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The saturation states of compact and diffuse components of OH megamaser galaxies

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Abstract. A sample of 9 OH megamaser galaxies detected in the soft X-ray domain was compiled. Using available OH and X-ray data a striking correlation was found between the X-ray luminosity and the width of the OH line. This correlation may indicate that the X-ray heating of a molecular gas may increase the collisional excitation of the maser emission. However, this result should be considered as a tentative one because of the insufficient number of galaxies. An analysis of the saturation states of compact and diffuse components of OH emission was performed. The results of the analysis support the assumption that both the compact and diffuse OH maser emissions in the megamaser galaxies are saturated. The diffuse component might show unsaturated masing under certain conditions, such as the appropriate relation between the intensities of compact and diffuse components and a relevant number of the IR photons to pump the maser emission.

Key words. masers – galaxies: general – X-rays: galaxies

1. Introduction

The OH megamasers are found among powerful infrared galaxies. Nearly 110 OH megamaser galaxies have been discovered (e.g. Martin 1989; Martin et al. 1989; Kandalyan 1996 and references therein; Baan et al. 1998; Darling & Giovanelli 2000, 2001, 2002a; Kent et al. 2002). The megamaser emission has been interpreted as a low-gain, unsaturated amplification of the nuclear radio continuum by the extended molecular cloud (e.g. Bann & Haschick 1984). As a pumping source, the powerful infrared radiation was suggested. This scenario was derived from the observed quadratic relation between the OH and FIR luminosities (Martin et al. 1988; Bann 1989). However, recently, Lonsdale et al. (1998), Diamond et al. (1999) and Darling & Giovanelli (2002a) have suggested that the unsaturated low-gain and IR-pumping model may explain the OH emission of the diffuse component. The collisional pumping and saturated amplification may account for the OH emission of the compact component (Kandalyan 1999; Diamond et al. 1999; Darling 2002).

The analysis of the OH $\sim$ FIR luminosity-luminosity relation showed that the slope is close to linear (Kandalyan 1996; Darling & Giovanelli 2002a; Zhi-yao 2003). However, Zhi-yao (2003) used many upper limits of the IRAS data points (for example, IRAS 21077+3358, 22116+0437 etc.) as the actual detections, and it is not indicated what formula was used in the calculations of the FIR luminosity. A linear dependence indicates the saturation of the compact OH component, although the extended component might have an unsaturated masing. Furthermore, the global VLBI observations of the megamaser galaxies (III Zw 35: Trotter et al. 1997; Diamond et al. 1999 and Pihlstrom et al. 2001; Arp 220: Lonsdale et al. 1998 and Rovilos et al. 2003; IRAS 17208-0014: Diamond et al. 1999; Mkn 273: Yates et al. 2000; Mkn 231: Richards et al. 2003) showed that the continuum emission is not associated with the OH masers (except Mkn 273, Yates et al. 2000, and perhaps, Arp 220, Rovilos et al. 2003), which indicates that megamasers have a high amplification factor (>100). The VLBI results of these galaxies suggest a dual component structure of the maser cloud: a diffuse component, that fits the low-gain unsaturated amplification model (quadratic relationship) and a compact component, produced by saturated masers in compact masing clouds (linear relationship). Pihlstrom et al. (2001) argued that the observed compact and diffuse components in III Zw 35 lie in a ring of 22 kpc radius. The compact and diffuse masers appear to be different because of the geometry of the ring and the path length effects. It is argued that in III Zw 35 the OH emission is an unsaturated low-gain maser.

The OH line observations of IRAS 21272+2514 have revealed the first variable megamaser galaxy (Darling & Giovanelli 2002b). The observed variability is partly due to the interstellar scintillation. There is evidence that

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IRAS 21272+2514 is composed of both the extended and compact components.

Thanks to the Arecibo Observatory OH megamaser survey (Darling & Giovanelli 2000, 2001, 2002a), the number of the known megamasers has doubled compared to that in 1996 (Kandalyan 1996). Our previous analysis of the OH ∼ FIR luminosity-luminosity relation of megamaser galaxies was based on a sample of 49 galaxies (Kandalyan 1996). Darling & Giovanelli (2002a) analyzed the OH ∼ FIR luminosity-luminosity relation using a sample of 95 megamasers, while Zhi-yao's (2003) analysis was based on a sample of 67 galaxies. Kandalyan (1999) argued that in the OH megamasers the collisional pumping and saturated amplification provide the unit slope of the OH ∼ FIR relation. The possible causes which may deviate the slope from unity are discussed by Kandalyan (1999). Several OH megamasers have been recently observed both in the OH line and radio continuum with the VLBI technique (Yates et al. 2000; Pihlstrom et al. 2001; Richards et al. 2003; Rovilos et al. 2003). The new VLBI observations, as well as the derived luminosity function (Darling & Giovanelli 2002c) and optical observations (Baan et al. 1998; Darling 2002) of megamasers have enlarged our knowledge in this field.

It is not clear whether the unsaturated low-gain and IR-pumping model may explain the OH emission of all diffuse components in megamaser galaxies. It cannot be ruled out that the collisional pumping and saturated amplification may account for the OH emission of both compact and diffuse components.

Both starburst and monsters can produce IR, X-ray and radio emission. Both energy sources may be present in the same galaxy, however quantitative data are needed to decide which is energetically dominant (Smith et al. 1998). According to Smith et al. (1998) a starburst can explain the bolometric luminosity of Arp 220. The hard X-ray sources in the nuclei of Arp 220 (Clements et al. 2002) and Mkn 273 (Xia et al. 2002) suggest that there is an active nucleus in these galaxies. Neufeld et al. (1994) have modelled the physical conditions present within dense circumnuclear gas, which is irradiated by X-ray emission from an active galactic nucleus, and it is argued that the X-ray heating may give rise to a collisional excitation of masers within a warm dusty medium. Therefore, if we suggest that the collisions may pump the OH maser levels, then observationally, the mechanism might be discriminated by searching for a correlation between the maser line parameters (both intensity and line width) and X-ray emission.

The investigation of the global properties of megamaser galaxies is important in setting up the correct conditions for these galaxies. In this work, we discuss the global properties of the OH megamasers, particularly the saturation states of compact and diffuse components and the possibility of the collisional excitation of megamasers by searching for a correlation between the maser line parameters and X-ray luminosity.

In Sect. 2, we describe the sample of 9 OH megamasers detected in the soft X-ray and the results of a regression analysis as well as the saturation states of compact and diffuse components. The results obtained are discussed in the final section.

2. Results

2.1. A sample of OH megamaser galaxies detected in the soft X-ray

In order to investigate the X-ray properties of OH megamaser galaxies, we have extracted from the literature all the megamasers detected in the soft X-ray (0.1–2.4 keV). There are 9 OH megamaser galaxies that have been observed with the ROSAT satellite in the soft X-ray (Rigopoulou et al. 1996; Wang et al. 1996; Bauer et al. 2000). The X-ray flux densities for IRAS 00509+1225 (Wang et al. 1996) and IRAS 12112+0305 (Bauer et al. 2000) have been converted from the (0.1–2.4 keV) band to the 1 keV (Schmidt & Green 1986). The X-ray flux densities at 1 keV for the remaining 7 galaxies have been taken from Rigopoulou et al. (1996). The IRAS 12112+0305, IRAS 15250+3609 and IRAS 22491-1808 galaxies have marginal detections in the soft X-ray at 2.5σ, 2σ and 2.5σ levels, respectively (Rigopoulou et al. 1996).

The relation between the observed flux density and luminosity is given by Schmidt & Green (1986) as: $L(E_1, E_2) = 4\pi C(z) A^2(z) F(E_1, E_2)$ for an energy band E_1 to E_2, where $C(z)$ is the K-correction term, $A(z)$ is the luminosity distance term, $F(E_1, E_2)$ is the observed flux density, and z is a red shift. For the power-law spectra with the energy index α and Friedman cosmology with the Hubble constant $H_o = 75$ km s^{-1} Mpc^{-1} and $q_o = 0.5$ the K-correction term $C(z)$ and the luminosity distance term $A(z)$ are given by $C(z) = (1+z)^{-(1+\alpha)}$, $A(z) = 2(c/H_o)[(1+z) - (1+z)^{0.5}]$.

The integrated OH flux density is approximated by the product of the peak flux density and the rest frame width of the line.

In our calculations we accept the following values of α: −0.5 (FIR band) (Rigopoulou et al. 1996; Boller et al. 1998), −0.7 (radio continuum) (Smith et al. 1998) and −1.3 (X-ray) (Boller et al. 1998).

The FIR and red shift data have been extracted from the NED[1] databases. The radio continuum data at 1.4 GHz are selected from the VLA-A observations of these galaxies (Kandalyan et al. 2003) except for IRAS 00509+1225 (Condon et al. 1998).

The above formulae have been used to calculate the corresponding monochromatic luminosity (L_{60}, $L_{\rm OH}$, $L_{1.4}$ and $L_{\rm X}$). Table 1 presents the list of 9 megamaser galaxies and is arranged as follows:

Column 1: IRAS name of galaxy.
Column 2: Red shift.
Column 3: Logarithm of the FIR luminosity L_{60}, at 60 micron, in erg s^{-1} Hz^{-1}.
Column 4: Logarithm of the OH luminosity $L_{\rm OH}$, in solar units.
Column 5: Logarithm of the radio continuum luminosity $L_{1.4}$ at 1.4 GHz, in erg s^{-1} Hz^{-1}.
Column 6: Logarithm of the X-ray luminosity $L_{\rm X}$, at 1 keV, in erg s^{-1} Hz^{-1}. Column 7: OH line width W in the rest frame, in km s^{-1}, at half of the peak intensity.

[1] The NASA-IPAC Extra-galactic Database (NED) which is operated by the Jet Propulsion Laboratory, Caltech under contract with the National Aeronautics and Space Administration (USA).

Table 1. Sample of 9 megamaser galaxies detected in the soft X-ray.

IRAS	z	L_{60}	L_{OH}	$L_{1.4}$	L_X	W	
		erg s^{-1} Hz^{-1}	$L_\odot$	erg s^{-1} Hz^{-1}	erg s^{-1} Hz^{-1}	km s^{-1}	Ref.
00509+1225	0.061	32.20	2.26	29.80	25.23	410	1
09320+6134	0.039	32.53	1.77	30.62	23.55	120	1, 2
11257+5850	0.010	32.33	1.17	29.83	23.76	246	1, 2
12112+0305	0.073	32.94	3.05	30.39	≤24.00	280	1, 2
12540+5708	0.042	33.04	2.83	30.94	24.03	290	1, 2
13428+5608	0.038	32.77	2.57	30.52	23.42	141	1, 2
15250+3609	0.055	32.63	2.51	29.91	≤23.65	100	1, 2
15327+2340	0.018	32.81	2.48	30.30	23.46	117	1, 2
22491–1808	0.077	32.79	2.43	29.66	≤23.82	171	1, 2

1. Martin 1989; 2. Martin et al. 1989.

Table 2. The correlation coefficient (r) and probability (p) derived for a sample of 8 megamasers.

	$\log L_{60}$	$\log L_{OH}$	$\log L_{1.4}$	$\log W$
$\log L_X$	$r = 0.41$	$r = 0.30$	$r = 0.07$	$r = 0.82$
	$p = 0.31$	$p = 0.47$	$p = 0.86$	$p = 0.01$

Column 8: References for the OH line data. The priority has been given to those articles where both the OH line intensity and line width were presented.

The IRAS 00509+1225 (1Zw 1) is a prototype of the Narrow-Line Seyfert 1 galaxies (NLSy1). Most of NLSy1 galaxies show rapid X-ray variability (Boller et al. 1996), including 1Zw 1 (e.g. Turner et al. 1999). Moreover, among 9 megamasers 1Zw 1 is the most X-ray luminous object and significantly deviates in its luminosity from the rest of the sample (Table 1). For this reason, we did not include 1Zw 1 in our statistics (Table 2). The correlation coefficients (r) between L_X and L_{60}; L_X and L_{OH}; L_X and $L_{1.4}$; L_X and W are presented in Table 2, where the X-ray detection levels of IRAS 12112+0305(2.5σ), IRAS 15250+3609(2σ) and IRAS 22491-1808(2.5σ) have been treated as the actual detections. The probability (p) that there is no correlation between the two variables is indicated. The least square fit of the OH line width and X-ray luminosity data is:

$$\log W = (0.65 \pm 0.18) \log L_X - (13.10 \pm 4.28). \quad (1)$$

If X-ray detected galaxies only are included in the regression analysis, the result of the least square fit is almost the same $\log W = (0.66 \pm 0.17) \log L_X - (13.35 \pm 4.08)$ ($r = 0.91$, $p = 0.03$, $N = 5$). Figure 1 shows the relationship between the OH line width and X-ray luminosity for 8 megamasers. The correlation coefficient between $\log L_X$ and $\log W$ is 0.81 ($p = 0.01$) for the whole sample of magamasers, including 1Zw 1. From Table 2 and Fig. 1, one can see that there is a tight correlation between L_X and W. The X-ray heating of a molecular gas may give rise to the collosional excitation of masers within a warm dusty medium (Neufeld et al. 1994).

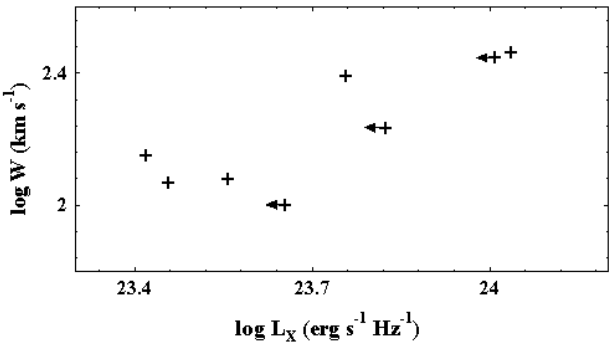

Fig. 1. The OH line width and X-ray luminosity relation.

The X-ray luminosity does not correlate either with the FIR, OH or radio continuum luminosity (Table 2). It is very difficult to understand the absence of correlation between L_X and L_{OH}. In fact, if we believe that the X-ray heating of a molecular gas may give rise to the collosional excitation of maser emission, we expect to observe a positive correlation between L_X and L_{OH}. Perhaps the OH line broadening due to collisions is more sensitive to X-ray emission than the maser product. However, these results should be considered as tentative because of the insufficient number of galaxies. It will be reasonable to check the X-ray and megamaser relation based on a statistically significant sample.

2.2. The compact and diffuse components of OH emission

The VLBI observations of megamaser galaxies in the OH line clearly reveal a dual structure of the OH line emission: a compact component, which accounts for the 20%–65% of the 1667 MHz flux density and a diffuse component. The compact component is not associated with a radio continuum emission. The lack of any background continuum and a linear relationship between L_{OH} and L_{FIR} strongly suggest that the compact maser is saturated. However, it was assumed (Lonsdale et al. 1998; Diamond et al. 1999; Darling & Giovanelli 2002a) that the unsaturated and FIR pumping model may explain the diffuse OH emission.

The analysis of the OH ∼ FIR luminosity-luminosity relation showed that the slope is close to linear ($S = 1.38 \pm 0.14$, Kandalyan 1996; $S = 1.2 \pm 0.1$, Darling & Giovanelli 2002a; $S = 1.41 \pm 0.11$, Zhi-yao 2003, here many upper limits of the IRAS data points are treated as the actual detections). Note that the listed slopes have been corrected for the Malmquist bias. In subsequent analysis we will use the value $S = 1.2 \pm 0.1$ (Darling & Giovanelli 2002a) for two reasons: (a) Darling & Giovanelli (2002a) have derived this value based on a sample of 95 megamasers, which is currently the largest published one; (b) Darling & Giovanelli (2002a) have converted all data to a single cosmology.

Kandalyan (1999) argued that in the OH megamasers the collisional pumping and saturated amplification provide the unit slope of the OH ∼ FIR relation. The possible causes which may deviate the slope from unity are discussed by Kandalyan (1999). In particular, a part of the FIR emission in megamasers which is unrelated to either AGN or starburst will increase the slope. Therefore we believe that the real slope of the OH ∼ FIR relation is 1. Since the statistically derived and theoretically predicted values of S are almost identical, the $S = 1$ value can be applied to individual galaxy for both qualitative and quantitative assessments. Nevertheless in subsequent analysis the value $S = 1.2 \pm 0.1$ (Darling & Giovanelli 2002a) is used. In addition, the statistical value of the slope for each individual galaxy is in the range of (1.1–1.3), and the allowed S values will not change our calculations significantly. In the following discussion, we will analyze the possible effects, which may be responsible for the maser emission of compact and diffuse components.

In general, the observed luminosity from galaxies is a result of superposition of individual components in the beam area of the telescope. Suppose that the observed OH luminosity is $L_{\rm OH} = L^{\rm c}_{\rm OH} + L^{\rm d}_{\rm OH}$, $L^{\rm c}_{\rm OH} = \sum_i L^{\rm c}_{{\rm OH}i}$, $L^{\rm d}_{\rm OH} = \sum_i L^{\rm d}_{{\rm OH}i}$, where $L^{\rm c}_{{\rm OH}i}$ and $L^{\rm d}_{{\rm OH}i}$ are the ith terms of the compact and diffuse OH components, respectively. The FIR emission in galaxies is predominantly thermal (e.g. Sanders & Mirabel 1996), therefore any compact-nonthermal emission can be neglected, namely $L^{\rm c}_{\rm FIR} << L^{\rm d}_{\rm FIR} = L_{\rm FIR}$. Although the FIR emission may consist of a number of diffuse components, it is assumed, however, that the FIR emission is associated with a common diffuse component and the maser sources are embedded in this FIR radiation field, without separating the FIR emission on many components (see further discussion).

The slope of the relationship between $L_{\rm OH}$ and $L_{\rm FIR}$ is given by

$$S = \frac{{\rm d}\log\left(L^{\rm c}_{\rm OH} + L^{\rm d}_{\rm OH}\right)}{{\rm d}\log L_{\rm FIR}} = S^{\rm c}\frac{L^{\rm c}_{\rm OH}}{L_{\rm OH}} + S^{\rm d}\frac{L^{\rm d}_{\rm OH}}{L_{\rm OH}}, \quad (2)$$

where

$$S^{\rm c} = \frac{{\rm d}\log L^{\rm c}_{\rm OH}}{{\rm d}\log L_{\rm FIR}} = \frac{1}{L^{\rm c}_{\rm OH}}\sum_i \left(S^{\rm c}_i L^{\rm c}_{{\rm OH}i}\right), \quad (3)$$

$$S^{\rm d} = \frac{{\rm d}\log L^{\rm d}_{\rm OH}}{{\rm d}\log L_{\rm FIR}} = \frac{1}{L^{\rm d}_{\rm OH}}\sum_i \left(S^{\rm d}_i L^{\rm d}_{{\rm OH}i}\right), \quad (4)$$

and $S^{\rm c}_i = \frac{{\rm d}\log L^{\rm c}_{{\rm OH}i}}{{\rm d}\log L_{\rm FIR}}$, $S^{\rm d}_i = \frac{{\rm d}\log L^{\rm d}_{{\rm OH}i}}{{\rm d}\log L_{\rm FIR}}$. The quantities $S^{\rm c}_i > 0$ and $S^{\rm d}_i > 0$ are the slopes of the $L^{\rm c}_{{\rm OH}i} \sim L_{\rm FIR}$ and $L^{\rm d}_{{\rm OH}i} \sim L_{\rm FIR}$ relationships for the ith terms of the compact and diffuse components, respectively. The $S^{\rm c}$ and $S^{\rm d}$ are the total slopes of compact and diffuse components, respectively.

From Eq. (2) and $L_{\rm OH} = L^{\rm c}_{\rm OH} + L^{\rm d}_{\rm OH}$ it follows that $S^{\rm c} = S^{\rm d} = S$, assuming that $L^{\rm c}_{\rm OH}$ and $L^{\rm d}_{\rm OH}$ are independent variables. It is a valid assumption because, on the one hand, the maser emission is a cluster of individual maser spots, and, on the other hand, it is believed that the compact and diffuse components have different saturation states. In addition, there is no observational evidence that the maser emissions of compact and diffuse components are correlated.

Let us discuss the case $S^{\rm d} = S$. It can be seen (Eq. (4)) that the nth term of the diffuse component is able to have a low-gain unsaturated masing if

$$S^{\rm d}_n = \frac{S^{\rm d}L^{\rm d}_{\rm OH} - \sum_{i=1}^{n-1}\left(S^{\rm d}_i L^{\rm d}_{{\rm OH}i}\right)}{L^{\rm d}_{{\rm OH}n}} = 2 \quad (5)$$

where $L^{\rm d}_{{\rm OH}n}$ is the OH luminosity of the nth cloud, and $n > 1$, because when $n = 1$, $L^{\rm d}_{\rm OH} = L^{\rm d}_{\rm OH1}$ and $S^{\rm d}_1 = S^{\rm d} < 2$. Meanwhile some of the diffuse clouds will have $S^{\rm d}_i < 2$. The same analysis can be applied to the compact components of OH emission ($S^{\rm c}_n = 2$).

It can be seen (Eqs. (2)–(4)) that

$$\sum_i \left(S^{\rm c}_i - S\right) L^{\rm c}_{{\rm OH}i} = \sum_i \left(S - S^{\rm d}_i\right) L^{\rm d}_{{\rm OH}i}, \quad (6)$$

therefore it is possible theoretically that $S^{\rm c}_i = S^{\rm d}_i = S < 2$ for all i, which means that none of the compact and diffuse components are able to have a low-gain unsaturated masing.

Pihlstrom et al. (2001) have measured two compact and two diffuse components of OH emission in III Zw 35. Following Pihlstrom et al. (2001) let us assume that one of the diffuse components (suppose the Northern component) is a low-gain unsaturated maser. Then the slope of the Southern diffuse component is ∼0.77, according to our analysis (Eq. (4) and $S^{\rm d} = 1.2$).

It should be noted that the main results of our analysis do not depend on whether the FIR emission is associated with one or a number of diffuse components, because the individual diffuse components in the FIR band are mutually independent, i.e. ${\rm d}L_{{\rm FIR}i}/{\rm d}L_{{\rm FIR}j} = 0$, $i \neq j$. In other words, any variation in one of them will not stimulate the corresponding variation of the other. In this case, for instance, $S^{\rm d} = \frac{L_{\rm FIR}}{L^{\rm d}_{\rm OH}}\sum_i (S^{\rm d}_i L^{\rm d}_{{\rm OH}i}/L_{{\rm FIR}i}) = S$, where $S^{\rm d}_i = \frac{{\rm d}\log L^{\rm d}_{{\rm OH}i}}{{\rm d}\log L_{{\rm FIR}i}}$, and Eq. (2) will have the same form, however with a different $S^{\rm c}$ and $S^{\rm d}$.

It is believed that the collisional pumping and saturated amplification may be responsible for the compact component of the maser emission (Kandalyan 1999; Diamond et al. 1999; Darling 2002; Rovilos et al. 2003). Therefore it can be assumed that $L^{\rm c}_{\rm OH}$ does not depend on $L_{\rm FIR}$, i.e. ${\rm d}L^{\rm c}_{\rm OH}/{\rm d}L_{\rm FIR} = 0$ and $S^{\rm c} = 0$ ($S^{\rm c}_i = 0$ for all i). In this case, the total slope of the diffuse component is $S^{\rm d} = \frac{S L_{\rm OH}}{L^{\rm d}_{\rm OH}} > 1$ (Eq. (2)) and $S^{\rm d} > S$.

On the other hand $\sum_i (S_i^{\rm d} L_{\rm OH\it i}^{\rm d}) = S L_{\rm OH}$, hence, the nth term of the diffuse component is able to have a low-gain unsaturated emission if

$$S_n^{\rm d} = \frac{S L_{\rm OH} - \sum_{i=1}^{n-1} \left(S_i^{\rm d} L_{\rm OH\it i}^{\rm d} \right)}{L_{\rm OH\it n}^{\rm d}} = 2. \quad (7)$$

If $i = 1$ (there are compact and diffuse components, $S_1^{\rm c} = 0$) $S_1^{\rm d} = S(1 + \frac{L_{\rm OH1}^{\rm c}}{L_{\rm OH1}^{\rm d}})$ and when $L_{\rm OH1}^{\rm c} \approx L_{\rm OH1}^{\rm d}$, then $S_1^{\rm d} \approx 2S$. There is a simple explanation, namely, a diffuse component may amplify the compact saturated maser emission. In particular, if the compact component of the OH emission is embedded in a diffuse region (recall that usually the maser emission is a cluster of individual maser spots) then a part of the radiation can be amplified by a diffuse component (the so-called self-amplification).

If $i = 2$ (there are two compact and two diffuse components, $S_1^{\rm c} = S_2^{\rm c} = 0$), then $S(L_{\rm OH1}^{\rm c} + L_{\rm OH2}^{\rm c}) = (S_1^{\rm d} - S)L_{\rm OH1}^{\rm d} + (S_2^{\rm d} - S)L_{\rm OH2}^{\rm d}$. Let us consider two cases: (a) $S_1^{\rm d} = S_2^{\rm d} = 2$, then $L_{\rm OH1}^{\rm c} + L_{\rm OH2}^{\rm c} \approx 0.7(L_{\rm OH1}^{\rm d} + L_{\rm OH2}^{\rm d})$ ($S = 1.2$). In III Zw 35 the $(L_{\rm OH1}^{\rm c} + L_{\rm OH2}^{\rm c})/(L_{\rm OH1}^{\rm d} + L_{\rm OH2}^{\rm d})$ ratio is ~0.4 in both the 1667- and 1665-MHz lines (Pihlstrom et al. 2001), therefore the diffuse components do not have a low-gain unsaturated masing. However, if we accept $S = 1.4$ (2σ range for S) the observed and estimated values of the $(L_{\rm OH1}^{\rm c} + L_{\rm OH2}^{\rm c})/(L_{\rm OH1}^{\rm d} + L_{\rm OH2}^{\rm d})$ ratio are similar, hence both diffuse components might have a low-gain unsaturated emission in III Zw 35. (b) $S_1^{\rm d} = 2$ and $S = 1.2$ (or 1.4), then $S_2^{\rm d} = \frac{S(L_{\rm OH1}^{\rm c} + L_{\rm OH2}^{\rm c} + L_{\rm OH1}^{\rm d} + L_{\rm OH2}^{\rm d}) - S_1^{\rm d} L_{\rm OH1}^{\rm d}}{L_{\rm OH2}^{\rm d}}$ and $1 < S_2^{\rm d} < 2$ in both lines for III Zw 35 .

Therefore we can conclude that only under specific circumstances may the unsaturated low-gain and IR-pumping model explain the OH emission of diffuse component. However, the majority of diffuse components are probably saturated masers, which may be pumped by a combination of the collisional and radiative processes.

One can suggest that OH megamasers have either a compact ($L_{\rm OH}^{\rm d} = 0$) or diffuse ($L_{\rm OH}^{\rm c} = 0$) component. In this case either $S^{\rm c} = S$ (see further discussion) or $S^{\rm d} = S$, and some diffuse components could be powered by an unsaturated low-gain maser. Pihlstrom et al. (2001) argued that as a result of geometrical effects and a ring-like structure of the maser emission, the maser spots at the tangent points in III Zw 35 appear as two compact maser features. This implies that there is no real compact component in III Zw 35. However, it is unlikely that all megamasers have the same structure like that in III Zw 35. For example, in Arp 220, on a large scale (several hundred milliarcseconds) the Eastern maser component shows rotation of the nuclear disk, while on a smaller scale (VLBI) the OH maser emission has peculiar characteristics, and the Northwestern maser component may have a cone-like structure (Rovilos et al. 2003). Unfortunately, a handful of OH megamasers have been studied with the VLBI technique (Trotter et al. 1997; Lonsdale et al. 1998; Diamond et al. 1999; Yates et al. 2000; Pihlstrom et al. 2001; Richards et al. 2003; Rovilos et al. 2003) and there is no detailed information on the component intensities, except those of III Zw 35 (Pihlstrom et al. 2001) and Mkn 273 (Yates et al. 2000). In Mkn 273 there are two diffuse clumps. The clump 1 (67 mJy beam^{-1} at 1667 MHz) consists of 22 maser spots and coincides spatially with the peak in the continuum, while the clump 2 (20 mJy beam^{-1} at 1667 MHz) consists of 11 maser spots and it is not associated with any continuum peak (Yates et al. 2000). Whatever the structure of clumps, the total slope of the $L_{\rm OH} \sim L_{\rm FIR}$ relation is a linear combination of the slopes of individual clumps. Therefore, if we suppose that Mkn 273 consists of two diffuse components ($L_{\rm OH}^{\rm c} = 0$), then $\sum_{i=1}^{i=2} (S_i^{\rm d} - S) L_{\rm OH\it i}^{\rm d} = 0$ and clump 1 cannot be a low-gain unsaturated maser (the clump 1 is believed to be an unsaturated maser, because it is spatially coincident with the peak in the continuum), otherwise clump 2 will have $S_2^{\rm d} < 0$. However, clump 2 may have $S_2^{\rm d} = 2$, then $S_1^{\rm d} \simeq 0.96(1.22)$. In these calculations we accept $S = 1.2(1.4)$. The application of a statistically obtained value of S to individual galaxies in some cases may quantitatively be incorrect. However this method can be useful for a qualitative analysis.

It is interesting that megamaser galaxies with compact emission alone ($L_{\rm OH}^{\rm d} = 0$) have not been observed; perhaps these will be a different type of OH megamaser, and future VLBI observations may address this possibility.

It was mentioned in Sect. 1 that OH megamasers are found among the powerful IR galaxies. We believe that, in general, the physical processes responsible for the maser emission are the same in these systems, although in some of them under specific conditions (such as the appropriate relation between the intensities of compact and diffuse components and a relevant number of the IR photons for pumping the maser emission) a diffuse component might have a low-gain unsaturated masing.

3. Discussion

The radiation in the saturated cosmic masers usually grows and becomes so intense that the stimulated emission begins to reduce the population inversion and hence the gain. In this case, one pump photon is needed for each maser photon and the intensity increases linearly with distance. The saturated maser amplifies its own spontaneous emission, then the beamed maser emission will emerge from both ends of a masing region. Meanwhile, a weak emission will emerge in the direction perpendicular to the beamed direction. In an unsaturated cosmic maser, the pumping efficiency is sufficiently strong to maintain the population inversion against the growing losses by stimulated emission, and the intensity increases exponentially through the masing medium (e.g. Cohen 1989). A background source or the maser's spontaneous emission may serve as an input radiation for the unsaturated maser. If the maser amplifies a background source, the maser emission will be beamed in the forward direction. The exponential gain of unsaturated maser leads to line narrowing and beaming. Note that, if a diffuse component has a low-gain unsaturated emission, its linear size should be smaller than that of saturated diffuse component.

In luminous infrared galaxies, no highly significant correlations are found between the presence or the strength of VLBI core continuum emission and the total radio continuum power (Smith et al. 1998). The VLBI core emission is either uncorrelated or correlated very weak with the quantities such as FIR luminosity, radio spectral index, molecular gas mass etc. (e.g., Smith et al. 1998 for more detail).

The main results of VLBI studies are: (1) The OH line emission consists of two components, the compact (a few pc) one and the extended (a few dozen pc) one; (2) No background continuum emission was detected coincident with the OH clouds (except Mkn 273, Yates et al. 2000, and perhaps, Arp 220, Rovilos et al. 2003). The lack of any background continuum implies a high value of the amplification factor (more than 100), which strongly suggests that the compact masers in these galaxies are saturated. Therefore these results and the almost linear relationship between the OH and FIR luminosities (Kandalyan 1996, 1999; Darling & Giovanelli 2002a) and the present analysis (Sect. 2), as well as the variability study of IRAS 21272+2514 (Darling & Giovanelli 2002b), suggest that the unsaturated amplification and the FIR pumping cannot explain the compact and diffuse OH emissions of the megamaser galaxies, although under specific circumstances the unsaturated and FIR pumping model may account for the extended OH emission. It is likely that the collisional pumping and saturated amplification may account for the OH emission of both compact and diffuse components, and the X-ray heating may stimulate the collisional excitation.

4. Conclusion

The main conclusions of this work may be summarized as follows:
(1) On the basis of 9 megamaser galaxies detected in the soft X-ray and using the available OH and X-ray data a striking correlation was found between the X-ray luminosity and OH line width, which may indicate that the X-ray heating of a molecular gas may give rise to the collisional excitation of the maser emission. However, this problem needs a detailed investigation based on a statistically significant sample. (2) It is argued that both the compact and diffuse OH maser emissions are saturated. Under certain circumstances, such as the appropriate relation between the intensities of compact and diffuse components and a relevant number of the IR photons to pump the maser emission, the diffuse component might have unsaturated masing.

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