Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Exploring galactic and extragalactic masers with LLAMA

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Abstract. LLAMA (Large Latin America Millimeter/submillimeter Array) is a new radio observatory that is being constructed in a collaboration between Argentina and Brazil. It will consist of a 12 meters diameter antenna that is being installed in Alto Chorrillos at 4850 m of altitude, in the Salta province of Argentina. Alto Chorrillos is a high-quality astronomical site similar to Chajnantor (Chile), where ALMA observatory operates. When completed, LLAMA will allow line, continuum and linear polarization observations between 35 and 700 GHz, approximately. For the first light, LLAMA will be equipped with ALMA-like receivers at bands 5 (163 - 211 GHz), 6 (211 - 275 GHz) and 9 (602 - 720 GHz). LLAMA is being planned to be a versatile astronomical facility that will serve the scientific community for the exploration of scientific topics as diverse as the molecular evolution of the Universe, black holes and their accretion disks, astrophysical jets, stellar formation and evolution, the structure of our galaxy and the Sun, planetary atmospheres and extragalactic astronomy. In this work, I will present the LLAMA project and the perspectives for this new astronomical facility in the context of the investigation of galactic and extragalactic masers.

Keywords. radio observatory, LLAMA, millimeter/submillimeter astronomy

1. Introduction

Between 2004 and 2015, the Argentine Institute of Radio Astronomy (IAR) carried out a series of atmospheric transparency monitoring campaigns in the Northwest of Argentina (Salta and Jujuy provinces), in order to select suitable high altitude sites for the installation of radio astronomical instruments that could operate at millimeter and submillimeter wavelengths (Bareilles *et al.* 2011). In 2009, based on the fact that there were sites with comparable quality to Chajnantor (Chile), Brazil and Argentina began to articulate the project of a binational radio observatory.

Thus, the Large Latin American Millimeter/submillimeter Array - LLAMA - is the joint scientific and technological undertaking of Argentina and Brazil whose goal is to install and to operate an observing facility capable of performing observations of the Universe at the higher frequencies of the radio atmospheric window (Lepine *et al.* 2021). At the end of the site search, the new observatory is being constructed at 4850 m above sea level in the Puna Saltea, northwest region of Argentina, where is the selected site, called Alto Chorrillos.

LLAMA was planning to be an appropriate (sub)millimeter wave single-dish telescope (similar in performance and instrumentation to an individual ALMA antenna and/or to APEX), with the ability to be integrated as an element in Very Large Baseline Interferometric networks (VLBI), and with the room for harboring new cutting-edge instruments. Despite its binational base, LLAMA is being developed with support and collaboration of many international institutions, what will be briefly described here. As a general purpose and very sensitive radio telescope, conceived and designed to be a long-lived user observatory, LLAMA can be used to study the emission from a wide variety of astronomical sources, including galactic and extragalactic masers.

2. Overview of the LLAMA Observatory

LLAMA will consist of a 12-m ALMA-like antenna with the addition of two Nasmyth cabins, similar to APEX telescope. The requirement for the shape of the parabolic disk is to reach less than 15 μm rms adjusting its panels by using holography (e.g. Baars *et al.* 2007). The roughness of the disk surface was planned to allow to point the antenna towards the Sun, making LLAMA a unique facility to explore high frequency solar emissions at several timescales. The antenna pointing precision was specified to be better than 2 arcseconds.

As said before, the observatory is being constructed in a new astronomical site at Alto Chorrillos, 4850 m above sea level. When completed, LLAMA will be equipped with six ALMA-like receivers covering bands 1, 2+3, 5, 6, 7, and 9 (35 - 700 GHz), which will populate the two Nasmyth cabins. Besides, invited instruments can be installed at the Cassegrain cabin. The concept of LLAMA cover the capability to obtain continuum, spectral, polarization and Solar observations, including the possibility for carrying out simultaneous observations at two or more bands. Each Nasmyth cabin can be equipped with one cryostat housing three ALMA-like receivers.

At the beginning of the scientific operations, it is expected to have three receivers at bands 5 (163 - 211 GHz), 6 (211 - 275 GHz) and 9 (602 - 720 GHz). While bands 6 and 9 receivers were made possible mainly in collaboration with NOVA-Groningen (Netherlands), band 5 receiver is a former prototype for ALMA Observatory refurbished by GARD (Gothenburg, Sweden), NOVA and offered by European Southern Observatory (ESO) for LLAMA as a permanent loan. Besides, a band 2+3 receiver (67 - 116 GHz) is being developed by the Universidad de Chile (Reeves *et al.* 2023), but it is not expected to be available for the first light.

One of the most complex developments for LLAMA is the Nasmyth Cabin Optical System (NACOS). It is the optical-electrical-mechanical instrument that will guide the mm/sub-mm waves collected by the antenna to the receivers. For the first light, only one of the cabins will be populated with a cryostat and three receivers (bands 5, 6 and 9). NACOS includes a robotic arm with three calibration loads (two hot and one at room temperature), subsystem being developed in collaboration with Universidad de Concepcin (Chile, Reeves *et al.* 2023). In Fig. 1 we can see a schematic view of NACOS for the first light, with the components of the Cassegrain and of one of the Nasmyth cabins. While NACOS is not complete, enabling the use of the second Nasmyth cabin, band 2+3 receiver is planned to be installed in the Cassegrain cabin for commissioning and initial science operations. Besides the construction of the expansion for the second Nasmyth Cabin, the long-term completion of NACOS implies in a redistribution of the receivers between the cabins and the replacement of flat mirrors by dichroics, what will allow simultaneous observations among some of the receivers in both and within a single Nasmyth cabin.

The site infrastructure has been evolving (Fig. 2). A road to access the site was constructed, as well as a flat area for the antenna assembly. The antenna foundation and anchor ring installation were successfully concluded at the beginning of 2023. All components of the antenna are in the site and its assembly must be completed by the end of this year. After that, the Assembly, Integration and Verification (AIV) phase will start. Some of the most important milestones of the project are the so-called "Eyes Opening",

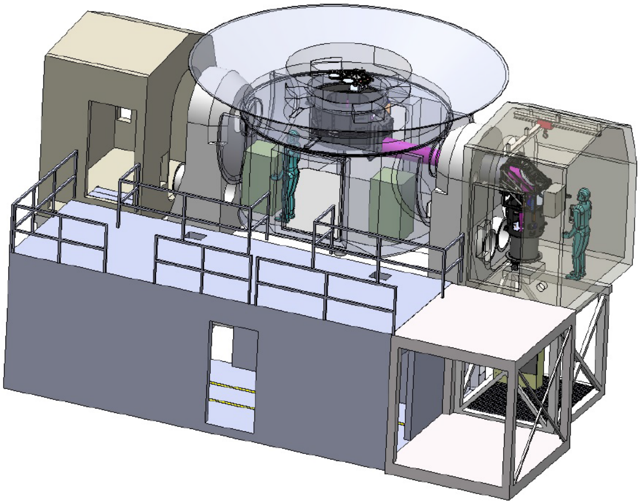

Figure 1. Schematic view of NACOS for LLAMA's first light, for which only one Nasmyth cabin will be populated.

Figure 2. View of LLAMA site at Alto Chorrillos (Argentina) from the approximated position where the holographic tower is now installed.

defined as the preliminary uncalibrated measurement of the continuum and spectrum of a standard object in one of the receivers, and the "First Light", the preliminary calibrated measurement of the continuum flux and spectrum of a standard object in one of the receivers. "Eyes Opening" is expected from the end of 2024 and the "First Light" should be reached six to twelve months after "Eyes Opening".

3. Cosmic Masers with LLAMA

Eight key scientific topics and niches were identified for LLAMA: planetary atmospheres, LLAMA as part of VLBI networks, time domain (sub)mm astronomy, solar physics, interstellar medium, astrochemistry, magnetic fields and extragalactic astronomy. Most of these subjects are related with or can be investigated through maser emission. Particularly interesting is the the variability detected in several maser species in different astronomical scenarios. Time domain submillimeter astronomy is a window of opportunities for future facilities like LLAMA, along with the importance of the improvement of submillimeter calibration techniques. LLAMA will be able to contribute by

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monitoring a large number of masers species with high temporal resolution and and large temporal coverage. It will probe different transitions and vibrational states simultaneously, which is crucial to find out the physical conditions and investigate the pumping mechanism producing the maser effect. Even as a single dish, LLAMA can be used to study the inner parts of AGNs orbited by clouds showing water megamaser emission.

During Cosmic Masers IAU Conference, several speaker reinforced the relevance of a new facility operating at LLAMA's frequencies. A few examples include SiO maser monitoring at 86 GHz (J=2-1; band 2+3) in AGB/RGB stars (Lorant Sjouwermans talk); HCN (around 176 GHz, band 5) to explore inner regions of CSE in Carbon-rich AGB stars (Lynn Matthews); H_2O at 183 GHz (band 5) in ULIRGs, including linear polarization measurements (Masatoshi Imanishis talk) and methanol masers at 349 GHz (band 7, Alberto Sannas talk). Surveys as Nearby Evolved Star Survey (NESS, Scicluna *et al.* 2022), using single dish observations obtained with JCMT and APEX, and Bulge Asymmetries and Dynamical Evolution (BAaDE, Stroh *et al.* 2019), based on ALMA observations at 86 GHz (band 2+3) are good examples of large survey programs that can be implemented and or extended using single dishes like LLAMA or through interferometric experiments at those and higher radio frequencies.

In fact, LLAMA is a promising observatory in the context of VLBI networks. In particular, the collaboration intends to be part of the next generation Event Horizon Telescope (ngEHT), as LLAMA could be a key station for that experiment (e.g. Raymond *et al.* 2021). The ngEHT has among its science cases the observation of maser spectral lines in Galactic star-forming regions and evolved stars at 86, 230 and 345 GHz (Richard Dodson's talk).

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