Chandra detection of reflected X-ray emission from the type 2 QSO in IRAS 09104+4109

K. Iwasawa, A.C. Fabian, and S. Ettori

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

ABSTRACT
We present X-ray imaging spectroscopy of the extremely luminous infrared galaxy IRAS 09104+4109 ($z = 0.442$) obtained with the Chandra X-ray Observatory. With the arcsec resolution of Chandra, an unresolved source at the nucleus is separated from the surrounding cluster emission. A strong iron K line at 6.4 keV on a very hard continuum is detected from the nuclear source, rendering IRAS 09104+4109 the most distant reflection-dominated X-ray source known. Combined with the BeppoSAX detection of the excess hard X-ray emission, it provides further strong support to the presence of a hidden X-ray source of quasar luminosity in this infrared galaxy. Also seen is a faint linear structure to the North, which coincides with the main radio jet. An X-ray deficit in the corresponding region suggests an interaction between the cluster medium and the jet driven by the active nucleus.

Key words: Galaxies: individual: IRAS 09104+4109 — X-rays: galaxies infrared: galaxies

1 INTRODUCTION
IRAS 09104+4109 (FSC 09105+4108) is one of the extremely luminous infrared galaxies detected in the IRAS survey and has been considered to be a dust-enshrouded type 2 QSO (Kleinmann et al. 1988; Hines & Wills 1993; Crawford & Vanderriest 1996; Granato, Danese & Franceschini 1996; Soifer et al. 1996; Taniguchi et al. 1997; Evans et al. 1998; Hines et al. 1999; Franceschini et al. 2000; Tran, Cohen & Villar-Martín 2000). The infrared source ($L_{\text{IR}} \simeq 6 \times 10^{12} h^{-2} L_\odot$) has been identified with a cD galaxy in a rich cluster at a redshift of 0.442 (Kleinmann et al. 1988). Extended X-ray emission was detected with the ROSAT HRI, and has been identified with the intracluster medium (ICM) in which a strong cooling flow is taking place (Fabian & Crawford 1995; Crawford & Vanderriest 1996; Allen & Fabian 1998). Although the cluster emission itself is of great interest, it makes an X-ray investigation of the active nucleus difficult for X-ray telescopes with a relatively low spatial resolution like ASCA (e.g., Fabian et al. 1994) and even XMM. The first X-ray evidence for a luminous active nucleus came from an observation in the hard X-ray band where cluster emission is negligible. The detection of a hard X-ray excess with BeppoSAX, although its significance is marginal (3σ) and subject to possible contaminating sources in the large field of view of the PDS detector (Frontera et al. 1997), suggests a strongly absorbed nucleus (Franceschini et al. 2000). The other way to access the active nucleus is to utilise a high spatial resolution to separate the nucleus from the diffuse emission in an appropriate energy range. With the one-arcsec resolution of the X-ray telescope (Weisskopf, O’Dell & van Speybroeck 1996) and the ACIS CCD detectors (Garmire et al. 2000), Chandra overcomes the difficulty. In this letter, we present the spatially resolved X-ray source associated with the nucleus of IRAS 09104+4109 and its spectral properties.

2 OBSERVATION AND DATA REDUCTION
IRAS 09104+4109 was observed with the Chandra X-ray Observatory on 1999 November 3. The galaxy was positioned near the aimpoint of ACIS-S3, which was operating in Faint mode. Events with the ASCA grade of 0, 2, 3, 4 and 6 were selected. The background of the ACIS-S3 chip remained within a factor of 2 of the mean count rate most of the time, but flared occasionally by up to a factor of 4. We have discarded the periods of unusually high background events for the data of extended emission, which left a total of 8.4 ks exposure. For a spectrum of the nuclear point source extracted from a small region of the detector, we consider the background variation to have no effect and used the full exposure of 9.1 ks.

The data were reduced using software in CIAO 1.1.4 with the most up-to-date calibration available from Chandra Science Center. The temperature of the focal plane detector is estimated to be $-110^\circ\text{C}$, and an appropriate Fits Embedded Function (FEF) file is selected accordingly in making the response matrix. The energy resolution of the spectrum above 3.5 keV is about 3 per cent (or $\sim 140$ eV at 4.5 keV where a Fe K line is expected for the galaxy’s redshift) in FWHM. X-ray spectra were extracted from the P.I. column and relevant response matrices were created by mkrmf and

---

* $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$ are assumed throughout this paper.
The radio jet is believed to emanate close to the plane of the sky (1993), which we believe is due to an inaccurate aspect solution in the South-West of the radio core measured by Hines & Wills the Chandra data. Notable is a faint linear feature at the point source extending to the NNW (at a position angle Wills 1993). However, this X-ray feature is very faint and it is difficult to assess its significance due to the non-uniform background.

Our estimate of the ux at 1 keV from the jet is

\[ 10^{-15} \text{erg cm}^{-2} \text{s}^{-1} \]

above the radio power measured with VLA (Hines & Wills 1993). The radio jet is believed to emanate close to the plane of the sky and its bulk velocity is \( \sim 0.1c \) (Hines et al 1999).

A spectral analysis was performed using XSPEC version 11.

3 RESULTS

3.1 X-ray image

The full-resolution raw image (1 pixel \( \sim 0.5 \) arcsec) of the central part of IRAS 09104+4109 in the 0.5–8 keV band is shown in Fig. 1. A bright point-like source is seen in the middle of the X-ray image surrounded by extended emission of an irregular shape. The image profile of the bright source is consistent with the point spread function. This point-like nature becomes clearer in the high energy band (e.g., 3–8 keV) image, in which most of the source photons are concentrated within 2 pixels in radius. The radial profile of the hardness ratios demonstrate the distinctly hard spectrum of the nuclear source (Fig. 2).

The position of the point source is located at \( \sim 1.5 \) arcsec to the South-West of the radio core measured by Hines & Wills (1993), which we believe is due to an inaccurate aspect solution in the Chandra data. Notable is a faint linear feature at \( \sim 10 \) arcsec from the point source extending to the NNW (at a position angle of \( \sim 340^\circ \)). The feature points to the bright central source and, assuming the central source to coincide with the active nucleus, it matches the radio structure of the preceding North radio lobe and hot spot, found in the VLA images (Kleinmann et al 1988; Hines & Wills 1993). However, this X-ray feature is very faint and it is difficult to assess its significance due to the non-uniform background of the complex cluster emission (about \( 2\sigma \) excess compared to the surroundings). Our estimate of the flux at 1 keV from the jet is

\[ 3 \pm 2 \times 10^{-15} \text{erg cm}^{-2} \text{s}^{-1} \]

more than one order of magnitude above the radio power measured with VLA (Hines & Wills 1993).

Figure 1. The 0.5–8 keV image of IRAS 09104+4109 obtained from the Chandra X-ray Observatory ACIS-S3. The unsmoothed full-resolution image is presented in logarithmic scale. In the image, North is up, East is to the left, and an angular scale of 5 arcsec is indicated. The brightest pixel of the image has 42 counts for a 9.1 ks exposure. Note that the North-West quarter of the extended emission has less X-ray surface brightness than the rest and at a P.A. \( \sim 340 \) (NNW), a faint linear feature, corresponding the North radio lobe and hot spot (see Hines & Wills 1993), is seen.

Figure 2. Radial profiles of hardness ratios, defined by \( HR = (H - S)/(H + S) \), where \( H \) and \( S \) are integrated counts per unit area in the hard and soft bands, respectively. The solid line represents the hardness ratio for H: 2–7 keV and S:0.3–0.8 keV, while the dashed line for H: 2–7 keV and S:0.8–2 keV. The x-axis is measured from the position of the nuclear point source and the profiles have been averaged azimuthally. Note the hard spectrum of the nuclear source.

Here, we mention the cluster emission briefly, and the further details will appear elsewhere. The large-scale X-ray envelope is elongated along the East-West direction, which is consistent with the flattened galaxy distribution of the cluster (Kleinmann et al 1988), while the X-ray morphology of the inner part is more complex. A significant radial temperature gradient is found: the temper-
ature of $7.8 \pm 1.5$ keV found at radii of 200 kpc drops to $3.3 \pm 0.3$ keV near the nucleus, when fitted to a single-temperature thermal emission model. This clearly indicates that strong cooling of the ICM is taking place in the dense core of the cluster, as previously suggested from the X-ray imaging and spectral analysis (Fabian & Crawford 1995; Allen & Fabian 1998; Ettori & Fabian 1999).

### 3.2 X-ray spectrum of central source

The spectral data of the central source were collected from a circular region with a 1-arcsec radius. Over 80 per cent of photons from a point source are expected to fall in this region. The count rate is $0.022$ ct s$^{-1}$ in the 0.6–7 keV band and the spectrum is shown in Fig. 3. A prominent feature in the spectrum is the strong line at 4.5 keV on the hard excess emission, which is identified with Fe Kα line (6.4 keV), which has an equivalent width of $\sim 1$ keV with respect to the hard continuum.

### 4 COMPARISON WITH THE BEPPOSAX DATA

The BeppoSAX PDS data (14–40 keV range) were taken from the archive to compare with the Chandra data. Franceschini et al. (2000) attributed the hard X-ray emission detected with the BeppoSAX PDS to a strongly absorbed, transmitted component. Using the spectral fit to the Chandra data, we find that this conclusion depends on the assumed spectral slope of the source illuminating the reflecting matter. Given the low signal-to-noise ratio of the PDS data, no good constraints can be obtained for the spectral slope.
however. We thus show only two cases of $\Gamma = 2$ and $\Gamma = 1.4$ for a primary source spectrum.

When $\Gamma = 2$, typical for a quasar, is assumed, even with an almost face-on setting of the reflection slab in pexrav model (which yields the hardest spectrum above 10 keV), the PDS data lie a factor of $\sim 5$ above the extrapolation of the cold reflection model for the Chandra nuclear spectrum. This suggests the presence of an extra high energy component due to transmitted radiation, as proposed by Franceschini et al. (2000). If an absorbed power-law is fitted to this excess component, the best-fit value of the column density is found to be $3.3 \times 10^{23} \text{cm}^{-2}$ (cf., Franceschini et al. 2000 obtained $6.6 \times 10^{22} \text{cm}^{-2}$). We note a large statistical error to the $N_{\text{H}}$ value and further ambiguities arising from Compton scattering and iron metalliclicity in such a high column density range (Matt, Pompilio & La Franca 1999; Wilman & Fabian 1999). Despite all the uncertainties, the Thomson depth of the X-ray absorber should exceed unity. The apparent lack of the transmitted component in the Chandra energy range sets the lower limit of the column density to be $2 \times 10^{22} \text{cm}^{-2}$, while the detection of the hard X-ray excess means $N_{\text{H}}$ is no larger than $10^{23} \text{cm}^{-2}$. A joint fit to the Chandra ACIS and BeppoSAX PDS spectra with this model gives $\chi^2 = 10.0$ for 18 degrees of freedom (see Fig. 4).

In the case of $\Gamma = 1.4$, which is on the flatter side of the photon index distribution of quasars (e.g., Reeves & Turner 2000), the PDS data are explained well by cold reflection best-fitting the ACIS data (as mentioned in the previous section, the quality of the fit to the ACIS data is not sensitive to the selection of slope) with $\chi^2 = 10.8$ for 20 degrees of freedom. In this case, no transmitted component is required and the column density of the X-ray absorber exceeds $10^{22} \text{cm}^{-2}$.

5 DISCUSSION

5.1 Buried QSO

A distinctive cold reflection feature is observed from the nucleus of IRAS 09104+4109 in the Chandra spectrum whilst no primary radiation is visible. Detection of the primary emission at higher energies with BeppoSAX (Franceschini et al. 2000) depends, as demonstrated above, on the assumed spectrum of the source.

If the PDS-detected X-rays are entirely due to reflection, only a lower limit of the primary source luminosity can be obtained which is a minimum requirement to produce the observed luminosity through cold reflection. The albedo ($\eta$) in the 2–10 keV band is calculated using the pexrav model for two inclination angles, $i = 20^\circ$ and $60^\circ$, for the reflecting slab subtending $2\pi$ in solid angle. For $\Gamma = 1.4$, $\eta = 0.066$ ($i = 20^\circ$) and 0.052 ($i = 60^\circ$). Therefore the luminosity of the primary source is larger than $5 \times 10^{43} \eta^{-1} \approx 7.6 \times 10^{44} \text{erg s}^{-1}$ and $9.6 \times 10^{44} \text{erg s}^{-1}$ for respective inclinations. Since the fraction of reflecting surface visible to us is likely to be less than unity, the true luminosity of the primary source should be larger than these values.

We discuss below the case in which the primary source has a power-law of $\Gamma = 2$ and hence its transmitted radiation is detected with the PDS. The 2–10 keV luminosity of the primary source corrected for the absorption (and effects of Compton scattering, Matt et al. 1999) is estimated to be $7.4 \times 10^{45} \gamma^{-2} \text{erg s}^{-1}$ ($\gamma \sim 1$ for a spherical obscuration, and it can go up to $\sim 3$ if absorption occurs at a small cloud in the line of sight when $N_{\text{H}} \approx 3 \times 10^{22} \text{cm}^{-2}$). The observed-to-intrinsic luminosity ratio in the 2–10 keV band is then $0.67\gamma^{-1}$ per cent for IRAS 09104+4109. If the ratio of the 2–10 keV to bolometric luminosities is assumed to be $f_{\text{HX/Bol}} = 0.05f_{\text{HX/Bol,0.05}}$, typical for quasars (e.g., Elvis et al. 1994), the bolometric luminosity is $1.5 \times 10^{46} \gamma^{-1} f_{\text{HX/Bol,0.05}} \text{h}^{-2} \text{erg s}^{-1}$. This is comparable to $L_{\text{bol}} = 2.3 \times 10^{46} \text{erg s}^{-1}$ and consistent with a picture where the bulk of the infrared emission is powered by a buried quasar through dust reradiation. The radio source has an intermediate power between FRI and FRII (Kleinmann et al. 1988; Hines & Wills 1993). However, without the nuclear obscuration, the wide band energy distribution of IRAS 09104+4109 would be closer to radio quiet AGNs.

The cold gas reflecting the observed X-rays is probably part of the clouds occulting the central source. An X-ray absorber with as large a column density as found in IRAS 09104+4109 is likely to be compact, probably parsec-scale in radius as for nearby Compton-thick Seyfert 2 galaxies (Matt 2000). The flat energy distribution in the infrared band indicates that hot dust at near sublimation temperature ($\sim 1000$ K) is present and the inner radius of the dusty torus is the order of 1 pc (Granato et al. 1996; Taniguchi et al. 1997). The mid-infrared spectrum obtained from ISO/CAM CVF (Taniguchi et al. 1997) fits well with the compact dusty torus model of Pier & Krolik (1992) with an edge-on view (also see Granato & Danes 1994; Granato et al. 1996) whereas optical polarization studies imply a moderately inclined torus (Hines et al. 1999; Tran et al. 2000). The characteristic dust temperature is about 120 K (e.g., Kleinmann et al. 1988). No IRAS detection at 100$\mu$m and the new SCUBA limit at 850$\mu$m (Deane & Trentham 2000) rule out the presence of cool dust, which is a common feature of local ULIGs. No detection of CO (Evans et al. 1998) is consistent with a relatively small obscuring torus with a modest mass. A large covering factor ($\gtrsim 0.9$) is favoured by all the observations.

The soft X-ray emission seen in the nuclear spectrum is probably due to photoionized gas in the inner nucleus. The highly polarized...
ized biconical reflection nebula imaged by HST (Hines et al 1999) is however not a likely source, since scattering by dust rather than electrons appears to be a dominant mechanism to induce the high polarization (Tran et al 2000). The inner wall of the obscuring torus is exposed to the intense radiation from the primary source and thus expected to be highly ionized. Provided the optical depth of the ionized gas is small, the Fe-L emission bump can be very strong (e.g., Band et al 1990). A sub-parsec scale ionized disk has indeed been imaged with the VLBA in the nucleus of the nearby Compton-thick Seyfert 2 galaxy NGC1068 (Gallimore, Baum & O’Dea 1997), and they predicted strong soft X-ray emission lines based on a photoionization computation. In this case, the luminosity of the emission from the photoionized gas should be larger than observed ($\sim 3 \times 10^{37} h^{-2} \text{erg s}^{-1}$ in the 0.5–2 keV band), as significant absorption is likely to occur during the escape from the nuclear region.

A possible alternative is hot stars near the nucleus, inferred from a Wolf-Rayet feature seen in the optical spectrum of the nuclear region (Tran et al 2000). However, the luminosity of this component alone is one order of magnitude more luminous than the nearby Wolf-Rayet galaxies observed with ROSAT (Stevens & Strickland 1998), and the high metallicity implied from the strong emission-line features is also unusual (but see Buote 2000).

5.2 Implications for other luminous IR galaxies

IRAS 09104+4109 is so far the only hyper-luminous infrared galaxy detected in X-rays (apart from PG1634+706 which is an unobscured quasar, see Nandra et al 1995 for the ASCA result), and the most distant reflection-dominated spectrum X-ray source known with a clear detection of the Fe K line. The small X-ray reflection fraction ($\sim 0.7$ per cent in the 2–10 keV band; $\sim 0.1$ per cent at the rest energy of 2 keV) estimated for IRAS 09104+4109 is still consistent with the limit obtained from the previous observations for other luminous infrared galaxies at high redshift (see Fabian et al 1997; Ogasaka et al 1997 for F15307+3252; Wilman et al 1998). Chandra and XMM are capable of detecting reflected X-ray light from F15307+3252, if the reflection fraction is similar to IRAS 09104+4109. Although a $2\sigma$ detection of the lensed object IRAS F10214+4724 with ROSAT HRI was reported (Lawrence et al 1994), an 80 ks ASCA observation failed to detect it (Iwasawa et al 1995; Trentham et al 1999). If ULIGs at high redshift are powered predominantly by AGN, as suspected by Trentham, Blain & Goldader (1999); Trentham (2000), their nucleus is Compton-thick and the X-ray reflection fraction is indeed as low as that in IRAS 09104+4109. On the other hand, the sources with a small X-ray optical depth, that are preferably detected in X-ray, may tend to have hotter dust (Wilman, Fabian & Gandhi 2000) which deters submillimetre detection.

Acknowledgements

We thank all the members of the Chandra team for building and operating the satellite and developing the data analysis software. Neil Trentham, Steve Allen and Carolin Crawford are thanked for helpful discussion. The Royal Society (ACF,SE) and PPARC (KI) are thanked for support.

REFERENCES

Magaluti, in press
Matt G., Pompilio F., La Franca F., 1999, New Astronomy, 4, 191