Evolution of the X-ray luminosity in young H II galaxies

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ABSTRACT

In an effort to understand the correlation between X-ray emission and present star formation rate, we obtained XMM–Newton data to estimate the X-ray luminosities of a sample of actively star-forming H II galaxies. The obtained X-ray luminosities are compared to other well-known tracers of star formation activity such as the far-infrared and the ultraviolet luminosities. We also compare the obtained results with empirical laws from the literature and with recently published analysis applying synthesis models. We use the time delay between the formation of the stellar cluster and that of the first X-ray binaries, in order to put limits on the age of a given stellar burst. We conclude that the generation of soft X-rays, as well as the Hα or infrared luminosities is instantaneous. The relation between the observed radio and hard X-ray luminosities, on the other hand, points to the existence of a time delay between the formation of the stellar cluster and the explosion of the first massive stars and the consequent formation of supernova (SN) remnants and high-mass X-ray binaries, which originate the radio and hard X-ray fluxes, respectively. When comparing hard X-rays with a star formation indicator that traces the first million years of evolution (e.g. Hα luminosities), we found a deficit in the expected X-ray luminosity. This deficit is not found when the X-ray luminosities are compared with infrared luminosities, a star formation tracer that represents an average over the last 10^8 yr. The results support the hypothesis that hard X-rays are originated in X-ray binaries which, as SN remnants, have a formation time delay of a few mega years after the star-forming burst.

Key words: galaxies: evolution – galaxies: starburst – X-rays: galaxies.

1 INTRODUCTION

X-ray emission in star-forming galaxies is dominated by a combination of high-mass X-ray binaries (HMXBs), hot O-stars, young SN remnants and hot plasma, all sources that are closely related to the presence of massive short-lived stars which directly trace the current star formation activity (Persic & Rephaeli 2002). Based on observations of local galaxies and the comparison with other tracers of recent star formation activity, several authors have proposed the use of the X-ray luminosity as a star formation tracer (e.g. David, Jones & Forman 1992; Grimm, Gilfanov & Sunyaev 2003; Ranalli, Comastri & Setti 2003). The locally observed correlations appear to hold also at high-z and an empirical L_X–SFR (star formation rate) relation based on observations of Lyman Break Galaxies (LBGs) in the 1 Ms CDF-N has been derived (Nandra et al. 2002). However, studies of LBGs suffer from the lack of other direct SFR tracers [e.g. Hα, far-infrared (FIR)], and additionally, LBGs whose emission is dominated by starburst events are too faint to be directly detected. Only the mean X-ray luminosities are attainable, making the possible contamination by obscured active galactic nuclei (AGN) difficult to quantify (Persic et al. 2004). Recent papers have confirmed the use of the X-ray emission as a direct tracer of star formation events (e.g. Laird et al. 2005; Rosa-González et al. 2007a); in contrast, Barger, Cowie & Wang (2007) found a poor correlation between the X-ray and radio emissions of star-forming galaxies that could question the use of X-rays as a reliable tracer of star formation activity. In a recent paper by Mas-Hesse, Ota-Floranes & Cerviño...
(2008), the different empirical relations between X-ray luminosities and the current SFRs were compared against evolutionary models. They found that under realistic assumptions (e.g. a young burst and an efficiency of a few per cent in the re-processing of mechanical energy) the observed relations confirm the use of the soft X-ray luminosity as a reliable tracer of the star formation activity in young systems.

This paper discusses the X-ray emission (as detected by XMM–Newton) of H II galaxies selected from the Terlevich et al. (1991) catalogue as having intense Hα and Hβ emission lines in their optical spectra.

H II galaxies are compact systems dominated by a strong and recent star formation burst event. The relative low mass – which implies a low contamination by low-mass X-ray binaries (LMXBs) – together with the absence of AGN activity makes these objects the best laboratories to study the relation between the X-ray luminosity ($L_X$) and the current SFR. By using other tracers of star-forming activity, we will discuss the validity of the existing X-ray calibrations in very young systems. In fact, H II galaxies, which are the youngest starbursts known in the local universe (Rosa-González et al. 2007b), could have a deficit of X-ray emission due to a time lag between the formation of the massive star cluster and the formation of the first HMXBs. In the following section, we discuss the sample selection. In Section 3, we discuss the data and their analysis. A comparison between the X-ray results and those obtained with other tracers of star formation is presented in Section 4. Section 5 is the discussion and conclusions are given in Section 6.

Throughout this work, a standard, flat Λ cold dark matter cosmology with $\Omega_\Lambda = 0.7$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is assumed.

### 2 SAMPLE SELECTION AND SFRs FROM OPTICAL EMISSION LINES

H II galaxies harbour intense and young star formation events revealed by the strong emission lines observed in the optical spectra. From the Spectrophotometric Catalogue of H II galaxies (Terlevich et al. 1991), we have selected those galaxies for which the corresponding SFR is greater than 4 M⊙ yr$^{-1}$. Based on the calibration given by Grimm et al. (2003) and the estimated SFR, we expect to find at least 12 HMXBs with luminosities greater than 10$^{38}$ erg s$^{-1}$ in each one of the selected galaxies. Due to the galaxies’ low mass, the expected number of LMXBs is a minimum. The selected sample is given in Table 1.

The luminosities of the hydrogen recombination lines are proportional to the number of ionizing photons so they trace the presence of massive stars with lifetimes not larger than a few million years. We estimate the SFR from the reddening corrected Hα luminosities [SFR(Hα)] using the relation (Kennicutt 1998)

$$\text{SFR(Hα)} (\text{M}_\odot \text{ yr}^{-1}) = 7.9 \times 10^{-42} L(\text{Hα}) (\text{erg s}^{-1})$$

Hα and Hβ fluxes are corrected for extinction using the Milky Way extinction curve (Seaton 1979) and assuming an intrinsic ratio Hα/Hβ of 2.87. The ionizing massive young clusters show in their spectra strong absorptions in the permitted lines (e.g. the H I Balmer series). The same species produces (at the same wavelengths) strong emission lines in the ionized gas and therefore the observed intensity of such lines is reduced by the underlying absorption, affecting the derived extinction.

For those galaxies for which the Hγ line flux was available, we estimate the correction due to the presence of the low mass underlying population following Rosa-González, Terlevich & Terlevich (2002). The final values of Av (the extinction in the V wavelength given in magnitudes) together with the Hα and Hβ fluxes and the derived SFRs are presented in Table 1.

Note that, as mentioned before, the SFR given by the Hα luminosity is tracing only the most massive stars (a few million years old), when a fraction of the expected HMXBs has yet to be formed. The time delay between the formation of the stellar burst and the formation of the first HMXBs is one of the main topics of this paper and we will discuss it in detail in Section 4.

### 3 XMM–NEWTON DATA ANALYSIS

14 objects have been observed with XMM–Newton (Jansen et al. 2001). The details of the observations are summarized in Table 2. The raw data have been processed using the standard Science Analysis System (SAS) v7.0.0 (Gabriel et al. 2004). The most up-to-date calibration files available in 2007 July have been used for the data reduction. The raw data have been filtered from high background flaring using the method described in Piconcelli et al. (2004). Detailed spatial and spectral analysis was possible only for four objects; net count rates were derived for all targets in the sample (Table 2).
Table 2. XMM–Newton observations ID, total and net exposure times after flaring removal, and background subtracted count rates in the different X-ray bands. The data were extracted from the EPIC-pn.

| Target   | Obs. ID      | Exposure time (ks) | Count rate (0.15–10 keV) (c s\(^{-1}\)) | Count rate (0.5–2 keV) (c s\(^{-1}\)) | Count rate (2–10 keV) (c s\(^{-1}\)) |
|----------|--------------|--------------------|------------------------------------------|--------------------------------------|------------------------------------|
| Mrk 52   | 0303560101   | 6.84, 4.3          | 0.020 ± 0.002                            | 0.0132 ± 0.0018                      | 0.0008 ± 0.0003                    |
| Cam 0902+1448 | 3035620101 | 6.84, 3.3          | 0.110 ± 0.011                            | 0.053 ± 0.006                        | 0.030 ± 0.008                      |
| Tol 1457–262 | 0303560601 | 9.33, 6.5          | 0.059 ± 0.004                            | 0.040 ± 0.003                        | 0.013 ± 0.003                      |
| Tol 1247–232 | 0303561001 | 11.5, 6.0          | 0.024 ± 0.003                            | 0.0150 ± 0.0019                      | 0.0058 ± 0.0014                    |
| Cam 08–82A | 0303561101 | 11.8, 6.7          | 0.010 ± 0.003                            | 0.0057 ± 0.0019                      | 0.004 ± 0.003                      |
| Tol 605   | 0303561701   | 7.93, 5.2          | <1.4 × 10\(^{-3}\)                       | <5 × 10\(^{-4}\)                     | <6 × 10\(^{-4}\)                   |
| Tol 2306–400 | 0303560401 | 10.9, 5.0          | <1.4 × 10\(^{-3}\)                       | <9 × 10\(^{-4}\)                     | <9 × 10\(^{-5}\)                   |
| Tol 930   | 0303560901   | 10.8, 2.4          | (4.6 ± 1.7) × 10\(^{-3}\)               | 0.0017 ± 0.0007                      | 0.0029 ± 0.0009                    |
| Tol 530   | 0303560501   | 6.84, 2.0          | (8 ± 3) × 10\(^{-3}\)                    | (5 ± 1.2) × 10\(^{-3}\)              | <4 × 10\(^{-4}\)                   |
| Tol 0420–414 | 0303561901 | 6.84, 2.8          | (8 ± 3) × 10\(^{-3}\)                    | (5 ± 1.2) × 10\(^{-3}\)              | <3 × 10\(^{-4}\)                   |
| Tol 0619–392 | 0303561401 | 6.84, 3.5          | (5.2 ± 2.3) × 10\(^{-3}\)               | (3.0 ± 1.4) × 10\(^{-3}\)            | 0.0020 ± 0.0015                    |
| Tol 421   | 0303561601   | 11.8, 5.7          | (7 ± 3) × 10\(^{-3}\)                    | (4.8 ± 1.5) × 10\(^{-3}\)            | <8 × 10\(^{-4}\)                   |
| Tol 444   | 0303561801   | 12.1, 3.6          | (7 ± 3) × 10\(^{-3}\)                    | (4.8 ± 1.5) × 10\(^{-3}\)            | <8 × 10\(^{-4}\)                   |

§Another observation of Cam 0902+1448 with ID 0303561201 is available. The results on spectral quantities derived from it, though less accurate, are compatible with those obtained from the 3035620101 observation so we used the latter for the analysis.

3.1 Imaging analysis

The majority of the sources are very weak in the X-ray band, allowing spatial analysis for only four of the galaxies: Mrk 52, Tol 1457, Tol 1247 and Cam 0902. We have generated smoothed images for these galaxies by applying the SAS task `assmooth` to the pn 0.2–2, 2–12 and 0.2–12 keV band images (Figs 1–4).

The images of Mrk 52 in different energy bands (Fig. 1) show a soft source, with no significant emission in the hard band. This is also the case of Tol 1247–232 (Fig. 4), although its emission in the hard band is stronger than in Mrk 52. The images of Cam 0902+1448 in the different energy bands are shown in Fig. 2. Tol 1457–262 is actually an H II galaxy pair. Both components are detected in the X-ray image but could not be resolved (Fig. 3). The images show that the south-west member is the weakest one of the pair, with a stronger contribution in the hard band, i.e. 2–12 keV.

3.2 Spectral analysis

For the majority of the sources (10 out of 14), the limited signal-to-noise ratio (S/N) did not allow spectral analysis with the European Photon Imaging Camera (EPIC). However, enough counts were detected to produce spectra for four sources: Mrk 52, Cam 0902, Tol 1457 and Tol 1247. Circular extraction regions of 400, 700, 550 and 650 pixels, respectively, were selected in order to maximize S/N in the 0.2–10 keV band (see details in Piconcelli et al. 2004). By using these regions, we are including between 80 and 90 per cent of the total energy as described in the XMM–Newton handbook. We also checked that we are not including X-ray emission from close sources and from pixels too close to the CCD edges.

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The high SN rate occurring in star-forming regions produces an acceleration of the electrons to relativistic velocities. The scattering of these electrons with FIR photons, enhanced by the star-forming process, results in non-thermal X-ray emission. This emission can, at first order, be modelled as a power law with an index in the range 1.6–1.8. However, observational studies on star-forming galaxies find that a thermal emission model with temperatures of the order of 8 keV provides also a satisfactory representation of the observed high-energy spectra. The average X-ray spectrum of a population of LMXBs and HMXBs can be described by a power law with an index $\Gamma \sim 1.2$ and a cut-off around 7.5 keV (Persic & Rephaeli 2003).

On the other hand, the diffuse emission mainly contributes to the soft X-ray band and can also be modelled as a thermal component but with a temperature one order of magnitude lower. Bearing this picture in mind, we have tested three different models to fit the source spectra: a single power law, a thermal emission model (specifically the mekal model in XSPEC; Liedahl, Osterheld & Goldstein 1995) and a combination of the best of the two previous ones with a second thermal emission model accounting for the soft emission. We also included a model for the photo electric absorption ($\text{zwabs}$ in XSPEC) using the Wisconsin cross-sections (Morrison & McCammon 1983).

The parameters fitted – by using a Levenberg–Marquart method – and the goodness of the fits are given in Table 3. The low number of detected counts does not allow us to fit more complex models. A single-component model provides acceptable fits to the data for all sources analysed, except for Cam 0902, for which a two-component fit is best. The derived fluxes and unabsorbed luminosities for each object are given in Table 4. In Figs 5 and 6, we illustrate the observed spectra and the best-fitting models for each galaxy. To illustrate the variation of the errors in the $\Gamma$ versus $N_H$ and the temperature versus $N_H$ planes, we plotted in Fig. 7 the corresponding error ellipses for Cam 0902.

We compare the obtained X-ray fluxes (Table 4) with those given by a starburst model described below (Table 5). The agreement is good but some discrepancies were found in the soft X-ray fluxes mainly due to the uncertainties in the $N_H$ value. In fact, differences in the goodness of the fit were found when the fit was made by fixing the value of the $N_H$ derived from the Hydrogen emission lines ($N_H = 1.79 \times 10^{21} \times \text{Av, cm}^{-2}$) as compared with the results obtained when the $N_H$ is a free parameter of the fitting procedure. The derived values of $\Gamma$ are somewhat higher than those found in the literature for similar type of objects and fix $\Gamma = 2$ created fits with large values of $\chi^2$. However, the data quality does not allow the discussion of the origin of this apparent systematic effect. In one case (Cam 0902), the best fit was obtained by adding to the power-law component a thermal model with a temperature of about 0.6 keV. That is consistent with temperatures of the hot plasma observed in other star-forming galaxies (Grimes et al. 2003).

In order to have a homogeneous data set, and due to the low number of photons that could be affecting the conclusions obtained from the spectra, the analysis presented in the next sections is based only on the count rates from Table 2. The count rates were calculated for the pn detector, extracted from a region of 15 arcsec free of any visible contamination. Background spectra have been extracted from a circular region located in the frame of the galaxy and free of any visible contaminating source. The associated ancillary and response matrices were obtained using the standard SAS tasks. EPIC-pn and the combined MOS 1 and 2 spectra of the four brightest objects were extracted. The spectra of Cam 0902+1448, Tol 1457−262 and Tol 1247−232 have been binned such that each bin contains at least 20 counts in order to apply the $\chi^2$ minimization technique. As not enough counts were detected in Mrk 52, we used the unbinned spectra to perform the analysis and therefore C-statistics were applied. The XMM–Newton spatial resolution and the limited S/N do not allow us to spectroscopically analyse each component of the pair Tol 1457 separately. Both members are included in the extraction region and therefore fluxes and luminosities refer to the pair’s combined emission. In all the galaxies, the spectral analysis has been performed using the v12.0 of XSPEC. The errors quoted are referred to the 90 per cent confidence level, i.e. $\Delta \chi = 2.71$ when $\chi^2$ statistics were applied. In all the cases, we fixed the Galactic column density to the values listed in Table 5 which were obtained through the Leiden/Argentine/Bonn Survey of Galactic H I (Kalberla et al. 2005).
Table 3. Spectral analysis.

| Target     | Model (1) | $N_H$ (10$^{21}$ cm$^{-2}$) | $\Gamma$ | $N_H$ (10$^{21}$ cm$^{-2}$) | K T (keV) | Goodness |
|------------|-----------|-----------------------------|----------|-----------------------------|----------|----------|
| Mrk 52     | A         | 6 ± 3                       | 6.5 ± 0.5 | -                           | -        | 489 for 3222 d.o.f.† |
|            | A†        | 5.5                         | 6.5 ± 0.5 | -                           | -        | 490 for 3223 d.o.f.† |
|            | B         | -                           | -        | 7.7$^{+1.5}_{-1.3}$         | 0.14 ± 0.02 | 497 for 3222 d.o.f.† |
|            | B†        | -                           | -        | 5.5                         | 0.18$^{+0.02}_{-0.03}$ | 505 for 3223 d.o.f.† |
| Cam 0902+1448 | A       | 4.6$^{+1.8}_{-1.2}$         | 5.2$^{+0.8}_{-1.2}$ | -                           | -        | 31 for 25 d.o.f.     |
|            | A†        | 3.4f                        | 5.3$^{+0.3}_{-0.4}$ | -                           | -        | 35 for 26 d.o.f.     |
|            | B         | -                           | -        | 0.8                         | 0.2      | 63 for 25 d.o.f.     |
|            | B†        | -                           | -        | 3.4f                        | 0.25     | 73 for 26 d.o.f.     |
|            | C         | 2.0$^{+1.5}_{-1.6}$         | 3.6$^{+1.2}_{-1.1}$ | -                           | 0.63$^{+0.16}_{-0.17}$ | 18 for 23 d.o.f.     |
| Tol 1457–262 | A        | 1.4$^{+1.0}_{-0.9}$         | 2.2$^{+0.5}_{-0.4}$ | -                           | -        | 16.2 for 12 d.o.f.   |
|            | B         | <1.4                        | 1.8$^{+0.4}_{-0.5}$ | <0.6                        | 4.6$^{+4}_{-1.5}$ | 18.7 for 12 d.o.f.   |
| Tol 1247–232 | A        | <1.4                        | 1.8$^{+0.4}_{-0.5}$ | -                           | -        | 5.1 for 6 d.o.f.     |
|            | B         | <1.4                        | 1.8$^{+0.4}_{-0.5}$ | <0.5                        | 7$^{+16}_{-4}$ | 7.6 for 6 d.o.f.     |

Notes: (1) Model A: zwabs*zpowerlaw; Model B: zwabs*mekal; Model C: zwabs(zpowerlaw+mekal); in boldface, the best-fitting model. †$N_H$ fixed to the value derived from Av. ‡C-statistics.

Table 4. Observed fluxes and unabsorbed luminosities in the soft and hard bands.

| Target     | Flux (0.5–2 keV) (10$^{-14}$ erg cm$^{-2}$ s$^{-1}$) | Flux (2–10 keV) (10$^{-14}$ erg cm$^{-2}$ s$^{-1}$) | Luminosity (0.5–2 keV) (10$^{39}$ erg s$^{-1}$) | Luminosity (2–10 keV) (10$^{39}$ erg s$^{-1}$) |
|------------|-----------------------------------------------------|--------------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Mrk 52     | 2.5 ± 0.5                                            | 0.08 ± 0.03                                       | 5.8 ± 1.2                                      | 1.0 ± 0.4 $\times$ 10$^{-3}$                  |
| Cam 0902+1448 | 8.5$^{+1.5}_{-1.4}$                                        | 1.5$^{+0.4}_{-0.3}$                                | 14$^{+3}_{-2}$                                 | 1.1$^{+0.3}_{-0.2}$                           |
| Tol 1457–262 | 5.5$^{+1.3}_{-1.2}$                                        | 8.5$^{+1.5}_{-1.3}$                                | 0.7 ± 0.2                                      | 0.55$^{+0.11}_{-0.14}$                         |
| Tol 1247–232 | 2.9$^{+0.8}_{-0.7}$                                        | 4.4$^{+0.7}_{-0.6}$                                | 1.6$^{+0.6}_{-0.9}$                            | 2.5$^{+0.4}_{-1.3}$                           |

Figure 5. Observed EPIC spectra, best-fitting model and residuals of left-hand panel: Mrk 52; right-hand panel: Cam 0902+1448.

Thermal emission) are normalized such that the flux ratio between the thermal and the power-law components in the 2–10 keV band is 0.03 (Persic & Rephaeli 2003, and references therein). The estimated fluxes in the soft (0.5–2 keV) and hard (2–10 keV) bands are shown in Table 5. Calculations were performed using PIMMS v3.9.2

2 PIMMS does not consider the cut-off power-law for fluxes/count rates estimates. Therefore, we have also applied a correction due to differences on flux estimation when a simple power-law model is used instead of a cut-off power law.

The fluxes and luminosities, also given in Table 5, were corrected from absorption using the extinction derived from published ratios between Hα and Hβ which include the absorption due to the Galaxy. Note that the values of the column density given in Table 5 were used only in the spectral analysis of Mrk 52, Cam 0902, Tol 1457 and Tol 1247. The errors were derived from the count rate uncertainties. However, we note that they should be considered lower limits of the real uncertainties, as they only include the Poisson error on the count rate. The uncertainty generated by considering different models is not included in the error budget. In this sense, when a single power-law model with $\Gamma = 2$ is applied instead of the
to the observed X-ray luminosities is estimated using the relation between the stellar mass and the luminosity due to LMXB (Grimm, Gilfanov & Sunyaev 2002),

\[ L_{\text{LMXB}} \ (\text{erg s}^{-1}) = 5 \times 10^{39} M_* \]  

(2)

where \( M_* \) is the stellar mass in solar units. Table 5 shows that the calculated \( L_{\text{LMXB}} \) are much smaller, on average less than 2 per cent and at most 20 per cent, than the observed X-ray luminosities. The general result is that the total X-ray luminosities of the low-mass galaxies selected here is probably not greatly affected by the LMXBs’ contribution.

4 EARLY EVOLUTIONARY PHASES: COMPARISON WITH SFR TRACERS

4.1 H\( \alpha \) luminosities

The recombination emission lines only appear during the early evolution of a starburst when the massive stars are hot enough to produce ionizing photons. Therefore, the deduced SFR(H\( \alpha \)) is tracing the first million years of the present starburst evolution. Fig. 8 shows the relation between the H\( \alpha \) luminosity and the X-ray luminosities both in the soft (top panel) and in the hard (bottom panel) bands. The solid lines show the empirical relation found by Ranalli et al. (2003) based on the study of nearby star-forming galaxies,

\[ \text{SFR} \text{soft} (\text{M}_\odot \text{yr}^{-1}) = 2.2 \times 10^{-40} L(0.5 - 2 \text{ keV}) \ (\text{erg s}^{-1}) \]  

(3)

\[ \text{SFR} \text{hard} (\text{M}_\odot \text{yr}^{-1}) = 2 \times 10^{-40} L(2 - 10 \text{ keV}) \ (\text{erg s}^{-1}) \]  

(4)

There is a good correlation between the \( L(H\alpha) \) and the soft X-ray luminosity (top panel), but there is one galaxy (Cam 0902+1448) for which the luminosity in X-rays is well above the one predicted by Ranalli’s law. In the bottom plot of this figure [hard X-rays versus \( L(H\alpha) \)], most of the galaxies are below the empirical correlation. Due to the presence of upper limits, we fit the luminosities by using survival analysis.3 The Buckley–James algorithm (BJ, e.g. Isobe, Feigelson & Nelson 1986), a non-parametric method which treats the residuals using the Kaplan–Meier description, was applied to the data in Fig. 8. In the case of the bottom panel, the non-parametric

3 See IRAF task stsdas.analysis.statistics.survival for an introduction to survival analysis.
Table 5. Galactic column density and derived fluxes and luminosities.

| Target   | \(N_H\) (10^{20}) (cm\(^{-2}\)) | \(F_{0.5-2\mathrm{keV}}\) (10\(^{-14}\)) (erg s\(^{-1}\) cm\(^{-2}\)) | \(F_{2-10\mathrm{keV}}\) (10\(^{-14}\)) (erg s\(^{-1}\) cm\(^{-2}\)) | \(L_{0.5-2\mathrm{keV}}\) (10\(^{41}\)) (erg s\(^{-1}\)) | \(L_{2-10\mathrm{keV}}\) (10\(^{41}\)) (erg s\(^{-1}\)) | \(L_{\text{thermal}0.5-2\mathrm{keV}}\) (10\(^{41}\)) (erg s\(^{-1}\)) | \(L_{\text{LMXB}}\) (10\(^{39}\)) (erg s\(^{-1}\)) |
|----------|----------------------------------|---------------------------------|---------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Mrk 52   | 1.9                              | 8.40 ± 0.88                     | 9.90 ± 1.04                     | 0.10 ± 0.01                   | 0.11 ± 0.01                   | 0.048 ± 0.005                 | 1.76 ± 0.53                   |
| Cam 0902+1448 | 3.7                      | 41.00 ± 4.13                    | 48.00 ± 4.84                    | 24.24 ± 2.44                  | 28.38 ± 2.86                  | 12.1 ± 1.22                   | 2.34 ± 0.70                   |
| Tol 1457–262 | 9.4                      | 20.00 ± 1.36                    | 24.00 ± 1.63                    | 1.30 ± 0.09                   | 1.56 ± 0.11                   | 0.651 ± 0.044                 | 0.47 ± 0.14                   |
| Tol 1247–232 | 6.6                      | 6.40 ± 0.77                     | 7.50 ± 0.90                     | 3.48 ± 0.42                   | 4.07 ± 0.49                   | 1.73 ± 0.209                 | <0.73                        |
| Tol 2259–398 | 1.1                      | 3.70 ± 1.11                     | 4.30 ± 1.29                     | 0.71 ± 0.21                   | 0.83 ± 0.25                   | 0.357 ± 0.107                 | 1.04 ± 0.31                   |
| Cam 08–82A    | 3.3                        | <0.43                           | <0.50                           | <0.25                         | <0.30                         | <0.127                       | <0.63                        |
| Mrk 605     | 1.9                        | <0.82                           | <0.97                           | <0.17                         | <0.20                         | <0.085                       | 1.36 ± 0.41                   |
| Tol 2306–400 | 1.3                        | 3.73 ± 1.40                     | 4.30 ± 1.61                     | 3.81 ± 1.43                   | 4.39 ± 1.65                   | 1.90 ± 0.714                  | 3.96 ± 1.19                   |
| Mrk 930     | 5.5                        | 1.40 ± 0.52                     | 1.61 ± 0.60                     | 0.10 ± 0.04                   | 0.12 ± 0.04                   | 0.051 ± 0.019                 | <0.08                        |
| UM 530      | 1.5                        | 2.74 ± 1.03                     | 3.18 ± 1.19                     | 3.27 ± 1.22                   | <3.79                         | 1.63 ± 0.612                 | 6.43 ± 1.93                   |
| Tol 0420–414 | 2.5                      | 0.58 ± 0.52                     | 0.69 ± 0.61                     | 0.05 ± 0.05                   | <0.06                         | 0.026 ± 0.023                 | <0.13                        |
| Tol 0619–392 | 7.6                        | 2.20 ± 0.97                     | 2.60 ± 1.15                     | 1.47 ± 0.65                   | 1.73 ± 0.77                   | 0.734 ± 0.325                 | 1.78 ± 0.53                   |
| UM 421      | 4.1                        | 1.50 ± 0.88                     | 1.80 ± 1.06                     | 0.56 ± 0.33                   | 0.67 ± 0.39                   | 0.280 ± 0.164                 | 2.28 ± 0.69                   |
| UM 444      | 2.1                        | 2.20 ± 0.94                     | 2.60 ± 1.11                     | 0.29 ± 0.12                   | <0.34                         | 0.144 ± 0.062                 | 0.54 ± 0.16                   |

Figure 8. X-ray (soft band in the top and hard band in the bottom panel) versus H\(\alpha\) luminosities. Here and in the following plots, solid circles mark those galaxies for which we extracted the X-ray spectrum. In both cases, the solid line is the result of converting the Ranalli law to H\(\alpha\) luminosities and the dashed one is a linear fitting that takes into account the presence of upper limits in the derived X-ray luminosities. In the bottom panel, the dotted line is the result of the fit obtained when leaving out the outlier Mrk 52.

4.2 Radio luminosity

Table 6 shows the radio fluxes at 1.4 GHz for the selected galaxies extracted from NASA/IPAC Extragalactic Database. The strong correlation known to exist between the radio and the FIR fluxes is taken as an indication that radio emission is a reliable tracer of the SFR. Yun, Reddy & Condon (2001) found, from a FIR selected sample of about 1800 star-forming galaxies, that their radio continuum may be used to infer the extinction-free SFR using the relation

\[
\text{SFR}(1.4\text{GHz})(\text{M}_\odot\text{yr}^{-1}) = 5.9 \times 10^{-29} L(1.4\text{GHz})(\text{erg s}^{-1} \text{Hz}^{-1}).
\]  

(5)

The values of SFR(1.4 GHz) for our XMM–Newton observed galaxies are also presented in Table 6. The empirical relation found by Yun et al. (2001) is well understood and it is based on the existence of a star-forming event in which the observed radio emission arises from accelerated electrons produced in the SN remnants and the infrared (IR) radiation comes from dust that is heated mainly by massive stars. The estimated SFR corresponds to continuous star formation occurring for the last 10^9 yr.

In Fig. 9, we compare the radio with the total soft X-ray luminosities together with the empirical relation given by Ranalli et al. (2003). In the left-hand panel, the X-ray luminosities were calculated by using a two-component model (thermal + power law as described in Section 3.2). Although the original calibration by Ranalli et al. (2003) is based on the relation between the radio and X-ray luminosities (solid line), a clear deviation from the empirical relation is obtained for our objects. Most of the galaxies are below the line defined by Ranalli and collaborators and seem to have low radio emission. These galaxies could be in an early stage previous to the synchrotron phase that appear with the first SN explosions. At this phase, the radio emission is dominated by free–free electrons produced in H\(\alpha\) regions close to massive stars.

To check if a better correlation is found when only the X-ray thermal emission is considered we use a thermal model to convert the counts to luminosities. We used \(\text{pms}\) and a thermal mekal \(kT = 0.8\text{ keV}\) model with solar metallicity to derive the luminosities for all the galaxies in the sample. In this model, we assume that we are counting photons produced by the interaction between the hot outflowing wind and the ambient gas in the host galaxy (Grimes et al. 2005). In the right-hand panel, the X-ray luminosities correspond to the so defined thermal component only. In both panels, the solid line represents the empirical relation of Ranalli and collaborators and the dashed line, the linear regression to our data.

The radio fluxes of five of the galaxies are just upper limits, so we implement the BJ algorithm to confirm the observed trends. The results are shown by the dot–dashed line in both panels of Figs 9 and 10.

4.3 IR and UV luminosities

As we mentioned before, the IR radiation is a good tracer of the SFR averaged over the last 10^8 yr. However, an unknown fraction of UV photons could have escaped the galaxy and consequently, the derived SFR would be underestimated. To solve this problem, Heckman et al. (1998) and Buat et al. (1999) proposed to add the
**Table 6.** Fluxes and SFRs from radio, IR, UV and total. The ratio between the soft X-ray and IR luminosities is shown in the last column.

| Name     | F(1.4 GHz) (mJy) | SFR(1.4 GHz) (M_⊙ yr⁻¹) | F(60 μm) (Jy) | SFR(IR) (M_⊙ yr⁻¹) | F(UV) (μJy) | SFR(UV) (M_⊙ yr⁻¹) | Log L_X/L_IR |
|----------|-----------------|--------------------------|---------------|---------------------|-------------|---------------------|---------------|
| Mrk 52   | 13.10 ± 0.60    | 1.10 ± 0.33              | 4.43 ± 0.03   | 6.65 ± 0.10         | 1.47 ± 0.44 | 3086.38 ± 36       | 0.61 ± 0.31   |
| Cam 0902+1448 | 86.84 ± 0.82 | 309 ± 93                 | 4.12 ± 0.21   | 6.98 ± 0.35         | 62 ± 19     | 1207.58 ± 24       | 10.41 ± 5.2   |
| Tol 1457−262 | 37.80 ± 1.80  | 14.5 ± 4.4               | 3.09 ± 0.18   | 3.68 ± 0.41         | 4.34 ± 1.3  | 1670.91 ± 21       | 1.52 ± 0.76   |
| Tol 1247−232 | 3.40 ± 0.50    | 10.9 ± 3.6               | 0.51 ± 0.05   | < 0.97              | 10.6 ± 3.2  | 943.07 ± 12        | 7.17 ± 3.6    |
| Tol 2259−398 | < 1.77         | 2.01                     |               |         |               | 477.96 ± 3.4  | 1.29 ± 0.64   |
| Cam 08−82A  | 3.06 ± 0.15    | 10.7 ± 3.2               | 0.58 ± 0.01   | 0.95 ± 0.16         | 8.32 ± 2.5  | 203.48 ± 3.9       | 1.68 ± 0.84   |
| Mrk 605 | < 1.56         | 1.90 ± 4.3               | 0.27 ± 0.04   | < 1.36              | 2.17 ± 0.65 | 172.18 ± 4.3       | 0.50 ± 0.25   |
| Tol 2306−400 | < 1.38        | 8.31                     |               | < 0.25              | < 0.86      | 325.57 ± 11        | 1.65 ± 2.3    |
| Mrk 930 | 12.20 ± 0.90   | 5.26 ± 1.6               | 1.25 ± 0.09   | < 2.15              | 3.52 ± 1.1  | 864.69 ± 18        | 0.88 ± 0.44   |
| UM 530 | 6.40 ± 0.60    | 45.0 ± 14                | 0.58 ± 0.07   | 0.63 ± 0.13         | 14.5 ± 4.3  | 340.44 ± 17        | 5.68 ± 2.8    |
| Tol 0420−414 | < 1.50        | 0.80                     |               | < 0.25              | < 0.90      | 160.44 ± 5.6       | 0.20 ± 0.10   |
| Tol 0619−392 | < 1.56        | 6.14                     | 0.42 ± 0.05   | < 1.59              | 10.8 ± 3.2  | 238.70 ± 7.8       | 2.23 ± 1.1    |
| UM 421 | 4.30 ± 0.50    | 9.46 ± 3.0               | 0.56 ± 0.07   | < 1.30              | 8.07 ± 2.4  | 101.48 ± 7.7       | 0.53 ± 0.26   |
| UM 444 | < 1.44         | 1.11                     | < 0.25         | < 0.90              | < 1.27      | 465.66 ± 7.8       | 0.85 ± 0.42   |

Figure 9. Radio versus soft X-ray luminosity (L_{0.5−2keV}) for the selected galaxies. The X-ray luminosities have been calculated by using a two-model component (thermal + power law) in the left-hand panel and a thermal component in the right-hand panel. Galaxies for which it was possible to extract the spectra are marked with solid circles, the other sources in our sample are indicated as crosses. In both panels, the galaxies studied by Ranalli et al. are represented by asterisks. The solid line shows the linear correlation found by Ranalli and collaborators. The results of a standard linear fit (dashed line) and the fit from the survival analysis (dot-dashed line) are also plotted.

Figure 10. Radio versus hard X-ray luminosities. Symbols as in Fig. 9.

SFR calculated from the ultraviolet (UV) that to based on the IR. By adding the two contributions, on the one hand one avoids the complex corrections that must be applied to the UV data and on the other hand, there is no need to correct for the UV escaping fraction that affects the IR measurements. We use the relations (Kennicutt 1998)

\[
\text{SFR(IR)}(\text{M}_⊙\text{ yr}^{-1}) = 4.5 \times 10^{-44} L_{\text{IR}}(\text{erg s}^{-1})
\]

(6) which are valid for the case of a universal Salpeter initial mass function with masses between 0.1 and 100 M_⊙. The UV data come from Galaxy Evolution Explorer (Multimission Archive at STScI) and our UV observations made with the Optical Monitor on board XMM–Newton. For those galaxies for which IRAS data exist, we estimate both the SFR(IR) and SFR(UV). The total SFR for them is calculated directly by adding the SFR(IR) and the SFR(UV) without applying any extinction correction. The results are given in Table 6. For those galaxies lacking IRAS data, the total SFR is calculated from the UV fluxes corrected by extinction, using equation (7). We use Calzetti’s law (Calzetti 2001) and the visual extinction calculated from the Balmer decrement (Table 1) to correct for extinction. We also take into account that due to gas surrounding the newly formed stars, they are more extinguished than the stars from which most of the UV radiation is coming (age selective extinction, e.g. Mayya et al. 2004), Cid Fernandes et al. (2005), based on the study of 50,362 galaxies from the Sloan Digital Sky Survey (SDSS), found that the relation between the visual extinction obtained from the Hα to Hβ ratio is A_V = 0.24 + 1.81A_α, where A_α is the extinction that is affecting the continuum light. The A_α values are the ones that we apply to correct the observed UV fluxes. The comparison of the total SFR with the X-ray luminosities is presented in Fig. 11. The ratio between the soft X-ray and IR luminosities can be

\[
\text{SFR(UV)}(\text{M}_⊙\text{ yr}^{-1}) = 1.4 \times 10^{-28} L_{\nu}(\text{erg s}^{-1} \text{ Hz}^{-1})
\]

(7)
the radio luminosities with the fraction of the soft X-ray luminosities due to thermal emission alone, a better agreement is found (see right-hand panel of Fig. 9). Note that when the BJ method is used to estimate the linear regression, a higher discrepancy is observed.

Radio versus hard X-ray luminosities are shown in Fig. 10. We can see that most of the galaxies are below the relation proposed by Ranalli et al. (2003), consistent with the lack of both SN remnants and HMXBs.

For galaxies with available IRAS data, the total SFR was calculated by adding the SFR(IR) and the SFR(UV) without correcting the UV fluxes for extinction. For those galaxies without IRAS fluxes, the total SFR was calculated from the extinction corrected UV luminosities. The total SFR is an average over the last 10^9 yr, providing enough time for a population of HMXB to be in place. In fact, there is a good correlation between the total SFR (averaged over the last 10^9 yr) and the X-ray luminosities both in the soft and in the hard band (Fig. 11), in fairly good agreement with the empirical Ranalli relation.

Note that all selected galaxies are classified as H II galaxies based on diagnostic diagrams of optical line ratios (Baldwin, Phillips & Terlevich 1981). However, an unknown contribution from a heavily obscured AGN could be present. This contribution is more important in the hard band, and the deviation from the Ranalli relation observed in Fig. 10 could be due to an excess of X-ray emission from an AGN instead of representing a deficit in radio. However, such deficit in radio is clear when the SFR(Hα) is compared with the SFR(1.4 GHz). Moreover, the excess of hard X-ray emission is not present when comparing the hard band X-ray luminosity with the total SFR (Fig. 11). We can safely conclude that the X-ray emission that we see is due to star formation processes.

Mas-Hesse et al. (2008) have concluded that assuming a reprocessing efficiency of the mechanical energy of a few per cent, the observed values of the ratio between the soft X-ray and IR luminosities can be reproduced with synthetic models of young starbursts. In fact, they obtain an average value of log L_{0.5–2 keV}/L_{IR} = −3.5 for efficiencies between 1 and 10 per cent for bursts with ages around 5 Myr. In our sample, the ratio log L_{0.5–2 keV}/L_{IR} (Table 6) has an average value of −3.20 ± 0.41 consistent with the theoretical estimations.

For continuous star formation, a value of log L_{0.5–2 keV}/L_{IR} = −3.5 is consistent with ages as large as 25 Myr. At this age, a significant number of stars have exploded as SN. The strong emission lines and the high SFR derived together with the lack of synchrotron emission observed in most of the sources suggest a star formation history characterized by a strong short burst.

Mrk 52 and Cam 0902 are outliers in some of the presented plots. Particularly, Mrk 52 is a bright blue galaxy with a derived SFR (Hα) = 14 M⊙ yr⁻¹. However, the extremely weak emission in the hard X-ray band (see the spectrum in Fig. 1) together with the deficit in radio makes this galaxy the most clear example of an extreme young burst with an age of about 3 Myr when the majority of SNe and HMXBs have not yet been formed. This age is consistent with Mrk 52 being a Wolf–Rayet galaxy as the dominant burst is going through an intense Wolf–Rayet phase (Schaerer, Contini & Pindao 1999; Fernandes et al. 2004).

6 CONCLUSIONS

We have analysed XMM–Newton observations of a sample of 14 star-forming galaxies with high SFR judging from their strong hydrogen recombination lines. The main conclusions of our analysis are as follows.
(i) The SFR obtained from the soft X-ray luminosity is comparable to that determined from the Hα luminosities. This is consistent with the X-ray luminosity as a good tracer of SFR even at early times when the massive stars dominate the energy generation. Due to the time delay between the formation of the burst and the formation of the first massive binary systems, a lack of hard X-ray luminosity is observed when compared with tracers of recent star formation activity (e.g. Hα, Fig. 8). This effect has already been observed in the Small Magellanic Cloud; we have extended the study to a larger sample of star-forming galaxies.

(ii) The weak radio emission observed in some of the objects (related to early phases in the starburst evolution) together with the values found for log $L_{0.5-2\text{keV}}/L_{\text{IR}} \sim -3.2$ suggests that the sample of galaxies is biased to galaxies dominated by young bursts with ages lower than 5 Myr and with star-forming histories characterized by long and low activity periods, followed by short strong episodes.

(iii) The relation of both soft and hard X-ray luminosity with the SFR traced by the IR and UV shows that the X-ray production is maintained by at least $10^8$ yr.

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