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Hunting for H_2O megamasers with the SRT

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Abstract. We outline a project that aims at using the SRT to detect 22 GHz water masers within the nuclei of galaxies. In some nuclei, the water masers populate accretion disks around the super-massive black holes, lying as close as 0.1 pc to the nuclear "monster". Once discovered, VLBI can be used to obtain a direct imaging of disk structures (typically obscured or not resolved by optical and infrared observations) and to derive important physical quantities (e.g. accretion rate, degree of disk warping and orientation, and the cosmic distance). Future extensions of this project to maser sources at cosmological distances, possibly leading to a direct measurement of the Hubble constant, are also briefly introduced. Technical and observing-time requirements for the outlined project are discussed.

1. Introduction

The name MASER is an acronym for Microwave Amplification by Stimulated Emission of Radiation and indicates a physical phenomenon in which incident radiation is amplified when passing through a cloud of molecular material where the molecule's energy levels involved in the transition are in an inverted state, i.e. the higher energy level is more populated than the lower one. When this condition is present (normally, in the cold interstellar medium, ISM, we have the opposite situation), it is said that the maser is "pumped". The maser can be pumped collisionally or radiatively (in the laboratory, also chemical pumping can be obtained). Among the five molecular species (i.e. CH, OH, H_2O, SiO, and H_2CO) from which maser emission has been detected in extragalactic sources, the water vapour maser lines are particularly relevant. The main H_2O maser line arises from the 6_{16}–5_{23} transition between two adjacent rotational levels of ortho-water at a rest frequency $\nu = 22.2$ GHz ($\lambda = 1.3$ cm).

The H_2O maser line traces molecular gas with a high density ($n(H_2) \geq 10^7$ cm^{-3}) and with a kinetic temperature $T_{\rm kin} \sim 400$ K. Peculiar of the water maser emission are the huge brightness temperature ($\sim 10^{12}$ K) associated with narrow line widths (usually a few km s^{-1}) that soon suggested a 'non-thermal' origin. In addition, individual maser spots in our Galaxy have been imaged using the Very Long Baseline Interferometry (VLBI), that provides extremely high spatial resolutions, indicating very small sizes of the emitting spots ($\leq 10^{14}$ cm).

Galactic water masers have been found in association with either star formation regions,

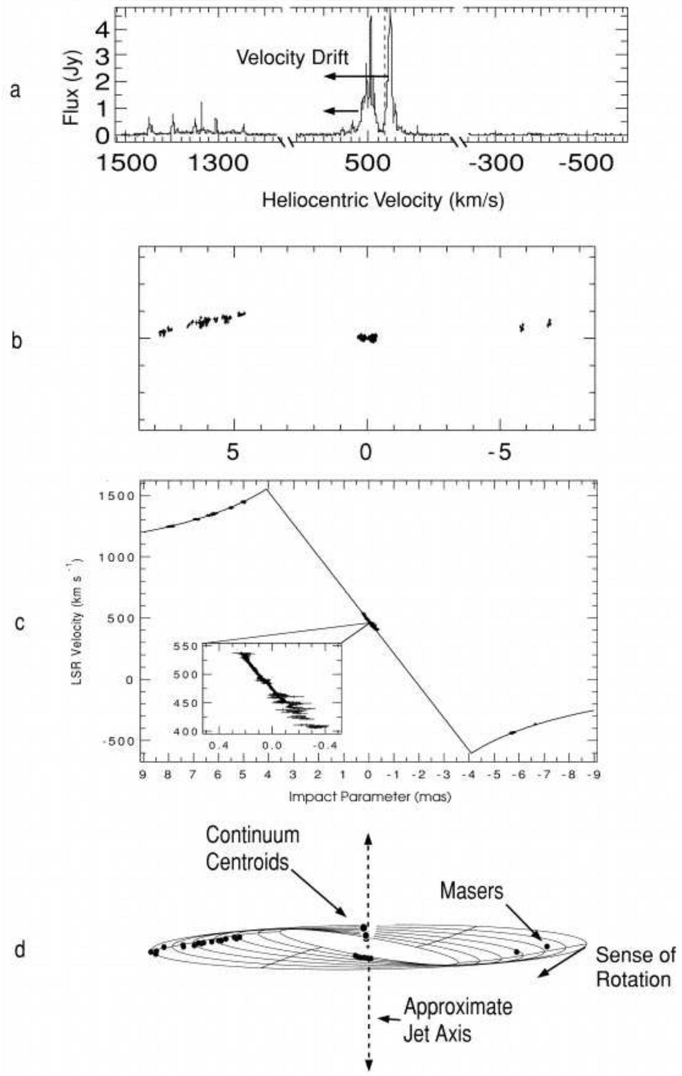

Fig. 1. Overview of the NGC 4258 system. (a) "Typical" spectrum of the water masers. (b) VLBA map (scale marked in milli-arcseconds) of the disk. (c) Velocity vs. impact parameter for the masers with Keplerian rotation curve fit plotted. (d) Schematic of warped disk with maser locations overlaid. The figure is taken from Bragg et al. (2000).

often spatially close to ultra-compact H II regions, or late-type stars. These masers have isotropic luminosities usually smaller or much smaller than 1 $L_\odot$, with the only exception of W49N that had a flare and reached about 1 $L_\odot$. Instead, extragalactic masers are usually stronger and can reach luminosities of hundreds or thousands of $L_\odot$, allowing us to observe them out to relatively large distances.

So far, there is evidence for a total of three distinct classes of extragalactic H_2O masers:

(1) those tracing accretion disks in active galaxies. They allow us to map nuclear accretion disks, to determine nuclear masses, and accurate distances to their parent galaxies, thus having an impact on the cosmic distance scale. NGC 4258 is the best studied target of this class (e.g. Greenhill et al. 1995; Miyoshi et al. 1995; Herrnstein et al. 1999; Bragg et al. 2000; Fig. 1).

(2) those in which at least a part of the H_2O emission is believed to be the result of an interaction between the nuclear radio jet and an

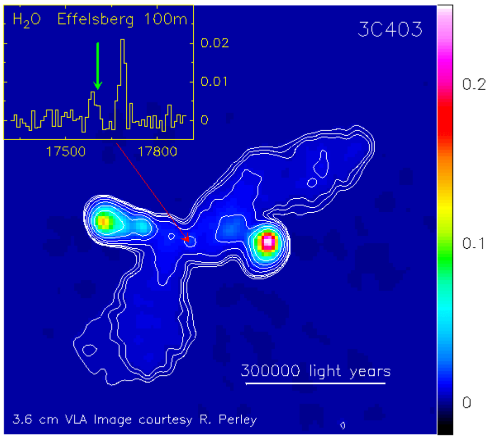

Fig. 2. NRAO Very Large Array image of the radio galaxy 3C 403 at a wavelength of 3.6 cm. The intensity range of gray scales (in Jy) is indicated at the right hand side. The arrow points to the galaxy's nucleus. The spectrum shown in the upper left hand inset was taken with the Effelsberg 100-m telescope (Tarchi et al. 2003). The y-axis is flux density (in Jy), while the x-axis gives the recession velocity (in km s^{-1}). The arrow in the inset points to the systemic radial velocity of the whole galaxy

encroaching molecular cloud. Monitoring line and continuum fluxes can provide estimates, through reverberation mapping, of the speed of the material in the jet (see e.g. Peck et al. 2003 on Mrk 348).

(3) those, typically with lower maser luminosities ($< 10\ L_\odot$; the 'kilomasers'), often associated with prominent star forming regions in large-scale galactic disks. This kind of masers can be used to pinpoint locations of high mass star formation and to determine distances through complementary measurements of proper motions and radial velocities (e.g. Greenhill et al. 1993). So far, these have been found in galaxies containing bright IRAS point sources (e.g. IC 10, Argon et al. 1994; NGC 2146, Tarchi et al. 2002).

In the following, we outline a possible project, mostly focusing on the first of the three classes of water maser described above, to be conducted taking advantage of the high sensitivity and 22-GHz receiver capabilities of the upcoming Sardinia Radio Telescope (SRT).

2. Past surveys and motivation for new water maser searches

Although extragalactic H_2O masers are much sought-after objects, detection rates in large surveys have been disappointingly low: in the most successful surveys, detection rates are a few percent (e.g. Braatz et al. 1996). Only recently, larger detection rates have been obtained observing *ad hoc* samples: i.e. galaxies with particularly high 100μm FIR flux density or Seyfert galaxies with jets oriented close to the plane of the disk (Henkel et al. 2005b). Water megamasers are mostly found in radio quiet active galactic nuclei (AGN; $S_{1\,\mathrm{GHz}} < 10^{22-23}$ WHz^{-1}), and in particular in galaxies classified as Sy2s or LINERs. Only one water megamaser may have been found in a Sy1-type AGN (Nagar et al. 2002) and another one is known to be associated with a radio-quiet elliptical galaxy, NGC 1052. Based on the assumption that the masers are situated in circumnuclear tori and that their amplification is unsaturated, one should expect a much higher detection rate in radio-loud galaxies. Unfortunately, until recently no maser was detected either in FRI galaxies (Henkel et al. 1998) or in the more powerful FRII-class radio galaxies observed by us (Tarchi et al. *in preparation*), and this was all the more surprising since molecular tori are expected to be present according to the AGN unification scheme (e.g. Urry & Padovani 1995).

However, in January 2003 we have observed a limited sample of narrow-line FRII galaxies (3 objects) with evidence for nuclear obscuration and redshift $z < 0.1$, and finally detected luminous water maser emission (a 'megamaser' of $\sim 1000\ L_\odot$) in one of the objects: 3C 403.

Follow-up interferometric observations of the maser clearly indicate that the emission from both lines is unresolved and comes from a position coincident (within sub-arcsecond accuracy) with the center of the radio galaxy (Fig. 2). Global VLBI observations are scheduled and will determine the origin of such maser emission associated either with the accretion disk around the central engine of the galaxy, or with the interaction between molecular material and the radio jet.

The first detection of maser emission from the classical radio galaxy 3C 403 (many of the numerous radio galaxies still need to be observed) and the increase in detection rates due to proper selection criteria of the samples constitute an important motivation to perform further maser searches. Furthermore, recently Henkel et al. (2005b) studied the entire sample of the detected extragalactic water masers, derived its luminosity function (LF), and, given the incompleteness and heterogeneity of the samples in which the masers were detected, concluded that only a tiny fraction of the luminous megamaser sources detectable with presently available instrumentation has been discovered to date and that if the LF is not steepening at very high luminosities, masers should be detectable with existing telescopes out to cosmological distances. The latter conclusion is somewhat supported by the new discovery of a very luminous megamaser in a Type 2 quasar at redshift 0.66 (Barvainis & Antonucci 2005; see also §3.2).

3. Using the SRT to search for H_2O maser emission in AGNs

A contribution to the search for 22-GHz H_2O masers within the nuclei of galaxies could definitely be provided by using the SRT to survey samples of galaxies not yet observed, or to increase, due to its high sensitivity, the depth of the maser search of previous shallow observing campaigns. In some nuclei, the water masers populate accretion disks around the super-massive black holes (SMBHs), lying as close as 0.1 pc to the nuclear "monster". Once discovered, VLBI observations (noticeable is the fact that SRT will be also an important element of the European VLBI Network, EVN) can be used to map the angular distribution of maser features throughout individual disks, and hence, to obtain a direct imaging of disk structures typically obscured or not resolved by optical and infrared observations (e.g. Miyoshi et al. 1995; Greenhill et al. 1995). So far, no other astronomical technique can provide images of accretion disks in such a proximity to the SMBHs. Depending on the properties of the galactic nucleus (e.g., orientation to the line-of-sight and black hole mass), important physical quantities can be derived from such images as e.g. accretion rate, the warp of the disk, and the cosmic distance scale. The latter is particularly important because the technique used to obtain the distance is entirely geometric and thereby independent of the luminosity calibrations that affect almost all other distance measurement techniques. The prototype of such studies is NGC 4258, although more and more works are published reaching comparable results in other megamaser sources, e.g. NGC 1068 and NGC 3079 (for a recent review on H_2O megamasers, see Henkel et al. 2005a).

A "geometric distance" is already available for the galaxy NGC 4258 (see Herrnstein et al. 1999), and it represents the most accurate distance measurement so far. Hopefully, geometric distances to NGC 4258 and similar galaxies will ultimately provide anchors in the local universe, against which calibration of the extragalactic distance scale can be checked to high accuracy.

3.1. Requirements for the SRT 22-GHz receiving system

For the project outlined above we can profit from the 22-GHz multi-beam receiver option, planned for the SRT, performing internal beam switching observations without losing time on the OFF position. We recommend a spectrometer that (at least) supports simultaneously two 200-MHz bands in two polarizations with 8192 spectral channels each. Alternatively, the SRT could be provided with a digital correlation spectrometer (e.g. the correlator spectrometer, named SAO4K, developed by the Harvard-Smithsonian Center for Astrophysics[1]) with bandwidths up to 400 MHz and 4096 spectral channels. This corresponds to about 1.3 km s^{-1} at the rest frequency of the H_2O line (22.2 GHz), enough for our detection purposes.

[1] `http://cfa-www.harvard.edu/ lincoln/swis/sao1k/html`

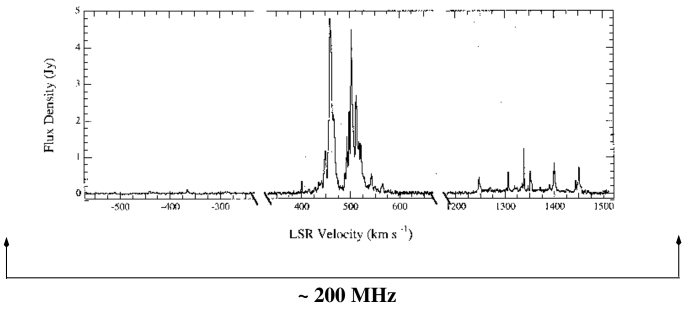

Fig. 3. A composition of the systemic and high-velocity satellite maser features in NGC 4258 shown as a compressed spectrum (velocities with no maser emission are not shown) to give an idea of the SRT bandwidth ($\geq$ 200 MHz) necessary at 22 GHz to detect them simultaneously. The spectrum is taken from Greenhill et al. (1995).

Such wide-band capabilities are necessary because known H_2O masers in AGNs typically display sub-Jy spectral lines distributed over a frequency interval of about 500 to 2000 km s^{-1}, where the interval is dictated by the rotation speed of the disk at radii where the maser action is excited (Fig. 3). Because it is impossible to predict such interval, the widest possible instantaneous bandwidth is critical for efficient surveys of large numbers of galaxies. However, present (and, even more, upcoming) digital backends offer capabilities, i.e. bandwidths and number of channels, more than sufficient to fulfill our requirements.

The isotropic luminosities $L_{\rm iso}$ of water megamasers range from 20 $L_\odot$ to 6000 $L_\odot$ (the "gigamaser" in TXFS2226-184; Koekemoer et al. 1995); but this limit seems now largely overtaken by the discovery of a 23000 $L_\odot$ maser (see next section). Widths of individual maser features tend to vary from source to source from $\delta v \sim 0.5$ km s^{-1} to almost 100 km s^{-1}. For pure detection purposes, we can take a prototypical line with $\delta v = 30$ km s^{-1} at a redshift z of 0.03. The isotropic luminosity of a maser line is given by the equation:

$$\frac{L_{\rm iso}}{[{\rm L}_\odot]} = 0.023 \cdot \frac{D^2}{[{\rm Mpc}]} \cdot \int \frac{S}{[{\rm Jy}]} \cdot \frac{{\rm d}v}{[{\rm km\,s^{-1}}]}$$

Hence, 20 and 6000 $L_\odot$ features at z = 0.03 (D = 120 Mpc, assuming H_0 = 75 km s^{-1}Mpc^{-1}) will have a peak flux density of 2 and 600 mJy, respectively. Therefore, the possibility to detect also the weakest megamasers ($L_{\rm iso}$ = 20 $L_\odot$) in a survey implies a sensitivity per channel not worse than 0.7 mJy (3σ). With the 80 K system temperature and an antenna efficiency of 56% at 22 GHz, the SRT should be able to obtain a sensitivity of 0.7 mJy in 60 or 25 hours, for channel widths of 1.3 or 5 km s^{-1}, respectively. Such long integration times and the large number of AGNs that can be observed suggest that a survey with the SRT should focus on the most interesting subclass: the high luminosity megamasers, with isotropic luminosities > 50 $L_\odot$. In this case integration times of (only) about 5 to 10 hours per target (depending on the channel width) are required.

3.2. Cosmological water megamasers

Standard K-Band receivers have nominal frequency bandwidths between 18 and 26 GHz. However, if the object that emits the water maser line(s) has a redshift $z > 0.25$, the maser line falls at frequencies < 18 GHz, i.e. outside the receiver bandwidth. Hence, to extend our survey to cosmologically-relevant water megamasers it would be necessary to extend the low-frequency coverage of the SRT 22-GHz receiver and/or to provide the SRT with *ad hoc* receivers capable to work at frequencies lower than 18 GHz (for example, the water maser line from a galaxy at redshift 1 would be detectable at a frequency of $\sim$ 11 GHz). The SRT would then be able to perform high-redshift water megamaser surveys (so far, none or very few such surveys have been performed). Of course, the integration times would rise by huge factors, limiting the possible survey detections only to very luminous objects ($L_{iso} > 500 - 1000 L_{\odot}$). However, as recently speculated, the number of such objects might be higher and their luminosity larger in the 'earlier' Universe than in the 'nearby' one (e.g. Townsend et al. 2001), because of enhanced AGN activity and merging phenomena. Indeed, the newly discovered luminous megamaser ($\sim 23000\ L_{\odot}$) in a type 2 quasar at redshift 0.66 (Barvainis & Antonucci 2005) fully supports this scenario. The result of such a survey would have far-reaching consequences, not only improving our knowledge on circumnuclear disks and on the cosmic distance scale, but also having a significant impact on research that will be carried out with the Square Kilometer Array (SKA) in the more distant future.

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