The X-ray emission of local luminous infrared galaxies

Miguel Pereira-Santaella, Almudena Alonso-Herrera, María Santos-Lleo, Luis Colina, Elena Jiménez-Bailón, Anna L. Longinotti, George H. Rieke, Martin Ward, and Pilar Esquej

1 Departamento de Astrofísica, Centro de Astrobiología, CSIC/INTA, Carretera de Torrelodones a Alcalá de Henares, km 4, 28850, Torrelodones, Madrid, Spain e-mail: mpereira@cab.inta-csic.es
2 XMM-Newton Science Operation Centre, European Space Agency, 28091, Villanueva de la Cañada, Madrid, Spain
3 Instituto de Astronomía, Universidad Nacional Autónoma de México, Apartado Postal 70-264, 04510, México DF, México
4 MIT Kavli Institute for Astrophysics and Space Research, 77 Massachusetts Avenue, NE80-6011, Cambridge, MA, 02139, USA
5 Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA
6 Department of Physics, Durham University, South Road, Durham, DH1 3LE, UK

Preprint online version: September 6, 2011

ABSTRACT

We study the X-ray emission of a representative sample of 27 local luminous infrared galaxies (LIRGs). The median IR luminosity of our sample is $L_{\text{IR}}/L_{\odot} = 11.2$, thus the low-luminosity end of the LIRG class is well represented. We used new XMM-Newton data as well as Chandra and XMM-Newton archive data. The soft X-ray (0.5-2 keV) emission of most of the galaxies (>80%), including LIRGs hosting a Seyfert 2 nucleus, is dominated by star-formation related processes. These LIRGs follow the star-formation rate (SFR) versus soft X-ray luminosity correlation observed in local starbursts. We find that ~15% of the non-Seyfert LIRGs have an excess hard X-ray emission relative to that expected from star-formation that might indicate the presence of an obscured AGN. The rest of the non-Seyfert LIRGs follow the SFR versus hard X-ray (2-10 keV) luminosity correlation of local starbursts. The non-detection of the 6.4 keV Fe Kα emission line in the non-Seyfert LIRGs allows us to put an upper limit to the bolometric luminosity of an obscured AGN, $L_{\text{bol}} < 10^{43}$ erg s$^{-1}$. That is, in these galaxies, if they hosted a low luminosity AGN, its contribution to total luminosity would be less than 10%. Finally we estimate that the AGN contribution to the total luminosity for our sample of local LIRGs is between 7% and 10%. We do not find significant AGN feedback effects in these galaxies.

Key words. Galaxies: active – Galaxies: starburst – X-ray: galaxies

1. Introduction

Luminous infrared galaxies (LIRGs) are galaxies with infrared (IR) luminosities ($L_{\text{IR}} = L_{\text{8-1000\mu m}}$) from $10^{11}$ to $10^{12} L_{\odot}$. They are powered by star-formation and/or an active galactic nucleus (AGN; see Sanders & Mirabel 1996 for a review). Together with ultraluminous infrared galaxies (ULIRGs; $L_{\text{IR}} > 10^{12} L_{\odot}$), they are the major contributors to the star-formation rate (SFR) density at $z \sim 1-2$ (Pérez-González et al. 2005; Le Floc’h et al. 2005; Caputi et al. 2007).

The star-formation in local LIRGs is distributed over few kpc scales (Alonso-Herrero et al. 2006; Hattori et al. 2004; Rodríguez-Zaurín et al. 2011). This is similar to local starbursts and $z \sim 2$ infrared bright galaxies (Daddi et al. 2007; Rigby et al. 2008; Farrah et al. 2008; Rujopakarn et al. 2010), but at odds with local ULIRGs where most of the activity is taking place in very compact regions (the central kpc). Similarly, the fraction of AGN dominated local ULIRGs increases with increasing IR luminosity. About 40% of the ULIRGs are classified as Seyfert (Veilleux et al. 1993; Kim et al. 1998). Thus the study of local LIRGs is motivated as they might be scaled-down versions of more distant IR bright galaxies.

The X-ray emission of starburst galaxies is mainly produced by high-mass X-ray binaries (HMXB), supernova remnants (SNR), O stars and hot gas heated by the energy originated in supernova explosions (Persic & Rephaeli 2002; Fabian 2006). The hard X-ray (2-10 keV) emission of most of the galaxies (>80%), including LIRGs hosting a Seyfert 2 nucleus, is dominated by star-formation related processes. These LIRGs follow the star-formation rate (SFR) versus soft X-ray luminosity correlation observed in local starbursts. We find that ~15% of the non-Seyfert LIRGs (3 out of 20) have an excess hard X-ray emission relative to that expected from star-formation that might indicate the presence of an obscured AGN. The rest of the non-Seyfert LIRGs follow the SFR versus hard X-ray (2-10 keV) luminosity correlation of local starbursts. The non-detection of the 6.4 keV Fe Kα emission line in the non-Seyfert LIRGs allows us to put an upper limit to the bolometric luminosity of an obscured AGN, $L_{\text{bol}} < 10^{43}$ erg s$^{-1}$. That is, in these galaxies, if they hosted a low luminosity AGN, its contribution to total luminosity would be less than 10%. Finally we estimate that the AGN contribution to the total luminosity for our sample of local LIRGs is between 7% and 10%.

It has been shown that there is a good correlation between the hard X-ray luminosity and the SFR for local starbursts (e.g. Ranalli et al. 2003; Grimm et al. 2003; Persic et al. 2004). However, the contribution to the hard X-ray luminosity from low-mass X-ray binaries (LMXB), which is not related to the current SFR, is not always negligible. For instance, Colbert et al. (2004) and Lehmer et al. (2010) estimated that the LMXB contribution is important for galaxies with low SFR/M$_{*}$. It should be noted that the X-ray emission of a star-formation burst is delayed with respect to other SFR tracer. Thus, an evolution with time is expected in the X-ray emission of the star-forming galaxies (Mas-Hesse et al. 2008; Rosa González et al. 2009). This evolution might explain part of the scatter in the X-ray luminosity vs. SFR correlations.
According to their IR luminosity, the SFR of LIRGs ranges from $\sim 20$ to $200 M_\odot \text{yr}^{-1}$ \cite{Kennicutt1998}. Therefore strong X-ray emission ($\sim 10^{41} \text{erg s}^{-1}$) associated to star-formation is expected from these galaxies. The AGN contribution to the X-ray emission of LIRGs is expected to be low. Pure Seyfert AGN emission is detected in $\sim 15\%$ of the LIRGs using optical spectroscopy \cite{Kim1998}, however a dust-embedded AGN could be present in some of the them. Thanks to X-ray observations of LIRGs we are be able to determine whether an obscured AGN is present, or, in the case of non-detection, set an upper limit to the AGN contribution.

Previous studies of the X-ray emission produced by star-formation have been focused on nearby starbursts \cite[e.g.,][]{Pttak1999,Jimenez-Bailon2003,Ranalli2003,Grimm2003,Persic2004,Colbert2004} or ULIRGs \cite[e.g.,][]{Rieke1988,Perez-Olea2004}. Additionally we extended the Alonso-Herrero et al. \citeyearpar{2006} sample to include all the galaxies in the IRAS RBGS that fulfill their selection criteria but were not included in their sample (mostly optically classified Seyfert galaxies, see \cite{Alonso-Herrero2011} in press).

In Fig. 1 we compare the $L_{\text{IR}}$ distribution (adapted to the cosmology used throughout this paper) of our sample with that of the extended Alonso-Herrero et al. \citeyearpar{2006} sample. The Kolmogorov-Smirnov two-sample test shows that it is not possible to reject ($p > 0.49$) that both samples come from the same distribution. According to their nuclear activity classification\footnote{The IRAS RBGS is a complete flux limited sample including all the extragalactic objects with a 60 $\mu$m flux density greater than $5.25$ Jy and Galactic latitude $|b| > 5^\circ$.}, 44\%+10\% and 46\%+13\% are H ii-type in the parent sample and in our sample respectively. On the other hand, Seyfert galaxies represent 22\%+7\% of the parent sample and 27\%+10\% of our sample. That is, our X-ray sample is not biased towards active galaxies. Thus these 27 galaxies constitute a representative sample of the local LIRGs in terms of both IR luminosity and nuclear activity. The median log $L_{\text{IR}}/L_\odot$ of the sample is 11.2, thus low luminosity LIRGs are well represented. The selected galaxies are listed in Table 1

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Comparison of the cumulative galaxy distributions as a function of the $L_{\text{IR}}$ of our sample of LIRGs and the extended parent sample (AAH06; see Sect. 2).}
\end{figure}

\textit{2. The sample of LIRGs}

\subsection{Definition of the sample}

Our sample of LIRGs contains 27 galaxies with \textit{XMM-Newton} or \textit{Chandra} data drawn from the volume limited sample of local LIRGs (40 Mpc $< d < 75$ Mpc) of Alonso-Herrero et al. \citeyearpar{2006}. The Alonso-Herrero et al. \citeyearpar{2006} sample was selected from the the \textit{IRAS Revised Bright Galaxy Sample} (RBGS; \cite{Sanders2003} to have $2750 < v_{\text{hel}}$ (km s$^{-1}$) $< 5200$ and $11.05 < \log L_{\text{IR}}/L_\odot < 11.88$. Such criteria were imposed to allow for narrow-band observations of the Pa$\alpha$ emission line with the NICMOS instrument on the \textit{HST}. Further details about the parent sample are given in Alonso-Herrero et al. \citeyearpar{2006}. Additionally we extended the Alonso-Herrero et al. \citeyearpar{2006} sample to include all the galaxies in the IRAS RBGS that fulfill their selection criteria but were not included in their sample.

In this paper we present a study of a sample of 27 local LIRGs (median log $L_{\text{IR}}/L_\odot = 11.20$) observed with \textit{XMM-Newton} and \textit{Chandra}. The sample is described in Sect. \ref{sample}. In Sect. \ref{xray} we describe the X-ray data reduction. In Sects. \ref{emission} and \ref{correlation} we present the spatial and spectral analysis of the X-ray data. The properties of the X-ray emission produced by star-formation and AGN related processes are discussed in Sects. \ref{starformation} and \ref{agn}, respectively. Sect. \ref{conclusions} summarizes the main conclusions.

Throughout this paper we assume a flat cosmology with $H_0 = 70$ km s$^{-1}$Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

\subsection{Star-formation rate and stellar mass}

The IR-formation is driven by massive young stars. The dust absorbs a large
They decomposed their count for the leaked UV light from young stars is included in the Kroupa (2001) initial mass function (IMF) over the stellar mass range from 0.08 to 100 $M_\odot$. A correction to account for the leaked UV light from young stars is included in the calibration. Alonso-Herrero et al. (2009a) estimated the AGN contribution at 24 $\mu$m in these LIRGs. They decomposed their Spitzer/IRS mid-IR spectra into AGN and starburst components using clumpy torus models and star-forming galaxy templates. We used these estimations to subtract the AGN luminosity at 24 $\mu$m before calculating the obscured SFR. The AGN fractions and the calculations of the obscured SFR are listed in Table 2.

Some galaxies were observed with the XMM-Newton optical monitor (OM) in the UVW2 band (2120 Å, see Sect. 3.3). We corrected the observed UV flux from Galactic extinction using the Fitzpatrick (1999) extinction curve and the Galactic color excess, $E(B-V)$, from the NASA Extragalactic Database (NED). For these galaxies we compared the SFR derived from the UV continuum with that from the IR luminosity. Assuming a flat continuum in $L_\nu$ in the IR range (1500–2800 Å) and scaling to a Kroupa IMF the SFR$_{\nu}$ can be expressed as:

$$SFR_{\nu} (M_\odot \, yr^{-1}) = 7.8 \times 10^{-10} L_{24 \mu m} (L_\odot) \times (7.6 \times 10^{-11} L_{24 \mu m} (L_\odot))^{0.485}. \quad (1)$$

For this calibration Rieke et al. (2009) assumed a Kroupa (2001) initial mass function (IMF) over the stellar mass range from 0.08 to 100 $M_\odot$. A correction to account for the leaked UV light from young stars is included in the calibration. Alonso-Herrero et al. (2011, in press) estimated the AGN contribution at 24 $\mu$m in these LIRGs. We used the X-ray luminosity at 24 $\mu$m before calculating the obscured SFR. The AGN fractions and the calculated SFR$_{\nu}$ are listed in Table 2.

### Table 1. The sample of local LIRGs

| Galaxy Name | IRAS Name | $v_{hel}^{a}$ (km s$^{-1}$) | $D_L$ (Mpc) | Nuclear Ref.$^c$ | log $L_{IR}^{a}$ (L$_\odot$) | Ref.$^c$ | X-ray data |
|-------------|-----------|------------------------|-------------|-----------------|---------------------------|--------|-----------|
| NGC23       | IRAS F00073+2538 | 4478 | 64.7 | composite 1 | 11.1 | 9 | Lehmmer et al. (2010) |
| NGC674      | IRAS F07215-0840 | 4778 | 69.1 | composite 8 | 8.1 | 11.1 | 9 | XMM-Newton (archive) |
| NGC2369     | IRAS F07160-6215 | 3196 | 46.0 | composite 5 | 8.2 | 11.1 | 9 | XMM-Newton (our data) |
| NGC3110     | IRAS F10015-6614 | 5014 | 72.6 | H II 11 | 11.3 | 9 |
| NGC3256     | IRAS F10257-4339 | 2790 | 40.1 | H II 5 | 11.7 | 9 | XMM-Newton (archive) |
| NGC3690$^*$ | IRAS F11257+5850 | 3057 | 44.0 | Sy2 4 | 11.4 | 2 |
| IC694$^*$   | " | 3089 | 44.6 | LINER 4 | 11.6 | 2 |
| ESO320-G030 | IRAS F11506-3851 | 3038 | 43.7 | H II 8 | 11.2 | 0 | XMM-Newton (our data) |
| IC860       | IRAS F13126+2455 | 3859 | 55.7 | ... 1 | 11.1 | 9 |
| MCG−03-34-064 | IRAS F13197-1627 | 5009 | 72.5 | Sy2 11 | 11.1 | 10 | XMM-Newton (archive) |
| NGC5135     | IRAS F13229-2934 | 4074 | 58.8 | Sy2 11 | 11.3 | 9 | Levenson et al. (2004) |
| NGC5653     | IRAS F14280+3126 | 3513 | 50.7 | H II 11 | 11.0 | 9 | XMM-Newton (our data) |
| NGC5734     | IRAS F14421-2039 | 3998 | 57.7 | composite 8 | 11.0 | 10 | XMM-Newton (our data) |
| NGC5743     | IRAS F14423-2042 | 4121 | 59.5 | H II 8 | 10.9 | 10 |
| IC4518W$^*$ | IRAS F14544-2455 | 4720 | 68.2 | Sy2 3 | 11.2 | 8 | XMM-Newton (archive) |
| Zw049.057   | IRAS F15107+0724 | 3858 | 55.7 | composite 7 | 11.2 | 9 | Lehmmer et al. (2010) |
| IC4686$^*$  | IRAS F19093-5744 | 4948 | 71.6 | H II 11 | 11.0 | 9 | XMM-Newton (our data) |
| IC4687$^*$  | IRAS F18341-5732 | 5105 | 73.9 | H II 11 | 11.3 | 8 |
| IC4734      | IRAS F18341-5732 | 4623 | 66.8 | H II 3 | 11.3 | 9 |
| MCG+04-48-002 | IRAS F20264+0744 | 3499 | 60.6 | H II 6 | 11.0 | 10 | XMM-Newton (archive) |
| NGC7130     | IRAS F21453-3511 | 4837 | 70.0 | Sy2 11 | 11.4 | 9 | Levenson et al. (2005) |
| IC5179      | IRAS F21312-3705 | 3363 | 48.6 | H II 11 | 11.2 | 9 | XMM-Newton (our data) |
| NGC7469     | IRAS F23007+0836 | 4840 | 70.0 | Sy2 1 | 11.6 | 9 | XMM-Newton (our data) |
| NGC7649     | IRAS F23485+1949 | 4128 | 59.6 | H II 11 | 10.8 | 8 |
| NGC7770$^*$ | IRAS F23485+1949 | 4128 | 59.6 | H II 11 | 10.8 | 8 |
| NGC7771$^*$ | IRAS F23485+1949 | 4302 | 62.1 | H II 11 | 1.3 | 3 | XMM-Newton (our data) |

Notes. (a) Heliocentric velocity from Spitzer spectra (Pereira-Santaella et al. 2010). (b) Classification of the nuclear activity from optical spectroscopy. Galaxies classified as composite are likely to be a combination of AGN activity and star-formation. (c) Reference for the optical spectroscopic data. (d) Logarithm of the IR luminosity, $L_{\nu}$ (8–1000 $\mu$m), calculated as defined in Sanders & Mirabel (1996). (e) Reference for the IR luminosity (adapted to the cosmology used throughout this paper). (f) The logarithm of the integrated $L_{IR}$ in solar units of these systems are: NGC 3690 + IC 694, 11.8; IC 4518W + IC 4518E, 11.2; IC 4686 + IC 4687, 11.5; and NGC 7770 + NGC7771, 11.4.

References. (1) Alonso-Herrero et al. (2009a); (2) Charmandaris et al. (2002); (3) Corbett et al. (2003); (4) García-Marín et al. (2006); (5) Lipari et al. (2000); (6) Masetti et al. (2006); (7) Parra et al. (2010); (8) This work; (9) Sanders et al. (2003); (10) Surace et al. (2004); (11) Yuan et al. (2010).
the Two Micron All Sky Survey (2MASS) large galaxy atlas (Jarrett et al. 2003) and the 2MASS extended source catalog (Jarrett et al. 2000). The near-IR emission is well suited to calculate the stellar mass since the contribution from young stars is usually negligible and the scatter in the mass-to-light ratio is relatively small (~0.4 dex). Following Bell & de Jong (2001) we used the K-band luminosity together with the J − H color to obtain the stellar mass. We adjusted the normalization for the Kroupa IMF:

$$\log \frac{M_\star}{M_\odot} = \log \frac{L_K}{L_\odot} + 1.44(J - H) - 1.17$$

(3)

The SFRs, IR/UV ratios and stellar masses for our sample are listed in Table 3.

### 3. X-ray observations

#### 3.1. XMM-Newton observations and data reduction

We obtained new XMM-Newton data for 9 galaxies (proposals 55046 and 60160). We also found in the XMM-Newton archive X-ray data for 12 more galaxies. Our proposal was focused on galaxies classified as H II galaxies based on their optical spectra whereas most of the galaxies from the archive are active galaxies (Seyfert and LINER activity). The observation IDs and effective exposure times are shown in Table 3. The analysis of the Chandra X-ray data for the other 6 galaxies in our sample is taken from the literature (see Sect. 3.2).

We reduced the observation data files (ODF) using SAS version 10.0.2. First we used the SAS epproc and emproc tasks to generate the calibrated events files from the raw European Photon Imaging Camera (EPIC) pn and MOS data respectively. A circular aperture (d=15″ depending on the source extent) was used to extract the spectra of the galaxies. We estimated the backgrounds from a region close to the source in the same CCD and free of any contaminating source. The background regions were ~4–5 times larger than the aperture used for the galaxies. Then we created the background and background+source light-curves that we used to filter out high-background periods. The background count rate threshold was chosen to just filter out the background and background+source light-curves that are shown in Table 3. The analysis of the Chandra X-ray data for the other 6 galaxies in our sample is taken from the literature (see Sect. 3.2).

We obtained X-ray images of these LIRGs as described in Sect. 3.1. Fig. 2 shows the soft (0.5–2 keV) and hard (2–7 keV) X-ray images for the LIRGs together with the OM ODF files and produces calibrated images taking into account the telescope tracking information and the flat fielding corrections. For some filters there was more than one exposure that we combined to increase the S/N ratio. Then we used aperture photometry to measure the fluxes. We estimated the background from the image with special care to avoid artifacts in the images such as the smoke rings, etc. (see the XMM-Newton/OM Calibration Status document). We corrected the count rate for the detector sensitivity degradation and coincidence loss. The count rates were converted into Jy using the conversion factors given in the XMM-Newton/OM Calibration Status document.

| Galaxy Name | Obs. ID. | Exposure (ks) |
|-------------|----------|---------------|
| NGC1614     | 0150480201 | 21.8          |
| NGC2369     | 0550460101 | 24.3          |
| NGC3110     | 0550460201 | 15.9          |
| NGC3256     | 0300430101 | 125.6         |
| NGC3690/IC694 | 012810101 | 17.1          |
| ESO320-G030  | 0550460301 | 23.9          |
| MCG–03-34-064 | 0206580101 | 42.7          |
| "            | 0506340101b | ...          |
| NGC5734/5743 | 0601600101 | 27.0          |
| IC4518W      | 0406140101 | 22.8          |
| IC4896/4687  | 0550460201 | 26.5          |
| IC4734       | 0550460701 | 18.6          |
| MCG+04-48-002 | 0512192301 | 23.0          |
| IC5179       | 0550460801 | 22.0          |
| NGC7469      | 011270301 | 23.0          |
| NGC7679      | 0301150501 | 17.9          |
| NGC7797/7770/7771 | 0093190301 | 30.0          |

Notes. (a) Exposure time after flare removal. (b) Only used for the XMM-Newton/OM UVW2 image of MCG–03-34-064.

#### 3.2. Chandra data from the literature

We found in the literature (Levenson et al. 2004, 2005; Lehmer et al. 2010) Chandra X-ray data for another 6 galaxies (two Seyfert 2 galaxies, two composite, one H II, and one without classification; see Table 4). For these galaxies we used the published galaxy integrated X-ray fluxes (Table 4).

### 4. Spatial analysis of the XMM-Newton data

#### 4.1. Morphologies

We obtained X-ray images of these LIRGs as described in Sect. 3.1. Fig. 2 shows the soft (0.5–2 keV) and hard (2–7 keV) X-ray images for the LIRGs together with the XMM-Newton/OM UV (2120Å) and near-IR Spitzer/IRAC (3.6 μm) images for comparison.

In our sample of LIRGs we find different X-ray emission morphologies. Most of them are dominated by the nuclear emission and appear as point-like (or slightly resolved)
At the distances of these LIRGs this corresponds to 0.9–2 keV and 2–10 keV absorption corrected luminosities from the 2MASS magnitudes. Integrated K-band flux from 2MASS. (J) Spitzer/MIPS 24 µm flux from Pereira-Santaella et al. (2011, in preparation). Logarithm of the stellar mass obtained from the K-band luminosity and the J – H color. AGN fractional contribution to the total 24 µm emission from Alonso-Herrero et al. (2011, in press). Star-formation rate based on the 24 µm luminosity. The AGN contribution to the 24 µm luminosity is subtracted. Ratio of the star-formation rates estimated from the IR and UV luminosities.

Table 4. Galaxies taken from the literature.

| Galaxy Name | $L_{0.5-2 \text{keV}}$ | $L_{2-10 \text{keV}}$ | Ref. |
|-------------|---------------------|---------------------|-----|
| NGC23       | 6.7                 | 4.2                 | 1   |
| IC860       | 0.3                 | 1.1                 | 1   |
| MCG–03-34-064* | 26.6            | 11.1               | 2   |
| NGC5135     | 17.9                | 18.9                | 3   |
| NGC5653     | 2.8                 | 1.5                 | 1   |
| Zw049.057   | 0.2                 | 1.5                 | 1   |
| NGC7710     | 15.4                | 15.4                | 4   |
| NGC7771     | 1630                | 1690                | 5   |

Notes. 0.5-2 keV and 2-10 keV absorption corrected luminosities of the galaxies taken from the literature adapted to the cosmology used throughout this paper. (1) For the galaxies with XMM-Newton observations we fitted the data using the best-fit model given in the corresponding reference. The S/N ratio in the hard XMM-Newton X-ray band of the H II galaxies is too low to accurately measure the size of the X-ray emitting region. The only exception is NGC 3256 that appears approximately as extended as its soft X-ray emission. The higher spatial resolution Chandra X-ray images of NGC 3256 reveal that both the soft and hard X-ray emissions are resolved into multiple point sources, besides the two nuclei, and diffuse emission [Lira et al. 2002]. The hard X-ray emission of the Seyfert galaxies is dominated by the AGN, thus they appear as point sources in this energy range.

4.2. Extranuclear sources

In two LIRGs observed with XMM-Newton (NGC 2369 and NGC 7771) we find bright extranuclear X-ray sources that show extended soft X-ray emission. This indicates that at least some of the sources responsible for the origin of the X-ray emission (X-ray binaries, SNR, diffuse hot plasma, etc.) are extended over several kpc (>1 kpc). Higher angular resolution images with Chandra of LIRGs confirm that the X-ray emission comes from both: multiple point sources and diffuse emission distributed over the galaxies [Zezas et al. 2003; Levenson et al. 2004, 2005; Lehmer et al. 2010].
might be ultraluminous X-ray sources (ULXs). Note that we can only isolate such X-ray sources if they are located more than 0.9–2 kpc away from the nucleus due to the spatial resolution of the images. That is, ULXs may exist in the rest of the sample within the central 0.9–2 kpc.

The two sources located at either side of the nucleus of NGC 7771 (NGC 7771 X-1 and NGC 7771 X-2) were studied by Jenkins et al. (2005). The spectra of both sources are well fitted with an absorbed power-law ($\Gamma = 1.6$ and 1.7) plus a soft component (thermal plasma at 0.3 keV and a blackbody disk at 0.2 keV). The unabsorbed luminosities ($L_{0.5-8\text{keV}}$) of these sources are $1.7 \pm 1.0 \times 10^{40}$ erg s$^{-1}$ and $1.4 \pm 0.8 \times 10^{40}$ erg s$^{-1}$.

5. Spectral analysis of the XMM-Newton data

At 60 Mpc (typical distance of these LIRGs) the $\text{XMM-Newton}$ spatial resolution ($\sim 7$) corresponds to 1.7 kpc. This means that we are not able to resolve individual emitting sources. Instead, the $\text{XMM-Newton}$ spectra of these LIRGs probably include the emission from X-ray binaries (low- and high-mass), SNRs and diffuse hot plasma. An AGN may be present as well. Therefore, ideally we would include in the X-ray model one component for each one. However, this is not possible because: (1) It is complicated to determine the characteristic spectrum of these objects and even more complicated to determine the characteristic integrated spectrum of these objects in a galaxy; and (2) the S/N ratio of our data is not sufficiently high to obtain statistically meaningful results with a very complex model. We used the $\text{XSPEC}$ package (version 12.5) to fit simultaneously the EPIC MOS and pn spectra. The RGS data, of the 3 galaxies with sufficient counts (see Sect. 5.1), are compatible with the fit obtained using just the EPIC data. Adding the RGS data does not improve significantly the constraints on the model parameters. Thus the RGS data are not used in the spectral analysis. The fits of some individual sources are discussed in Appendix A.

5.1. The X-ray spectra of star-forming galaxies

We fit the spectra of the star-forming galaxies using a simple model consisting of a soft thermal plasma ($\text{mekal}$) plus an absorbed power-law. The absorption of the thermal plasma component is not well constrained and it is compatible with no absorption for most of the galaxies. It was only necessary in the fit of the NGC 3256 and NGC 3690 spectra. The thermal plasma represents the soft X-ray emitting gas heated by SN shocks, whereas the power-law reproduces the observed hard X-ray continuum produced by X-ray binaries and/or AGN. We also added to the model the absorption due to the Galactic hydrogen column density ($N_{\text{H}}$) (Kalberla et al. 2005). The absolute value of the plasma metallicity is not well constrained for our relatively low S/N ratio spectra. However the $\text{[Fe/O]}$ ratio can be determined since the most prominent spectral features in the soft X-ray range are produced by these elements (the Fe L-shell and the O K-shell). Thus, the plasma abundances were fixed to the solar values except for the Fe abundance. The latter was left as a free parameter in order to calculate the $\text{[Fe/O]}$ ratio. It should be noted that a degeneracy exists between the plasma abundances and temperatures. This model provides a reasonable fit to the data ($\chi^2_{\text{red}} < 1.2$) for most of the galaxies. We included a Gaussian line when a Fe Kα emission line was present in the spectrum (NGC 3256, NGC 3690, and IC 694). For those galaxies with the 6.4 keV emission line undetected we calculated the upper limits for a narrow emission line. Fig. 4 shows...
NGC1614

NGC2369

NGC3110

NGC3256

Arp299 (NGC3690 and IC694)

Fig. 2. XMM-Newton/EPIC pn 0.5-2 keV and 2-7 keV images (first and second panels), XMM-Newton/OM UVW2 (2120 Å) images for the galaxies observed with this filter (third panel). The third panel of Arp299 and MCG+04-48-002 corresponds to the XMM-Newton/OM UVM2 (2310 Å) filter. Spitzer/IRAC 3.6 μm images (forth panel). For reference we represent in the third and forth panels the smoothed 0.5-7 keV contours. The white line in the right panels represents 5 kpc at the distance of the galaxy. All images are shown in a square root scale. North is up and east is to the left.
Fig. 2. Cont.
Fig. 2. Cont.
Fig. 2. Cont.
Fig. 4. Observed EPIC pn (black) and combined EPIC MOS (red) 0.3-10 keV spectra, best-fitting model and residuals of the LIRGs observed by XMM-Newton.
Fig. 4. Cont.
Table 5. X-ray model fits. Starburst model.

| Galaxy Name | \(N_{\text{H,Gal}}\) (10^{19} \text{ cm}^{-2}) | \(N_{\text{H,1}}\) (10^{22} \text{ cm}^{-2}) | \(\Delta T\) (keV) | \(\text{Fe/O}^\circ\) | \(N_{\text{H,2}}\) (10^{22} \text{ cm}^{-2}) | \(\Gamma\) | \(\chi^2/\nu\) | \(F_{0.5–2\text{ keV}}\) \((\times 10^{38} \text{ ergs cm}^{-2} \text{ s}^{-1})\) | \(F_{2–10\text{ keV}}\) \((\times 10^{38} \text{ ergs cm}^{-2} \text{ s}^{-1})\) | \(L_{0.5–2\text{ keV}}\) \((\times 10^{45} \text{ ergs s}^{-1})\) | \(L_{2–10\text{ keV}}\) \((\times 10^{45} \text{ ergs s}^{-1})\) | \(L_{\text{plasma}}\) (%) |
|------------|---------------------------------|---------------------------------|------------------|------------------|---------------------------------|-----|--------|------------------|------------------|------------------|------------------|------------------|------------------|
| NGC1614    | 0.06                            | -0.26                           | 0.53±0.01        | 0.66±0.04        | 0.44±0.11                       | 0.38±0.14 | 1.97±0.12 | 199/152          | 17.7±2.4         | 27.6±2.1         | 19.4             | 16.4             | 2.1              |
| NGC2369    | 0.10                            | 0.11                            | 0.51±0.25        | 0.66±0.05        | 0.13±0.28                       | 0.14±0.11 | 1.49±0.18 | 87/96            | 3.7±0.1          | 10.1±0.1         | 3.0              | 4.4              | 0.9              |
| NGC580*    | ...                             | ...                             | ...              | ...              | ...                             | ...      | ...      | ...              | ...              | ...              | ...              | ...              | ...              |
| NGC3110    | 0.03                            | -0.35                           | 0.53±0.03        | 0.66±0.03        | 0.28±0.13                       | 0.27±0.12 | 2.02±0.12 | 92/75            | 9.7±1.4          | 35.6±3.9         | 9.6              | 33.3             | 3.0              |
| NGC3256    | 0.18±0.01                       | 0.11±0.06                       | 0.37±0.03        | 0.69±0.10        | 0.14±0.03                       | 0.20±0.14 | 1.51±0.14 | 561/355          | 71.1±2.9         | 49.2±2.4         | 29.5             | 9.7              | 12.3             |
| IC694      | 0.01                            | -0.18                           | 0.46±0.03        | 0.67±0.01        | 0.37±0.12                       | 0.38±0.18 | 1.98±0.18 | 168/142          | 30.0±2.6         | 45.8±2.9         | 11.2             | 10.8             | 1.9              |
| ESO320-490 | 0.28                            | 0.07                            | 0.56±0.03        | 0.67±0.01        | 0.18±0.04                       | 1.30±0.17 | 1.12±0.17 | 78/88            | 7.3±0.6          | 9.0±0.6          | 4.7              | 3.8              | 0.7              |
| NGC5734    | 0.07                            | -0.28                           | 0.50±0.07        | 0.66±0.01        | 0.20±0.04                       | 0.21±0.18 | 1.13±0.18 | 62/67            | 5.8±0.5          | 4.5±0.6          | 2.0              | 1.1              | 2.0              |
| IC4686     | 0.07                            | -0.12                           | 0.41±0.01        | 0.64±0.01        | 0.30±0.07                       | 0.38±0.18 | 1.18±0.18 | 61/71            | 5.4±0.6          | 9.6±1.1          | 2.9              | 4.1              | 0.5              |
| IC4687     | 0.07                            | -0.19                           | 0.54±0.16        | 0.69±0.06        | 0.23±0.03                       | 2.22±0.28 | 1.93±0.28 | 100/78           | 7.7±2.1          | 7.7±2.8          | 10.7             | 5.6              | 3.0              |
| IC4734     | 0.07                            | -0.08                           | 0.53±0.13        | 0.64±0.06        | 0.14±0.03                       | 2.22±0.28 | 1.93±0.28 | 100/78           | 7.7±2.1          | 7.7±2.8          | 10.7             | 5.6              | 3.0              |
| IC5179     | 0.01                            | -0.06                           | 0.55±0.08        | 0.68±0.06        | 0.10±0.03                       | 1.44±0.12 | 1.24±0.12 | 91/100           | 12.7±0.6         | 15.4±1.2         | 3.9              | 4.4              | 1.4              |
| NGC7679    | 0.05                            | -0.10                           | 0.50±0.14        | 0.69±0.01        | 0.70±0.03                       | 1.44±0.12 | 1.24±0.12 | 172/172          | 35.6±3.3         | 66.3±3.7         | 27.7             | 44.5             | 0.2              |
| NGC7698    | 0.04                            | -0.10                           | 0.50±0.14        | 0.69±0.01        | 0.70±0.03                       | 1.44±0.12 | 1.24±0.12 | 172/172          | 35.6±3.3         | 66.3±3.7         | 27.7             | 44.5             | 0.2              |
| NGC7771    | 0.04                            | -0.10                           | 0.50±0.14        | 0.69±0.01        | 0.70±0.03                       | 1.44±0.12 | 1.24±0.12 | 172/172          | 35.6±3.3         | 66.3±3.7         | 27.7             | 44.5             | 0.2              |

Notes. The model used for the fits was \(\text{Abs}(N_{\text{H,Gal}})[\text{Abs}(N_{\text{H,1}})(\mu\text{metal})\mu(T, \text{Fe/O}) + \text{Abs}(N_{\text{H,2}})[\text{power-law}(\Gamma)]\), where Abs is a photo-electric absorption model and \(\mu\text{metal}\) is a thermal plasma (with variable metal abundances). \(\mu\text{metal}\) is a thermal plasma (with variable metal abundances). \(\text{Fe/O}\) is the absolute hydrogen column density from \cite{Kalberla2003}. \(\text{Fe/O}\) is abundances ratio with respect to the solar values of \cite{AndersGrevesse1989}. \(\Delta T\) is the fraction of the 2–10 keV luminosity from the thermal plasma component. \(\chi^2/\nu\) is the goodness of fit. \(F_{0.5–2\text{ keV}}\) is the X-ray luminosity corrected for Galactic extinction \(N_{\text{H,Gal}}\). \(F_{2–10\text{ keV}}\) is the X-ray luminosity corrected for Galactic extinction \(N_{\text{H,Gal}}\). \(L_{0.5–2\text{ keV}}\) is the X-ray luminosity corrected for Galactic extinction \(N_{\text{H,Gal}}\). \(L_{2–10\text{ keV}}\) is the X-ray luminosity corrected for Galactic extinction \(N_{\text{H,Gal}}\). \(L_{\text{plasma}}\) is the plasma component. \(\chi^2/\nu\) is the goodness of fit. \(F_{0.5–2\text{ keV}}\) is the X-ray luminosity corrected for Galactic extinction \(N_{\text{H,Gal}}\). \(F_{2–10\text{ keV}}\) is the X-ray luminosity corrected for Galactic extinction \(N_{\text{H,Gal}}\). \(L_{0.5–2\text{ keV}}\) is the X-ray luminosity corrected for Galactic extinction \(N_{\text{H,Gal}}\). \(L_{2–10\text{ keV}}\) is the X-ray luminosity corrected for Galactic extinction \(N_{\text{H,Gal}}\).
the observed X-ray spectra together with the model for all the galaxies with XMM-Newton data.

The parameters of the fits are listed in Table 5. The typical values of the model parameters are: $\Gamma \sim 1.3-2.2$, $N_H \sim 1 \times 10^{21}-5 \times 10^{21} \, \text{cm}^{-2}$, $kT \sim 0.5-0.7 \, \text{keV}$ and $[\text{Fe}/\text{O}] \sim -0.5-0.1$. The measured $N_H$ corresponds to $A_V \sim 0.5-2.3 \, \text{mag}$ using the Güver & Özel (2009) conversion factor. In general, the X-ray derived absorption is lower than that obtained from the near-IR colors ($\sim 3 \, \text{mag}$) and the Pa$_\alpha$/H$\alpha$ ratio ($\sim 2-5 \, \text{mag}$) for these galaxies (Alonso-Herrero et al. 2006). The temperature of the plasma and its contribution to the hard X-ray emission of these LIRGs are comparable with those of local starbursts ($0.8 \, \text{keV}$ and $3\%$, Persic & Rephaeli 2003). However the power-law component is slightly steeper than in local starbursts, $\Gamma = 1.2$ (Persic & Rephaeli 2003) versus $\Gamma = 1.8$ in these LIRGs.

The upper limits and fluxes of the Fe K emission line are listed Table 6.

5.2. AGN X-ray spectra

The X-ray spectra of two galaxies, IC 4518W, MCG+04-48-002, are not well fitted by the star-formation model described above. The hard X-ray emission of these galaxies is dominated by the AGN (Fig. 5). We added to the star-formation model an absorbed power-law and a Gaussian emission line at $6.4 \, \text{keV}$ to account for the AGN emission. For IC 4518W we added another Gaussian emission line at $7.1 \, \text{keV}$. For these galaxies the power-law index of the star-formation component is not well constrained due to the AGN contribution to the hard X-ray emission. Hence we fixed it to the median value obtained for the other LIRGs ($\Gamma = 1.85$). This model provides a good fit to the data, $\chi^2_{\text{red}} \leq 1$, for the two galaxies. For this reason, we did not include an AGN reflection component ($\text{pexrav}$). By doing this we may underestimate the absorbing column density towards the AGN. This model fits well the soft X-ray emission of these galaxies. However this does not imply a star-formation origin of the soft X-ray emission since the thermal plasma and the power-law continuum can be produced by an AGN. The origin of the soft X-ray emission is discussed in Section 6. The model parameters for these two galaxies are given in Table 7.

5.3. Literature X-ray data

The X-ray luminosities taken from the literature are listed in Table 5. This table includes the 6 galaxies observed with Chandra plus 2 galaxies observed with XMM-Newton. For these two objects, MCG−03-34-064 and NGC 7469, we repeated the fits of the XMM-Newton data using the models given by Miniutti et al. (2007) and Blustin et al. (2003), respectively, to take advantage of the latest calibration.

6. X-ray emission from star-formation activity

6.1. Soft X-ray emission versus SFR

At soft energies ($0.5-2.0 \, \text{keV}$), the X-ray emission is produced by both diffuse hot gas heated by supernova explosions and X-ray binaries. Therefore the soft X-ray emission is expected to be correlated with the SFR (Ranalli et al. 2003; Rosa González et al. 2009).

| Galaxy Name | $E^a$ | $EW$ | $F_{\text{Fe K}}$ |
|-------------|------|-----|----------------|
| NGC23       | ...  | ... | ...            |
| NGC1614     | 6.4  | $<0.62$ | $<16$               |
| NGC2369     | 6.4  | $<0.34$ | $<5.7$               |
| NGC3110     | 6.4  | $<0.76$ | $<3.0$               |
| NGC3256     | 6.4  | $<0.07$ | $<3.5$               |
| NGC3690     | 6.6$^{+0.10}_{-0.04}$ | 0.2 | 8.2 |
| IC694       | 6.4  | $<0.2$ | $<9.4$               |
| NGC5135     | 6.6$^{+0.10}_{-0.11}$ | 0.85 | 60 |
| IC4518W     | 6.39$^{+0.03}_{-0.03}$ | 0.46 | 120 |
| IC4686      | 6.4  | $<0.8$ | $<5.1$               |
| IC4687      | 6.4  | $<1.4$ | $<8.7$               |
| IC4734      | 6.4  | $<3.5$ | $<11$               |
| NGC7130F    | 6.4$^{+0.05}_{-0.05}$ | 1.8 | $<35$               |
| IC5179      | 6.4  | $<0.41$ | $<6.3$               |
| NGC7469     | 6.42$^{+0.03}_{-0.03}$ | 0.070 | 203 |
| NGC7679     | 6.4  | $<0.42$ | $<30$               |
| NGC7770     | 6.4  | $<1.8$ | $<3.5$               |
| NGC7771     | 6.4  | $<8.5$ | $<9.6$               |
| NGC7771     | 6.4  | $<0.47$ | $<10$               |

Notes. Observed fluxes and EW of the Fe K emission lines. Upper limits are calculated assuming an unresolved Gaussian emission line at $6.4 \, \text{keV}$. ($^a$) Rest frame energy of the emission line. When no uncertainties are quoted the value was fixed. ($^b,c$) Data from Levenson et al. (2004) and Levenson et al. (2005) respectively.

The correlation found by Ranalli et al. (2003) between the soft X-ray and the far-infrared (FIR, 40–500 $\mu$m) luminosities is not linear. The galaxies in their study cover a large range in FIR luminosities and it is possible that, for those galaxies with the lowest SFR, the total SFR is not dominated by the obscured SFR traced by the FIR luminosity (see Pérez-González et al. (2006) and Kennicutt et al. 2009). To account for the obscured star-formation we used the near-UV (2267 Å) fluxes from Gil de Paz et al. (2007) that we translated into SFR (see Sect. 3). We found near-UV fluxes for 65% of the Ranalli et al. (2003) sample. To calculate the obscured SFR we used the IRAS fluxes to obtain the total IR luminosity ($8-1000 \mu$m). Then we used the calibration of Kennicutt (1998) correcting for our adopted Kroupa IMF. We added both IR and UV SFR to obtain the total SFR. The SFR traced by the UV light contributes to the total SFR between 5% and 60% with a median contribution of 20% for the galaxies of the Ranalli et al. (2003) sample. In the case of the LIRGs we neglected the unobscured star-formation as it contributes less than 10% for most of the galaxies (see Table 2 and Howell et al. 2010).
for our sample of LIRGs together with the nearby galaxies of [Ranalli et al. 2003]. The best fit slope in log-log space is 1.1 $\pm$ 0.1, which is compatible with a linear relation. Assuming a constant $SFR_{IR+UV}/L_{0.5-2\,\text{keV}}$ ratio we found:

\[
SFR_{IR+UV} (M_\odot \, \text{yr}^{-1}) = 3.4 \times 10^{-40} L_{0.5-2\,\text{keV}} (\text{erg s}^{-1}) \quad (4)
\]

with a 0.24 dex scatter. [Mas-Hesse et al. 2008] modeled the soft X-ray luminosity expected from a starburst. They assumed that the mechanical energy from the starburst (SN and stellar winds) heats the interstellar diffuse gas with an efficiency 1–5%. After correcting for the different IMF normalization, their calibration for a young extended burst is consistent with Equation 4 within the scatter.

The Seyfert 2 galaxies in our sample of LIRGs lie on the correlation (NGC 3690 and IC 4518W), or have a small (less than a factor of 3) soft X-ray emission excess (MCG–03–34–064, NGC 5135, and NGC 7130). In Type 2 Seyferts the absorbing hydrogen column density towards the AGN is high and thus most of the soft X-ray emission coming from the AGN is absorbed. Therefore we conclude that when a sufficiently powerful starburst is present it may contribute significantly to the observed soft X-ray emission. The two Seyfert 1s (NGC 7469 and NGC 7679) in our sample have a soft X-ray emission excess relative to their SFR due to the AGN emission. Two objects (IC 860 and Zw 049-057) lie below the correlation. The low number of counts of these galaxies does not allow us to correct properly the soft X-ray fluxes for their internal absorption. In addition, the large 9.7 $\mu$m silicate absorption of these galaxies [Alonso-Herrero et al. 2011, in press] suggests that they are highly obscured, thus this correction is likely to be large [Shi et al. 2006].

6.2. Hard X-ray emission versus SFR

HMXB dominate the hard X-ray (2–10 keV) emission of a starburst galaxy when an AGN is not present. Thus the hard X-ray emission is also a tracer of the SFR [Ranalli et al. 2003; Grimm et al. 2003; Persic et al. 2004; Lehmer et al. 2010].

The right panel of Fig. 5 shows that there is a good correlation between the hard X-ray emission and the SFR when there is no AGN. The best fit slope is 1.1 $\pm$ 0.1 (in log-log space). Thus assuming a directly proportional relation between the $SFR_{IR+UV}$ and the $L_{2-10\,\text{keV}}$ we obtained:

\[
SFR_{IR+UV} (M_\odot \, \text{yr}^{-1}) = 3.9 \times 10^{-40} L_{2-10\,\text{keV}} (\text{erg s}^{-1}) \quad (5)
\]

with a 0.27 dex scatter. In the fit we used all the H II galaxies (excluding MGC–04–48–002 whose X-ray spectra resembles that of a Seyfert 2 galaxy, see Appendix A) and the galaxies of the [Ranalli et al. 2003] sample. This calibration agrees, within the uncertainties, with that of [Ranalli et al. 2003]. However, [Lehmer et al. 2010] found a highly non-linear relation (slope = 0.76) between the SFR and the $L_{2-10\,\text{keV}}$. In their fit they included high-luminosity LIRGs and ULIRGs. These galaxies are underluminous in the 2–10 keV range (see [Iwasawa et al. 2009; Lehmer et al. 2010]), thus this may affect the relation slope.

Due to the low number of galaxies with SFR of less than $\sim 4M_\odot \, \text{yr}^{-1}$ in our sample, it is uncertain whether the correlation is still valid in the low SFR range or not. Actually a change in the slope of the $L_{2-10\,\text{keV}}$ versus SFR relation is expected for this range [Grimm et al. 2003]. For these galaxies with low SFR if a bright HMXB is present it can dominate the galaxy integrated hard X-ray luminosity.

As can be seen in the right panel of Fig. 5, the hard X-ray emission of 3 Seyfert galaxies (NGC 3690, NGC 5135, and NGC 7130) is compatible (within 2$\sigma$) with that expected from star-formation. These galaxies are known to host powerful starbursts that might dominate their energy output [González Delgado et al.]

---

Fig. 5. Soft (0.5–2 keV; left) and hard (2–10 keV; right) X-ray luminosity corrected for absorption vs. SFR calculated combining the UV and IR luminosities (Sect. 3). Red stars are H II galaxies. The best fit for our sample of LIRGs together with the nearby galaxies is $1.1 \pm 0.1$. Assuming a constant SFR/L$_{0.5-2\,\text{keV}}$ (Shi et al. 2006). The dashed lines indicate the $\pm 1\sigma$ dispersion in this relation.

---

4 We only used for the fit the galaxies classified as H II and the galaxies of [Ranalli et al. 2003]
...the Hit would not be the main cause of the observed scatter.

of the SFR versus hard X-ray luminosity correlation, thus our sample of LIRGs. This is much lower than the scatter to the integrated hard X-ray luminosity is less than 15\% for this equation we estimate that the contribution of LMXB and $\beta$.

...active galaxies, it has been found in starbursts (e.g., M 82 and...\textit{Chandra} images were used to isolate and quantify the AGN emission, which was found to be approximately 70\% of the total hard X-ray emission (Zezas et al. 2003; Levenson et al. 2004, 2005).

In the previous fit we neglected the contribution of the LMXB to the hard X-ray luminosity. The emission of the LMXB is proportional to the stellar mass of the galaxy (Gilfanov 2004), and LMXBs may be important for galaxies with the lowest SFR/M$^*$ ratios. Assuming that there is a linear correlation between the 2–10 keV galaxy integrated emission of LMXB and HMXB with the stellar mass and the SFR respectively, Lehmer et al. (2010) constrained the relation:

$$L_{\text{2–10 keV}} = \alpha M_* + \beta \text{SFR} \tag{6}$$

for a sample of nearby normal galaxies, LIRGs, and ULIRGs. They found $\alpha = (9.05 \pm 0.37) \times 10^{28} \text{ erg s}^{-1} \text{ M}_\odot^{-1}$ and $\beta = (1.62 \pm 0.22) \times 10^{39} \text{ erg s}^{-1} \text{ yr}^{-1} (\text{M}_\odot \text{ yr}^{-1})^{-1}$. From this equation we estimate that the contribution of LMXB to the integrated hard X-ray luminosity is less than 15\% for our sample of LIRGs. This is much lower than the scatter of the SFR versus hard X-ray luminosity correlation, thus it would not be the main cause of the observed scatter.

Fig. 3 shows that the predicted X-ray luminosity using Equation 6 agrees with that observed for most of the HII galaxies in our sample of LIRGs. Likewise, most of the Seyfert galaxies have hard X-ray luminosities 10 times larger than that expected from star-formation. The 3 Seyferts (NGC 3690, NGC 5135, and NGC 7130) that lie within 2$\sigma$ of the expected relation for star-formation are those with powerful starbursts.

6.3. \textit{Fe K$\alpha$} line from star-formation

Although the \textit{Fe K$\alpha$} emission line is detected mainly in active galaxies, it has been found in starbursts (e.g., M 82 and...the AGN contribution to the total energy output of the galaxy (see Sect. 7.1).

The detection of the ionized iron line at 6.7 keV in IC 694 and NCG 3256 (Table 3) indicates the presence of hot gas ($kT > 3$ keV) in these galaxies. Therefore their hard X-ray emission may be dominated by hot gas as is the case in high luminosity LIRGs and ULIRGs (Iwasawa et al. 2009, 2011; Colina et al. 2011, submitted). This is in contrast with local starbursts where the hard X-ray emission is mostly due to HMXB. Fig. 7 shows that the upper limit
for the 6.4 keV line in NGC 3256 is smaller than the expected value for HMXB. This provides further support for a noticeable contribution from hot gas to the hard X-ray emission, at least, in some LIRGs.

For Seyfert galaxies the observed to expected from star-formation Fe Kα emission ratio is larger than ~50, reaching ~300 in some cases. It is clear that the Fe Kα emission is dominated by the AGN in these galaxies.

6.4. Metal abundances of the thermal plasma

The soft X-ray spectrum of starburst galaxies is dominated by the emission of a diffuse thermal plasma with temperatures in the range 0.1 to 1 keV. It is believed that it is heated by shock-fronts generated by SN explosions and stellar winds (Persic et al. 2003). Table 5 shows the Fe/O ratio for our sample. Due to the limited S/N ratio of the spectra we cannot obtain the absolute abundances. The average Fe/O ratio respect to the solar abundance is 0.5 ± 0.2. The underabundance of Fe relative to α elements has been observed in nearby starbursts (Strickland et al. 2000; Grimes et al. 2005) and local (UL)IRGs (Iwasawa et al. 2011).

Various processes have been proposed to explain these results. In the dwarf starburst galaxy NGC 1559 the α elements abundance with respect to Fe is consistent with the enhanced production of α elements in Type II SN (Martin et al. 2002). Indeed the Fe/O ratio measured in these LIRGs is consistent with the IMF-averaged Fe relative to α elements ratio expected from Type II SN (Gibson et al. 1997). Alternatively Strickland et al. (2000) suggested that the X-ray emission is produced in the boundary layer between the cold interstellar medium and the SN winds, thus the underabundance of Fe could be due to the Fe depletion into dust grains. To distinguish between Fe depletion and enhanced α elements production in Type II SN it is needed to determine the abundances relatives to hydrogen and compare them with the galaxy metallicity (Strickland et al. 2004)."
observed in a sample of local Swift/BAT selected AGNs (Figure 6 of Winter et al. 2009). MCG−03-34-064 has the highest ratio and also the steepest continuum (Γ ~ 2.7). Likewise, IC 4518W has the lowest ratio and the lowest photon index (Γ ~ 1.6). Thus the continuum slope might affect the $L_{2–10keV}/L_{14–195keV}$ ratio. However, the Swift/BAT flux contamination by nearby sources, the uncertainty in the contribution of the AGN reflected continuum to the 14–195keV luminosity (which represents about 40% of the total AGN emission at 30keV, Ueda et al. 2003), and the AGN variability may be important factors affecting the observed $L_{2–10keV}/L_{14–195keV}$ ratio.

The other 3 Seyfert 2s in our LIRGs sample (NGC 3690, NGC 5135, and NGC 7130) might be Compton thick AGN. In fact, NGC 5135 and NGC 7130 have been classified as Compton thick based on their large FeKα EW (see Levenson et al. 2004, 2005). The FeKα EW of NGC 3690 is 0.93keV (see Table 8). It is slightly less than the typical values of Compton thick AGN (>1keV). However the star-formation contribution to the hard X-ray continuum is ~30% in NGC 3690 (see Sect. 5.2) and thus it decreases the observed EW of the FeKα emission line. To estimate the AGN X-ray luminosity of these objects we used the flux of the FeKα emission line since it seems to be a good indicator of the intrinsic AGN luminosity (Ptak et al. 2003; Levenson et al. 2006; LaMassa et al. 2009). We assumed $L_{FeKα}/L_{X}\alpha\propto2×10^{-3}$ (Levenson et al. 2006). However we note that this ratio depends on both the geometry of the AGN obscuring material and the column density in our line of sight (Li & Wang 2010; Yaqoob et al. 2010; Murphy & Yaqoob 2009). Thus a large uncertainty, a factor of ~5, is expected in the intrinsic AGN luminosities of these galaxies.

None of these 3 Compton thick candidates are detected in the Swift-BAT 14–195keV survey. The 14–195keV luminosity upper limits are slightly lower than the expected luminosity for their 2–10keV emission. The large scatter (a factor of 6) in the $L_{14–195keV}/L_{2–10keV}$ ratio for the detections and the uncertainties discussed above might explain this.

The 2–10keV and 14–195keV luminosities are listed in Table 8. For completeness, the two Seyfert 1 galaxies in our sample are also included in the table.

7.3. AGN contribution to the LIRGs luminosity

We calculated the fraction of the bolometric luminosity produced by AGN in our sample of LIRGs. We used the $L_{IR}(8–1000\mu m)$ as the total luminosity of the LIRGs. The AGN luminosity was estimated from the X-ray data.

There are 8 active galaxies in our sample. This represents 30% of the sample, although the AGN does not dominate the luminosity of any of them. For these galaxies we estimated the AGN luminosity from their X-ray spectral model or from their FeKα line luminosity (Sect. 7.2). To obtain the AGN bolometric luminosity we applied the bolometric correction of Marconi et al. 2004. Comparing the bolometric AGN luminosity with the IR luminosity (Table 8) we find that the median AGN contribution is 25% and it ranges from less than 1% to 35% for the Seyfert LIRGs. For the rest of the sample we used the upper limit of the FeKα line luminosity to obtain the upper limit for the AGN luminosity (Sect. 7.2).

The AGN luminosity of the active LIRGs contributes 7% of the total luminosity of the sample. If we also consider the upper limits of the AGN luminosity of the star-forming galaxies, the AGN contribution is < 10%. That is, AGN contribution between 7% and 10% to the total energy output of our sample of local LIRGs. This is in agreement with the value obtained for local LIRGs by Petric et al. (2011), 12%, and Alonso-Herrero et al. (2011, in press) using mid-IR diagnostics.

8. Conclusions

We have analyzed the X-ray properties of a representative sample of 27 local LIRGs. The median log $L_{IR}/L_{X}$ is 11.2, thus the low-luminosity end of the LIRG class is well represented. The main results are as follows:

1. For most of the galaxies the soft X-ray emission (0.5–2keV) can be associated to the star-formation activity. This is true even for some Seyfert 2s that host powerful starbursts and highly obscured AGN. We find a proportional correlation between the SFR (unobscured plus obscured) and the $L_{0.5–2keV}$ (Equation 4). This relation is compatible with that obtained from synthesis models (Mas-Hesse et al. 2008). Only LIRGs hosting Seyfert 1 deviate significantly from this correlation.

2. We find that the hard X-ray (2–10keV) emission of those LIRGs classified as H II like is also proportional to the SFR (Equation 5). This correlation is compatible with that found for nearby starbursts (Ranalli et al. 2003; Persic et al. 2004). In this relationship LIRGs hosting Seyfert nuclei (type 1 and type 2) show in general an excess of 2–10keV emission clearly attributed to the AGN. However, some LIRGs hosting a Seyfert 2 nucleus and with powerful starbursts relative to their obscured AGN also lie on the correlation.

3. The soft X-ray emission can be modeled with a thermal plasma. The plasma abundance has subsolar Fe/O ratios. This can be explained by the α elements enrichment due to Type II SNe or by the Fe depletion into dust grains. The data analyzed in here does not allow us to reject any of these possibilities.

4. We do not detect the FeKα emission line at 6.4keV in most (>90%) of the H II LIRGs. Only in one H II LIRG (MCG−04-48-002) is the presence of an obscured AGN evident from the X-ray data. Thus we can rule out the presence of luminous obscured (or Compton thick) AGN in these H II LIRGs. If present, the AGN contribution to the bolometric luminosity would be less than 10%.

5. Three Seyfert LIRGs (10%) in our sample are Compton thick AGN candidates based on their large FeKα EW. The rest are Seyfert 2s (2, 7%) with $N_H < 10^{24}$ cm$^{-2}$ or Seyfert 1s (2, 7%). The median AGN contribution to the bolometric luminosity of those LIRGs hosting a Seyfert nucleus is 25%, ranging from 1% to 35%.

6. The AGN emission represents about 7% of the total energy output of the sample. Taking into account the upper limits for the AGN contribution in the H II LIRGs, the AGN contribution is between 7% and 10%. This is in agreement with the values estimated from mid-IR data (Alonso-Herrero et al. 2011, in press; Petric et al. 2011).

Acknowledgements. We thank the anonymous referee for useful comments and suggestions. The authors thank C. Done for helpful discus-
Table 8. AGN luminosity

| Galaxy Name   | Type | $L_{2-10 \text{ keV}}$ | $L_{14-195 \text{ keV}}$ | $L_{bol}^{\text{int}}$ | $L_{bol}/L_{bol}^{\text{int}}$ |
|---------------|------|-----------------|-----------------|-----------------|-----------------|
| NGC3690       | Sy2  | 3.9$^a$         | <10             | 55              | 19              |
| MCG–03-34-064 | Sy2  | 15              | 20              | 290             | 1.7             |
| NGC5135       | Sy2  | 10$^b$          | <16             | 180             | 3.9             |
| IC4518W       | Sy2  | 2.2             | 18              | 26              | 21              |
| MCG+04-48-002 | –    | 6.9             | 38              | 120             | 3.0             |
| NGC7130       | Sy2  | 10$^b$          | <23             | 180             | 5.1             |
| NGC7469       | Sy1  | 17              | 39              | 340             | 5.0             |
| NGC7679       | Sy1  | 0.4             | 15$^c$          | 4.1             | 120             |

Notes. Intrinsic AGN 2–10 keV, 14–195 keV and bolometric luminosities. We used the bolometric corrections of Marconi et al. (2004). (a) Observed Swift/BAT 14–195 keV luminosity from Tueller et al. (2010). For non-detections we assumed a flux $<3.9 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which is the 4.8 $\sigma$ sensitivity achieved for 95% of the sky in this survey. (b) Estimated from the 6.4 keV Fe K$\alpha$ emission line luminosity using the relation $L_{\text{FeK}\alpha}/L_{2-10 \text{ keV}} = 2 \times 10^{-3}$ from Levenson et al. (2004). (c) The $L_{14-195 \text{ keV}}$ of NGC 7679 is likely to be contaminated by the nearby Seyfert 2 NGC 7682.

Appendix A: Notes on individual sources

In this Appendix we discuss the X-ray spectral analysis of some galaxies with XMM-Newton data.

NGC 3256 It is the most luminous nearby (z<0.01) merger system. Its energy output is dominated by a powerful starburst. Previous ASCA, Chandra and XMM-Newton X-ray observations of this galaxy have been analyzed in detail by Moran et al. (1999), Lira et al. (2002) and Jenkins et al. (2004), respectively. We used a simple model (absorbed vmekal + power-law) to fit the XMM-Newton spectrum. It provides an acceptable fit ($\chi^2_{\text{red}} \sim 1.7$) for our analysis.

Jenkins et al. (2004) tentatively detected a Fe K$\alpha$ emission line at $\sim$6–7 keV. The higher S/N ratio data analyzed here shows clearly an emission line at 6.66$^{\pm0.10}_{-0.04}$ keV (Table 6). The energy of the line suggests that it is produced by ionized Fe, possibly related to supernovae activity. The upper limit for the EW of a neutral FeK$\alpha$ line at 6.4 keV is $<70$ keV (Table 6). This low EW is not compatible with that expected from a luminous Compton thick AGN.

IC 4518W It is a Seyfert 2 galaxy. Its XMM-Newton and INTEGRAL observations are described by de Rosa et al. (2008). This is the only galaxy in the sample in which we detect two prominent emission lines in the hard X-ray spectrum, one at 6.39$^{\pm0.03}$ keV and a weaker emission line at 7.1$^{\pm0.1}_{-0.2}$ keV. The former is compatible with Fe K$\alpha$ emission from neutral Fe. The latter may be FeK$\beta$ produced by highly ionized iron, Fe K$\beta$ or these lines blended.

MCG+04-48-002 This galaxy is classified as Seyfert 2. Its XMM-Newton and Suzaku observations are described by Winter et al. (2009). We detect an emission line at 6.47$^{+0.06}_{-0.04}$ that is compatible with Fe XXVI K$\alpha$ emission line.

Arp 299 (NGC 3690 and IC 694) It is a luminous infrared ($L_{\text{IR}} = 6 \times 10^{11} L_\odot$) merger system. It hosts one of the most powerful starbursts in local galaxies (Alonso-Herrero et al. 2009b). The X-ray emission below 10 keV is dominated by star-formation, however a Compton thick AGN is found in the system (Della Ceca et al. 2002). The hard X-ray spectrum of the nucleus of NGC 3690 indicates that the obscured AGN is probably located there (Zezas et al. 2003). Ballo et al. (2004) detected the Fe K$\alpha$ emission feature in both system components NGC 3690 and IC 694. They found that the energy of the emission line in NGC 3690 is consistent with neutral iron, however in our fit the energy of the emission line is not well constrained (Table 6). The measured 6.4 keV Fe K$\alpha$ flux is $\sim$10 times larger than that expected from star-formation suggesting the presence of an AGN in NGC 3690. The energy of the emission line in IC 694 is consistent with the Fe K$\alpha$ from ionized iron that may be produced in highly ionized gas around the AGN or SN explosions (Ballo et al. 2004). For the fit we used a model consisting of an absorbed thermal plasma plus a power-law. We included a Gaussian profile to account for the Fe K$\alpha$ emission lines.

Appendix B: Notes on individual sources

This Appendix includes a detailed analysis of the X-ray spectrum of Arp 299. It is a peculiar S0 galaxy with a Compton thick AGN and a starburst. The X-ray spectrum is dominated by a thermal component produced by star-formation and photoionized gas. The AGN component dominates the spectrum, with a weaker Fe K$\alpha$ emission line at 6.4 keV. The AGN absorbed component is consistent with neutral iron. A detailed analysis of the X-ray spectrum of Arp 299 was presented by Winter et al. (2009).
patible with neutral Fe Kα. The high hydrogen column density ($N_{\text{H}} = 63.2^{+10.0}_{-5.5} \times 10^{22} \text{cm}^{-2}$) towards the AGN and the powerful star-formation might explain why no AGN signatures are found in its optical spectrum.

NGC 7679 is a composite Seyfert 1/starburst galaxy. It is sometimes misclassified as Seyfert 2 (see Shi et al. 2010). The hard X-ray spectrum is well reproduced by a power-law model, but we had to add a soft thermal plasma component to account for the soft X-ray excess. Della Ceca et al. (2001) reported X-ray fluxes $\sim 7$ times larger in the soft and hard bands from the analysis of contemporaneous (1998) ASCA and BeppoSax observations of this galaxy. Previous X-ray observations of NGC 7679 are available with Einstein (1981) and ROSAT (1990). The fluxes in the 0.2–4 keV (Einstein) and 0.1–2.4 keV (ROSAT) bands are factor of $\sim 2$ larger than those measured in the XMM-Newton data (Della Ceca et al. 2001). These flux variations reflect the long term variability of the X-ray emission of this galaxy.

Appendix B: Optical classification

The optical spectra of 7 galaxies in the parent sample of LIRGs (Alonso-Herrero et al. 2006, 2011, in press) without a previous activity classification were obtained as part of the six-degree Field (6dF) Galaxy Survey (6dFGS DR3; Jones et al. 2004, 2009). Only 4 of these 7 LIRGs are members of the subsample studied in this paper. However we present the optical spectra of all of them since in Section 2 we compare the nuclear activity of both samples.

The optical spectra were obtained with the 6dF multi-object fibre spectrograph on the United Kingdom Schmidt Telescope (UKST) over 2001 to 2006. The R光纤 angular diameter is 6 arcsec. Each object was observed with two gratings of the subsample studied in this paper. However we do not plot this galaxy in Fig. B.2. We do not detect the H β emission line in the spectrum of IC 4280, so we do not plot this galaxy in Fig. B.2. This does not affect the H II activity classification of this galaxy (see Fig. B.2).

Table B.1. Observed optical emission line ratios and classification

| Galaxy Name | [N II]/Hα | [O III]/Hβ | Class. |
|-------------|-----------|-----------|-------|
| NGC 2469    | 0.58      | 1.00      | composite |
| ESO320–G030 | 0.48      | 0.20      | H II    |
| IC4280      | 0.41      | <0.40     | H II    |
| ESO221–IG010 | 0.50      | 0.28      | H II    |
| NGC5734     | 0.59      | 1.10      | composite |
| NGC5743     | 0.43      | 0.35      | H II    |
| IC4518E     | 0.57      | ...       | ...     |

Fig. B.2. [N II]λ6584/Hα versus [O III]λ5007/Hβ diagnostic diagram for the nuclear spectra of 6 LIRGs. The black lines show the empirical separation between H II, AGN, and composite galaxies of Kewley et al. (2006).
Corbett, E. A., Kewley, L., Appleton, P. N., et al. 2003, ApJ, 583, 670
Daddi, E., Dickinson, M., Morrison, G., et al. 2007, ApJ, 670, 156
de Rosa, A., Bassani, L., Ubertini, P., et al. 2008, A&A, 483, 749
Della Ceca, R., Ballo, L., Tavecchio, F., et al. 2002, ApJ, 581, L9
Della Ceca, R., Pellegrini, S., Bassani, L., et al. 2001, A&A, 375, 781
Fabbiano, G. 2006, ARA&A, 44, 323
Farrah, D., Lonsdale, C. J., Weedman, D. W., et al. 2008, ApJ, 677, 957
Fitzpatrick, E. L. 1999, PASP, 111, 63
Franceschini, A., Braito, V., Persic, M., et al. 2003, MNRAS, 343, 1181
García-Marín, M., Colina, L., Arribas, S., Alonso-Herrero, A., & Mediavilla, E. 2006, ApJ, 650, 850
Gil de Paz, A., Boissier, S., Madore, B. F., et al. 2007, ApJS, 173, 185
Gilfanov, M. 2004, MNRAS, 349, 146
González Delgado, R. M., Heckman, T., Leitherer, C., et al. 1998, ApJ, 505, 174
Grimes, J. P., Heckman, T., Strickland, D., & Ptak, A. 2005, ApJ, 628, 187
Grimm, H., Gilfanov, M., & Sunyaev, R. 2003, MNRAS, 339, 793
Güver, T. & Özel, F. 2009, MNRAS, 400, 2650
Hattori, T., Yoshida, M., Ohtani, H., et al. 2004, AJ, 127, 736
Howell, J. H., Armus, L., Mazzarella, J. M., et al. 2010, ApJ, 715, 572
Iwasawa, K., Sanders, D. B., Evans, A. S., et al. 2009, ApJ, 695, L103
Iwasawa, K., Sanders, D. B., Teng, S. H., et al. 2011, A&A, 529, A106
Jarrett, T. H., Chester, T., Cutri, R., et al. 2000, AJ, 119, 2498
Jarrett, T. H., Chester, T., Cutri, R., Schneider, S. E., & Huchra, J. P. 2003, AJ, 125, 525
Jenkins, L. P., Roberts, T. P., Ward, M. J., & Zezas, A. 2004, MNRAS, 352, 1335
Jenkins, L. P., Roberts, T. P., Ward, M. J., & Zezas, A. 2005, MNRAS, 357, 109
Jiménez-Bailón, E., Piconcelli, E., Guainazzi, M., et al. 2005, A&A, 435, 449
Jiménez-Bailón, E., Santos-Lleo, M., Mas-Hesse, J. M., et al. 2003, ApJ, 593, 127
Jones, D. H., Read, M. A., Saunders, W., et al. 2009, MNRAS, 399, 683
Jones, D. H., Saunders, W., Colless, M., et al. 2004, MNRAS, 355, 747
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775
Kennicutt, R. C., Hao, C., Calzetti, D., et al. 2009, ApJ, 703, 1672
Kennicutt, Jr., R. C. 1998, ARA&A, 36, 189
Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 961
Kim, D., Veilleux, S., & Sanders, D. B. 1998, ApJ, 508, 627
Kroupa, P. 2001, MNRAS, 322, 231
LaMassa, S. M., Heckman, T. M., Ptak, A., et al. 2009, ApJ, 705, 568
Le Floc’h, E., Papovich, C., Dole, H., et al. 2005, ApJ, 652, 107
Lee, J. C., Hwang, H. S., Lee, M. G., Kim, M., & Kim, S. C. 2011, MNRAS, 414, 702
Lehmer, B. D., Alexander, D. M., Bauer, F. E., et al. 2010, ApJ, 724, 559
Levenson, N. A., Heckman, T. M., Kroluk, J. H., Weaver, K. A., & Zychi, P. T. 2006, ApJ, 648, 111
Levenson, N. A., Weaver, K. A., Heckman, T. M., Awaki, H., & Terashima, Y. 2004, ApJ, 602, 135
Levenson, N. A., Weaver, K. A., Heckman, T. M., Awaki, H., & Terashima, Y. 2005, ApJ, 618, 167
Lípari, S., Díaz, R., Taniguchi, Y., et al. 2000, AJ, 120, 645
Lira, P., Ward, M.; Zezas, A., Alonso-Herrero, A., & Ueno, S. 2002, MNRAS, 330, 259
Liu, T. & Wang, J.-X. 2010, ApJ, 725, 2381
Marconi, A., Risaliti, G., Gilli, R., et al. 2004, MNRAS, 351, 169
Martin, C. L., Kobulnicky, H. A., & Heckman, T. M. 2002, ApJ, 574, 663
Mas-Hesse, J. M., Ott-Floranes, H., & Cerviño, M. 2008, A&A, 483,
