XMM-NEWTON DETECTION OF A COMPTON-THICK AGN IN THE 1 Jy ULIRG/LINER F04103−2838

STACY H. TENG, S. VEILLEUX, AND A. S. WILSON
Department of Astronomy, University of Maryland, College Park, MD 20742

A. J. YOUNG
Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139

D. B. SANDERS
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822

AND
N. M. NAGAR
Astronomy Group, Departamento de Fıısica, Universidad de Concepcio´ n, Casilla 160-C, Concepcio´ n, Chile

Received 2007 June 27; accepted 2007 October 25

ABSTRACT

We report on the detection of Fe Kα emission in F04103−2838, an ultraluminous infrared galaxy [ULIRG; log(LIR/L⊙) ≥ 12] optically classified as a LINER. Previous Chandra observations suggested the presence of both a starburst and an active galactic nucleus (AGN) in this source. A deeper (≈20 ks) XMM-Newton spectrum reveals an Fe Kα line at rest-frame energy ≈6.4 keV, which is consistent with cold neutral iron. The best-fit spectral model indicates that the Fe Kα line has an equivalent width of ≈1.6 keV. The hard X-ray emission is dominated by a Compton-thick AGN with an intrinsic 0.2−10 keV luminosity of ≈1044 ergs s−1, while the soft X-ray emission is from ≈0.1 keV gas attributed to the starburst. The X-ray spectrum of this source bears a striking resemblance to that of the archetypal luminous infrared galaxy NGC 6240, despite differences in merger state and infrared properties.

Subject headings: galaxies: active — galaxies: individual (F04103−2838) — galaxies: starburst — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

The primary energy source (whether an active galactic nucleus [AGN] or starburst activity) of ultraluminous infrared galaxies [ULIRGs; log(LIR/L⊙) ≥ 12] is still a matter of debate. Optical and infrared emission-line spectra suggest that the energy output of most local ULIRGs is dominated by starbursts, but the “warm” infrared colors and quasarlike spectra of the more luminous ULIRGs indicate that black hole–driven activity plays an increasingly important role in these objects (e.g., Veilleux et al. 1995, 1997, 1999a, 1999b; Genzel et al. 1998; Surace & Sanders 1999; Tran et al. 2001). The dusty, gas-rich nature of ULIRGs implies, however, that observations in energy bands other than radio and X-ray may not always probe the true nuclear energy source of these objects. Since the luminosity of ULIRGs in the radio is insignificant, X-ray observations remain arguably the best option to solve this energy source mystery.

Unresolved hard X-ray emission is, in principle, a telltale sign of a dominant AGN. However, if a large column density of gas (∼1024 cm−2) is located in front of the nucleus, then directly viewed X-rays from the AGN will be strongly attenuated. For such cases, Fe Kα lines with large equivalent widths (∼1 keV) are expected, due to scattering from circumnuclear material (e.g., Ghisellini et al. 1994; Krolik et al. 1994). Thus, the discovery of such Fe Kα lines may be the best evidence for energetically dominant AGNs in highly obscured ULIRGs.

In recent years, three X-ray surveys have added considerably to our knowledge of ULIRGs. Ptak et al. (2003) performed a volume-limited (z < 0.045) survey of ULIRGs with Chandra. On the basis of their dust temperatures (IRAS f25/f60 ratio) and X-ray luminosities, three of the eight ULIRGs sampled by Ptak et al. (2003) were classified as AGN dominated (Mrk 231, Mrk 273, and F05189−2524). In the same year, Franceschini et al. (2003) published the results of a similar survey with XMM-Newton that focused on the brightest local ULIRGs (only one ULIRG in their sample had z > 0.082). Of the 10 ULIRGs sampled by Franceschini et al. (2003), three were AGN dominated (Mrk 231, F19254−7245, and F20551−4250), and two had X-ray signatures of both a starburst and an AGN (F20100−4156 and F23128−5919). All of the AGN-dominated ULIRGs showed strong Fe K emission lines (Maloney & Reynolds 2000; Braine et al. 2003, 2004; Ptak et al. 2003; Franceschini et al. 2003). These two pioneering surveys proved the viability of using the X-ray emission as a diagnostic for AGN activity in ULIRGs. However, they only studied a small set of the nearest and brightest ULIRGs, and therefore were not able to draw general conclusions on the issue of the energy source among ULIRGs as a class.

In an attempt to expand this type of study to a more characteristic sample of ULIRGs, our group (Teng et al. 2005, hereafter Paper I) conducted a snapshot (10 ks target−1) survey of 14 ULIRGs from the 1 Jy sample.2 These sources were carefully selected to sample the full range of infrared luminosities and infrared colors that characterize the entire class of local ULIRGs. All 14 galaxies were detected by Chandra, although most (11 of 14) had less than 40 counts. The analysis showed that the two brightest

2 The 1 Jy sample of ULIRGs is comprised of IRAS galaxies with fluxes at 60 μm exceeding 1 Jy, LIR ≥ 1012 L⊙. Galactic latitude ∣b∣ > 30°, f(60 μm) > f(12 μm) (to avoid stars), IRAS color log(f60/f120) > −0.3 (to favor luminous infrared systems), and redshift 0.018 < z < 0.268 (Kim & Sanders 1998).
galaxies in the sample have optical and X-ray spectral characteristics of Seyfert 1 nuclei. Most others have X-ray photon indices (estimated using hardness ratios) and hard X-ray to far-infrared flux ratios similar to those of starbursts.

One exception, F04103–2838, had a hardness ratio (deduced from only 30 counts) that suggested the presence of a starburst coexisting with an AGN. The low signal-to-noise ratio (S/N) data could not distinguish between a Compton-thick AGN and an incoexisting with an AGN. The low signal-to-noise ratio (S/N) data from only 30 counts) that suggested the presence of a starburst. In fact, this is the warmest of all IRAS f galaxies in the sample have optical and X-ray spectral characteristics. Most others have X-ray photon indices (estimated using hardness ratios) and hard X-ray to far-infrared flux ratios similar to those of starbursts.

The implications of these results are discussed in § 3.1. We describe the distribution of the X-ray emission from F04103–2838. In § 3.2, we point out the lack of variability of this object. A detailed analysis of the X-ray spectrum and iron complex is presented in § 3.3.

3. ANALYSIS

In § 3.1, we describe the distribution of the X-ray emission from F04103–2838. In § 3.2, we point out the lack of variability of this object. A detailed analysis of the X-ray spectrum and iron complex is presented in § 3.3.

3.1. Morphology

To improve the S/N of the images, the PN and MOS1/2 events were combined using the SAS task emosaic, and then smoothed with a $5''$ Gaussian using asmooth to match the spatial resolution of XMM-Newton. The resultant image is displayed in Figure 1 (left). A comparison of the 0.2–2 keV (smoothed) radial profile with the XMM-Newton point-spread function (PSF) at 1 keV indicates that the source is unresolved (see Fig. 1, right). Only
the EPIC PN data were used for the radial profile calculations because of the small number of counts detected by the MOS1/2 cameras. The PSF of the PN camera is well described by a King profile\(^3\) and was normalized so that the total number of counts per square pixel under the curve matches the total number of detected counts per square pixel. The Chandra data from Paper I verify that the source is unresolved.

3.2. X-Ray Variability

The time interval covered by our observation was divided into four equal bins of 5234 s to search for significant X-ray variability, another potential indicator of dominant AGN activity. The 0.2–10 and 2–10 keV EPIC PN count rates were calculated for both source and background. Figure 2 shows the 0.2–10 and 2–10 keV light curves of the source and background. To within the errors, the source is not significantly variable on the 5–6 hr timescale of our observations.

3.3. X-Ray Spectra

The extracted source and background spectra from each detector were binned using the FTOOLS gsgrppha to at least 3, 5, and 15 counts bin\(^{-1}\). The binned and unbinned spectra were then analyzed using XSPEC, version 11.3.2t. The quoted errors on the derived best-fitting model parameters correspond to a 90% confidence level (\(\Delta \chi^2/\Delta C\)-stat = 2.706). The \(\chi^2\) goodness-of-fit test was used to judge the fits to the spectrum binned to at least 15 counts bin\(^{-1}\). The Cash statistics (C-stat) option in XSPEC was used for spectra binned to at least 3 and 5 counts bin\(^{-1}\), and for the unbinned data. The spectral model was applied to the EPIC PN data only (see § 2). All models were corrected for Galactic absorption using \(N_{\text{H, Galactic}} = 2.45 \times 10^{20} \text{atoms cm}^{-2}\) (Dickey & Lockman 1990).

3.3.1. Effects of Binning

By definition, spectra binned to at least 15 counts bin\(^{-1}\) have the highest S/Ns, while the spectra binned to at least 3 counts bin\(^{-1}\) show the most spectral details. The first task is to determine whether the mode of binning affects the spectral parameters derived from the best-fit model.\(^4\) Since Cash statistics were developed for the modeling of unbinned data, we also modeled the unbinned spectrum for comparison.

Two simple models were applied to the spectra. Model A is an absorbed power-law distribution. Model B is the same as A, except for the inclusion of a Gaussian component to model the Fe K\(^\alpha\) emission at 6.7 keV (rest frame). Table 1 lists the best-fit parameters of each model, and Figure 3 shows each set of spectra with the best-fit models. The significant improvement in fitting statistics of model B over model A suggests that there is indeed an emission line at an energy consistent with Fe K\(^\alpha\) emission.

\(^3\) PSF = \(A[1 + (r/r_0)^{-\alpha}]^{-\alpha}\), where \(A \sim 4.756\), \(r_0 \sim 5.5\) pixels, and \(\alpha \sim 1.6\) (Kirsch et al. 2006).

\(^4\) Gaussian statistics apply to data binned to at least 15 counts bin\(^{-1}\), while Poisson statistics apply to the data binned to at least 3 or 5 counts bin\(^{-1}\) and unbinned data. Since the difference of two Gaussian distributions remains a Gaussian distribution, a background-subtracted spectrum binned to at least 15 counts bin\(^{-1}\) retains the properties of a Gaussian distribution and can be modeled normally. However, the same is not true for a Poisson distribution. Therefore, the background cannot be simply subtracted for data binned to at least 3 or 5 counts bin\(^{-1}\) and unbinned data, and then modeled. One way of treating the background is to model the background spectrum separately, and then add the background model to the continuum model when fitting the source spectrum. For this paper, the background is modeled using a simple, relatively flat power law (\(\Gamma \sim 1.0\)). This treatment of the background is applied to all modeling of data binned to at least 3 and 5 counts bin\(^{-1}\) and the unbinned spectrum. A representation of the background spectrum and model is shown in Fig. 4 (bottom).

However, since the number of counts is relatively low (especially when the data are binned to only 3 or 5 counts bin\(^{-1}\)), the F-test cannot be used to determine whether the addition of the Gaussian component to model A is significant. The likelihood of the line being a result of statistical variations was tested using simulations. To this end, 10,000 spectra were created using the fakeit command in XSPEC for each set of binned or unbinned data. The simulated spectra were created using model A. Then these spectra were fitted by both models A and B. If the line is a result of statistical variations, then one would expect a large fraction of the simulated spectra to be well described by model B. The fitting statistics were used to calculate \(\Delta C\)-stat (A–B) or \(\Delta \chi^2\) (A–B) for the 15 counts bin\(^{-1}\) data, which was then compared to the values presented in Table 1. For the 15 counts bin\(^{-1}\) data, 1000 of 10,000 (10.0%) had \(\Delta \chi^2\) greater than 3.76. This implies that model B (with the inclusion of the emission line) is significant at the 90.0% level (a 1.6 \(\sigma\) detection). Similarly, the simulations show that the line is significant at the 96.87% level (313 out of 10,000; 2.2 \(\sigma\)) for the 5 counts bin\(^{-1}\) data, at the 93.5% level (507 out of 10,000; 1.8 \(\sigma\)) for the 3 counts bin\(^{-1}\) data, and at the 94.0%
## Table 1: Best-Fit Parameters to Models A, B, and C

| Parameters | Model A | Model B | Model C |
|------------|---------|---------|---------|
|            | 15 counts bin⁻¹ | 5 counts bin⁻¹ | 3 counts bin⁻¹ | Unbinned | 15 counts bin⁻¹ | 5 counts bin⁻¹ | 3 counts bin⁻¹ | Unbinned | Unbinned |
| $N_{H}^{a}$ | ... | ... | ... | ... | 0.20±0.28 | 0.00±0.04 | 0.00±0.04 | 0.00±0.04 | 0.30±0.36 | 0.00±0.06 | 0.00±0.06 | 0.00±0.06 | 0.36±0.33 | 0.06±0.03 |
| $\Gamma$ | 1.42±0.61 | 1.01±0.21 | 1.00±0.21 | 1.00±0.21 | 1.80±0.90 | 1.12±0.22 | 1.11±0.26 | 1.09±0.27 | 1.36±0.97 | ... | ... | ... | ... |
| $E_{\text{kin}}$ | ... | ... | ... | ... | 6.57±0.20 | 6.37±0.17 | 6.42±0.29 | 6.43±0.28 | 6.43±0.30 | 6.42±0.29 | ... | ... | ... | ... |
| $\sigma^{b}$ | ... | ... | ... | ... | 0.00±0.00 | 0.14±0.14 | 0.23±0.28 | 0.25±0.28 | 0.26±0.28 | 0.13±0.06 | ... | ... | ... | ... |
| $\text{EW}^{b}$ | ... | ... | ... | ... | 1.95±0.95 | 1.33±0.94 | 1.37±1.33 | 1.39±1.02 | 1.62±1.12 | ... | ... | ... | ... | ... |
| $kT^{b}$ | ... | ... | ... | ... | ... | ... | ... | ... | 1.00±0.08 | ... | ... | ... | ... | ... |
| Stat./dof | 12.4/11 | 66.5/40 | 83.0/67 | 858.2/1958 | 1.16±0.40 | 1.39±0.06 | 1.40±0.06 | 1.44±0.11 | ... | ... | ... | ... | ... |
| $F_{total}^{a}$ | 0.96±0.71 | 1.07±0.29 | 1.07±0.29 | 1.05±0.20 | 8.68 | 58.8/37 | 77.1/64 | 852.1/595 | 848.1/593 | ... | ... | ... | ... | ... |
| $F_{2-10 \text{ keV}}^{a}$ | ... | ... | ... | ... | 3.96±0.37 | 4.70±0.38 | 4.73±0.62 | 4.85±3.75 | ... | ... | ... | ... | ... | ... |
| $L_{total}^{a}$ | 0.29±0.12 | 0.31±0.09 | 0.31±0.09 | 0.31±0.06 | 0.86±0.20 | 0.31±0.05 | 0.31±0.06 | 0.31±0.05 | 0.64±0.26 | ... | ... | ... | ... | ... |
| $L_{2-10 \text{ keV}}^{a}$ | ... | ... | ... | ... | 0.86±0.20 | 0.31±0.05 | 0.31±0.06 | 0.31±0.05 | 0.64±0.26 | ... | ... | ... | ... | ... |
| $F_{total}^{c}$ | ... | ... | ... | ... | 1.16±0.40 | 1.39±0.06 | 1.40±0.06 | 1.44±0.11 | ... | ... | ... | ... | ... | ... |
| $L_{total}^{c}$ | ... | ... | ... | ... | 1.07±0.20 | 1.35±0.06 | 1.36±0.06 | 1.40±0.06 | 1.35±0.30 | ... | ... | ... | ... | ... | ... |

**Notes.**
- Model A: $\text{Absorption}_{\text{Galactic}} \times \text{Absorption}_{\text{source}} \times \text{PL}$. Model B: $\text{Absorption}_{\text{Galactic}} \times \text{Absorption}_{\text{source}} \times \text{(PL + Line)}$. Model C: $\text{Absorption}_{\text{Galactic}} \times [\text{MEKAL} + \text{Absorption}_{\text{source}} \times \text{(PL + Line)}]$, where MEKAL is the Mewe, Kaastra, and Liedahl thermal plasma model (see the XSPEC manual for details), PL is a power-law model representing the AGN, Line is the Fe K emission line with a Gaussian profile, $\text{Absorption}_{\text{Galactic}}$ is the absorption from $N_{H}^{a} = 2.45 \times 10^{20}$ atoms cm⁻², and $\text{Absorption}_{\text{source}}$ is the intrinsic absorption within the source.
- $^{a}$Intrinsic (i.e., within the galaxy) column density in units of $10^{22}$ atoms cm⁻².
- $^{b}$Fe K line energy (rest-frame) width, equivalent width, and thermal gas temperature, all in keV.
- $^{c}$Fitting statistics per degrees of freedom. Cash statistics are used for unbinned spectra and spectra binned to at least 3 and 5 counts bin⁻¹, while $\chi^{2}$ statistics are used for spectra binned to at least 15 counts bin⁻¹.
- $^{d}$Absorption-corrected flux in units of $10^{-14}$ ergs cm⁻² s⁻¹. The AGN value includes the flux from both the power-law component and the iron line.
- $^{e}$Absorption-corrected luminosity in units of $10^{42}$ ergs s⁻¹. The AGN value includes the flux from both the power-law component and the iron line.
level (608 out of 10,000; 1.9σ) for the unbinned data. From these simulations, the line is significant to at least the 90.0% level.

The 3 counts bin data also suggest that the iron line can be decomposed into two narrower emission lines with centroid energies at 6.3 (EW: 6 keV) and 6.7 keV (EW: 4 keV) in the rest frame. These energies are consistent with emission arising from neutral iron and Fe XXV, respectively. The fitting statistics of the double-line model to the unbinned data is only slightly better than that of the single-line model. The detection of these narrow lines in the Fe K complex is significant at only the 60% level, based on 10,000 simulations of the unbinned data. Therefore, the detection of the doublet needs to be confirmed with data of higher spectral resolution and S/N.

Our modeling and simulations show that Cash statistics give consistent results for the unbinned spectrum and the spectra binned to at least 5 counts bin−1. Since Cash statistics were designed for unbinned spectra, we will use only the unbinned spectrum in subsequent modeling. Since the iron line is most prominent in the data binned to at least 5 counts bin−1, we use the spectrum binned to at least 5 counts bin−1 as a visual and qualitative check for the model of the unbinned data.

3.3.2. AGN + Starburst Continuum Models

Aside from the models A and B mentioned above, we modeled the unbinned spectrum with slightly more complex models to account for the possibility that a starburst may coexist with the AGN in F04103−2838. Guarding against overinterpreting data with only modest S/Ns, even these more “complex” models were kept as simple as possible.

The first model (model C) is a combination of absorbed power-law and MEKAL spectra (with metallicity fixed at solar), which represent the emission from the AGN and starburst, respectively. The second model (model D) is a combination of two absorbed power laws, with one power law representing the AGN and the other representing the high-mass X-ray binaries (HMXBs) associated with the possible starburst in this object. Finally, a third
model (model E) is a combination of the two above-mentioned models: a power law for the AGN, a power law for the HMXBs, and a MEKAL model for the hot gas. For all of these models, a Gaussian with centroid energy between 6 and 7 keV was included to model the iron line.

While all of these models give better fitting statistics than the simpler power law models, only model C is a realistic fit to the data. Models D and E are rejected on the grounds that the best-fit power law values are physically unrealistic descriptions of AGNs. Therefore, we adopt model C as the “best-fit model” (Fig. 4), and list the fitting parameters in Table 1. This is perhaps not surprising, given that ULIRGs are known from observations at optical and infrared wavelengths to show the presence of both an AGN and a starburst (e.g., Genzel et al. 1998; Kim et al. 1998); F04103–2838 does not appear to be an exception.

4. DISCUSSION
4.1. The Soft Component

The results from the spectral fitting suggest that the soft X-ray (0.2–2 keV) flux is best described as thermal emission from hot gas with $kT \sim 0.1$ keV ($T \sim 1.2 \times 10^4$ K). This is somewhat lower than the range of gas temperatures (0.6–0.8 keV) found in LINERs (González-Martín et al. 2006). The results for F04103–2838 are also somewhat lower than the results from Grimes et al. (2005), who performed a Chandra archival study of the soft X-ray emission from starburst galaxies ranging in luminosity from dwarf galaxies to ULIRGs. The authors found that the soft X-ray thermal emission of these starburst galaxies tends to fall in the temperature range $kT \sim 0.25$–0.8 keV, with ULIRGs occupying the upper end. These large temperatures can all be attributed to powerful starbursts.

The soft X-ray emission in F04103–2838 is likely the result of thermal bremsstrahlung from a hot gas produced by the merger-induced starburst or by intrinsically extended soft X-ray emission heated by the AGN. If the ion density equals that of the electrons, the relationship between the electron density ($n_e$) and the luminosity of an emitting region of a given volume $V$ is

$$L_{\text{Fe}} \approx 1.7 \times 10^{-25} n_e^2 f V \text{ ergs s}^{-1},$$

where $f$ is the filling factor for the hot gas. The non-AGN contribution of the nominal 0.2–2 keV luminosity from the best-fit model (model C) for F04103–2838 is $1.6 \times 10^{41}$ ergs s$^{-1}$. Assuming that the emitting region is spherical with a diameter of $<5''$, the average electron density has a lower limit of $\sim 0.19 f^{-1/2}$ cm$^{-3}$. This value is consistent with simulation results for the warm ($10^5 < T < 10^6$ K) component in the wind models of Strickland & Stevens (2000).

Observationally, this hot gas component is difficult to probe because of its low density and emissivity. Strickland & Stevens (2000) performed hydrodynamic simulations of starburst-driven galactic winds with various ISM models. The authors found that, in general, the soft X-ray emission comes from gas with low filling factors ($10^{-3} < f < 10^{-1}$; see also Cecil et al. 2002 and Strickland et al. 2004a, 2004b for observational constraints). Using these values for $f$, the electron density of the hot gas in F04103–2838 is $\sim 0.6–5.9$ cm$^{-3}$, which is consistent with values derived by Netzer et al. (2005) in NGC 6240.

The soft X-ray emission detected in F04103–2838 may thus be the result of superwinds from the starburst. X-ray superbubbles have been observed in Arp 220 (Iwasawa et al. 2005) and NGC 6240 (Netzer et al. 2005). Furthermore, powerful outflow events are now thought to take place in most ULIRGs (e.g., Rupke et al. 2002, 2005a, 2005b, 2005c, although their sample did not include F04103–2838).

4.2. The Iron Feature

F04103–2838 joins the growing list of ULIRGs with Fe K detections (e.g., Arp 220 [Iwasawa et al. 2005], Z11598–0112 [Paper I], F19254–7245 [Franceschini et al. 2003; Braito et al. 2003], Mrk 231 [Maloney & Reynolds 2000; Ptak et al. 2003; Braito et al. 2004], F05189–2524 [Ptak et al. 2003], Mrk 273 [Ptak et al. 2003], and UGC 05101 [Imanishi et al. 2003; Ptak et al. 2003]), supporting the view that an obscured AGN exists in many of these objects. The presence of an AGN in F04103–2838 was first suggested by Paper I, based on the large hard X-ray to far-infrared flux ratio; the XMM-Newton detection of

---

5. Eq. (1) is based on eq. (5.14b) and Fig. 5.2 of Rybicki & Lightman (1979) for $T = 10^8$ K in the energy range of 0.2–2 keV.

6. While the selection of a $<5''$ emitting region is based on the spatial resolution of the telescope, it should be noted that the linear diameter of $5''$ at the distance of F04103–2838 is less than a factor of 2 larger than the soft X-ray (0.5–2.5 keV) emitting region of NGC 6240 (Komossa et al. 2003). Therefore, the assumption of a $<5''$ diameter is reasonable, even though it was chosen based on the instrument PSF.
Fe K now indicates that the luminosity of this AGN has probably been underestimated.

Few LINERs have detected Fe K lines. Terashima et al. (2002) studied a sample of 53 LINERs and low-luminosity Seyfert galaxies using the Advanced Satellite for Cosmology and Astrophysics (ASCA). Of the 21 LINERs in their sample, Fe emission lines were detected in only five galaxies (NGC 1052, NGC 3998, NGC 4261, NGC 4579, and NGC 4736). Of these five objects, only four (i.e., those excluding NGC 4261) have centroid line energies consistent within the uncertainties of the measurements with Fe Kα emission due to neutral iron (E \sim 6.4 \text{ keV}).

Three other LINERs have known Fe K detections; all three are powerful luminous or ultraluminous infrared galaxies. These galaxies are Arp 220 (Iwasawa et al. 2005), NGC 6240 (Ptak et al. 2003; Komossa et al. 2003), and UGC 5101 (Imanishi et al. 2003; Ptak et al. 2003). Chandra observations of Arp 220, the archetypal ULIRG, show an iron line at 6.7 ± 0.1 keV. This is consistent with emission due to Fe xx up to Fe xxvi, but not with neutral iron at 6.4 keV (Iwasawa et al. 2005). Komossa et al. (2003) detected Fe K emission from each of the two nuclei in NGC 6240. Their analysis showed that the iron lines in each nucleus are consistent with Fe Kα and Fe Kβ emissions.

In Figure 5, we show the distribution of published Fe K equivalent widths of all LINERs and ULIRGs known to have line emission. Arp 220, NGC 6240, and F04103−2838 appear to have iron emission with the greatest EW measurements of all the LINERs and ULIRGs. These large Fe K features could be the results of the blending of multiple narrower lines. Komossa et al. (2003) did not publish the EWs of the lines from each of the nuclei in NGC 6240. The result quoted here is from Ptak et al. (2003). The authors did not distinguish Fe Kα emission from Fe Kβ emission, and the EW measurement is likely dominated by the brighter southern nucleus alone. The large equivalent widths of the ULIRGs are telltale signs of obscured AGNs, where line-of-sight columns of material exceeding 10^{24} \text{ cm}^{-2} prevent a direct view of the AGN; the 2–10 keV flux is dominated by light scattered from dust or electrons (e.g., Ghisellini et al. 1994; Krolik et al. 1994). The large amount of molecular gas (∼10^{12} M_\odot \text{ pc}^{-2}) within 400 pc from the nuclei of NGC 6240 (e.g., Bryant & Scoville 1999) is sufficient to cause this obscuration. A similar explanation likely applies to F04103−2838, although we are not aware of any CO measurements in this system.

Interestingly, the Fe K complex in NGC 6240 breaks up into a number of narrow lines. Both Netzer et al. (2005) and Boller et al. (2003) detected Fe K lines due to neutral iron (6.41 ± 0.2 keV), Fe xxv (6.68 ± 0.02 keV), and Fe xxvi (7.01 ± 0.04 keV) in NGC 6240. Komossa et al. (2003) also detected lines at 6.4 and 6.95 keV. The centroid energies of the lines due to neutral iron and Fe xxv in NGC 6240 are consistent with the respective centroid energies suggested by the doublet in the 3 counts bin−1 data for F04103−2838. Although simulations suggest that the two-line model is only significant at the ~60% level, a FWHM of ~30,000 km s\(^{-1}\) (σ ~ 0.3 keV) seems too broad, and the two-component interpretation may be more likely. The Fe xxvi line in NGC 6240 is much fainter than the other lines, so it is not surprising that we were unable to detect it in the modest S/N data of F04103−2838.

Despite their X-ray similarities, F04103−2838 is ~2.5 times more infrared luminous than NGC 6240. These objects also differ in terms of IRAS f_{25}/f_{60} ratios (0.15 for NGC 6240 and 0.30 for F04103−2838) and merger state (NGC 6240 is in a premerger phase, with a nuclear separation of ~1.3 kpc, while F04103−2838 is in the postmerger stage, with a single coalesced nucleus). There is growing observational evidence (e.g., Veilleux et al. 2002, 2006; Ishida 2004; Dasyra et al. 2006a, 2006b, 2007) and theoretical motivation (e.g., Hopkins et al. 2005) that mergers of gas-rich galaxies often produce “cool” (f_{25}/f_{60} < 0.2) luminous infrared galaxies that evolve into “warm” (f_{25}/f_{60} > 0.2) ULIRGs before becoming optical quasars. If this evolutionary sequence applies to NGC 6240 and F04103−2838, the first object may actually be the precursor to the latter.

4.3. Energy Source of the ULIRG

The lack of short-timescale variability (see § 3.2) is to be expected if most of the primary X-ray flux is being absorbed or reprocessed. As discussed in § 4.2, the large equivalent width of the iron line in F04103−2838 implies the presence of a highly obscured AGN. It is very difficult in such cases to estimate the intrinsic luminosity of the AGN without measurements of the >10 keV flux from the buried AGN (e.g., Mrk 231; Braito et al. 2004). Here we follow the method of Maloney & Reynolds (2000) to estimate the intrinsic luminosity of F04103−2838.

In their analysis of an ASCA observation of Mrk 231, they discussed two ways of estimating the intrinsic AGN flux. The observed X-ray flux is due to a combination of two effects: reflection and scattering. Maloney & Reynolds (2000) estimated the intrinsic AGN flux from the reflection and the scattering components separately. In their geometry, the observer has an obstructed view of the central engine reflected off of the circumnuclear torus; the amount of reflection depends on the size of the reflecting surface and the composition of the torus. On the other hand, the scattered component...
is light from the central engine (unobstructed by the torus) scattered into the line of sight. Based on their spectral fitting of the ASCA data, Maloney & Reynolds (2000) found that the X-ray flux of Mrk 231 is scattering dominated, with 75% scattered and 25% reflected light.

Due to the low S/N of our data on F04103–2838, we could not perform the same spectral fitting done by Maloney & Reynolds (2000). The large equivalent width of the Fe Kα line (~1.6 keV) above 1 keV suggests a reflection-dominated spectrum. However, the width of the line implies that it could be a blend of narrower Fe Kα and ionized iron emission lines (as suggested by the 3 counts bin−1 data). If this is the case, the Fe Kα EW may be more consistent with a scattering-dominated spectrum. Therefore, we consider two cases as we attempt to estimate the intrinsic X-ray luminosity of the AGN: (1) that the majority of the observed flux is due to reflection, and (2) that the majority of the observed flux is due to scattering.

After correction for absorption, the nominal 0.2–10 keV flux of the buried AGN in F04103–2838 derived from our best-fit model (model C) is 1.83 × 10^{42} ergs s^{-1}. In the first scenario, we assume that the reflection component is 75% and that the scattering component is 25% of the total observed flux. This implies that L_{\text{scattered}} = 0.45 × 10^{42}\text{ ergs s}^{-1} and that L_{\text{reflected}} = 1.38 × 10^{42}\text{ ergs s}^{-1} for the AGN in F04103–2838. In Maloney & Reynolds (2000), the luminosity from the reflected portion is scaled up by a factor of 25 in their modeling of the reflection process. The reflection process differs for different galaxies; it depends on the ionization state of the mirror and the steepness of the photon position is only significant at the 1 Jy ULIRG/LINER F04103–2838 range in luminosity overlaps with that of quasars (~10^{44}\text{ ergs s}^{-1}; e.g., Elvis et al. 1994; Piconcelli et al. 2005) and is similar to that of NGC 6240 (~0.7–2 × 10^{44}\text{ ergs s}^{-1}, after correction for an HI column density of 1–2 × 10^{24}\text{ cm}^{-2}; Vignati et al. 1999). The ratio log(L_{0.2–10\text{ keV}}/L_{\text{IR}}) for F04103–2838 corrected for scattering and reflection is ~2.2 to ~1.7. These values fall precisely within the range found in radio-quiet PG quasars (~3 to ~1; Sanders et al. 1989).

Assuming that F04103–2838 has the same X-ray to bolometric luminosity ratio as radio-quiet QSOs (Elvis et al. 1994; L_{X}/L_{bol} ~ 3%), the AGN contribution to the bolometric luminosity of F04103–2838 is ~15%–38%. Therefore, within the large uncertainties, the AGN in F04103–2838 does not dominate the total energy output of the galaxy.

5. SUMMARY

The results from our analysis of the XMM-Newton spectrum of the 1 Jy ULIRG/LINER F04103–2838 can be summarized as follows:

1. The soft (0.2–2 keV) X-ray flux of F04103–2838 is attributed to hot gas with kT ∼ 0.1 keV. This temperature is similar to that derived in other starburst galaxies and LINERs. The electron density in F04103–2838 is ~0.5–5 cm^{-3}, which is consistent with theoretical predictions and observational estimates in wind systems.

2. An Fe Kα line located at ~6.4 keV, with an equivalent width of ~1.6 keV, is detected in F04103–2838. The line could be intrinsically broad or could be made up of two narrow lines located at rest-frame energies of ~6.3 and 6.7 keV, but this decomposition is only significant at the ~60% level, so it needs to be verified with higher resolution spectra.

3. The large equivalent width of the Fe Kα line suggests that the AGN is Compton thick. Using simple assumptions, we estimate that the intrinsic 0.2–10 keV luminosity of this AGN is 0.6–1.4 × 10^{44}\text{ ergs s}^{-1}. If these assumptions are correct, and the galaxy has a QSO-like X-ray to bolometric luminosity ratio, the AGN detected by our observations does not dominate the bolometric luminosity of F04103–2838.

4. The X-ray spectral characteristics of F04103–2838 are strikingly similar to those of the local luminous infrared galaxy NGC 6240. Given the similarities in X-ray properties, but differences in merger state and in infrared color and luminosity, objects like NGC 6240 could conceivably be the precursors of ULIRGs like F04103–2838.

We are grateful for the referee’s comments and suggestions, which helped improve this paper. Thanks are due to Chris Reynolds, Cole Miller, and Yuxuan Yang for useful discussions. This research is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. We made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, Caltech, under contract with NASA. We acknowledge support from the NASA/XMM-Newton Guest Observer Program under grant NNX06AF51G.

REFERENCES

Boller, T., Keil, R., Hasinger, G., Costantini, E., Fujimoto, R., Anabuki, N., Lehmann, I., & Gallo, L. 2003, A&A, 411, 63

Braithwaite, V., et al. 2003, A&A, 398, 107

———. 2004, A&A, 420, 79

Bryant, P. M., & Scoville, N. Z. 1999, AJ, 117, 2632

Cecil, G., Bland-Hawthorn, J., & Veilleux, S. 2002, ApJ, 576, 745

Dasyra, K. M., et al. 2006a, ApJ, 638, 745

———. 2006b, ApJ, 651, 835
Dasyra, K. M., et al. 2007, ApJ, 657, 102
Dickey, J., & Lockman, F. 1990, ARA&A, 28, 215
Elvis, M., et al. 1994, ApJS, 95, 1
Franceschini, A., et al. 2003, MNRAS, 343, 1181
Gehrels, N. 1986, ApJ, 303, 336
Genzel, R., et al. 1998, ApJ, 498, 579
Ghisellini, G., Hardee, F., & Matt, G. 1994, MNRAS, 267, 743
Gonzalez-Martín, O., Masegosa, J., Marquez, I., Guerrero, M. A., & Dultzin-Hacyan, D. 2006, A&A, 460, 45
Grimes, J. P., Heckman, T., Strickland, D., & Ptak, A. 2005, ApJ, 628, 187
Hopkins, P. F., Hernquist, L., Cox, T. J., Di Matteo, T., Martini, P., Robertson, B., & Springel, V. 2005, ApJ, 630, 705
Ishida, C. M. 2004, Ph.D. Thesis, Univ. of Hawaii
Imanishi, M., & Terashima, Y. 2004, AJ, 127, 758
Imanishi, M., Terashima, Y., Anabuki, N., & Nakagawa, T. 2003, ApJ, 596, L167
Iwasawa, K., Sanders, D. B., Evans, A. S., Tretham, N., Miniutti, G., & Spoon, H. W. W. 2005, MNRAS, 357, 565
Kim, D.-C., & Sanders, D. B. 1998, ApJS, 119, 41
Kim, D.-C., Veilleux, S., & Sanders, D. B. 1998, ApJ, 508, 627
———. 2002, ApJS, 143, 277
Kirsch, M., & EPIC Consortium 2006, XMM-EPIC Status of Calibration and Data Analysis, http://xmm.vilspa.esa.es/docs/documents/CAL-TN-0018.pdf
Komo, S., Burwitz, V., Hasinger, G., Predehl, P., Kaasra, J. S., & Ikebe, Y. 2003, ApJ, 582, L15
Krolik, J. H., Madeo, P., & Zycki, P. T. 1994, ApJ, 420, L57
Lutz, D., Veilleux, S., & Genzel, R. 1999, ApJ, 517, L13
Maloney, P. R., & Reynolds, C. S. 2000, ApJ, 545, L23
Netzer, H., Lenz, D., Kaspi, S., George, I. M., Turner, T. J., Lutz, D., Boller, T., & Chehouni, D. 2005, ApJ, 629, 739
Piconcelli, E., Jimenez-Bailon, E., Guainazzi, M., Schartel, N., Rodriguez-Pascual, P. M., & Santos-Lleo, M. 2005, A&A, 432, 15
Ptak, A., Heckman, T., Levenson, N. A., Weaver, K., & Strickland, D. 2003, ApJ, 592, 782
Rupke, D. S., Veilleux, S., & Sanders, D. B. 2002, ApJ, 570, 588
———. 2005a, ApJS, 160, 87
———. 2005b, ApJS, 160, 115
———. 2005c, ApJ, 632, 751
Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: Wiley)
Sanders, D. B., Phinney, E. S., Neugebauer, G., Soifer, B. T., & Matthews, K. 1989, ApJ, 347, 29
Strickland, D. K., Heckman, T. M., Colbert, E. J. M., Hoopes, C. G., & Weaver, K. A. 2004a, ApJ, 606, 829
———. 2004b, ApJS, 151, 193
Strickland, D. K., & Stevens, I. R. 2000, MNRAS, 314, 511
Surace, J. A., & Sanders, D. B. 1999, ApJ, 512, 162
Taniguchi, Y., Yoshino, A., Ohyama, Y., & Nishiura, S. 1999, ApJ, 514, 660
Teng, S. H., Wilson, A. S., Veilleux, S., Young, A. J., Sanders, D. B., & Nagar, N. M. 2005, ApJ, 633, 664 (Paper I)
Terashima, Y., Iyomoto, N., Ho, L. C., & Ptak, A. F. 2002, ApJS, 139, 1
Tran, Q. D., et al. 2001, ApJ, 552, 527
Veilleux, S., Kim, D.-C., & Sanders, D. B. 1999a, ApJ, 522, 113
———. 2002, ApJS, 143, 315
Veilleux, S., Kim, D.-C., Sanders, D. B., Mazzarella, J. M., & Soifer, B. T. 1995, ApJS, 98, 171
Veilleux, S., Sanders, D. B., & Kim, D.-C. 1997, ApJ, 484, 92
———. 1999b, ApJ, 522, 139
Veilleux, S., et al. 2006, ApJ, 643, 707
Vignati, P., et al. 1999, A&A, 349, L57