X-ray observations of the ultraluminous infrared galaxy IRAS 19254–7245 (the Superantennae)

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ABSTRACT
We present ROSAT High Resolution Imager (HRI) and ASCA observations of the well-known ultraluminous infrared galaxy (ULIRG) IRAS 19254–7245 (the ‘Superantennae’). The object is not detected by ROSAT, implying a 3σ upper limit of X-ray luminosity $L_X \sim 8 \times 10^{41}$ erg s$^{-1}$ in the 0.1–2 keV band. However, we obtain a clear detection by ASCA, yielding a luminosity in the 2–10 keV band of $2 \times 10^{42}$ erg s$^{-1}$. The X-ray spectrum of IRAS 19254–7245 is very hard, equivalent to a photon index of $\Gamma = 1.0 \pm 0.35$. We therefore attempt to model the X-ray data using a ‘scatterer’ model, in which the intrinsic X-ray emission along our line of sight is obscured by an absorbing screen while some fraction, $f$, is scattered into our line of sight by an ionized medium; this is the standard model for the X-ray emission in obscured (but non Compton-thick) Seyfert galaxies. We obtain an absorbing column density of $N_H = 2 \times 10^{23}$ cm$^{-2}$ for a power-law photon index of $\Gamma = 1.9$, an order of magnitude above the column estimated on the basis of optical observations; the percentage of the scattered emission is high (~20 per cent). Alternatively, a model where most of the X-ray emission comes from reflection on a Compton-thick torus ($N_H > 10^{24}$ cm$^{-2}$) cannot be ruled out. We do not detect an Fe line at 6.4 keV; however, the upper limit (90 per cent) to the equivalent width of the 6.4 keV line is high (~3 keV). Overall, the results suggest that most of the X-ray emission originates in a highly obscured Seyfert 2 nucleus.

Key words: galaxies: active – galaxies: individual: IRAS 19254–7245 (the Superantennae) – galaxies: starburst – X-rays: galaxies.

1 INTRODUCTION
The IRAS ultraluminous infrared galaxies (ULIRGs), $L_B \geq 10^{12}$ L$_\odot$, are among the most luminous objects in the Universe. ULIRGs emit most of their energy in the far-infrared (see Sanders & Mirabel 1996 for a recent review). The nature of this powerful emission has been hotly debated. The far-infrared emission is clearly produced by thermal re-radiation by dust. However, it remains unclear whether the heating of the dust is caused by a hidden active galactic nucleus (AGN) and/or by massive star-forming regions.

Optical and near-infrared imaging surveys (e.g. Duc, Mirabel & Maza 1997) show that most ULIRGs are close interacting or merging systems. Optical spectroscopic surveys show that a large fraction (about 30 per cent) of ULIRGs are associated with Seyfert nuclei (Kim et al. 1995; Duc et al. 1997; Sanders et al. 1998a). The rest appear to host either star-forming or low-ionization nuclear emission region (LINER) nuclei. Lutz, Veilleux & Genzel (1999) have reached similar conclusions using far-infrared spectroscopy from the ISO mission. The ULIRGs that have AGN-like spectra, may be associated with the long-sought population of type-2 quasi-stellar objects (QSOs), i.e. high-redshift AGN with narrow-line Seyfert 2 type spectra but with bolometric luminosities comparable with those of QSOs. X-ray observations at high energies that remain largely unaffected by absorption are vital in checking for the presence of an AGN in the nuclei of an ULIRG.

Recently, a handful of ULIRGs have been observed using the ASCA X-ray satellite: IRAS 09104+4109 (Fabian et al. 1994), IRAS 15307+3252, IRAS 20460+1925 (Ogasaka et al. 1997), IRAS 23060+0505 (Brandt et al. 1997), NGC 6240, Arp 220, Mrk 273 and 231 (Iwasawa & Comastri 1998). All have been detected apart from IRAS 15307+3252. Most of the ULIRGs listed above have $L_X \geq 10^{42}$ erg s$^{-1}$, clearly suggesting the presence of a buried AGN. These high-X-ray luminosity objects have power-law spectra absorbed by large neutral hydrogen columns, typically $N_H > 10^{22}$ cm$^{-2}$; the spectra also show evidence for an Fe–K line at 6.4 keV that again suggests the presence of a large amount of neutral matter near the nucleus.

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However, the origin of the X-ray emission in Arp 220 and Mrk 231 appears to be thermal (Iwasawa & Comastri 1998).

1.1 IRAS 19254–7245 (the Superantennae)

The Superantennae ($L_B = 1.1 \times 10^{12} L_\odot$) is a remarkable ULIRG with a redshift of $z = 0.0617$ (Mirabel, Lutz & Maza 1991). It presents giant tails extending to an unprecedented size of 350 kpc. These emanate from a merger of two giant gas-rich galaxies, the nuclei of which are separated by 10 kpc. The southern nucleus is heavily obscured (AV $\sim 4–5$) and the optical observations give a Seyfert 2 classification (Mirabel et al. 1991). Mid-infrared spectroscopy (Lutz et al. 1999) of the Superantennae again suggest an AGN classification. Despite the classification of the southern galaxy as a Seyfert 2 on the basis of optical and far-infrared spectra, spectropolarimetric observations of the Superantennae (Heisler, Lumsden & Bailey 1997), revealed no scattered broad-line component. The authors attributed this to geometric effects. According to their model the scattering particles, which produce the observed polarized lines, must lie very close to or within the plane of the torus (see also Miller & Goodrich 1990), so that if we see the galaxy edge-on, we cannot observe the polarized flux. At near-infrared wavelengths the Seyfert nucleus dominates the emission; at 10 μm it is more than five times brighter than the northern component (Sanders & Mirabel 1996) and it is likely to be the source of the far-infrared emission detected by IRAS (Mirabel et al. 1991). Melnick & Mirabel (1990) reported the presence of substantial quantities of molecular gas $M_{CO} = 3 \times 10^{10} M_\odot$, 10 times larger than that in our Galaxy. The mass of the ionized gas in the emission-line regions is $M_e = 1.1 \times 10^9 M_\odot$ (Colina, Lipari & Macchetto 1991). The latter authors find that the starburst produces too few high-energy photons to explain the observed line intensities, and thus infer that the Superantennae must contain a luminous ($>10^{45}$ erg s$^{-1}$) AGN. Rush et al. (1996) presented results from the ROSAT All-Sky Survey observation of the Superantennae. They did not detect the object, and the 3σ upper limit to the count rate is <0.03 count s$^{-1}$. The estimated upper limit to the 0.1–2 keV luminosity is $4.5 \times 10^{42}$ erg s$^{-1}$ (using a power law of $\Gamma = 2.3$ and assuming Galactic absorption). Here we present the analysis of ROSAT High Resolution Imager (HRI) and ASCA data of the Superantennae galaxy. The latter are the first observations in the hard X-ray band and, as such, are important in testing models featuring a highly obscured, high-luminosity nucleus.

2 OBSERVATIONS AND DATA REDUCTION

The Superantennae were observed by ASCA on 1996 October 16. The net exposure time for each GIS is $\sim 30$ ks, while the SIS-0 net exposure time is $\sim 22$ ks and the SIS-1 is $\sim 10$ ks. We have used the ‘Revision 2’ processed data from the Goddard Space Flight Center (GSFC) and data reduction was performed using ftools. A circular extraction cell for the source, of 3 arcmin radius, has been used. Background counts were estimated from source-free annuli centred on the source cell. The observed flux in the 2–10 keV band is $f_{2-10\,\text{keV}} = 2.4 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ while the observed flux in the 1–2 keV band is $f_{1-2\,\text{keV}} = 3.2 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$, assuming the best-fitting power-law model described in Section 3 ($\Gamma = 1$).

ROSA observed the Superantennae with HRI for $\sim$8 ks between 1993 April 17 and 1993 April 20. There were no X-rays detected and the 3σ upper limit for emission from a point source obtained in the 0.1–2 keV band is $3.2 \times 10^{-3}$ counts s$^{-1}$, corresponding to a flux of $f_{1-2\,\text{keV}} = 9.5 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$, well above the flux measured by ASCA. Throughout this paper we adopt $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$.

3 SPECTRAL ANALYSIS

The spectral analysis was carried out using xspec v10. We bin the data so that there are at least 20 counts in each bin (source plus background). Quoted errors for the best-fitting spectral parameters are 90 per cent confidence regions for one parameter of interest. We first performed spectral fitting, allowing the normalization for each ASCA detector to vary, and we obtained reasonably consistent results. We have therefore jointly fitted the spectra from all four detectors, tying their normalizations together. The

| Model | $\Gamma$ | $N_{HI}$ | $kT_1$ | $kT_2$ | R or $n_{HI}$ | $f_{2-10\,\text{keV}}$ | $L_{2-10\,\text{keV}}$ | $\chi^2$/d.o.f. |
|-------|---------|---------|--------|--------|----------------|---------------------|------------------|----------------|
| Single | 1.03 $\pm$ 0.35 | 0.06 | – | – | – | 2.4 | 1.9 | 39.8/35 |
| power law | 0.98$^{+0.34}_{-0.37}$ | 0.0$^{+0.35}_{-0.46}$ | – | – | – | 2.4 | 2.0 | 39.3/34 |
| ‘scatterer’ | 1.9 | 21$^{+79}_{-18}$ | – | – | – | 0.82$^{+1.08}_{-0.17}$ | 2.5 | 4.3 | 36.8/34 |
| Reflection | 1.9 | 3.5$^{+0.4}_{-0.3}$ | 0.06 | – | – | 3.6 | 2.6 | 75.3/35 |
| Reflection plus a scattered power law | 1.9 | 0.06 | – | – | 34.8$^{+23}_{-19}$ | – | 3.8 | 3.0 | 36.4/33 |
| Absorbed power law plus thermal component | 1.9 | 1.8$^{+0.2}_{-0.9}$ | 0.8 | – | – | 1.7 | 1.7 | 43.16/34 |
| Two thermal plasma model | – | 0.06 | 0.8 | >12 | – | 1.9 | 1.6 | 41.0/34 |

$^a$ Observed 2–10 keV flux in units of $10^{-13}$ erg s$^{-1}$ cm$^{-2}$.

$^b$ Unobserved 2–10 keV luminosity in units of $10^{42}$ erg s$^{-1}$. 
results of the spectral fits are given in Table 1. Entries with no associated uncertainties were fixed at this value during the spectral fit.

3.1 Obscured AGN models

Given that the optical and mid-infrared observations of the Superantennae suggest an AGN classification, we fit the GIS and SIS data with a simple power-law model including absorption. We obtain a flat slope of $1.0 \pm 0.35$ with no requirement for absorption above the level of Galactic absorption. The best-fitting model, together with the data points and the data-to-model ratio, are plotted in Fig. 1. Data have been rebinned for clarity.

This slope is much flatter than that seen in radio-quiet AGN and the low absorption is not consistent with the $A_V$ estimates from the narrow lines or the absence of broad-line emission. A hard continuum is, however, often seen in Seyfert 2 galaxies (e.g. Georgantopoulos et al. 1999 for Mrk 3). While the simple power-law model is formally acceptable, we have also tried a ‘scatterer’ model in which the X-ray source is covered by an absorption screen and a fraction of the X-ray emission is scattered into our line of sight. Fixing the slope at the value of 1.9, typical of the underlying continuum of Seyfert galaxies, we obtain an absorbing column of $2 \times 10^{23}$ cm$^{-2}$ and $\chi^2 = 36.8$ for 34 degrees of freedom (d.o.f.), a marginal improvement on the simple power-law model. Using this model we derive an intrinsic 2–10 keV luminosity of $4.3 \times 10^{42}$ erg s$^{-1}$.

Most Seyfert galaxies show strong narrow-iron K emission lines and these features are usually enhanced in Seyfert 2s. When we add a Gaussian emission line to the scatterer model, constraining the energy and width at 6.4 (rest frame) and 0.01 keV, we do not obtain a significant detection of line emission but can only set a 90 per cent upper limit to the equivalent width of such a feature ($\sim$3 keV).

Alternatively, the flat power-law slope might suggest that Compton reflection dominates in the ASCA energy range (e.g. Matt et al. 1996). For this reason we have also tried a pure reflection model. This assumes that the reflection originates from a slab of neutral material, subtending a solid angle of $2\pi$ sr to an X-ray source located above the slab. Again, fixing the intrinsic power-law slope at 1.9 we obtain a completely unacceptable fit ($\chi^2 = 75.3$ for 34 d.o.f.). Relaxing the constraint on the power-law slope does improve the statistical acceptability of this model ($\chi^2 = 39.9$ for 33 d.o.f.) but results in a power-law slope of $\Gamma = 3.45 \pm 0.22$, much steeper than that seen in AGN other than some narrow-line Seyfert 1s.

Furthermore, introducing a reflection model that includes a scattered power law when the absorption is fixed at the Galactic value, and $\Gamma$ is fixed at 1.9, gives a similar quality of fit as that of the scatterer model with $\chi^2 = 36.4$ for 33 d.o.f. We constrain the spectral indices of the two power-law components to take the same value, as this is what is expected from the elastic scattering of the primary emission by the warm plasma. The addition of a Gaussian line at 6.4 keV (rest frame) does not improve the fit ($\chi^2 = 35.5$ for 34 d.o.f.).

3.2 Thermal models

While the optical emission line strengths are highly suggestive of a luminous AGN at the core of the Superantennae, some fraction of the X-ray emission must come from the numerous star-forming regions. Recent studies of starburst galaxies such as NGC 3690 (Zezas, Georgantopoulos & Ward 1998) provide evidence for a hard thermal component in the spectrum of luminous star-forming galaxies. For completeness therefore, we have investigated a model in which the emission consists of two thermal (Raymond–Smith) components. We have fixed the temperature of the soft component to 0.8 keV following Zezas et al. (1998), while we...
assumed a Galactic absorption and a solar metallicity. This again provides a reasonable statistical description of the data ($\chi^2 = 41.0/34$ d.o.f.), albeit with a poorly constrained temperature for the hard component ($>12$ keV). Fixing the temperatures of the two components to the values determined by Zezas et al., but allowing the thermal components to be absorbed, improves the fit of this model ($\chi^2 = 37.9$), and gives column densities of $\sim 7 \times 10^{21}$ cm$^{-2}$, similar to that inferred from the value of $A_\nu$ and $\sim 10^{23}$ cm$^{-2}$.

3.3 Mixed models

Given the evidence of a strong starburst in the object and the case for an AGN nucleus, it is not unnatural to investigate a model in which X-ray emission from both components contribute to our ASCA spectrum. We adopt as a baseline for this model a power law ($\Gamma = 1.9$) to represent the nuclear emission, and a Raymond–Smith thermal component to represent the starburst. We allow the power-law component to have additional absorption over and above that of the thermal component. Again, we fix the temperature of the thermal component at 0.8 keV. This results in an acceptable fit with $\chi^2 = 43.2$ for 34 d.o.f. with a column of $N_H = 1.80 \times 10^{22}$ cm$^{-2}$ for the power-law. Furthermore, as found in Section 3.2, allowing the thermal component to be absorbed improves the fit ($\chi^2 = 36.7$ for 33 d.o.f.) with a column density of $\sim 8 \times 10^{21}$ cm$^{-2}$.

4 DISCUSSION

It becomes evident that the X-ray data alone are not sufficient to define the nature of this enigmatic object. The X-ray data are well fitted by both power-law models and thermal models. The temperatures in the latter are not inconsistent with those found by Zezas et al. (1998) in the case of the luminous IRAS galaxy NGC 3690, that clearly shows no sign of AGN activity. The derived luminosity ($L_X \sim 10^{43}$ erg s$^{-1}$) for the Superantennae is also comparable with that of NGC 3690.

However, as the optical spectrum reveals a Seyfert 2 nucleus in the southernmost of the two merging nuclei (Colina et al. 1991), it is most probable that a large fraction of the X-ray emission comes from the active nucleus. Indeed, the hard X-ray spectrum observed ($\Gamma = 1.0 \pm 0.35$) is reminiscent of highly absorbed Seyfert 2 galaxies ($N_H \sim 10^{23-24}$ cm$^{-2}$) such as Mrk 3 (Georgantopoulos et al. 1999). Alternatively, the possibility remains that, even in the ASCA band, we are not sensitive to the intrinsic nuclear emission of the Superantennae. This would require the source to be totally obscured by a Compton-thick absorber ($N_H > 10^{24}$ cm$^{-2}$) in a similar fashion to NGC 1068 (Ueno et al. 1994), or to Circinus (Matt et al. 1996). Indeed, both the Compton-thin (power law and scatterer model) and Compton-thick (reflection plus a scattered power-law component) models give comparable $\chi^2$-values making it difficult to distinguish between the two possibilities. In the Compton-thin case, the hard X-ray emission should emerge from an optically thick screen (possibly in the form of the torus); the derived $N_H \sim 10^{23}$ cm$^{-2}$ is comparable to those encountered in obscured Seyfert galaxies (see e.g. Smith & Done 1996; Risaliti et al. 1999). The absorption inferred by the optical extinction is $9.3 \times 10^{21}$ cm$^{-2}$ (Colina et al. 1991); thus it appears that the X-ray absorbing column is at least one order of magnitude higher than the optical one. This discrepancy could then be explained either by assuming that there is a strong absorption inside the broad line region or that the gas-to-dust ratio of IRAS 19254–7245 is higher than that of our Galaxy. In the Compton-thin case we find that the power-law slope is compatible with the ‘canonical’ intrinsic AGN spectral index, $\Gamma = 1.9$ (Nandra & Pounds 1994). The observed soft X-ray emission is therefore thought to be scattered radiation from a warm ionized medium (the temperature of this medium should be comparable with the energy of the soft X-ray photons, so that elastic scattering takes place). The above model has become the standard model for the X-ray emission in obscured Seyfert nuclei (Mushotzky, Done & Pounds 1993). The scattered component and the intrinsic hard X-ray emission together with high amounts of obscuration or reflection can easily mimic a flat spectrum (e.g. as in the case of IRAS 23060+0505; Brandt et al. 1997). In the case of IRAS 19254–7245, we find that the scattered emission towards our line of sight is about 20 per cent. This is higher than typically found for the obscured Seyfert (Seyfert 1.9–2.0) nuclei, where the scattered component is usually of the order of few per cent. Colina et al. (1991) suggested that massive star formation should take place in order to explain the properties of the Superantennae (see also Mirabel et al. 1991). In this scenario the excess in the soft X-ray emission could be explained by a star-forming component. The inferred soft X-ray luminosity in the 1–2 keV band $L_X \sim 10^{41}$ erg s$^{-1}$ is quite typical of that expected in massive star-forming galaxies (e.g. Zezas et al. 1998). If instead we assume that all the soft X-ray emission is mainly a result of scattering, we can derive interesting constraints on the location of the scattering medium. If we require the ionization parameter of the scattering medium to be log $\xi = 3$ and the electron density $n_e = 10^5$ cm$^{-3}$, comparable with the values encountered in Mrk 3 (Griffiths et al. 1998), we can derive the distance $R$ between the scattering medium and the continuum source. We obtain $R \sim 0.1$ pc, suggesting that the scattering medium lies close to the nucleus.

In the Compton-thick case, the X-ray emission comes from both a reflection and a scattered power-law component. The geometry is similar to the one observed above in the case of the Compton-thin model, with the exception that now the torus is optically thick ($N_H > 10^{24}$ cm$^{-2}$). We note that in both the Compton-thick and -thin cases we should detect a strong Fe line at 6.4 keV. In the Compton-thick case especially, the equivalent width of the line could reach a few keV as in the case of NGC 6240 (Iwasawa & Comastri 1999). Our data do not show strong evidence for an Fe K emission line. However, the upper limit obtained for the equivalent width (3 keV) does not in this case rule out the Compton-thick possibility. It was recently shown by Vignati et al. (1999, using BeppoSAX data) that the ULIRG NGC 6240 hosts a Compton-thick ($N_H \sim 2 \times 10^{23}$ cm$^{-2}$) Seyfert 2 type nucleus. NGC 6240 has a LINER classification in the optical, while on the basis of infrared spectroscopy it is classified as an H II galaxy (Lutz et al. 1999). The LINER classification most probably arises from low-ionization gas in a superwind. It is interesting that although the Superantennae has similar X-ray properties to NGC 6240, it also presents strong AGN characteristics in the optical. This difference may be related to the distribution of obscuring material in the galaxy.

Further clues on the nature of the hidden AGN can be found by studying the isotropic properties of the galaxy. Here, we will consider as isotropic emission the infrared, the hard X-ray emission (in the case of Compton-thin absorption) and the [O III]λ5007-line emission produced in the narrow line region and consequently free of viewing-angle effects. The advantage of studying isotropic properties is that they act as an indicator of the
strength of the nuclear source. Maiolino et al. (1998) have proposed that the measurement of the unabsorbed hard X-ray flux (2–10 keV) against the [O III] λ5007 flux is indeed a powerful diagnostic tool. Of course, this tool may be less efficient in the case of ULIRGs that contain large amounts of dust. Moreover, although the line is emitted on narrow line region (NLR) scales, the host galaxy disc might obscure part of the NLR and should be corrected for the extinction deduced from the Balmer decrement (Maiolino & Rieke 1995). To estimate the corrected flux we used the observed [O III] λ5007 flux from Colina et al. (1991), corrected for the optical reddening using the following relation (Bassani et al. 1994):

\[ F_{\text{[OIII]}} = F_{\text{[OIII]obs}} \times \left( \frac{\text{H}a/\text{H}b}{\text{H}a/\text{H}b_0} \right)^{1.94} \]  

(1)

Assuming an intrinsic Balmer decrement (\( \text{H}a/\text{H}b_0 = 3 \)), the \( L_{\text{X}2-10\text{keV}}/L_{\text{[OIII]}} \) ratio of Superantennae is ~0.01 which favours the Compton-thick interpretation for IRAS 19254–7245. Then, on the basis of the mean \( L_{\text{X}2-10\text{keV}}/L_{\text{[OIII]}} \) ratio, the intrinsic luminosity of the Superantennae should exceed \( 10^{41} \text{erg s}^{-1} \), suggesting that obscuration in our line of sight prevents us from seeing any of the nuclear X-ray emission directly. Furthermore, following Mulchaey et al. (1994) we use the infrared to hard X-ray flux ratio as an indicator. The infrared flux is given by (Mulchaey et al. 1994)

\[ F_{\text{IR}} = (S_{25\mu m} \times \nu_{25\mu m}) + (S_{60\mu m} \times \nu_{60\mu m}) \]  

(2)

where \( S_\lambda \) is the flux density at wavelength \( \lambda \). They showed that the expected \( f_{\text{IR}}/f_X \) (the infrared to unabsorbed hard X-ray flux ratio) is ~0.9. We find that for the Superantennae this ratio is ~3, clearly indicating a deficit in the hard X-ray emission compared with that expected from a Compton-thin Seyfert 2 galaxy. This again suggests a high column density in our line of sight, which absorbs the photons in the ASCA band. We should note here that the \( f_{\text{IR}}/f_X \) in the ULIRGs may be high owing to excess infrared emission from a starburst component. However, ISO observations suggest an AGN classification for the Superantenna (Lutz et al. 1999), indicating that the AGN contribution to the infrared flux dominates over the star-forming one.

5 CONCLUSIONS

We have presented ROSAT HRI and ASCA X-ray observations of the ULIRG IRAS 19254–7245 (the Superantenna). This object was not detected by the ROSAT HRI. However, we detected hard X-ray emission with ASCA that had a very flat spectrum in the 1–10 keV band, reminiscent of the spectra of highly obscured local AGN. Therefore, the X-ray data indirectly argued in favour of the existence of a supermassive black hole in IRAS 19254–7245. In particular, the X-ray data can be modelled using a power-law spectrum with a photon index slope of \( \Gamma = 1.9 \) emerging through a Compton-thin torus (\( N_H \approx 10^{23} \text{cm}^{-2} \)). A scattered component (of the order of 20 per cent of the nuclear component at 1 keV) or alternatively a large star-forming component (\( L_X \approx 10^{41} \text{erg s}^{-1} \)) is also present. We do not detect any Fe line at 6.4 keV, with the 90 per cent upper limit on the equivalent width being 3 keV. The X-ray data are also well modelled by a Compton-thick, reflection-dominated model with some fraction of the nuclear emission scattered into the line of sight. However, the limited quality of the data does not allow us to distinguish between the above two models. Future observations using higher effective area missions such as Chandra and XMM will be able to provide much better constraints on the origin of the soft X-ray emission as well as the geometry of the obscuring material, thus shedding further light on the nature of ULIRGs.

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