On the X-ray properties of OH megamasers sources: Chandra snapshot observations

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ABSTRACT
We present Chandra snapshot observations for a sample of seven sources selected from the Arecibo OH megamaser (OHM) survey at \(z \approx 0.13–0.22\) and with far-infrared (FIR) luminosities in excess of \(10^{11}\) \(L_\odot\). In contrast with the known H$_2$O megamasers, which are mostly associated with powerful active galactic nuclei (AGN), the situation is far less clear for OHMs, which have been poorly studied in the X-ray band thus far. All of the observed sources are X-ray weak, with only one OHM, IRAS FSC 03521+0028 (\(z = 0.15\)), being detected by Chandra (five counts). The results from this pilot programme indicate that the X-ray emission, with luminosities of less than \(\approx 10^{42}\) \(\text{erg s}^{-1}\), is consistent with that from star formation (as also suggested in some cases by the optical spectra) and low-luminosity active galactic nuclei (LLAGN) emission. If an AGN is present, its contribution to the broad-band emission of OHM galaxies is likely modest. Under reasonable assumptions about the intrinsic X-ray spectral shape, the observed count distribution from stacking analysis suggests absorption of \(\approx 10^{22}\) \(\text{cm}^{-2}\).

Key words: galaxies: active – galaxies: interactions – galaxies: nuclei – galaxies: starburst – X-rays: galaxies.

1 INTRODUCTION
Extragalactic hydroxyl (OH) megamaser (OHM) emission has been studied since the early 1980s when it was discovered in Arp 220 (Baan, Wood & Haschick 1982). To be produced, OHM activity requires (i) high molecular density (\(n_{\text{H}_2} = 10^{6–7} \text{cm}^{-3}\); Baan 1991); (ii) a ‘pump’ to invert the hyperfine population of the OH ground state; and (iii) a source of 18-cm continuum emission to stimulate maser emission (Burdyuzha & Komberg 1990), whose main lines are at 1667 and 1665 MHz and have luminosities \(L_{\text{OH}} = 10^{13–4} \text{L}_\odot\).

The galaxy merger environment is able to supply all of these requirements: the merger/interaction concentrates molecular gas in the merger nuclei, creates strong far-infrared (FIR; 8–1000 \(\mu\)m) dust emission from reprocessed starburst and active galactic nuclei (AGN) activity and produces radio continuum emission. The FIR radiation field and/or collisional shocks in the molecular gas can invert the OH population and thus allow maser emission.

Not surprisingly, all known OHMs have been observed in luminous infrared galaxies (LIRGs; \(L_{\text{FIR}} > 10^{11} \text{L}_\odot\)), often favouring the most FIR luminous (e.g. Baan 1991; Baan, Salzter & LeWinter 1998; Darling & Giovannelli 2002a, hereafter DG02a; Lo 2005), the ultraluminous infrared galaxies (ULIRGs; \(L_{\text{FIR}} > 10^{12} \text{L}_\odot\)). The high FIR luminosities of ULIRGs are commonly thought to arise from dust absorption and FIR re-emission of an intense but obscured starburst and/or AGN radiation field. While it was known early on that ULIRGs nearly always show evidence for interactions (i.e. collisions/mergers; e.g. Clements et al. 1996; Sanders & Mirabel 1996; Borne et al. 2000; Farrah et al. 2001, 2003), many investigators have debated the luminosity dependence of the fraction of interacting systems among the ULIRG population and the possibility that these sources may represent the transition stage between galaxy mergers and quasars (e.g. Farrah et al. 2001; Tacconi et al. 2002; see also Yun et al. 2004).

OHM studies provide powerful diagnostics of the physical conditions in the innermost regions of luminous FIR galaxies. There is evidence that the OH emission is often produced by an ensemble of many masing regions in the nuclear regions of (U)LIRGs on scales of a few hundred parsecs or less (Diamond et al. 1999). Very long baseline interferometry (VLBI) observations of a few nearby OHMs have demonstrated that OH maser emission can arise in circumnuclear discs or tori such as for III Zw 35 (Pihlström et al. 2001) or Mrk 231 (Klöckner, Baan & Garrett 2003), or, as for Arp 220 (Rovilos et al. 2003), the emission can show a complicated, irregular morphology and velocity structure. Blueshifted/redshifted line components in several OHMs (Baan, Haschick & Henkel 1989;
Pihlström et al. (2005) have been interpreted as due to bulk outflows/inflows of molecular gas; this is expected given the tidal streaming and starburst-driven winds associated with major mergers. It is noteworthy that most VLBI studies of OHMs show unresolved maser spots of surprising velocity width (tens of km s$^{-1}$), often attributed to turbulence and suggestive that compact OHM emission may not be pumped by the FIR radiation field alone (e.g. Lonsdale et al. 1998). A notable exception is the infrared (IR) quasar Mrk 231, which lacks a compact maser component contrary to expectation (Klöckner et al. 2003; Lonsdale et al. 2003). The relationship of OHMs to starbursts versus AGN thus remains murky: all manner of masing is seen coupled with all manner of optical classifications. To obtain deeper insight into the OHM phenomenon, we require a minimal-obscuration means to quantify the role of AGN versus starburst in masing regions. The radio–FIR relation hints at some difference between masing and non-masing (U)LIRGs (DG02a), but there is a degeneracy between starbursts and AGN in this relation.

In contrast with H$_2$O megamasers, which are likely pumped by an AGN X-ray radiation field (e.g. Baan 1997; Braatz, Wilson & Henkel 1997; Henkel et al. 1998; Townsend et al. 2001; Maloney 2002; Braatz et al. 2003, 2004; Henkel et al. 2005), the AGN content of OHMs has not been investigated with a minimal-obscuration probe of AGN activity, aside from radio continuum observations of radio-loud AGN that lie well off the radio–FIR relation. A previous optical study of OH maser sources (most of which were OHMs) found comparable fractions of AGN- and starburst-dominated galaxies (Baan et al. 1998) and a non-negligible fraction of composite spectra (i.e. showing evidence of both AGN and starburst activity) in the OH maser population. Because of their penetrating nature, X-rays represent an efficient tool to provide constraints on the engine powering OHMs. Furthermore, X-rays typically provide maximal contrast between the AGN emission and that of the host galaxy and/or starburst component (e.g. Vignati et al. 1999).

Hereafter, we adopt $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ in a $\Lambda$-cosmology ($\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$, Spergel et al. 2003).

### 2 Sample Selection and Source Properties

The goal of the present paper is to provide basic constraints on the X-ray emission of OHM galaxies using Chandra snapshot observations. Past studies have shown evidence for a correlation between the OH line width and the X-ray luminosity in the soft band (Kandalyan 2003) using a compilation of OH masers from the literature (mostly from Baan et al. 1998) detected by ROSAT. This was interpreted as suggesting that X-ray heating of molecular gas provides additional collisional excitation to the maser emission, although further studies are required to investigate this issue. We note, however, that the compilation of OHMs chosen by Kandalyan (2003) is heterogeneous, because it was not drawn from a well-defined sample. For these reasons, we prefer to focus, in this pilot Chandra programme, on the sample of OHMs selected from the Arecibo Observatory OHM survey, which is a flux-limited survey designed to quantify the relationships between merging galaxies and the OHMs that they produce, with the goal of using OHMs as luminous tracers of mergers (and, possibly, of star formation; Townsend et al. 2001) at high redshifts (Darling & Gioanelli 2000, 2001, 2002b, hereafter DG00, DG01, and DG02b, respectively). This survey was conducted over about one-quarter of the sky to a distance limit of roughly 1 Gpc. Candidates for observations with the Arecibo Observatory were selected from the Point Source Catalogue redshift survey (Saunders et al. 2000), which is a flux-limited ($IRAS f_{60} \mu m > 0.6$ Jy) redshift survey of $\approx 15$ 000 IRAS galaxies over 84 per cent of the sky. The Arecibo survey detected 50 new OHMs in the redshift range 0.11–0.27 (DG02a,b), thus doubling the sample of known OHMs and increasing the $z > 0.1$ sample sevenfold. Thanks to this survey, it is now evident that the fraction of OHMs in (U)LIRGs is an increasing function of $L_{\text{FIR}}$: about one-third of the ‘warmest’ (i.e. with higher dust temperatures) ULIRGs are characterized by OHMs (DG02a).

The OHM galaxies proposed for observation with Chandra have been chosen using the catalogue published by DG01 available at the time of Chandra Cycle 5 proposals (six of the seven OHMs described in the following); our targets are among the highest luminosity members ($L_{\text{OH}} > 10^4 L_\odot$; $\approx 30$–$40$ per cent of the OHM population in the Arecibo survey) of the maser population (filled circles in Fig. 1). They also constitute a complete sample, because they were targeted in order of right ascension. One additional OHM, characterized by lower OH luminosity (filled triangle in Fig. 1), has been included using an archival Chandra observation. It is worth noting that our OHMs lie at higher redshifts than most of the OHMs with X-ray detections in the literature (e.g. Arp 220 at $z = 0.018$, Mrk 231 at $z = 0.042$, etc.). On the basis of the merger/interaction scenario for OHMs discussed in Section 1, the present sample, with all of the seven OHMs being characterized by double nuclei and/or tidal tails (Darling et al., in preparation), can be considered representative of the OHM population overall. Furthermore, their IR colour ($\log (f_{100}/f_{60})$) distribution shows no significant evidence for

![Figure 1. Logarithm of the OH luminosity versus FIR luminosity (both in units of $L_\odot$) for the Arecibo OHM final sample (DG02b). The filled symbols indicate the OHMs with X-ray observations, while the filled triangle shows the X-ray detected OHM. The short-dashed lines indicate the permitted range of $L_{\text{FIR}}$ when the flux density at 100 $\mu$m is only available as an upper limit (see DG02b); in the case of OHMs with X-ray observations, both circles are filled. Note that all of the OHM galaxies have $L_{\text{FIR}}$ in the LIRG regime, with a significant fraction ($\approx 35$ per cent) being ULIRGs.](https://academic.oup.com/mnras/article-abstract/364/1/99/1155126/fig1)
Chandra of the seven OHM galaxies with galaxies (see Fig. 2). possibly related to a contribution from an active nucleus) or 'cold' any observational bias towards 'warm' (i.e. lower $f_{\alpha 0}$ values, possibly related to a contribution from an active nucleus) or 'cold' galaxies (see Fig. 2).

2.1 Notes on individual sources and optical spectra

In the following, we report on the OH line and optical properties of the seven OHM galaxies with Chandra observations. A detailed description of their optical spectra is presented in Darling et al. (in preparation).

(i) 01562+2528: this source shows the presence of two nuclei (one much brighter than the other) in the optical (with a separation of 6.3 arcsec, i.e. 17.9 kpc), suggestive of a multiple merger. The eastern component has a starburst classification, while for the western component there is not enough signal for a spectral classification (see Table 2 for references).

(ii) 02524+2046: this object has the most unusual spectrum of the Arecibo OHM survey, showing multiple strong narrow components in both OH lines. The optical morphology is elliptical-like with a single tidal tail (Darling et al., in preparation), while the optical spectrum is typical of a starburst galaxy.

(iii) 03521+0028: this source comprises a close pair; both components, separated by 1.3 arcsec (corresponding to 3.4 kpc), are visible in the Sloan Digital Sky Survey (SDSS) but not in the Digital Palomar Sky Survey. This object has been classified as a starburst according to the Infrared Space Observatory (ISO) spectrum (Lutz, Veilleux & Genzel 1999) and a low-ionization nuclear emission-line region (LINER) galaxy according to the optical spectrum (Nagar et al. 2003).

(iv) 08201+2801: the HST image shows two nuclei (with a separation of 1.1 arcsec, corresponding to 3.2 kpc), having a starburst classification, and a tidal tail, suggesting an advanced merger (DG01). The National Radio Astronomy Observations, (NRAO) Very Large Array (VLA) Sky Survey (NVSS) flux density reported in DG01 is associated with a source at a distance of $\approx 23$ arcsec. Nagar et al. (2003) reported a flux-density upper limit of 0.8 mJy at 15 GHz, roughly corresponding to a 1.4–15 GHz spectral slope of $\gtrsim 0.75$.

(v) 08279+0956: the optical image of this source (classified as a LINER) shows the presence of three tidal tails (Darling et al., in preparation).

(vi) 09531+1430: this galaxy is an interacting system whose components are blended in the images from the automatic plate measurement (APM) facility; the 2 Micron All Sky Survey position is on the western component (having a Seyfert 2 spectrum), while the Faint Images of the Radio Sky at Twenty centimetres survey (FIRST) position is on the eastern component (characterized by a starburst spectrum; Darling et al., in preparation).

(vii) 09531+1430: this galaxy is an interacting system whose components are blended in the images from the automatic plate measurement (APM) facility; the 2 Micron All Sky Survey position is on the western component (having a Seyfert 2 spectrum), while the Faint Images of the Radio Sky at Twenty centimetres survey (FIRST) position is on the eastern component (characterized by a starburst spectrum; Darling et al., in preparation).

Table 1. Chandra Cycle 4 and 5 observations of OH megamaser galaxies: observation log.

| Src. name       | IRAS FSC   | $z$    | $\omega_{2000}$ | $\delta_{2000}$ | X-ray obs. Date | Exp. time (ks) | Reference                  |
|-----------------|------------|--------|----------------|----------------|----------------|-----------------|---------------------------|
| 01562+2528      | 0028       | 0.1658 | 01:59:02:261    | +25:42:35:4     | 2003 Nov. 08-09 | 4.00           | (1)                      |
| 0028           | 02524      | 0.1815 | 02:55:17:09     | +20:58:56:5     | 2003 Nov. 08   | 4.31           | (1)                      |
| 0028           | 03521      | 0.1522 | 03:54:22:21     | +00:37:03:8     | 2002 Dec. 25   | 9.78           | (1)                      |
| 0028           | 08201      | 0.1680 | 08:23:12:62     | +27:51:39:6     | 2003 Nov. 20   | 4.41           | (2)                      |
| 0028           | 08279      | 0.2085 | 08:30:39:38     | +09:46:36:1     | 2004 Jan. 13   | 4.38           | (2)                      |
| 0028           | 09531      | 0.2151 | 09:55:50:11     | +14:16:07:9     | 2003 Dec. 09   | 4.03           | (2)                      |
| 0028           | 09539      | 0.1290 | 09:56:34:30     | +08:43:06:1     | 2004 Jan. 06   | 4.81           | (2)                      |

Notes: the optical positions have been derived from the Digital Palomar Sky Survey (POSS2) R-band images using 6xTRACTOR (Bertin & Arnouts 1996). References: (1) Darling & Giovanelli (2002a) (DG02a); (2) Darling & Giovanelli (2001) (DG01).

Figure 2. Logarithm of the OH luminosity (in units of $L_\odot$) versus IR colour ($\log f_{\alpha 0}/f_{\alpha 10}$) for the OHM galaxies from DG02b. Symbols are the same as in Fig. 1.

3 X-RAY OBSERVATIONS AND DATA REDUCTION

Six out of the seven OHMs presented here were targeted by Chandra during Cycle 5. IRAS FSC 03521+0028, found at the aim point of a Chandra archival observation, was observed in Cycle 4. This source was targeted in a Chandra programme aimed at observing a sample of ULIRGs (see Teng et al. 2005); we are confident that the inclusion of this object does not bias our ‘original’ sample in terms of AGN content (see Section 4). The observation log is shown in Table 1. All of the sources were observed with the Advanced CCD Imaging Spectrometer (ACIS; Garnine et al. 2003) with the S3 CCD at the aim point. Standard data reduction was adopted (see section 2 of Vignali et al. 2005 for a detailed description) using the Chandra
## Table 3. X-ray counts and full-band count rates.

| Source       | X-ray Counts | CR       |
|--------------|--------------|----------|
|              | (0.5–2 keV)  | (2–8 keV) | (0.5–8 keV) |
| 01562+2528   | <3.0         | <6.4     | <6.4*       | <1.60       |
| 02524+2046   | <4.8         | <4.8     | <6.4        | <1.49       |
| 03521+0028   | 3.0*         | <6.4     | 4.9*        | 0.50–0.35    |
| 08201+2801   | <3.0         | <3.0     | <3.0        | <0.68       |
| 08279+0956   | <6.4         | <3.0     | <6.4*       | <1.46       |
| 09531+1430   | <3.0         | <6.4     | <6.4        | <1.59       |
| 09539+0857   | <6.4         | <3.0     | <6.4        | <1.33       |

The two X-ray counts are contiguous. Errors on the X-ray counts were computed according to Gehrels (1986). The upper limits are at the 95 per cent confidence level and were computed according to Kraft, Burrows & Nousek (1991). For the sake of clarity, upper limits of 3.0, 4.8 and 6.4 indicate that 0, 1 and 2 X-ray counts, respectively, have been found within an extraction region of radius 2 arcsec centred on the position of the OHM source (considering the background within this source extraction region to be negligible). Count rates (CR) are in units of 10^{-3} count s^{-1}.

Interactive Analysis of Observations (CIAO) Version 3.2 software. Source detection was carried out with WAVDETECT (Freeman et al. 2002) using a false-positive probability threshold of 10^{-6}. We searched for Chandra sources within ≈0.8 arcsec of the optical position. IRAS FSC 03521+0028 is the only detected source (filled triangle in Fig. 1), with five counts in the observed 0.5–8 keV band; we note that this is also the source with the highest指望 energy by Chandra (see Table 1). Given the adopted threshold and the small number of pixels being searched due to the known source position, we decided to follow a more conservative approach and report these sources to the position of the OHM source (considering the background within this source extraction region to be negligible). Count limits of 3.0, 4.8 and 6.4 indicate that 0, 1 and 2 X-ray counts, respectively, have been found within an extraction region of radius 2 arcsec centred on the position of the OHM source (considering the background within this source extraction region to be negligible). Count rates (CR) are in units of 10^{-3} count s^{-1}.

Table 3 summarizes the X-ray photometric results in the soft band (0.5–2 keV), the hard band (2–8 keV) and the full band (0.5–8 keV) using circular apertures centred on the optical source position and an extraction radius of 2 arcsec. Although two X-ray photons falling in adjacent pixels can be considered in some circumstances a detection (given the low background level of Chandra observations; see, for example, Vignali et al. 2005), we prefer to follow a more conservative approach and report these sources in the present sample (see Table 3) as X-ray undetected.

The final catalogue of OHMs from the Arcobello survey (DG02b) was also cross-correlated with the ROSAT and XMM–Newton archives; we obtained no further X-ray detections. X-ray constraints from ROSAT observations (available for nine OHMs) are generally loose because of the large off-axis angles of the sources and the shallow exposures of the pointed Position Sensitive Proportional Counter (PSPC) and High Resolution Imager (HRI) observations; hence, these constraints will not be used in this paper. One OHM was targeted by XMM–Newton (IRAS FSC 13218+0552 at z = 0.205, with net exposures of 8.6–9.7 ks in the European Photon Imaging Camera (EPIC) Metal Oxide Semiconductor (MOS)/pn cameras) but only an upper limit, consistent with the values we obtained for our sources (see Section 4 and Table 2), was derived (Bianchi et al. 2005). Recently, it has been suggested that this source, characterized by an extremely red IR continuum (Low et al. 1989) and a blueshifted component in the [O iii] line (e.g. Zheng et al. 2002), might harbour a Compton-thick AGN (i.e. with $N_H > 10^{24}$ cm^{-2}), surrounded by...
a strong starburst (see section 4.4 and fig. 6 of Bianchi et al. 2005). We also note that IRAS FSC 13218+0552 has the warmest \( f_{\text{IR}} / f_{\text{X}} \) colour in Fig. 2 (i.e. it is the left-most object in the plot), suggestive of an AGN contribution at IR wavelengths.

4 WHAT ARE X-RAYS TELLING US ABOUT THE NATURE OF THE OH MEGAMASERS?

The broad-band properties of the OHM sample targeted by Chandra are reported in Table 2. Both the photon index and X-ray luminosity can provide constraints on the nature of the high-energy emission from OHM galaxies. However, such constraints, with the current data, are basic due to the low counting statistics. All of the X-ray sources have rest-frame 2–10 keV luminosities at most of \( \approx 10^{42} \text{ erg s}^{-1} \) (see Table 2), which is consistent with both star formation (e.g. Zezas, Alonso-Herrero & Ward 2001; Alexander et al. 2002) and low-luminosity active galactic nuclei (LLAGN) activity (e.g. Terashima et al. 2002; Terashima & Wilson 2003). The possibility that the observed X-ray emission is largely due to star formation finds support from Fig. 3, where the FIR luminosity is plotted versus the 0.5–8 keV luminosity. Our sources are located in the left-most part of the diagram, where either starbursts (e.g. Arp 220) or starburst-dominated (i.e. with little apparent contribution from the AGN to the bolometric emission; see Alexander et al. 2005a) sub-mm sources typically lie. However, some X-ray obscured AGN whose broad-band emission is dominated by star formation are also present in this region; a fraction of these sources are lower redshift OHM sources (e.g. Mrk 273 and UGC 5101); the possibility that our sources could contain absorbed AGN will be discussed in detail using X-ray stacking analysis (see Section 4.1).

Optical/near-infrared (NIR) spectroscopy (see Section 2.1) indicates that 50 per cent of our sources show the typical signatures of starburst galaxies, 25 per cent have a LINER classification and 25 per cent a Seyfert 2 classification (according to the classification reported in Darling et al. (in preparation); see also column (16) in Table 2); IRAS FSC 09531+1430 is counted twice because both nuclei were spectroscopically identified (see Darling et al., in preparation). However, we note that the optical classification of these sources is difficult: when more than one nucleus is present, unless the projected physical separation of the nuclei is larger than the resolution of the spectrograph, optical spectra will be a blend of nuclei, dominated by the optically dominant (i.e. the least obscured and/or most optically luminous in emission lines) nucleus. However, OHMs seem to favour the dustiest environments and may select the optically ‘subordinate’ nucleus. Therefore, there may be little correlation between OHM properties and optical spectral type. Furthermore, we note that optical and NIR studies are sometimes not adequate to unveil the engine of the X-ray emission. An emblematic, though perhaps extreme, case of different classification at different wavelengths is provided by the ULIRG NGC 6240, which is classified as a starburst in the NIR (Genzel et al. 1998), a LINER in the optical (Veilleux et al. 1995) and a Compton-thick AGN in the hard X-ray band (Vignati et al. 1999; also see Komossa et al. 2003). Some further cases similar to that of NGC 6240 are presented by Maiolino et al. (2003).

Finally, it is interesting to note that the X-ray luminosity and the X-ray-to-FIR luminosity ratio of the only X-ray detected OHM in the present sample do not appear to be different from those of the other sources; given the number of observed counts (see Table 3), the detection of this source has been possible because of the exposure time, which is double that of the other OHMs.

4.1 X-ray stacking analysis

We can place tighter constraints on the average X-ray properties of the OHMs under investigation by ‘stacking’ their counts. Our sources have \( 8.2 \pm 0.8 \) counts in the 0.5–2 keV band and \( 7.3 \pm 0.6 \) counts in the 2–8 keV band. Monte Carlo simulations in regions close to our targets (see Vignali et al. 2005 for details about the adopted procedure) indicate that the background in all of the seven fields does not contribute more than 0.14 and 0.31 counts in the soft and hard bands, respectively; therefore, we are confident we obtain secure detections in both bands by stacking the counts from the seven OHMs.\(^2\) The ratio of the observed hard- versus soft-band source counts (0.85\(^{+0.65}_{-0.43}\)) suggests that our sources have, on average, a photon index flatter (\( \approx 0.7^{+0.8}_{-0.3} \)) than \( \Gamma = 1.8 \pm 2.1 \), which is typically used for AGN and starburst galaxies at hard X-ray energies (e.g. Ptak et al. 2003).
1043 erg s\(^{-1}\) by Compton-thick absorption (e.g. Mrk 231, Gallagher et al. 2002; Braito et al. 2004; Gallagher et al. 2005; UGC 5101, Maiolino et al. 2003).

Although the presence of obscuration is uncertain and needs to be confirmed by deeper observations with Chandra for an extended sample of OHMs and, possibly, with XMM–Newton for the most ‘promising’ sources, the column density allowed by the current data is consistent with the X-ray absorption observed in many H\(_2\)O megamasers. However, these sources are mostly associated with X-ray bright (\(\approx 10^{42}\) erg s\(^{-1}\)) and obscured (\(N_{\text{HI}} \gtrsim 10^{22} \text{cm}^{-2}\)) Seyfert 2 galaxies (e.g. Maloney 2002; Braatz et al. 2003), where the amplifying water vapour molecules are most likely pumped by collisional processes resulting from X-ray heating in parsec-scale molecular tori with densities of \(\approx 10^{-8} \text{ cm}^{-3}\) (e.g. Neufeld, Maloney & Conger 1994). Column densities of \(\approx 10^{22} \text{cm}^{-2}\) are not uncommon in local (U)LIRGs (e.g. Risaliti et al. 2000) and LLAGN (e.g. Terashima et al. 2002; Terashima & Wilson 2003). Given the presence of double nuclei and/or indications of past mergers in the OHMs of our sample, it is possible that the starburst itself can produce the obscuration, as suggested by some authors (e.g. Fabian et al. 1998; Ohsuga & Umemura 2001; Wada & Norman 2002).

4.2 X-ray observations of ‘bona fide’ OHMs from the literature

We obtained further constraints on the X-ray emission from OHM galaxies using the sample of 54 ‘bona fide’ OH masers (both kilo-masers and megamasers) from the literature (mostly from Baan et al. 1998), listed in tables 7 and 8 of DG02a. We caution the reader against overinterpretation of the results we present in this section: this sample is not well defined, lacks either published OH spectra or measurements of the 1667-MHz OH line in about 50 per cent of the cases and includes some suspect OH detections, as pointed out by DG02a.

24 OH masers have accessible pointed X-ray observations in the ROSAT, Chandra and XMM–Newton archives (for one additional source, the XMM–Newton data are not public yet); all of these galaxies are OHMs. 17 sources are X-ray detected; the high detection rate (\(\approx 70\) per cent) is due to the fact that most of these sources were targeted by the sensitive X-ray instruments on-board Chandra and XMM–Newton, while the X-ray non-detections are mostly due to ROSAT observations where the sources are located at large off-axis angles. For most of the sources with sensitive observations, X-ray information is available from published work (Gallagher et al. 2002; Xia et al. 2002; Franceschini et al. 2003, hereafter F03; Maiolino et al. 2003; Ptak et al. 2003; Ballo et al. 2004; Braito et al. 2004; Imansish & Terashima 2004; Satyapal, Sambruna & Dudi 2004; Gallagher et al. 2005; Iwasawa et al. 2005); for a couple of sources, Chandra data have been retrieved from the archive and analysed using standard procedures.

We find that AGN emission (with intrinsic X-ray luminosities above \(\approx 10^{42}\) erg s\(^{-1}\)) is present in eight OHMs. Four of these OHMs are likely characterized by Compton-thick absorption (UGC 05101, Maiolino et al. 2003; NGC 3690 in the galaxy pair Arp 299 system, Della Ceca et al. 2002; Ballo et al. 2004; NGC 4418, Maiolino et al. 2003; Mrk 231, Gallagher et al. 2002; Braito et al. 2004; Gallagher et al. 2005). However, Compton-thick absorption cannot be ruled out in some low signal-to-noise ratio sources and in Arp 220 (Iwasawa et al. 2001, 2005).

To provide a more appropriate comparison with our Chandra targets, from the subsample of literature OHMs with X-ray coverage, we selected those within the same redshift interval, the same \(L_{\text{X}}\) range, or the same \(L_{\text{X}}\) range as our seven OHMs observed by Chandra. The paucity of objects in the same redshift range (two, with only one X-ray detection) does not allow for any reasonable comparison with our sample; however, it highlights the relevance of the present work, where the redshift range of OHMs with X-ray constraints has been extended significantly. If we select the literature OHMs using the same interval of OH or FIR luminosities as our targets, we find a larger number of objects (12 and nine, respectively). AGN emission is clearly present in three objects (one Compton thick, Mrk 231, and the other two Compton thin, Mrk 273 and PKS B1345+145), corresponding to \(\approx 25–33\) per cent of the chosen subsamples. LLAGN could still be present in some of the remaining sources, although the X-ray emission from these objects can be well explained by a thermal gaseous component from a starburst plus a hard, moderately absorbed power-law component due to the unresolved binary population (e.g. F03; Teng et al. 2005).

As a further test, we compared the X-ray spectral results for our seven OHMs (see Section 4.1) with those obtained by F03 with XMM–Newton for their five ‘bona fide’ lower redshift OHMs without a dominant AGN component (i.e. excluding Mrk 231). We found that our stacked spectrum is generally harder than the X-ray spectra of the F03 OHMs. This result can be ascribed to the different spatial resolutions of the Chandra ACIS and XMM–Newton EPIC cameras and different source-extraction regions. To test this possibility, we used a sample of three starburst galaxies observed by Chandra (Ptak et al. 2003) and XMM–Newton (F03). The soft thermal component appears spatially more extended than the hard component, i.e. it likely provides a stronger contribution to the broad-band X-ray spectrum if large source-extraction regions are chosen (as in the case of XMM–Newton spectra, extracted from circular regions of radius 20 arcsec). Motivated by these considerations, we
rescaled the source-extraction regions of our OHMs to match those adopted by F03 (taking into account the different redshift range of the two samples), obtaining a somewhat softer X-ray spectrum ($\Gamma \approx 1.6 \pm 0.3$), consistent with F03 results.

In light of the results obtained from the study of the literature OHMs and keeping in mind all the caveats described above, starburst emission with moderate absorption probably within the binary population is likely to explain the average X-ray properties of our seven OHMs (Section 4.1).

5 SUMMARY

We have analysed Chandra snapshot observations for a sample of seven galaxies selected from the Arecibo OHM survey at $z \approx 0.13–0.22$ and with FIR luminosities in excess of $10^{11} L_{\odot}$. The principal results of this work are as follows:

(i) All of the observed sources are X-ray weak; only one OHM, IRAS FSC 03521+0028 ($z = 0.15$), was detected by Chandra, with five counts in the 0.5–8 keV band.

(ii) The X-ray emission is consistent with that from star formation (as also suggested by the comparison with most of the literature OHMs with X-ray constraints) and LLAGN; however, if an AGN is present, its contribution to the broad-band emission of OHM galaxies is probably modest.

(iii) Under reasonable assumptions about the intrinsic X-ray spectral shape, the observed count distribution from stacking analysis suggests absorption of $\approx 10^{22}$ cm$^{-2}$.

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