Astrophysical Masers:
Unlocking the Mysteries of the Universe
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Masers! What can VLBI do for you?

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Abstract. Very Long Baseline Interferometry (VLBI) is providing key information to the study of maser processes in the Universe, from star formation regions or circumstellar envelopes around evolved stars, to Galactic structure and cosmology, through precise astrometry. VLBI networks offer various capabilities and, most importantly, support to users, to ensure that these infrastructures are fully accesible and that the best science can emerge. In this paper we describe the advances in VLBI that enable exciting maser studies.

Keywords. masers, radio lines: ISM, radio lines: stars, radio lines: galaxies, stars: evolution, techniques: high angular resolution, techniques: interferometric

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1. Introduction

Special conditions in the interstellar medium make possible microwave amplification by stimulated emission of radiation (maser) processes in the Universe. These can be found in star formation regions, in circumstellar envelopes around evolved stars (mainly AGB and post-AGB stars), and in our and other galaxies. Since maser emission can become very bright and compact, high resolution VLBI observations are a tool to study their distribution and other characteristics, therefore providing clues to derive the conditions in the regions where they occur.

The advent of recent technological developments and instruments make it now possible to study cosmic masers in a more efficient way. For example, the capability to observe several maser lines simultaneously provides unique information to constrain models of the maser emission.

2. What can VLBI do for masers?

Very Long Baseline Interferometry (VLBI) provides the sharpest view of cosmic objects in the Universe. For maser research, there are many applications where the VLBI technique produces superbly high spatial resolution data, complementary to that of other astronomical techniques. A few examples are described in Sec. 3. We now present which VLBI networks are available, in some detail.

2.1. *Available VLBI networks*

Nowadays there are several VLBI networks operating around the world, each with their own specific characteristics (number and size of radio telescopes, frequency coverage, location and governance). Also they are technically compatible to operate as a global VLBI array, when required. The largest ones are the European VLBI Network (EVN,

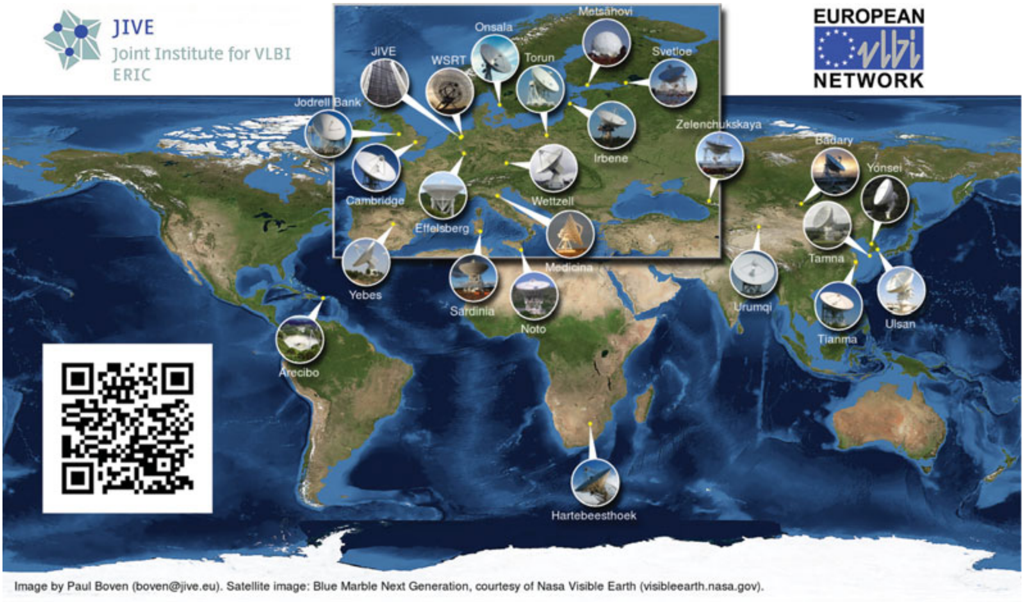

Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

Figure 1. The European VLBI Network (EVN/JIVE).

with its correlator at the Joint Institute for VLBI ERIC - JIVE), and the Very Long Baseline Array (VLBA, operated by the US Long Baseline Observatory, LBO).

The EVN is a network of radio telescopes located primarily in Europe and Asia, with additional antennas in South Africa and Puerto Rico. It is the most sensitive VLBI array in the world, thanks to the collection of extremely large telescopes that contribute to the network (Effelsberg 100-m, Lovell 76-m, SRT 64-m, Yebes 40-m, etc.; see Fig. 1). It recently introduced real-time capability (*e*EVN). The EVN operates in frequency bands from 1.4 to 45 GHz (wavelenghts from 21 cm to 7 mm).

The EVN calls for observing proposals on Feb 1, June 1 and Oct 1, scheduling observations in three sessions each year. Selection of frequency bands for each session is based on proposal pressure. “Target of Opportunity” (ToO) and short observations can be submitted at any time. The EVN facility is open to all astronomers, and selection of proposals is based only on scientific merit and technical feasibility. Use of the network by astronomers not specialised in VLBI techniques is encouraged (see Sec. 2.2). The current Call for Proposals is available at: `http://www.evlbi.org/proposals/`

JIVE is the central organisation in the EVN. Its primary missions are to operate and further develop the EVN VLBI Data Processor and provide user support. The Institute also carries out a broad range of research and development activities in VLBI-related fields, such as radio astronomy data processing, and innovative applications of VLBI and radio astronomy technologies. JIVE staff carry out a range of cutting-edge research in various fields of Galactic and extragalactic radio astronomy and planetary and space sciences. The Institute is actively involved in a number of large international projects, such as the SKA. JIVE acts as the coordinator of several projects funded by the European Commission. JIVE is located in Dwingeloo, the Netherlands, and is hosted by ASTRON – the Netherlands Institute for Radio Astronomy. For more information, visit the websites of the EVN (`http://www.evlbi.org/`) and JIVE (`http://www.jive.eu/`).

The Very Long Baseline Array (VLBA) is a network of 10 identical antennas spread across the USA. Combining the VLBA with the phased Jansky VLA, the GBT, Arecibo, and Effelsberg, defines the High Sensitivity Array (HSA), offered for proposals with the same open-skies policy as the EVN. Combination of the VLBA with the EVN defines Global VLBI, while with some other European antennas capable of observations at 3mm wavelength collaborate in the Global Millimeter VLBI Array (GMVA). For more information, visit the websites of the GMVA (`http://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/`) and the LBO/VLBA (`https://www.lbo.us/`).

A new capability for multiline studies has been introduced through technological development in broadband receivers and the capability to perform simultaneous observations in different frequency bands. One very successful case is the Korean VLBI Network (KVN, Han *et al.* 2013), where receivers centered at 22, 43, 86 and 129 GHz allow the study of H_2O and several lines of SiO at the same time. This instrument is producing a great advance in the observational field of masers in AGBs (see e.g. Yun *et al.* 2016). However it lacks very long baselines; in this context, it should be noted that a system has been installed at the IGN Yebes 40-m radio telescope (in Guadalajara, Spain) that allows the simultaneous observation of the frequency bands centered at 22 and 43 GHz. The receiver for 86 GHz is expected to be installed in 2018, which will enhance the technical capabilities for these kinds of studies. The KVN multifrequency receivers are being installed also at the VERA array in Japan, which together with antennas in China, constitute the KaVa and East-Asia VLBI Network (EAVN). For more information, visit the websites of the KVN (`https://www.kasi.re.kr/eng/pageView/89`), VERA (`http://veraserver.mtk.nao.ac.jp/outline/index-e.html`), KaVa (KVN+VERA, `https://radio.kasi.re.kr/kava/about_kava.php`).

All these VLBI networks may cooperate in the near future to construct the *Earth VLBI Array*, a coordinated facility where astronomers can submit proposals for optimum assignment of resources and user support.

2.2. *Support to (new) VLBI users*

JIVE's mission includes supporting EVN users and operations of the EVN as a facility. These activities are conducted by a team of JIVE Support Scientists, and include proposal preparation (to be submitted using the tool NorthStar), scheduling, quality assurance for correlator data products, and/or data analysis. In this way, usage of the EVN becomes easier for astronomers not specialised in the VLBI technique. For more information, see: `http://www.jive.eu/european-vlbi-network-user-support-jive` and `http://proposal.jive.nl`

2.3. *Developments*

Under the umbrella of the EC H2020 Radionet project, a new prototype receiver for the $1.5 - 15.5$ GHz band is being developed. This receiver, known as *BRAND EVN*, will be capable of registering many maser lines simultaneously, in particular those of OH (1.6, 1.7, 4.9 and 6.0 GHz) and Methanol (6.7 and 12 GHz). The prototype will be available in 2020, and then to be considered for installation on telescopes of the EVN.

A compact version of the KVN multifrequency system can be developed for those antennas of the EVN (or other VLBI networks) which are capable of observing at higher frequencies. As mentioned above, the IGN Yebes 40-m radio telescope has installed this capability, but for other antennas, a smaller version is needed. Combined with *BRAND*, these two receivers would be all that is needed to cover the frequencies of interest between 1.5 and 110 GHz, including bands in which masers of water (22 GHz), SiO (43 and 86 GHz), HCN (89 GHz) and also methanol (44 and 95 GHz, maybe also 36 GHz) can be simmultaneously studied.

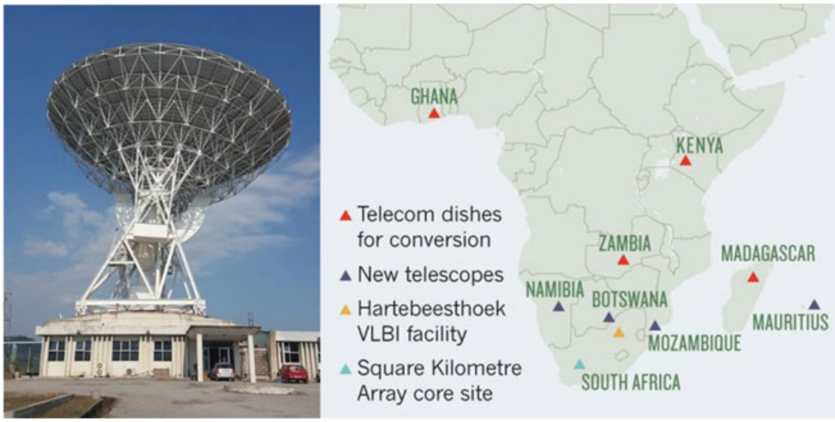

Figure 2. The Kutunse antenna in Ghana, first of the African VLBI Network (AVN) under construction.

JUMPING JIVE (for "Joining up Users for Maximizing the Profile, the Innovation and Necessary Globalization of JIVE") is an EC H2020 project that aims to enhance VLBI, and advocate JIVE and the EVN as globally recognized centres of excellence in radio astronomy. The project, coordinated by JIVE, brings together scientists and engineers to define the future of VLBI for scientific applications, and identify the necessary technological innovations. The project work packages cover a number of topics. Some of them are strategic, like encouraging existing telescopes to join the EVN, and finding new JIVE partners to expand the membership base. Others are aimed at improving the user experience, for example by developing new global interfaces (SCHED, remote control of systems), geodetic/astrometric capabilities, connecting with future instruments (like VLBI with the SKA, and training to the staff of the African VLBI Network). In addition, there are resources for dedicated outreach efforts. For more information, see `http://www.jive.eu/jumping-jive`

The African VLBI Network (AVN) aims to establish a 30-m class radio telescope in each of the partner countries (Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia, and Zambia) and link these together and with South Africa in a VLBI network, which will operate in tandem with the EVN (Fig. 2). This will be achieved through a combination of converting ex-telecommunications dishes and newly built antennas. The AVN is a vital part of the effort towards building SKA on the African continent over the next decade. The AVN dishes will provide a focus for the development of radio astronomy in each partner country so that a skilled local team is ready to install, maintain and operate the SKA outstations when they are deployed. Moreover, the aim is to establish astrophysics education and research communities in these counties as a springboard for wider technical and economic developments. The efforts are supported by the NEWTON, DARA (Developments in Africa with Radio Astronomy) networks, and JUMPING JIVE (see above) programs. The conversion at the Kutunse site in Ghana reached an important milestone with the first detection of VLBI fringes, announced in July 2017.

In order to get VLBI ready for future users, data processing also needs to be addressed. ParselTongue is developed as a scripting language based on Python that allows one to process VLBI data with classic AIPS using a modern programming language, thus making complex automated data reduction possible. The excellent support for today's web standards in Python facilitates the development of pipelines that interact easily with other programs. There is also support for accessing data in FITS files, and full access to the visibilities in AIPS UV data is also available. For more information, see: `http://www.jive.nl/jivewiki/doku.php?id=parseltongue:parseltongue` The Common Astronomy Software Applications package (CASA) is being developed by NRAO and collaborators. The package can process both interferometric and single dish data. JIVE is involved in tasks specific to VLBI, such as calibration and fringe fitting. For more information, see: `https://casa.nrao.edu/`

3. (Some) VLBI success cases on maser research

The present conference proceedings include some very good examples of the application of VLBI to the study of astrophysical masers.

Late–type stars on the Asympthotic Giant Branch (AGB) have circumstellar envelopes (CSEs) rich in molecules, in different layers, whose masers are being studied by VLBI (mostly SiO, H_2O and OH in the case of O–rich envelopes). Observations of SiO masers performed in various vibrational and rotational transitions by VLBI techniques have provided extremely valuable information on the spatial structure and dynamics of the inner circumstellar shells around AGB stars (see e.g. Desmurs *et al.* 2000, Diamond & Kemball 2003, Soria-Ruiz *et al.* 2004, Desmurs *et al.* 2014, Yun *et al.* 2016, etc.). VLBI mapping systematically shows emission clumps distributed in ring-like structures, consistent with tangential ray amplification at about 10^{14} cm from the star (~ 2 stellar radii). Comparing the observed brightness distributions in different vibrational/rotational states can be indicative of which excitation mechanisms dominate. The v=1,2 J=1→0 maser lines often occupy similar regions, but their clumps are rarely spatially coincident and the v=2 emission ring tends to be closer to the star. Recent observations by KaVA confirm this scenario by precise astrometric analysis (Yun *et al.* 2016). The standard theoretical models predict that the v=1 J=1→0 and the v=1 J=2→1 lines, with nearby energy levels and thus requiring a similar pumping mechanism, must come from the same clumps; however, observations show that the J=2→1 maser clumps occupy a clearly larger shell in the circumstellar envelope (Soria-Ruiz *et al.* 2004). However, all VLBI observations cann be affected by missing maser flux (Desmurs, these proceedings).

The observed total intensities and spatial distributions of all lines are being accurately measured only recently thanks to very good relative astrometry (see e.g. Imai, Yoon, these proceedings). Line overlap seems to be a basic phenomenon that can explain observed properties and models seem to work, at least qualitatively. In particular, they allow one to reconcile the 43 and 86 GHz observed maser distributions. These models, however, do not include the important clumpiness actually observed in VLBI maps. SiO masers can be used as well to map the magnetic field in the near stellar environment, since highly polarized ($> 20\%$) masers are probably probing the magnetic field within a few stellar radii (Vlemmings *et al.* 2005; Tobin, these proceedings).

Water masers at 22 GHz have been extensively studied by VLBI, in particular by the EVN and in combination with MERLIN. Recent developments in instrumentation explained in Sec. 2.3 now make possible simultaneous observations of multiple SiO masers (Cho, Dodson, these proceedings).

Many interesting results on star formation are being provided by instruments like VERA, in combination or cooperation with the EVN and VLBA. A multiepoch VLBI study of 22 GHz water masers in the Orion KL region detected the annual parallax to be 2.29 ± 0.10 mas, corresponding to a distance of 437 ± 19 pc from the Sun, a much more accurate value than previously obtained, with an uncertainty of only 4% (Hirota *et al.* 2007). VERA operates a dual-beam receiving system, which provides simultaneous phase-referencing VLBI astrometry. In addition, absolute proper motions of the maser features suggest an outflow motion powered by the radio Source I. Magnetic fields can also be measured using water masers, for example for the synchrotron protostellar jet in W3(H_2O) (Goddi, these proceedings).

Methanol class II masers at 6.7 GHz are well known tracers of high-mass star-forming regions. However, their origin is still not clearly understood. Studies with the EVN have provided high sensitivity images with milliarcsecond angular resolution (Bartkiewicz *et al.* 2016; Moscadelli, these proceedings). VLBI imaging of a 44 GHz class I methanol maser was performed by KaVa (Matsumoto, 2014; Kim, these proceedings), and polarization has been studied for G10.34-0.14 (Kang, these proceedigns). Attempts to detect Methanol Class-I masers at 95 GHz with VLBI have not been successful so far.

Hundreds of trigonometric parallaxes and proper motions for masers associated with young, high-mass stars have been measured with the VLBA, EVN and VERA, some with accuracies of ±10 microarseconds (Reid *et al.* 2014; Honma in these proceedings). These measurements provide strong evidence for the existence of spiral arms in the Milky Way, accurately locating many arm segments, with the widths of spiral arms increasing with distance from the Galactic center.

The combination of gas and stellar astrometry (as being provided by Gaia) will be a powerful tool to distinguish several dynamical models of galaxy rotation. Long Period Variables (LPVs), showing a well defined Period Luminosity Relation, are important distance indicators. VLBI observations of OH, H_2O and SiO masers can provide accurate distances to significant numbers of LPVs and a critical check on Gaia parallaxes of LPVs (Zhang, these proceedings).

Water megamasers can be used to test the unified model for AGNs, the need for a torus, and the physics of the central engine; actually they currently provide the only way to map the structure of circumnuclear accretion disks within a parsec of AGN supermassive black holes. Maser distance estimations can also be used to measure H_0 accurately and constrain cosmological parameters. This is the aim of the MCP (Braatz, these proceedings). OH megamasers can probe magnetic fields in starbust galaxies (Robishaw, these proceedings). SiO, H_2O and OH masers in AGB stars in the Magellanic Clouds have been used to study dust formation and mass-loss under low–metallicity conditions (van Loon *et al.* 2001). No significant differences between Galactic and MC CSEs have been found.

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