SOFT X-RAY PROPERTIES OF ULIRGs BASED ON A LARGE AND COMPLETE SAMPLE

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ABSTRACT

We report on the results of the cross-correlation of a sample of 903 Ultraluminous IRAS galaxies (ULIRGs) with the ROSAT-All Sky Survey Bright Source Catalogue and the ROSAT archived pointing observations. The sample of ULIRGs has been compiled from the PSCz redshift survey. In total, 35 ULIRGs are securely detected by the ROSAT All-Sky Survey and pointing observations, five of which are blazars. The statistical properties of these sources in the soft X-ray band are determined and compared with their properties in other wavebands. We find that the ratio of the soft X-ray to the far-infrared flux spans about 5 orders of magnitude and reaches values of about unity. This ratio is a good indicator of the main energy source of ULIRGs. Those with soft X-ray to far-infrared flux exceeding 0.01 are probably powered by accretion onto central supermassive black holes while those with ratios smaller than 0.001 are probably caused by starbursts or other heating processes, or are Compton thick sources. Some ULIRGs have energy contributions from both. This ratio is low for most ULIRGs and hyperluminous infrared galaxies, which explains their low detection rate by ROSAT and ASCA. We also find that some ULIRGs have a similar soft X-ray luminosity vs. temperature relation to that for groups of galaxies and elliptical galaxies, suggesting a common origin of these systems. Our study also reveals a correlation between the hardness ratio and the soft X-ray luminosity for Seyfert 1s/QSOs.

Subject headings: Infrared: galaxies – X-rays: galaxies: – galaxies: active – galaxies: Seyfert – galaxies: interactions
1. INTRODUCTION

The Ultraluminous IRAS galaxies (ULIRGs) are an important sample for galaxy merging and formation processes. There have been many studies of these galaxies in many wavebands (see Sanders & Mirabel 1996 for a review), including the soft X-ray band. In the past ten years observations by ROSAT, ASCA and BeppoSAX, such as for NGC 3690 (Zezas et al. 1998), NGC 6240, Mrk 231, Mrk 273, Arp 220 (Iwasawa & Comastri 1998; Iwasawa 1999; Vignati et al. 1999), IRAS 19254-7245 (Pappa et al. 2000), IRAS 09140-4109 (Fabian et al. 1994), IRAS 20460+1925 (Ogasaka et al. 1997), and IRAS 23060+0505 (Brandt et al. 1997) have been carried out. These studies are, however, usually restricted to a single galaxy or a small sample of ultraluminous or hyperluminous IRAS galaxies (Wilman et al. 1998). Rigopoulou et al. (1996) performed a statistical study of the soft X-ray properties for six ULIRGs selected from the IRAS Bright Source Catalogue. More recently, Risaliti et al. (2000) carried out a statistical study in the hard X-ray band for a fairly large sample of luminous IRAS galaxies (including about 20 Ultraluminous IRAS galaxies) based on ASCA and BeppoSAX observations.

While it has become clear that Ultraluminous IRAS galaxies (ULIRGs) are strongly interacting or merging (e.g. Clements et al. 1996), or multi-merger systems (Borne et al. 2000), there is still a debate about the dominant power source for the tremendous far infrared luminosities of ULIRGs. For some ULIRGs, the dominant energy source appears to be AGN based on the near-infrared spectral properties (Lutz et al. 1999) or hard X-ray properties (e.g. IRAS 05189-2524 and NGC 6240), however they resemble starburst galaxies in the optical or soft X-ray. On the other hand, some ULIRGs are classified as Seyfert 1s /QSOs based on their optical spectra, but they are X-ray quiet and both their soft and hard X-ray properties do not resemble typical optically-selected Seyfert 1s/or QSOs (e.g. Mrk 231 and IRAS 07598+6508, see Lawrence et al. 1997; Lipari, 1994; Lipari et al. 1994).
The debate about the dominant power source in the object itself hints that star formation and the AGN phenomenon probably occur at the same time. This implies that galaxy formation and the formation and fueling of black holes (BHs) are closely coupled. This is also supported by the prevalence of BHs in nearby galaxies (Magorrian et al. 1998). The implementation of this coupling in semi-analytical studies can explain many properties of quasars (e.g. Kauffmann & Haehnelt 2000). It is therefore interesting to explore the relative contribution of starbursts and AGNs in another part of the energy-spectrum, the soft-X rays.

In the past, many authors have considered the multiple-merger process (e.g. Mamon 1987; Barnes 1985; Barnes 1988, 1999; Schweizer 1989; Weil & Hernquist 1996). Recent high resolution images of ULIRGs from HST lend support to this scenario since many ULIRGs have multi-nuclei and may have resided in compact groups (Borne et al. 2000). The so-called over-luminous elliptical galaxies have X-ray properties similar to groups of galaxies (Ponman et al. 1994; Mulchaey & Zabludoff 1999; Vikhlinin et al. 1999), and may also have formed in multi-merging processes. The soft X-ray emission in normal elliptical galaxies is assumed to be from hot gas left over from heating processes during their formation or from hot gas expelled from evolving stars (e.g. Mathews & Brighenti 1998). Since most ULIRGs are merging systems and some of these are at the final stage of forming ellipticals (Zheng et al. 1999), it is therefore interesting to compare their soft X-ray properties with those of normal elliptical galaxies and groups of galaxies.

For all the above considerations, ULIRGs are an important (local) sample to study the connections between galaxy merging, the formation of elliptical galaxies, and the active galactic nuclei (AGNs). In this paper, we will discuss the properties in soft X-ray band for the largest ULIRG sample based on the PSCz catalogue; we use the X-ray data from ROSAT All Sky Survey and pointing observations, and ASCA observations. The outline
of the paper is as follows, in Sect. 2, we discuss how our ULIRG sample is obtained, and the procedure used to identify the X-ray luminous ULIRGs in the ROSAT data. In Sect. 3, we discuss the statistical properties of our sample, and finally in Sect. 4, we summarize and discuss our results. Throughout this paper, we assume an Einstein-de Sitter ($\Omega_0 = 1$) cosmology and adopt $H_0 = 50\,\text{km}\,\text{s}^{-1}\text{Mpc}^{-1}$.

2. SAMPLE SELECTION

2.1. THE ULIRG SAMPLE

The sample of ULIRGs was compiled from the PSCz redshift survey (Saunders et al. 2000). The PSCz catalogue is a complete galaxy redshift survey selected mainly from the IRAS Point Source Catalogue. It includes 15411 IRAS galaxies across 84\% of the sky. The PSCz redshift survey is complete down to a flux limit $f_{60\mu m}$ of 0.6 Jy and $b_j < 19.5^m$. This catalogue is complete and uniform to a few percent at high latitudes and 10\% at low latitudes. The PSCz catalogue includes the galaxies from the QDOT survey (Lawrence et al. 1999) and the 1.2Jy sample (Fisher et al. 1995). In the adopted cosmology, we find that 903 objects have far-infrared luminosities $L(40 - 120\mu m) > 10^{12}L_\odot$, and hence qualify as ULIRGs according to the criterion of Sanders & Mirabel (1996). This is currently the largest complete sample of ULIRGs. We will correlate this sample with X-ray data as described below.

2.2. THE X-RAY SAMPLE

There are three catalogues of ROSAT archival data. The first is the ROSAT All Sky Survey Bright Source Catalogue (RASS-BSC, Voges et al. 1999). The RASS-BSC contains 18811 sources and the sky coverage is 92\%. Sources in RASS-BSC were detected
to a limiting count rate of 0.05 count s\(^{-1}\) in the 0.1-2.4 keV energy band with at least 15 source counts and a detection likelihood of at least 15 (for a definition of likelihood, see Cruddace et al. 1988). The public PSPC and HRI catalogues contain 74301 and 59911 targets, respectively. All three catalogues give source coordinates, count rate, exposure time, hardness ratio and other useful parameters.

### 2.3. IDENTIFYING X-RAY EMITTING ULIRGs

We have correlated the ULIRGs sample obtained from the PSCz catalogue with the RASS-BSC catalogue and the ROSAT pointing observations from both PSPC and HRI. We describe the details below.

First, we correlate the positions of the ULIRGs with those of the RASS-BSC sources and archived ROSAT pointing PSPC and HRI observations resulting in a list of candidate identifications. The largest difference allowed between the soft X-ray and the infrared positions is 36 arcseconds. For two objects (IRAS 10026+4347 and IRAS 18216+6418), the offset is about 36 arcseconds in one observational run, but less than 20 arcseconds in another run. Moreover, for 90\% of the targets, the differences between the infrared position and the position given in the ROSAT archive catalogues are about or much less than 20 arcseconds, which is roughly the pointing uncertainty of the ROSAT PSPC detector. Notice that if both ULIRGs and RASS-BSC sources are randomly distributed over all the sky, the expected number of pairs of sources that are within 36 arcseconds of each other is only 0.1, so clearly most of our sources are not due to chance alignment; nevertheless, we take additional steps to ensure secure identifications.

We examine visually by overlaying the X-ray emission contours on optical images from the Palomar Digitized Sky Survey for RASS-BSC identified objects. For a secure
identification, the X-ray emission must be spatially coincident with an optical counterpart of the IRAS galaxy. The procedure is the same as of Boller et al. (1998) except that we use the RASS-BSC catalogue instead of the RASS II catalogue and apply a higher detection threshold (15 source counts compared to 6 source counts used by Boller et al.) For pointing source identification, we examine the X-ray image visually and make sure that the PSCz position is coincident with the X-ray image. In addition, we only retain a source if the X-ray source count is larger than 15. There are 19 and 26 identified ULIRGS from the RASS-BSC and the pointing observations, respectively. Taking into account the overlapping sources, there are 35 ULIRGs securely detected by the ROSAT observations.

The basic parameters for the RASS-BSC and the secure pointing identifications are given in Tables 1 and 2, respectively. Many of the X-ray properties of these sources are already available from the ROSAT archives.

To obtain further properties (such as their spectral, spatial behavior and model dependent soft X-ray luminosities), we have analyzed the X-ray data mainly based on the PSPC and HRI observations using the EXSAS software at MPE. For point sources with detected photons larger than 100, we have performed spectral fitting and also tested variability (see Sect. 3.5). The best spectral fitting results are listed in Table 4. For extended sources with enough detected photons, such as NGC 3690, NGC 6240, Mrk 273 and Arp 220, we perform a spectral analysis based on the PSPC data and a spatial analysis based on the HRI data. Our results for these 4 sources generally agree with previously published results (e.g. Iwasawa 1999; Fricke & Papaderos 1998; Schulz et al. 1998), and so will not be shown here.
3. STATISTICAL RESULTS

The main X-ray properties of the secure identifications with the RASS-BSC are presented in Table 3 together with their far-infrared properties. Table 4 lists the basic X-ray and other waveband properties for the ROSAT pointing identifications. For objects with more than 100 source photons (cf. column 4 in Table 4) the X-ray spectral properties have been derived from a power-law fit with free spectral index and absorbing column density. The absorption is required to be at least as large as the Galactic value taken from Stark et al. (1992) (these cases have error bars in the $N_{\text{Hfit}}$ value at column 6 of Table 4); for IR 10026+4347, we use $\Gamma = 3.2$ and $N_{\text{Hfit}} = (2.3 \pm 1.3) \times 10^{20}\text{cm}^{-2}$ from the RASS data fitting result (Xia et al. 1999). For objects with less than 100 source photons we use a simple power-law model, with the photon index fixed to $\Gamma = 2.3$ (which is typical for extragalactic objects discovered by ROSAT, see Voges et al. 1999), and an absorption column density $N_{\text{Hgal}}$ of hydrogen fixed to the Galactic value along the line of sight.

The power-law fit is excellent for most Seyfert 1s/QSOs, all of which have a point-like soft X-ray morphology. There are also five bright radio loud QSOs or BL Lac objects in the sample: 3C 48, 3C 273, 3C 345, OJ 287 and 3C 446. To see clearly the effects of these blazars, we show statistical results with and without these sources. We also used different models to fit the spectra for objects with extended emission, such as NGC 6240, Mrk 273, NGC 3690 and Arp 220 (Iwasawa 1999). The hot plasma model usually fits better although the power-law fit is also acceptable based on the ROSAT data alone. As the energy resolution of ROSAT is lower than that of ASCA, we shall discuss some correlations based on ASCA results from the literatures in section 3.4.
3.1. THE SOFT X-RAY LUMINOUSITY

In Figure 1, we plot the $L_X/L_{\text{FIR}}$ as a function of the infrared luminosity. It is clear from this figure (and Tables 3 and 4) that the ratio of the soft X-ray luminosity to the far infrared luminosity of ULIRGs spans about five orders of magnitude and reach the value about unity. If we exclude the five blazars, this range of ratios is about a factor of 3 smaller. Since the ROSAT All Sky Survey has relatively short exposure time, the sources detected in this survey are mainly soft X-ray luminous objects (the soft X-ray luminosities $\gtrsim 10^{44}\text{erg s}^{-1}$) except NGC 3690 and NGC 6240, at very low redshift. Further investigation reveals that most RASS sources are Seyfert 1s/QSOs (see column 11 of Table 3). Moreover, some of them are Seyfert 1s/QSOs with extremely strong FeII emission and their soft X-ray spectrum can be fitted well with very steep power-laws. A good example, IRAS 10026+4347, has been presented in Xia et al. (1999).

In comparison, for sources detected in pointing observations, the soft X-ray luminosities extend to fainter levels and cover a somewhat broader range. The most luminous objects in the soft X-ray band are Seyfert 1s/QSOs and their soft X-ray emission is mainly from a central AGN. However, some infrared Seyfert 1s/QSOs, such as Mrk 231, IRAS 07598+651 and IRAS 00275-2859, are relatively weak in soft X-rays compared to their far infrared luminosities.

From Figure 1, Table 3 and Table 4, it appears reasonable that those with $L_X/L_{\text{FIR}} > 0.01$ are dominated by AGNs while those with ratios smaller than 0.001 are dominated by starbursts, or Compton thick sources; those galaxies in between may have contributions from both. This dichotomy shows up also in the soft X-ray morphologies and the spectra. This result is in good agreement with the hard X-ray statistical results for a luminous IRAS galaxy sample by Risaliti et al. (2000), which includes about 10 objects in our sample.
Since the most X-ray luminous ULIRGs are Seyfert 1s/QSOs and given that fewer than 10% ULIRGs are Seyfert 1s/QSOs (Lawrence et al. 1999), it is easy to understand why the ROSAT detection rate of ULIRGs is very low. Even the most hyperluminous IRAS galaxies are not detected, which yields a mean upper limit of $L_X/L_{bol} \lesssim 2.3 \times 10^{-4}$ (Wilman et al. 1998). We return to the properties of this luminous IRAS Seyfert 1s/QSOs sample in section 3.5.

### 3.2. THE CORRELATION WITH $L_K$

We have compiled the K-band luminosities from Surace et al. (2000), and Surace & Sanders (1999) for identified ULIRGs. Their data are listed in Table 4. Most of these galaxies have $L_X/L_{FIR} < 10^{-3}$, so their energy budget is probably dominated by starbursts. Figure 2 shows the correlation of soft X-ray luminosities with the luminosities in the K bands for thirteen sources, excluding all blazers, including one blazer 3C 273. The X-ray luminosity is clearly correlated with the K-band luminosity. Excluding 3C 273, the correlation coefficient is 0.61 with 99.7% significance. Moreover, the scatter for the K-band luminosity for a given $L_X$ is only about one order of magnitude. This is in sharp contrast with the large scatter seen in $L_X/L_{FIR}$ (see Fig. 1). This relatively tight correlation can be understood as follows:

As discussed by Iwasawa & Comastri (1998), the optical depths at 2.2$\mu$m and the soft X-ray band are similar if the standard gas to dust ratio is assumed and the powerful K band continuum is the sign of the presence of a large number of red giants and supergiants. Therefore, the correlation between $L_X$ and $L_K$ shows that at least a part of the soft X-ray emission in these ULIRGs (mostly with small $L_X/L_{FIR}$ ratio) is from starbursts.
3.3. THE HARDNESS RATIO

The hardness ratio is defined as

\[ HR = \frac{f_{0.5-2.0} - f_{0.1-0.4}}{f_{0.5-2.0} + f_{0.1-0.4}}, \]  

where \( f_{0.5-2.0} \) and \( f_{0.1-0.4} \) are the fluxes in the 0.5-2.0 keV and 0.1-0.4 keV ranges, respectively \((-1 \leq HR \leq 1)\). For most of our targets, we obtain the hardness ratio from the RASS-BSC and pointing archive catalogues directly; for the remaining small fraction, we obtain this by spectral fitting. For the overlapping sources between the RASS-BSC sample and pointing observations, we take the hardness ratio as the one from the pointing observations. From the left panel in Fig. 3, it can be seen that there is a weak correlation between the hardness ratio and the soft X-ray luminosity for all our targets. However, for the 16 ULIRGs with \( L_X > 10^{44} \) erg s\(^{-1}\), which are mainly Seyfert 1s or QSOs, the correlation is tighter. We find that the correlation coefficient is 0.47 with 93.6\% significance. If we exclude the five blazars, the correlation coefficient is 0.43 with 80.4\% significance. This correlation indicates that the Seyfert 1s/QSOs with relatively low soft X-ray luminosities also tend to have very soft X-ray spectra. Given that QSO’s soft X-ray luminosity is higher than Seyfert 1’s, this result is consistent a scenario where the soft X-ray excess for low-luminosity AGNs is due to the so-called ‘Big Blue Bump’; this feature is less prominent for the more luminous QSOs in the soft X-ray and hence their spectra are harder (see Reeves & Turner 2000). We caution, however, that the correlation is not highly significant for the current sample, especially if we exclude the blazars.

3.4. THE HOT GAS OF ULIRGs

As mentioned above and discussed in detail by Iwasawa (1999), for ULIRGs with relatively low soft X-ray luminosities, the power-law fitting to the soft X-ray spectra is not
as good as the hot plasma model fitting. Also, the soft X-ray emissions are extended for these objects from the ROSAT HRI observations. Examples include NGC 3690, NGC 6240, Arp 220 and Mrk 273 (Zezas et al. 1998; Iwasawa 1999). Because the energy resolution of ROSAT is lower than that of ASCA, we collect the ASCA data in the soft X-ray band for these objects. For objects with enough detected photons to perform the analysis, the two-temperature model provides the best fit to the observational data. Iwasawa (1999) pointed out that the low temperature component is more extended spatially than the high temperature component. He argued that the high temperature component is from a central massive starburst region. Table 5 lists the soft X-ray luminosities and the hot plasma model fitting temperatures available. For those fitted with a two-temperature model, we only take the value for the low temperature component since we are interested in the extended emission in the outer region.

For comparison, we also collect the soft X-ray luminosity and temperature data for Hickson compact groups from Ponman et al. (1996) and for elliptical galaxies from Buote & Fabian (1997). The Hickson compact groups data are based on ROSAT PSPC observations and data for elliptical galaxies are based on ASCA observations (the $L_X$ is in 0.5-2 keV band). There are also 5 soft X-ray over-luminous elliptical galaxies (OLEGs) data from Vikhlinin et al. (1999) and Mulchaey & Zabludoff (1999) in Table 5. The temperature of OLEGs by Vikhlinin et al. has been determined from the $L_X - T$ relation of clusters and groups of galaxies (Hwang et al. 1999). Figure 4 shows the $L_X$ vs. temperature relation for ULIRGs, groups of galaxies, elliptical galaxies and 5 OLEGs. The most important feature is that the ULIRGs occupy the same region in the $L_X$ and $T$ plane as groups of galaxies and elliptical galaxies. The OLEGs clearly have higher soft X-ray luminosity and temperature than compact groups and elliptical galaxies.

The data therefore indicate that the low temperature component hot gas in ULIRGs
may have the same origin as the hot gas in groups of galaxies and elliptical galaxies. Hence it hints at an evolutionary connection between ULIRGs, groups of galaxies and elliptical galaxies.

3.5. SOFT X-RAY PROPERTIES OF IRAS SEYFERT 1s/QSOs

It is clear from Tables 2 and 3 that about two thirds (22 out of 35) of ROSAT detected ULIRGs are Seyfert 1s/QSOs or BL Lac objects. Given that a large fraction of Seyfert 1s/QSOs selected from ULIRGs are strong or extremely strong optical FeII emitters (Lawrence et al. 1999; Zheng et al. 2000, in preparation), this Seyfert 1s/QSOs sub-sample is suitable for investigating the correlations between optical emission line properties and soft X-ray properties.

From Tables 3 and 4 we see that most Seyfert 1s/QSOs have a soft X-ray luminosity \( L_X \gtrsim 10^{44} \text{erg s}^{-1} \) and the ratio of soft X-ray to far infrared luminosity is larger than 0.01 with a few exceptions: Mrk 231, IRAS 07598-6508, IRAS 00275-2859, IRAS 21219-1757 and IRAS 10479-2818. All these 5 objects are QSOs from NED. Furthermore, four of these 5 objects (except IRAS 10479-2818) have extremely strong/or very strong FeII emissions. Mrk 231 and IRAS 07598-6508 are well known broad absorption line quasars. IRAS 10479-2818 is not an FeII emitter and has very broad permitted emission lines (Clowes, Leggett & Savage 1991). However the ratio of H\(\alpha\) to H\(\beta\) is much larger than 3.1, the value for normal Seyfert 1s/QSOs, which means that there is heavy absorption in this object. Therefore, the low soft X-ray luminosity for these 5 IR QSOs is probably due to heavy absorption.

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\(^6\) The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
absorption (see Brandt et al. 2000).

For Seyfert 1s/QSOs with high soft X-ray luminosity and high $L_X/L_{\text{FIR}}$ ratio, the soft X-ray spectra can be fitted very well by power-laws with spectral index around 2.3 for most of them and these fit the description of classical Seyfert 1s/QSOs. However, for IRAS 10026+4347, IRAS 04505-2958, IRAS 11598 – 0122 and PG 0157+001, the power-law slopes are steeper with a photon index $\Gamma \gtrsim 3$, or the spectra are very soft (For a power-law spectrum there is a one-to-one correspondence between the hardness ratio and spectral index.) The soft X-ray spectra for the first 3 objects are very soft as shown in column 13 of Table 4. These three Seyfert 1s/QSOs are also extremely strong/strong optical FeII emitters. Therefore their soft X-ray loudness, steep spectral index and strong optical FeII emission resemble the narrow-line Seyfert 1 galaxies (NLS1, Boller et al. 1996), although their permitted emission line widths for IRAS 10026+4347 and PG 0157+001 are not as narrow as a typical NLS1 – their H$\beta$ widths are larger than 2000 km s$^{-1}$ (Zheng et al. 2001, in preparation). Also comparing the counts rate and soft X-ray luminosities in Tables 3 and 4, one clearly sees variability for some of the Seyfert 1s/QSOs. However, the variabilities are up to about a factor of two, except for IRAS 10026-4347, so these ULIRGs may have variabilities between the typical NLS1s and normal Seyfert 1s/QSOs.

To summarize, the sub-sample of 22 Seyfert 1s/QSOs exhibit very different properties in their soft X-ray luminosity, spectral slope or hardness ratio and there does not seem to be a simple correlation with optical spectral properties. Some of the diversity may be caused by large and varying dust obscuration, but some may be intrinsic.
4. SUMMARY AND DISCUSSION

We have correlated a sample of 903 ULIRGs selected from the PSCz IRAS galaxy redshift survey catalogue with the ROSAT All-Sky Survey Bright Source Catalogue and ROSAT PSPC and HRI pointing archival data. The identification of ULIRGs as X-ray emitters is based on X-ray contour plots overlaid on optical images taken from the Digitized Sky Survey or the visual coincidence of the soft X-ray image and the PSCz position. In total, 35 ULIRGs have been securely detected by ROSAT observations, including five blazars.

We have determined the main soft X-ray properties for the identified objects and studied their properties in other wavebands. Our statistical results depend somewhat on whether we include the five blazars or not, but not to a very significant degree. The most striking result is the ratio between the soft X-ray and the far-infrared flux which covers five orders of magnitude, much more than the K-band luminosity vs. $L_X$. The highest $L_X/L_{\text{FIR}}$ ratios reach close to one, and these soft X-ray luminous ULIRGs are most likely powered by accretions onto central massive black holes, while lower ratio systems may be powered by starbursts or Compton thick sources. It is clear that the X-ray energy source in these ULIRGs may be quite different.

Two thirds of our identified ULIRGs are Seyfert 1s/QSOs, while the remaining are not. For several extended objects that do not classify as Seyfert 1s/QSOs, we have used published ASCA data to study the origin of the hot gas. We find that the hot gas seems to follow the same $L_X$ vs. $T$ trend as in groups of galaxies and in luminous elliptical galaxies. This suggest that some ULIRGs are evolutionally linked with groups of galaxies and elliptical galaxies. The Seyfert 1s/QSOs in the ULIRGs have different properties, some have relatively weak soft X-ray emission, while some have higher luminosities ($L_X > 10^{44}$ erg s$^{-1}$); the latter can be further divided into the ones with steep slopes and those with slopes that
are typical for classical Seyfert 1s/QSOs. Optical spectra have recently been obtained for this unique sample of Seyfert 1s/QSOs. The results of the analysis will be discussed in detail in a forthcoming paper.

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Table 1: Ultraluminous IRAS galaxies selected from PSCz redshift survey catalogue and ROSAT All-Sky Survey Bright Source catalogue. Column 1 gives the object name in the IRAS Faint Source Catalogue or the name given in the NED database. The PSCz position and the RASS-BSC position (in degrees) are listed in columns 2 to 5. Columns 6 to 9 gives the IRAS fluxes in the 12, 25, 60 and 100\(\mu\)m band. The differences of PSCz and RASS-BSC position are listed in column 10. Objects with * or ** were also detected by ROSAT PSPC or by both PSPC and HRI (see Tables 2 and 4). Objects with a † sign are blazars.
Table 2: Ultraluminous IRAS galaxies detected in ROSAT pointings. The object name as given in the IRAS Faint Source Catalogue or in the NED is listed in Column 1. The PSCz and ROSAT positions (in degrees) are given in columns 2 to 5. Column 6 lists the redshift of objects. The 12, 25, 60, and 100\(\mu\)m fluxes are given in column 7 to 10. The differences of PSCz and ROSAT PSPC position are listed in columns 11. Objects with * were detected by both PSPC and HRI. Objects with a † sign are blazars.
Table 3: Soft X-ray properties of Ultraluminous IRAS galaxies obtained from ROSAT All-Sky Survey observations. Object name, RASS count rate (or reduced count rate), the RASS exposure times, and the number of source photons are given in columns 1 to 4, respectively. The Galactic absorption column density of neutral hydrogen taken from Stark et al. (1992) is given in column 5. The redshift is given in column 6. The 0.1–2.4 keV and the 40-120 µm luminosities are listed in columns 7 and 8, respectively. The luminosity ratios in these two bands are at column 9. Column 10 lists the hardness ratios from ROSAT All Sky Survey Bright Source Catalogue and the optical classifications from literatures are in Column 11. Objects with a † sign are blazars.
Table 4: Soft X-ray and other waveband properties of ULIRGs detected in ROSAT pointings.

The object name, count rate, exposure times and the number of source photons are given in columns 1 to 4. The Galactic absorption column density and the best power-law model fit’s absorbing column density are given in column 5 and 6. The fitting photon index are given in columns 7. The soft X-ray luminosities, infrared luminosities and K band luminosities from literatures are listed in columns 8, 9 and 10. The ratios of soft X-ray to far-infrared luminosities are listed at column 11. Column 12 and 13 list the hardness ratios and optical classifications. Objects with a † sign are blazars.
| (1) | (2)   | (3)       | (4)                        | (5)                         |
|-----|-------|-----------|----------------------------|-----------------------------|
| name | log $L_X$ | T (KeV)   |                           | Model                      |
| NGC 3690 | 41.67   | 0.83±0.03  | Zezas et al.               | Two Temp. R-S model fit    |
| Mrk 231    | 41.95   | $0.88^{+0.27}_{-0.17}$ | Iwasawa  | Two Temp. thermal model fit|
| Mrk 273    | 41.99   | $0.47^{+0.24}_{-0.15}$ | Iwasawa  | thermal model fit          |
| Arp 220    | 40.95   | $0.76^{+0.13}_{-0.11}$ | Iwasawa  | thermal model fit          |
| NGC 6240   | 42.19   | $0.60^{+0.07}_{-0.10}$ | Iwasawa  | Two Temp. thermal model fit|
| IRAS 19254-7245 | 41.29 | 0.8       | Pappa et al.               | fixed Temp.                 |
| IRAS 20460+1925 | 42.93   | 1.0       | Ogasaka et al.             | fixed Temp.                 |
| NGC 1132   | 43.00   | 1.11±0.02  | Mulchaey et al.           | R-S model fit               |
| 1159+5531  | 43.34   | 2.2       | Vikhlinin et al.          | cluster & group $L_X$-$T$ relation |
| 1340+4017  | 43.40   | 2.3       | Vikhlinin et al.          | cluster & group $L_X$-$T$ relation |
| 2114-6800  | 43.30   | 2.1       | Vikhlinin et al.          | cluster & group $L_X$-$T$ relation |
| 2247+0337  | 43.61   | 2.8       | Vikhlinin et al.          | cluster & group $L_X$-$T$ relation |

Table 5: The soft X-ray (0.1-2.0 keV) luminosities and temperatures for ultraluminous IRAS galaxies above the horizontal line and for soft X-ray over-luminous ellipticals (OLEGs) below that line. All data are from the literature and most are based on ASCA observations with high energy resolution. The $L_X - T$ relation of clusters and groups of galaxies is from Hwang et al. (1999).
FIGURE CAPTIONS

Fig. 1.— The ratio of soft X-ray luminosity to infrared luminosity vs. infrared luminosity. The open and solid circles are for the RASS-BSC and pointing samples, respectively; the (five) blazars are shown as filled triangles from the RASS-BSC sample and as open triangles from pointing observations. The three solid lines indicate lines with $L_X = 10^{42}, 10^{44}, 10^{46}$ erg s$^{-1}$, respectively. The ULIRGs above the top horizontal dashed line are probably dominated by AGNs while those below the bottom horizontal dashed line are dominated by starbursts. The ULIRGs between these two lines may have contributions from both.

Fig. 2.— X-ray luminosity vs. K-band luminosity for the ULIRGs listed in Table 4. The open circle is for the only blazar in the figure, 3C 273.

Fig. 3.— The left panel shows the hardness ratio (defined in eq. 1) vs. $L_X$ for the sample with 35 objects, while the right panel shows that for objects with $L_X > 10^{44}$ erg s$^{-1}$. The open circles indicate the five blazars. The solid (dashed) straight line is the best linear regression through the points in the right panel without (with) the five blazars. The ULIRG sample is given in Table 3 and 4.

Fig. 4.— The soft X-ray luminosity vs. the temperature of the hot gas. The solid circles are for selected ULIRGs. For comparison, we also plot the data for Hickson compact groups from Ponman et al. (1996) as open squares and for elliptical galaxies from Buote & Fabian (1998) as solid squares. The five open circles at top right are for overluminous ellipticals from Vikhlinin (1999) and Mulchaey & Zabludoff (1999).
