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Multiwavelength study of the OH megamaser galaxy IRAS 1510+0724 *

J.M. Martin [1], L. Bottinelli [2], M. Dennefeld [3], L. Gouguenheim [2], T. Handa [4], A.M. Le Squeren [1], N. Nakai [4], and Y. Sofue [4, 5]

[1] Observatoire de Paris, Section de Meudon, F-92195 Meudon Cedex, France
[2] Observatoire de Paris, Section de Meudon, F-92195 Meudon Cedex and Université Paris Sud, F-91405 Orsay Cedex, France
[3] Institut d'Astrophysique de Paris, 98 bis boulevard Arago, F-75014 Paris, France
[4] Nobeyama Radio Observatory, Minamisaku, 384-13 Nagano, Japan
[5] Department of Astronomy, University of Tokyo, 113 Tokyo, Japan

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Summary. A low luminosity OH megamaser has been found in the moderately luminous IR galaxy IRAS 1510+0724. A combined optical, radio decimetric and radio millimetric study leads to the following conclusions: (i) The OH 1667 MHz isotropic luminosity $L_{OH} = 10\,L_{\odot}$ is among the smallest observed among the class of megamasers, (ii) the H I absorption and OH emission line profiles show strikingly similar velocity structures suggesting that they come from similar regions, (iii) the star formation efficiency, as measured by the ratio of IR luminosity to molecular hydrogen mass, $L_{IR}/M(H_2) = 48$ (in solar units), and the relatively high dust temperature $T_d \approx 40$ K are in the range expected for interacting or merging (high IR luminosity) IRAS galaxies.

Key words: galaxies – molecules – OH masers – 21 cm line

1. Introduction

OH "megamasers" as a class of galaxies are characterized by a strong IR luminosity, up to 10^{11}–$10^{12}\,L_{\odot}$, and extremely powerful OH maser emission. The well-known prototype is Arp 220 (Baan et al., 1982) with an OH (1667 MHz) luminosity $L_{OH} = 380\,L_{\odot}$.

Extensive OH 18 cm surveys conducted mainly at Arecibo, Jodrell Bank and Nançay of strong IR emitters from the Infrared Astronomical Satellite (IRAS) data (Joint IRAS Science Working Group, 1985) have led to the discovery of a relatively small number of galaxies sharing similar properties, mainly: (i) strong IR luminosity, (ii) dominant emission from the OH 1667 MHz main line and (iii) evidence of large optical thickness as judged from the IRAS flux ratios and optical spectra.

However, it appears that the OH luminosity spans a relatively large range of 3 orders of magnitudes, from $1.5\,L_{\odot}$ (NGC 4418, Bottinelli et al., 1987a) to about $1200\,L_{\odot}$ (IRAS 17208−0014, Bottinelli et al., 1985).

Send offprint requests to: J.M. Martin

* Based on observations collected at the European Southern Observatory, Chile, Haute-Provence Observatory and Nançay Radioastronomy Station, France, and the Nobeyama Radio Observatory, Japan

The present study of IRAS 1510+0724 is dealing with the subclass of relatively "dwarf" megamasers with an OH luminosity of $10\,L_{\odot}$. It is based on optical and radio observations performed at the European Southern Observatory (ESO), the Observatoire de Haute-Provence (OHP), Nançay (18 cm and 21 cm) and Nobeyama (2.6 mm CO line). The detection in the 21-cm line and OH lines (1667 and 1665 MHz) was first reported by Bottinelli et al. (1986 and 1987b). An independent H I and OH detection has recently been reported by Baan et al. (1987).

2. Observations

2.1. Optical observations

The IRAS source located at $\alpha_{1950} = 15^h10^m45\overset{s}{.}7$ and $\delta_{1950} = +07°24'42''$ is identified with the galaxy Zw 49.057 (Zwicky et al., 1961); this galaxy is possibly associated with Zw 49.046 at 5′ NW.

Optical observations were first made at ESO. A calibrated IDS spectrum, obtained with the 3.6 m telescope in the center of the galaxy is displayed in Fig. 2 and shows the characteristic features of IRAS galaxies, with prominent H_{α} and [N II] lines and no conspicuous H_{β}, indicating at least 3 magnitudes of visual absorption. A strong extinction is confirmed by the presence of the Na D absorption line and by the high value of the 25 to 12 μm flux ratio. The derived heliocentric systemic radial velocity is (3800 ± 150) km s^{-1}.

CCD pictures were then obtained with the ESO 2.2 m telescope. The galaxy is seen nearly edge-on and presents a fairly symmetrical outer structure, as seen for example on a 10 min I exposure (Fig. 1a). However, the major axis of the inner parts is oriented differently than for the outer parts. This shows up more clearly on the V image (10 min exposure, Fig. 1b) which presents evidence for a warped disk. When examined under different intensity cuts however, the north east extremity could also suggest the presence of a separate component (see for instance the image published in Bottinelli et al., 1987b). To investigate the possibility that this northeastern spot could be an interacting companion, a long slit CCD spectrum was subsequently obtained with the 1.93 m telescope at Haute-Provence Observatory (OHP) with the slit oriented along the major axis. This spectrum confirms the main features, including a strong NaD absorption, and the

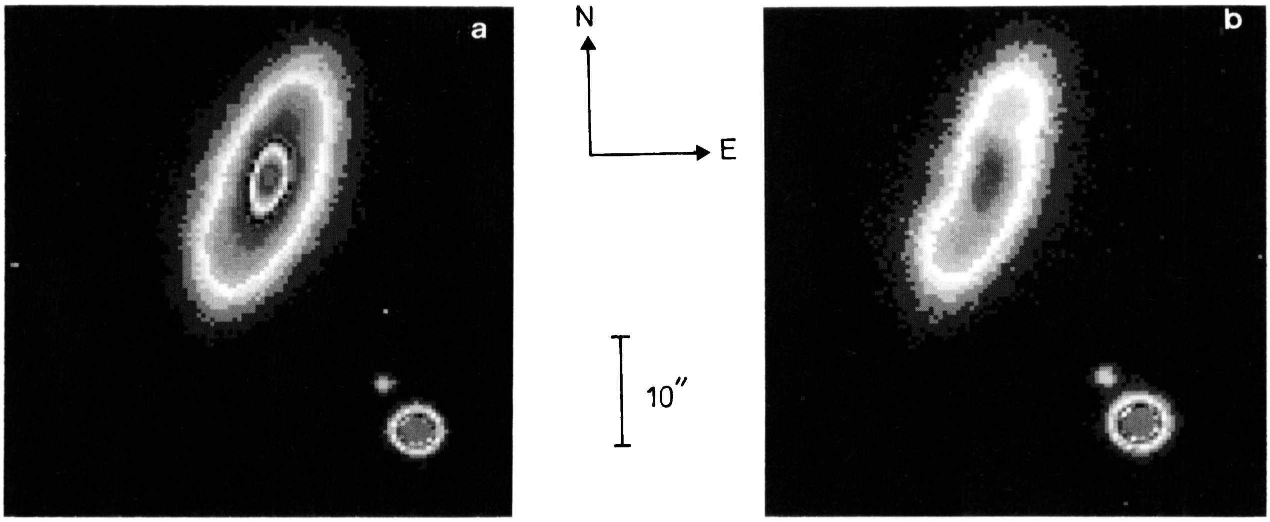

Fig. 1. CCD pictures of IRAS 1510+0724 obtained with the ESO 2.2 meter telescope. **a** I band, 10 mn exposure, **b** V band, 10 mn exposure

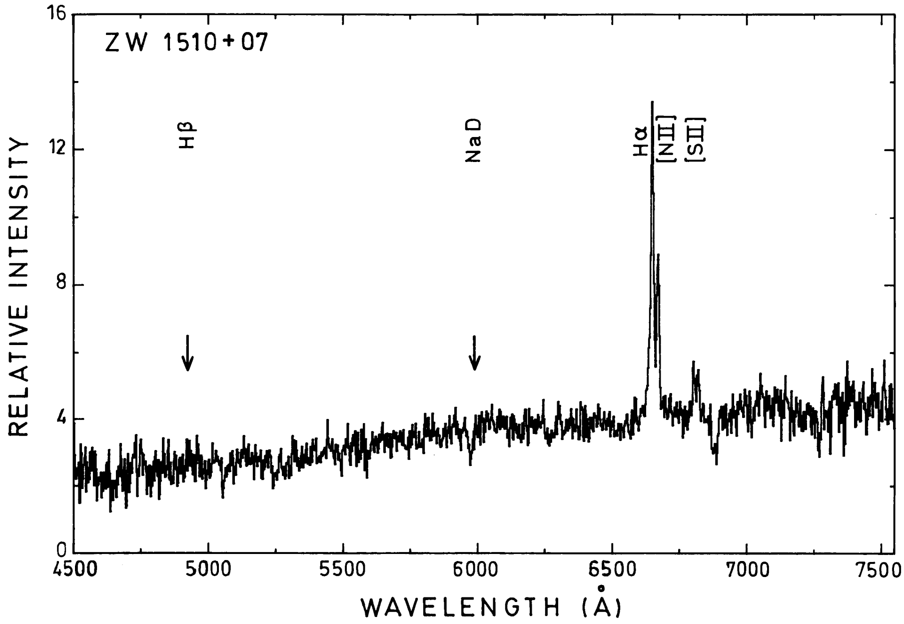

Fig. 2. Calibrated IDS spectrum of IRAS 1510+0724 obtained with the ESO 3.6 meter telescope. The main features are identified, as well as the position of the undetected H_β

measured heliocentric velocity is (3815 ± 150) km s^{-1}, in excellent agreement with our previous ESO measurement. No obvious asymmetry could be detected over the total 20″ extent of the galaxy. Recalling that in merging galaxies the starburst is generally appearing in only one of the two components (e.g. Joseph, 1986), while here the H_α emission extends all along the major dimension, and furthermore that this galaxy is not one of the extreme IR emitters, we conclude that there is no obvious evidence for an on-going interaction.

2.2. *Radio decimetric observations*

They were performed with the Nançay 300-m radio telescope during observing runs of selected IRAS galaxies between June and September 1985. The HPBW is 3.′5 (EW) × 19′ (NS) at 18-cm wavelength and 4′ (EW) × 22′ (NS) at 21-cm (at the declination +07°).

The dual channel receivers at both wavelengths have a total system temperature of ≈40 K. The 1024-channel autocorrelation spectrometer covering a total bandwidth of 6.4 MHz was split into 4 banks for the two orthogonal linear polarizations and the two OH main lines, providing a channel spacing of 4.5 km s^{-1} at 18-cm and into 2 banks for the two orthogonal linear polarizations, providing a channel spacing of 2.6 km s^{-1} at 21-cm. The spectra were obtained by using 4 minutes scans and spatial on-off switching and were smoothed to a resolution of 9 and 10.5 km s^{-1} at 18 and 21 cm respectively.

2.2.1. 18-cm OH and continuum observations

The OH spectrum was obtained in 526 min, including the comparison field. The average spectrum (including both linear polarizations) is given in Fig. 3a: both the 1667 and 1665 MHz main lines are detected in emission with a peak intensity of the 1667 MHz line

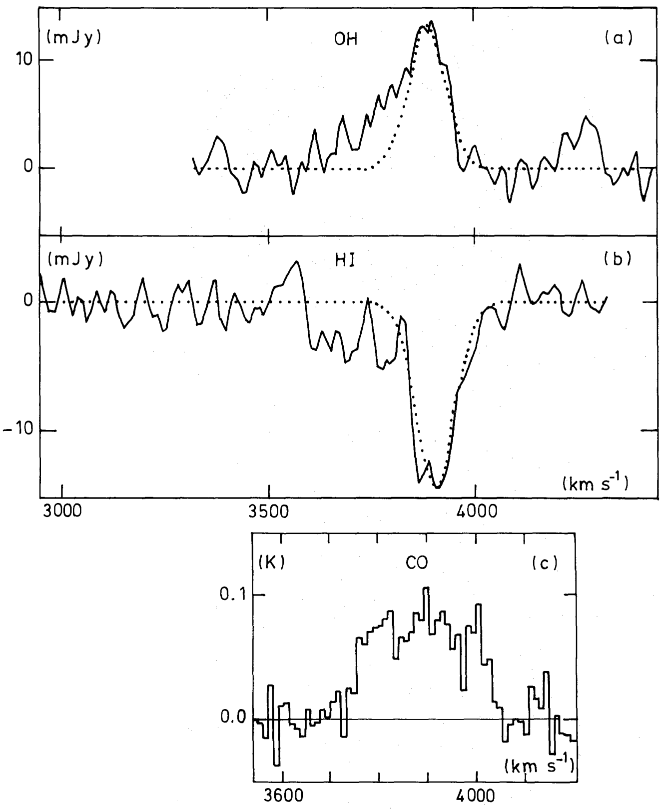

Fig. 3. a OH spectrum of IRAS 1510+0724 centered for the rest frequency of the 1667 MHz transition with a velocity resolution of 9 $km s^{-1}$; The secondary feature, at about 4300 $km s^{-1}$, corresponds to the 1665 MHz transition. **b** H I profile of IRAS 1510+0724 with a velocity resolution of 10 $km s^{-1}$. **c** CO ($J=1-0$) spectrum of IRAS 1510+0724 with a velocity resolution of 10 $km s^{-1}$; antenna temperature T_a^* is given in Kelvins. Radial velocities are expressed in terms of the heliocentric redshift $c(\Delta\lambda/\lambda_0)$

of 14 mJy and an intensity ratio of the two lines of about 3. The main line profile is asymmetrical with a steeper edge towards higher velocities. The systemic velocity corresponding to the midpoint at half-maximum intensity is (3880 ± 20) $km s^{-1}$, higher than the optical velocity of (3528 ± 300) $km s^{-1}$ from Soifer et al. (1987), but in excellent agreement with our own velocity determinations. The full width at half maximum intensity of the 1667 MHz main line is equal to (150 ± 20) $km s^{-1}$. The peak of the 1665 MHz line appears in Fig. 3a at the abscissa $\approx 4265 km s^{-1}$ which corresponds to a radial velocity of $\approx 3913 km s^{-1}$ when taking into account the relative redshift of 352 $km s^{-1}$ between the 1665 MHz and 1667 MHz transitions. As indicated in Fig. 3a, the peak and the steep edge of the main line can be fitted by a gaussian centered at 3890 $km s^{-1}$ with a FWHM = 110 $km s^{-1}$. Thus, it remains an extra OH emission extending from about 3650 to 3850 $km s^{-1}$ with a mean intensity $\approx$4 mJy.

The 18-cm continuum radio flux has been measured at Nançay by adding 15 drift scans. It is evaluated to (60 ± 15) mJy, taking into account the confusion limitation. Then the peak line flux to continuum flux ratio is about 0.25. Assuming that the OH lines are due to the amplification of background radio continuum by molecular clouds with inverted OH populations (Baan and Haschick, 1984), that the maser is not saturated and that we deal with a case of pure radiation pumping with a reasonable Doppler broadening of 10 $km s^{-1}$ and a negligible self-emission of the foreground clouds, we find that the inverted OH column density needed to get the required amplification is equal to $1.2\ 10^{13}$ mol cm^{-2}.

Assuming $H_0 = 75 km s^{-1} Mpc^{-1}$, the distance of IRAS 1510+0724 is 52 Mpc and its isotropic luminosity at 1667 MHz is $L_{1667} = 10 L_\odot$ – thus 2 orders of magnitude less luminous than the most luminous megamasers. The far IR luminosity L_{IR} is computed from the F_{IR} flux (in $W m^{-2}$), using:

$$F_{IR} = 1.75\ 10^{-14} (12.7 f_{12} + 5.00 f_{25} + 2.55 f_{60} + 1.01 f_{100}),$$

where the 12, 25, 60, and 100 µm fluxes f_{12}, f_{25}, f_{60}, and f_{100}, expressed in Jansky, are taken from the IRAS catalogue (Joint IRAS Science Working Group, 1985). It results $L_{IR} = 13\ 10^{10} L_\odot$. The ratio $L_{1667}/L_{IR} = 0.7\ 10^{-10}$ is in the range found for Arp 220 ($0.3\ 10^{-10}$), both L_{1667} and L_{IR} being smaller by about two order of magnitude for IRAS 1510+0724.

2.2.2. 21-cm H I line observations

The 21-cm line profile obtained in 140 min (including the comparison field and averaging both orthogonal polarizations) is given in Fig. 3b. It shows a main absorption feature having a FWHM of (110 ± 10) $km s^{-1}$ with no conspicuous emission component, centered at the velocity of (3890 ± 10) $km s^{-1}$, defined as the velocity of midpoint at half-maximum intensity. This velocity is in excellent agreement with the central velocity observed for the 1667 MHz OH line, although, two separate features can be guessed near the main peak, in Fig. 3a as well as in Fig. 3b. A single gaussian (FWHM = 110 $km s^{-1}$ and central velocity 3890 $km s^{-1}$) fits quite well the main absorption feature as indicated in Fig. 3b. In addition there is a hint of low-velocity wing extending from about 3600 to 3800 $km s^{-1}$ at a level of $\approx -(3\text{–}4)$ mJy. It is noticeable that the main H I absorption structure agrees remarkably with the OH emission profile described above, this point will be discussed below. However, the H I main line width is much smaller (FWHM = 110 $km s^{-1}$) than those observed in more luminous megamasers such as Arp 220 or IRAS 17208 – 0014 ($\approx$660 $km s^{-1}$ for the latter, from Bottinelli et al., 1987c), suggesting less violent motions of the H I clouds along the line of sight in front of the nuclear continuum source. These motions seem to be the largest for the strongest IR emitters, thus suggesting a relation with the stronger star formation activity.

Assuming that the absorbing H I covers the continuum nuclear source and adopting a H I peak intensity of –14 mJy, the optical depth is $\tau = 0.27$. The H I column density N_{H_I} obtained in terms of the spin temperature T_s from $N_{H_I}/T_S = 1.82\ 10^{18} \int \tau\, dv$ is equal to $5\ 10^{19} cm^{-2} K^{-1}$, which is typical of column densities in disk galaxies. Note that by using the 21-cm flux density of (45 ± 5) mJy measured by Baan et al. (1987) instead of our determination (60 ± 15) mJy, it results a peak optical depth of the H I absorption line $\tau = 0.37$ in perfect agreement with Baan et al's result and an H I column density N_{H_I}/T_S of $8\ 10^{19} cm^{-2} K^{-1}$. The FWHM (83 $km s^{-1}$) given by Baan et al. (1987) is smaller than ours (110 $km s^{-1}$) and it produces a smaller H I column density ($6\ 10^{19} cm^{-2} K^{-1}$); indeed, the value ($5.2\ 10^{18} cm^{-2} K^{-1}$) quoted by Baan et al. (1987) is erroneous by a factor of $\approx$10.

2.3. CO ($J = 1 \rightarrow 0$) observations at 2.6 mm

The CO data were obtained with the 45 m millimeter radiotelescope of the Nobeyama Radio Observatory (Japan), in May 1987, during an observing run of selected IRAS galaxies. The beam size is 17″ (HPBW) for the $J=1\rightarrow 0$ 115 GHz line, and is thus smaller than the galaxy's apparent diameter. The main beam efficiency and the forward spillover and scattering efficiency were $(45\pm 5)\%$ and 0.6 ± 0.1 respectively. The observation was made in position-switching mode, with a one minute cycle. Only one "ON" position has been measured. The "OFF" position was azimuthally shifted by 4′. Pointing accuracy has been checked every hour on the near SiO maser S-SER. Telescope pointing error has been found to be less than 4″, as there was no wind. The total system temperature was ≈ 1000 K, the partial vapour water pressure being rather high (10 mbar).

Three acousto-optical spectrometers were used simultaneously, to recover in case of failure and to check on eventual baseline effects due to the spectrometers. Their bandwidth was 250 MHz, which corresponds to a velocity range of 650 km s^{-1}, and is just sufficient compared to the width of the CO line of IRAS 1510+0724.

Data reduction has been done on the site, and particular care was taken not to confuse megamaser CO lines (which can have widths up to 600 km s^{-1}) with baseline curvature.

The observed profile is given in Fig. 3c and results from an integration of 75 min (on + off source). The central velocity is equal to (3900 ± 10) km s^{-1}, in good agreement with our optical and radio determinations. The line width is equal to (275 ± 10) km s^{-1}, larger than the main H I and OH features previously discussed. The shape of the CO profile is truly non-gaussian, but symmetrical, with two rather steep edges; this is typical of a complete disk of molecular material, while the H I absorption and OH maser emission are observed in a more specific region of this molecular disk, in front of the continuum emission.

The CO integrated intensity, corrected for beam efficiency, $I(\mathrm{CO}) = 33$ K km s^{-1} and the adopted distance of 52 Mpc yield a CO luminosity within the telescope beam $d_b = 4.28$ kpc, of 480 K km s^{-1} kpc^2. The corresponding molecular hydrogen mass within the telescope beam is then equal to $2.9\ 10^9\ M_\odot$ assuming $M(\mathrm{H_2}) = 6\ 10^6\ L(\mathrm{CO})$ (Sanders et al., 1984).

3. Discussion

There is a striking similarity between the structure of the H I absorption and OH emission profiles, with a main gaussian component centered at 3890 km s^{-1} and a FWHM of 110 km s^{-1}, and a low-intensity wing extending from ≈ 3600 to 3800 km s^{-1}. This can be understood because both the H I absorption and the OH emission are closely related to the continuum radiation and therefore take place along the line of sight in front of the radiosource(s). The two different features of the line profiles may be related to the possible double structure of the optical image (see Sect. 2.1). A higher resolution map is clearly needed. However, note that our H I low-velocity wing is only marginally detected owing to the rms noise (1.3 mJy) of the H I profile and the poor S/N (≈ 3) of this feature. Moreover, from their higher sensitivity (rms noise = 0.5 mJy) H I profile, Baan et al. (1987) concluded that "There is no clear evidence ... of an H I component at this velocity". The apparent double structure at the H I peak (Fig. 3b) is not evident in Baan et al. (1987) but the one observed at the OH peak (Fig. 3a) is also present, although marginally significant, in Baan et al. (1987) result.

IRAS 1510+0724 belongs to the subclass of "dwarf" megamasers with relatively low IR and OH luminosities, which confirms that the ratio of far-infrared to OH luminosity is nearly constant in megamasers over a wide range (≈ 3 order of magnitude) of luminosities (Bottinelli et al, 1987b; Martin, 1988).

Young et al. (1986) have shown that IRAS galaxies follow two different (L_{IR}, L_{CO}) relationships with:

$$L_{\mathrm{IR}} = 1.6\ 10^9\ L_{\mathrm{CO}}^{0.77} \tag{1a}$$

for interacting or merging galaxies, which have also the largest intrinsic IR luminosities, and:

$$L_{\mathrm{IR}} = 2.6\ 10^8\ L_{\mathrm{CO}}^{0.7} \tag{1b}$$

for isolated galaxies.

From its observed CO luminosity, the IR luminosity of IRAS 1510+0724 deduced from relations (1a) and (1b) should be $1.8\ 10^{11}\ L_\odot$ and $1.9\ 10^{10}\ L_\odot$ respectively. The observed IR luminosity as derived above is $1.3\ 10^{11}\ L_\odot$ (or $\approx 10^{11}\ L_\odot$ when using, as Young et al. (1986) did, only fluxes at 60 μm and 100 μm and the IRAS catalogue formulae), thus IRAS 1510+0724 clearly follows the first relation. The dust temperature deduced from the 60/100 μm flux ratio, under the (questionable) assumption that a single temperature holds for the dust component (with a dust emissivity $\propto \nu$), is equal to 40 K, well in the range (35–45 K) encountered for interacting galaxies.

The lower IR luminosity and the fact that the optical evidence for interaction is somewhat scarce (compared for example to Arp 220) could then indicate that IRAS 1510+0724 is a merging system seen after the maximum of activity.

The infrared luminosity to molecular hydrogen mass ratio, $L_{\mathrm{IR}}/M(\mathrm{H_2})$, which reflects the globally averaged star formation efficiency (SFE) in a galaxy, is equal to 48, in solar units. This is comparable to the values found in other megamasers, respectively 133, 81, 53, and 27 for NGC 3690, Arp 220, III Zw 35, and Zw 475.056 (Mirabel and Sanders, 1987); it is larger by a factor of about 20 than the value obtained for our Galaxy. This result confirms that, if the far IR emission originates from dust heated by stellar light, (Young et al., 1986a) the megamaser phenomenon takes place in galaxies having the higher efficiency of star formation.

Young et al. (1986b) have shown that interacting galaxies have on the average a larger SFE (72) than isolated ones (12). The value 48 found here for IRAS 1510+0724 agrees with its belonging to the class of interacting galaxies. But, the megamaser phenomenon spans a rather large luminosity range, which could be due to a variation in SFE. The megamaser galaxy IRAS 1510+0724 which is characterized by an intermediate value of $L_{\mathrm{IR}}/M(\mathrm{H_2})$, falls indeed on the lower end of the luminosity range for this class and could thus be called a "dwarf" megamaser.

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