

A histogram of the ratio between the 1.4 GHz radio flux density and the 1 keV X-ray flux density for the high redshift QSOs in our survey area is given in Fig. 5. It includes 22 radio-loud QSOs and 9 radio-quiet QSOs with z > 1.6 (an upper limit of 2.5 mJy was adopted for the sources with no radio detection in the NVSS catalogue). It demonstrates again that the radio-loud objects with high redshift are more numerous than the radio-quiet objects in the RASS, however the amount of radio-quiet high redshift QSOs was obviously underestimated in earlier studies. This histogram shows clearly that the radio-
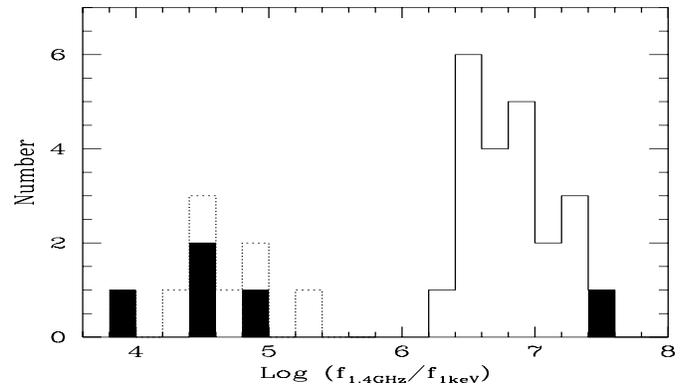

Fig. 5. The histogram of distributions of $Log(f_{1.4\,GHz}/f_{1keV})$ for QSOs with z > 1.6 detected by the RASS in the sky area with b $> 35°$. The solid and dotted lines refer to the radio-loud QSOs and radio-quiet QSOs respectively. The shaded area shows the contribution of the new QSOs in our sample.

loud QSOs and radio-quiet QSOs are well separated and there is a strong distinction between these two populations of X-ray loud QSOs; it is clear from Fig. 5 that all radio-loud high redshift QSOs have $f_{1.4\,GHz}/f_{1keV}$ larger than 10^6 while all radio-quiet QSOs have $f_{1.4\,GHz}/f_{1keV}$ less than 10^6. They seem to support the suggestion that radio-loud QSOs and radio-quiet QSOs may have different physical properties. This has already been shown and discussed in earlier papers. For example, the differences of the X-ray color and the X-ray spectra of radio-quiet QSOs and radio-loud QSOs at high redshift have been found by Bechtold et al. (1994), and these differences may imply that the central engine and the environment of these two kinds of QSOs are probably different. It has also been found that the X-ray spectra of the radio loud high redshift QSOs are significantly harder compared to the radio quiet population (Schartel et al. 1996; Brinkmann, et al. 1997). It is thus possible that an additional spectral component is necessary in order to explain the observations. Such a component may be contributed by the beamed radiation from a highly relativistic plasma jet aligned nearly to our direction (Wilkes & Elvis 1987; Kollgaard 1994).

For high redshift QSOs, the spectral region of the soft X-ray excess found with ROSAT is shifted partially out of the observable window and with the spectral resolution of ROSAT it is difficult to distinguish the soft excess and the power law component. However, a strong soft X-ray excess with an ex-

tension to higher energies is probably responsible for the high X-ray fluxes of the radio-quiet high redshift QSOs. The origin of the soft X-ray excess is extensively discussed in the literature, but no firm conclusion can be drawn currently (Piro, Matt & Ricci 1997). Many authors have proposed the inner regions of the accretion disk as emission region (e.g. Arnaud et al. 1985; Saxton et al. 1993; Brunner et al. 1997). Spectroscopic ASCA observations have shown that narrow-line Seyfert 1's and low redshift radio-quiet QSOs have generally steeper intrinsic hard X-ray continua (Brandt, Mathur & Elvis 1997; Reeves et al. 1997). But whether the X-ray luminous, radio-quiet high redshift QSOs have similar X-ray spectral properties as narrow line Seyfert 1's (e.g. Boller, Brandt & Fink 1996) and low redshift radio-quiet QSOs is still unclear (see Vignali et al. 1998). We expect that the future broad band spectroscopic observations on these QSOs using XMM and AXAF will lead to significant progress in understanding the X-ray emission mechanism of them.

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