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IC 485: A new disk-maser galaxy?

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Extragalactic maser sources associated with the Active Galactic Nuclei (AGNs), named megamasers, are unique tools to derive fundamental physical quantities of the host galaxies. Those associated with accretion disks around the supermassive black holes (SMBHs) are used to trace the disk geometry, to estimate the BH mass and to measure accurate distances to their host galaxies. Masers associated with radio jets and/or nuclear outflow are used to provide important information about the interaction region of the jets/outflow with the interstellar medium. In order to perform such studies, high angular resolution measurements are fundamental and, in particular, those obtained by using the Very Long Baselines Interferometry (VLBI) technique through existing arrays. In this proceeding, we present preliminary results about the megamaser LINER galaxy IC 485, part of a Ph.D project. The outcome reveals a maser emission resolved in two main groups of features, spatially distinguished and separated in velocity by about 500 km/s, one centered at the systemic velocity of the nuclear region of IC 485 and the other one red-shifted. Our study is discussed in the framework of a new possible disk and/or jet maser source in the galaxy.

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1. Introduction

The galaxies named Active Galactic Nuclei (AGNs) are characterized by intense emission observed toward their nuclear regions. Numerous studies carried out over the years have led to the realization of the paradigmatic Unified Model, which collects all observed components according to the line of sight as described by [1], (represented in Fig. 1). One of the main characteristics that distinguishes this class of galaxies is the radio activity of the nuclear regions, which allows us to divide them between "radio load" and "radio quiet" AGN. Two typologies of radio quiet-AGN of interest for the study presented in this proceeding are Seyfert and LINERs. Seyfert galaxies, generally observed with spiral morphology, are classified on the basis of the widths of the nuclear emission lines. The spectra of type 1 Seyfert show strong and dominant broader component of hydrogen and helium lines, characterized in term of the full width at half maximum, FWHM $\geq$ 1000 km s^{-1}; spectra of type 2 Seyfert show relatively narrow emission lines with FWHM$\sim$300 – 1000 km s^{-1}, [2]. LINERs (Low Ionization Nuclear Emission Line Regions) are generally observed with an elliptical morphology with some spiral exception. LINERs are spectrally defined by their optical emission lines from low and/or high ionization species. Their position in the correlation between star formation rate and accretion suggests a very inefficient accreting system, [3]. X-ray domain can provide AGN signature of the galaxy thus confirming the membership to this class (often debated for this typology of AGN), [3].

Astrophysical masers are unique tools to investigate the nuclear regions of the AGN and to map accretion disks and tori orbiting around supermassive black holes (SMBHs) and better understand the paradigmatic Unified Model of AGN. Extragalactic and luminous H_2O maser sources associated with AGN are called megamasers and they are typically found in nearby Seyfert 2 and/or LINERs. The three different typologies, so far observed, allow us to derive fundamental physical quantities of the host galaxies. 1) Disk masers characterized by triple-peaked pattern permit to map molecular material around the SMBHs, estimate BH masses, [4, 5], distances to the parent galaxies and cosmological measurement of H_0, [6, 7]. 2) Jet masers provide important information about the evolution of radio jets and their hotspots, [8, 9]. 3) Outflow / dusty-torus masers permit to trace the velocity and geometry of nuclear winds at some parsec from the nucleus, [10, 11]. Such studies are possible thanks to the high angular resolution reachable with the technique of the Very Long Baselines Interferometry (VLBI) through the existing arrays. VLBI is necessary also to discriminate the spectral signature of a new "exotic" category of maser proposed by [12]: the "inclined maser disk". This typology of maser would be detectable thanks to amplification path and beamed radiation in accretion disks within few degree of edge-on, but maser radiation could also be detected via the gravitational lensing or deflection by massive black holes in inclined accretion disks (more than 10 degrees from edge-on).

2. The target galaxy IC 485

The present study is part of an ongoing Ph.D project focused on an observational and interpretative effort aimed at a detailed study of water megamasers associated with (relatively) radio quiet AGN galaxies, classified as Seyfert and/or LINERs. The final goals of the project are: i) to increase the physical and geometric informations of the maser phenomenon through maps at VLBI scale of

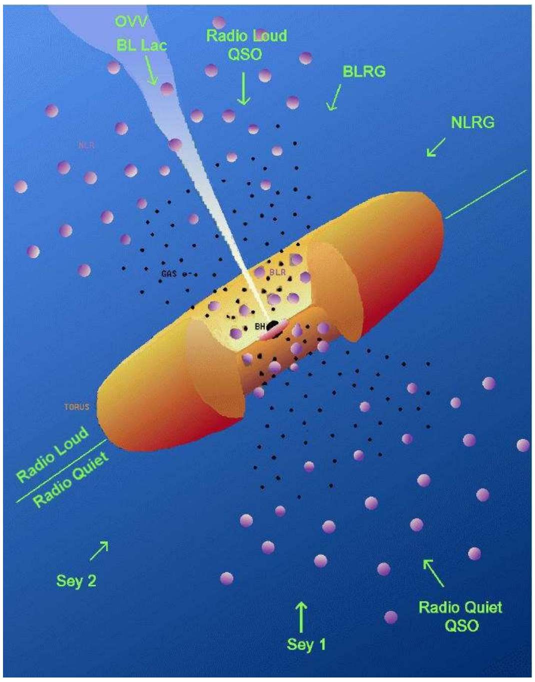

Figure 1: Artistic representation of the Unified Model of AGN (Urry & Padovani, [1]).

the nuclear regions and 3D-modeling of the maser sources; ii) to expand the number of cases in which to study the distribution and the dynamics of the molecular gas in the nuclear regions, and thus collect evidence for (or against) the Unified Model. Indeed, the galaxy IC 485 is one of the targets included in the sample of this project. IC 485, with systemic velocity[1] V_{sys} = 8338 km s^{-1}, has been optically classified as a Sa spiral galaxy located at the distance of 112.0 ± 8.5 Mpc, assuming H_0 = 70 km s^{-1} Mpc^{-1}, [13]. The spectroscopic classification of the galaxy is not clear yet. The galaxy is reported as a LINER by [12]. On the other hand [13] classify it as a Seyfert 2. A broad multicomponent maser with a peak of 78 ± 2 mJy and a high luminosity ($L_{\rm iso}$ = 868 ± 46 $L_{\odot}$) has been observed with Very Large Array (VLA) observations by [12], that also candidates the galaxy as “inclined maser disk”. The same author reported an unresolved and faint continuum radio source, with a peak flux of 77 ± 15 µJy beam^{-1}, detected at 20 GHz and a detection at 1.4 GHz (4.4 mJy) was associated to a region of star formation that not exclude the presence of an AGN. Additional informations about the continuum of IC 485 have been recently acquired by our own group and are reported by Castangia P. et al. (in this volume).

3. Observations and data reduction

IC 485 was observed with the Very Long Baseline Array (VLBA) on February 26, 2018 and on October 30, 2018 under project BT142_A1 and BT145_A1 (PI: A.Tarchi). In order to measure absolute positions, we relied on phase-referencing using J0802 + 2509 within 3 degrees from the target, for both epochs; the observations were conducted with cycle phase-reference –

[1]Optical definition in the heliocentric frame.
[2]https://safe.nrao.edu/wiki/bin/view/Main/MegamaserCosmologyProject

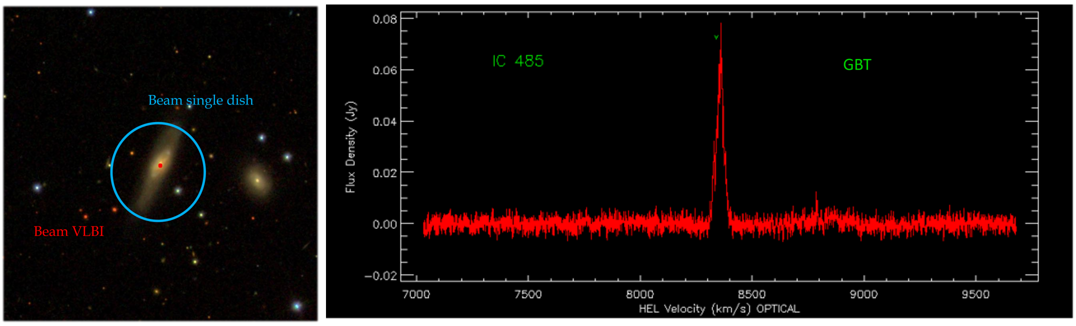

Figure 2: Left panel: Image in the optical band of the galaxy IC 485 obtained by the optical survey Sloan Digital Sky Survey (SDSS). In the picture are represented the K-band GBT beam (in blue) compared with a K-band VLBI beam (in red); Right panel: GBT spectrum of IC 485 from the catalog of the Megamaser Cosmology Project. [2]

Project name	Epoch	IF	Bandwidth	Polarization	IF Central velocity[a]
BT142_A1	2018.16	1	64 MHz	dual (RR & LL)	8338 km s^{-1}
BT145_A1	2018.83	1	64 MHz	dual (RR & LL)	8338 km s^{-1}
		2	64 MHz	dual (RR & LL)	9040 km s^{-1}

Table 1: Observational details of the two epochs analyzed. The columns report the name of the projects; the epochs; the IFs used during the observation and their specifications, in particular: the bandwidth; the polarization and the velocity position in which the IFs are centered.
[a] Velocity in optical definition in the heliocentric frame.

target of 45 s – 45 s. Some details of the observing setup of the two epochs are summarized in Table 1. The main difference of the two epochs was the number of sub-band used (IFs): a single one sub-band in VLBA 2018.16 and two in VLBA 2018.83. The sub-bands mentioned had a width of 64 MHz with two polarizations to cover the broad maser line (~ 10 MHz). A single DiFX pass allowed us to have 4096-channels for both IFs and we recorded at 1024 Mbps in the two epochs. This allowed to cover the broad maser emission line with a velocity resolution of 0.2 km s^{-1} and to leave enough line-free channels for continuum subtraction and to produce a K-band continuum image. The integration time on the source was 2.5 hours in VLBA 2018.16 and 3.5 hours in VLBA 2018.83 with a total observing time of 6 and 8 hours, respectively. The data were calibrated using the software Astronomical Image Processing System (AIPS[3]) and the spectra were analyzed with the software CLASS[4]. We applied a standard procedure of calibration. Indeed, after standard steps (e.g. ionospheric corrections, earth orientation parameters corrections), we performed a cycles of self-calibration on the phase reference (the results of the improvement are shown in Fig. 3). Finally, we transferred the final solution to IC 485 to produce the image cubes and the continuum maps. The noise in the cube map for VLBA 2018.16 was ~ 3 mJy beam^{-1} channel^{-1} and ~ 64 µJy beam^{-1} in the continuum map, respectively. For VLBA 2018.83, the noise was ~ 6 mJy beam^{-1} channel^{-1} in the cube map and and ~ 66 µJy beam^{-1} in the continuum map, respectively.

[3]http://www.aips.nrao.edu/
[4]https://www.iram.fr/IRAMFR/GILDAS

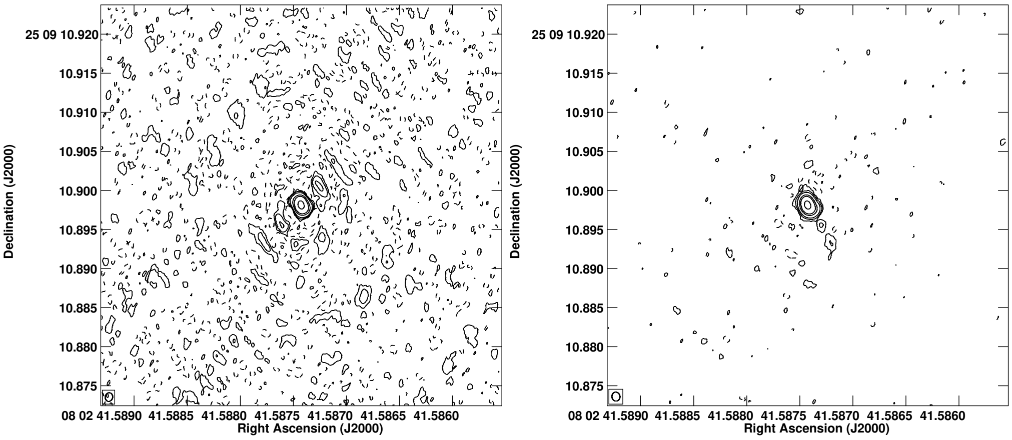

Figure 3: The self-calibration procedure applied to the phase reference J0802 + 2509 for the epoch 2018.16. Left panel: the contours map of J0802 + 2509 before the self-calibration. Right panel: the final (contours) map of the phase reference at the end of the procedure of self-calibration. The figures are realized with the final noise calculated after the last cycle of self-calibration. The levels are 73 µJy × (-3,3,9,24,96,192, 768).

Epoch (VLBA)	Maser	RA (α_{2000}) [$^{h}:^{m}:^{s}$]	Dec (δ_{2000}) [$^{\circ}:':''$]	Peak velocity [$\mathrm{km\,s^{-1}}$]	L_{iso} ($L_{\odot}$)
2018.16	M1	08:00:19.75253	26:42:05.0523	8353.6 ± 0.1	524 ± 56
2018.83	M1	08:00:19.75252	26:42:05.0525	8354.8 ± 0.5	529 ± 38
	M1B	08:00:19.75247	26:42:05.0520	8355 ± 2	76 ± 18
	M2	08:00:19.75252	26:42:05.0528	8827 ± 1	24 ± 16

Table 2: Parameters of the maser features. The columns indicate the epoch of detection, the name of the maser features, right ascension, declination, the peak velocity and the isotropic luminosity.

4. Results and preliminary discussion

The main feature at the systemic velocity, M1, was detected in the two epochs and its position is consistent within the relative error between the two maps. A red-shifted feature, M2, was observed in the epoch VLBA 2018.83 thanks to the velocity coverage offered by the second IF. The spectrum of the two features is shown in Fig. 4.

The isotropic luminosity of all features observed was evaluated according to the relation, [14]:

$$\frac{L_{H_2O}}{L_{\odot}} = 0.023 \times \frac{SdV}{[\mathrm{Jy\,km\,s^{-1}}]} \times \frac{D^2}{[\mathrm{Mpc}]},$$

where S is the peak flux, dV is FWHM and D is the distance. The results of the line properties are summarized in Table 2. The main feature M1 shows consistent values of the isotropic luminosity of $\sim 530\,\mathrm{L_{\odot}}$, in the two epochs. In the second epoch, a tentative systemic feature, M1B, was detected. The feature M1B differs from the main one in position by few milli-arcseconds and it has an isotropic luminosity of $\sim 80\,\mathrm{L_{\odot}}$. About M2, we observed a $L_{\mathrm{iso}} \sim 20\,\mathrm{L_{\odot}}$. In the continuum maps, some sources unresolved or slightly resolved were detected over 5σ in the epoch 2018.83.

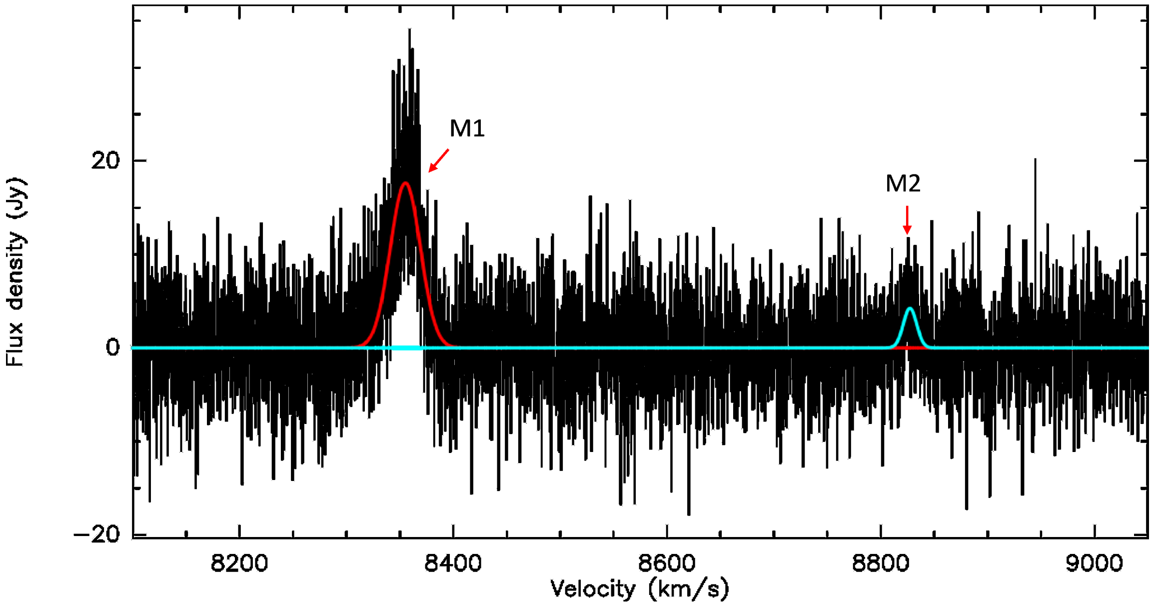

Figure 4: The spectrum of the main feature and the red-shifted component observed in the epoch VLBA 2018.83. The spectrum is zoomed in the velocity range 8100 – 9050 km s^{-1}. The red Gaussian fit underline the systemic feature M1, meanwhile the blue Gaussian fit underline the component M2.

We compared these sources with the corresponding map area in the work of [12]. We can conclude that the diffuse area observed in the latter is resolved-out by our interferometer.

The two features M1 and M2 are displaced by ∼ 0.4 mas (equivalent to 0.2 pc at the distance of IC 485) in the North-South direction. If the spectrum is composed of three features, as it is possible to infer from the spectrum in [15], we can hypothesize a nature of disk-maser. In our hypothesis of disk-maser, we can then assume the existence of the blue-shifted component diametrically opposite to the red-shifted one. Assuming a Keplerian rotation, the relation $v^2 = GMR^{-1}$ give the black hole mass in the center of the nuclear region. According to the relation:

$$\frac{M_{BH}}{M_{\odot}} = 1.12 \times \left(\frac{v_r}{[\mathrm{km\,s^{-1}}]}\right)^2 \times \left(\frac{\theta}{[\mathrm{mas}]}\right) \times \left(\frac{D}{[\mathrm{Mpc}]}\right),$$

where v_r is the velocity of the rotation of the disk ; θ is the disk radius and D is the distance of the galaxy ([13]). From the values that can be gained from the single dish spectra and our VLBI data, it is possible to estimate a black hole mass of:

$$M_{BH} \approx 10^7 M_{\odot} .$$

This value is consistent with the one expected for a supermassive black hole in a Seyfert or a LINER galaxy, [16]. Finally, the position of the systemic tentative, M1B, spatially distinct from M1 is detached by the hypothetical disk and it suggests a distinct origin, possible associate with a jet or an outflow maser. This feature opens the hypothesis of a composite nature for IC 485, already known and observed in the literature (e.g. NCG1068, in [17]).

5. Summary and follow-ups

In this proceeding, we present the first results of two-epochs VLBA K-band observations of the nuclear region of the megamaser LINER galaxy IC 485. The detection of two main groups of features M1 and M2 at the systemic and at a red-shifted velocity respectively, suggest a nature for the maser associated with a rotating disk. The width of the systemic feature M1, and the characteristics and the position of the tentative M1B do not allow us, however, to rule out a composite (disk+jet/outflow) maser origin. Further studies with an high sensitivity array and a setup that include the velocity range of the blue-shifted line would be necessary to detect all the three characteristic peaks of the aforementioned class and to confirm the hypothesized nature of the maser. Confirming the association of the maser in IC 485 with an edge-on disk would also confidently ruled out the scenario for the maser in IC 485 to be an "inclined maser" candidate.

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