

RADIO ASTRONOMY IN MEXICO: AN HISTORICAL PERSPECTIVE

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Abstract: Radio astronomy in Mexico developed comparatively late, beginning in the late 1970s, and for several decades progressed without national radio facilities. This review traces the historical evolution of the field in Mexico, emphasizing the role of individual researchers, institutional frameworks, and international collaborations that enabled the growth of a nationally based radio astronomy community. Early progress relied heavily on open-skies access to major international facilities, particularly those of the U.S. National Radio Astronomy Observatory, and led to Mexican participation in key instrumental developments such as the upgrade of the Very Large Array.

A major milestone was the design and construction of the Large Millimeter Telescope in Mexico, which in due course became a crucial element of the Event Horizon Telescope and contributed to the first images of supermassive black holes. Alongside instrumental advances, Mexican radio astronomers have made influential contributions to a wide range of research areas, most notably star and planet formation, including protostellar jets,

protoplanetary and debris disks, astrochemistry, and proto-brown dwarfs, as well as to stellar radio astronomy, ultra-high precision astrometry, exoplanet searches, radio surveys, and studies of galaxies and black holes.

By situating these scientific achievements within their historical and institutional context, this review highlights how radio astronomy in Mexico evolved from an emerging activity into an internationally visible body of work, and discusses its prospective role in future facilities such as the next-generation Very Large Array.

Keywords: history of radio astronomy; Mexico; astronomical institutions; radio telescopes; Large Millimeter Telescope; Very Large Array; international scientific collaboration; scientific heritage.

1 INTRODUCTION [L.F.R.]

Astronomy has always been a part of Mexican culture. The pre-Hispanic civilizations, in particular the Mayan, had a detailed knowledge of the cycles of celestial bodies like Venus and the Moon (e.g., [Aveni, 2010](#)). After the Spanish conquest, astronomical activity was severely reduced, although during the Colonial period¹ there were always a few active astronomers who kept the tradition alive. It was only at the end of the nineteenth century that astronomy recovered relevance with the foundation, in 1878, of the National Observatory by President Porfirio Díaz (1830–1915).

By 1960, optical astronomy in Mexico was well established. During the previous decade, Guillermo Haro (1913–1988) and his collaborators had made several significant contributions, among them the co-discovery of the Herbig–Haro objects and the detection of many flare stars, planetary nebulae, blue objects, including quasars at high Galactic latitude (in the direction of the Galactic poles), and galaxies with bursts of star formation ([Peimbert, 2014](#)).

However, all activity had been confined to the optical window of the electromagnetic spectrum. The first excursion outside this window was made by Eugenio Mendoza, who in 1966 used the infrared telescopes of the Lunar and Planetary Laboratory of the University of Arizona to discover the infrared excesses that characterize young stars ([Mendoza, 1966](#)).

1.1 The First Radio Astronomers

In 1978, Luis F. Rodríguez received his PhD in Astronomy from Harvard University and returned to Mexico in search of a position. He wrote his thesis on the topic of radio recombination lines ([Rodríguez, 1978](#)), studying the ionized gas in Galactic HII regions and in the Galactic Center, under the direction of Eric J. Chaisson. In 1974, Rodríguez had arrived in Cambridge, Massachusetts, with the intent to do research in optical astronomy, following the Mexican tradition. However, once there, he discovered that astronomy was being made all across the electromagnetic spectrum and concluded that bringing one of these ‘new’ astronomies to his country would be a good idea. The link with the Mexican lore was not entirely bro-

ken because, while in the radio, he studied photoionized gas, the area of his undergraduate thesis in physics, researched under the advice of Silvia Torres-Peimbert.

At the time, radio astronomy was a very mature field in developed nations, and it was possible for investigators of countries without radio facilities to obtain time at observatories in those nations. This was true in the case of the National Radio Astronomy Observatory of the United States of America, which maintained a policy of ‘open skies’ and thus allocated time to competitive projects from any country. Rodríguez and young Mexican and Spanish radio astronomers, such as Salvador Curiel, Jose A. García-Barreto, Yolanda Gómez, Jose M. Torrelles, and Guillem Anglada, took advantage of this policy and started doing research and forming young investigators in radio astronomy.

Over the years, the number of radio astronomers working in Mexico grew to its present number of about 25, most of them at the Institute of Radio Astronomy and Astrophysics (IRyA) of the National Autonomous University of Mexico (UNAM), and at the National Institute of Astrophysics, Optics and Electronics (INAOE). This may appear small, but one has to remember that the total number of astronomers in Mexico at present is only around 160. The Mexican radio astronomers benefitted from their collaboration with US institutions, in particular the National Radio Astronomy Observatory (NRAO). An important instance was the participation of Mexico in the upgrade of the Very Large Array (VLA), which transformed it into the Karl G. Jansky VLA. Although in monetary terms the participation of Mexico was modest, it was provided very early in the game, and contributed to build the first set of 7 mm receivers and thus stimulate the rest of the project. A similar collaboration years later went into installing hardware on the NRAO Very Large Baseline Array (VLBA) interferometer that helped to significantly improve its sensitivity.

A very important instrumental project for Mexico was the design and construction of the Large Millimeter Telescope, as a collaboration between INAOE and the University of Massachusetts. This radio telescope has been used both as a single dish to study different astronomical sources and, importantly, as part of the

Event Horizon Telescope, the interferometer that secured the first images of the surroundings of supermassive black holes.

The major challenge for the future is to secure the participation of Mexico in the next generation VLA (ngVLA), the most powerful centimeter interferometer for the twenty-first century. This instrument will not only provide unprecedented sensitivity and angular resolution, but will also be a logistic test, with more than 200 antennas distributed in the South of the US and the North of Mexico.

In what follows, we describe the contributions of radio astronomers in Mexico to different areas of astronomy. We also recount the design and construction of the first Mexican radio facilities, and Mexico's participation in past and future international collaborations.

1.2 Star and Planet Formation

By 1980, the field of star formation was at an impasse. The birth of new stars and planets was expected to be characterized by infall motions, as the maternal cloud fed a protoplanetary disk and, in turn, this disk fed the growing star. But these infall motions were nowhere to be found. Surprisingly, in 1980, two groups (Rodríguez et al., 1980; Snell et al., 1980) reported powerful outflow motions in two regions of star formation. How was this possible? It took several years of work by several groups to come up with the solution: in star formation, infall and outflow motions coexist and, as a matter of fact, have a symbiotic relationship. The infall motions are hard to detect but they, in fact, feed the protoplanetary disk with mass and angular momentum. For mass to be accreted by the star, it needs to lose angular momentum. Magnetic fields accelerate and collimate a bipolar outflow that removes the excess angular momentum (Blandford and Payne, 1982).

These outflows usually have a bipolar morphology, with one lobe approaching us and the other one receding, and are best detected in molecular emission. Hence, they became known as bipolar molecular outflows. They can be associated with shocked regions visible in the optical: the Herbig–Haro objects discovered decades before by George H. Herbig (1951) and Guillermo Haro (1952). Over time, a large number of bipolar molecular outflows were detected (e.g., Bachiller, 1996).

2 PROTOSTELLAR JETS [C.C.]

Mexican radio astronomers have been fundamental in the discovery and subsequent study of protostellar jets; they have produced hundreds of pioneer works about radio jets and

their association with protostars. The earliest clear evidence of material outflowing from a protostar was obtained through radio maps of the molecular emission in the Cepheus A star-forming region (Rodríguez et al., 1980). See Figure 1.

The earliest detections of radio emission associated with the driving sources of the outflows were performed during the 1980s and 1990s; tens of works reported these radio sources and their association with outflows (e.g., Curiel et al., 1989a; 1989b; 1990; 1993; Rodríguez et al., 1989a; 1989b; 1994a; 1994b; 1997; Rodríguez and Reipurth, 1989; Estalella et al., 1991; Anglada et al., 1991; 1992; Raga et al., 1993; Rodríguez and Reipurth, 1994). At the end of the 1990s, the number of radio sources was enough to perform statistics. It was established that the radio continuum emission is due to shock ionized gas in collimated winds or jets, and these sources came to be known as thermal radio jets

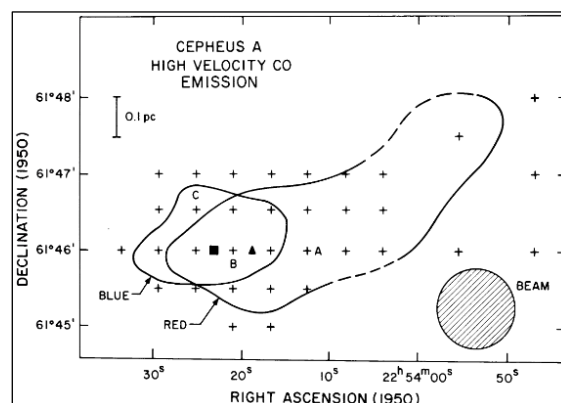


Figure 1: First detection of a molecular outflow associated with a protostar in the Cepheus star-forming region (after Rodríguez et al., 1980: L150).

(Anglada et al., 1998; Rodríguez et al., 1999). During the 2000s more systems were detected and, more importantly, observations with higher angular resolution allowed discerning the elongated morphology of the jets and measuring the proper motions of knots (e.g., Rodríguez et al., 2000; 2001; 2003). Most of the initial detections were in low-mass protostars in nearby star-forming regions, but the higher resolution permitted the identification of jets associated with massive protostars, which are commonly located further away (e.g., Rodríguez et al., 2005; 2008; Curiel et al., 2006; Trinidad et al., 2006; Zapata et al., 2009; 2011a). With multiwavelength observations, it was possible to characterize the radio spectrum and detect disks at shorter wavelengths (e.g., Carrasco-González et al., 2008; 2009; 2010a; 2012). Since the earliest detections, some objects showed hints of non-thermal emission, which was confirmed as synchrotron emission thanks to the detection of polarization (Carrasco-González et al., 2010b).

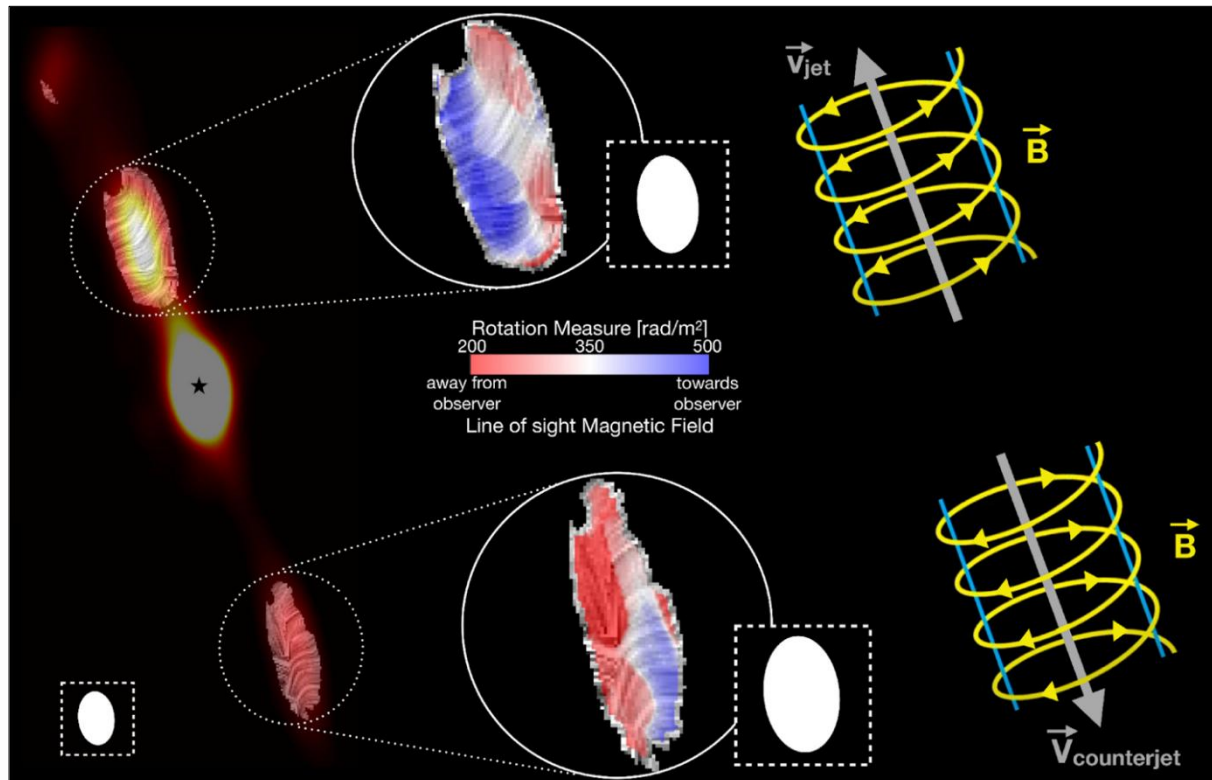


Figure 2: Mapping of a helical magnetic field in the HH 80-81 protostellar jet (after Rodríguez-Kamenetzky et al., 2025: 6).

A series of works in the 2010s concluded that non-thermal emission in protostellar jets is due to a small population of relativistic particles accelerated in strong shocks against the ambient medium (Rodríguez-Kamenetzky et al., 2016; 2017; 2019). Deep radio observations of the polarization properties also allowed the mapping of a helical magnetic field for the first time in a protostellar jet (Figure 2), which confirmed the fundamental role of magnetic fields in jet collimation (Rodríguez-Kamenetzky et al.,

2025). In recent years, thanks to much higher angular resolution, it has been possible to resolve the launch and collimation regions of jets, and to distinguish between different collimation mechanisms (Carrasco-González et al., 2015; 2021; Rodríguez-Kamenetzky et al., 2022). Most of what is currently known about radio emission from protostellar jets is summarized in a recent review by Mexican astronomers (Anglada, et al., 2018).

3 PROTOPLANETARY DISKS [C.C.]

The earliest attempts to detect dust emission in disks around protostars were made with Very Large Array (VLA; Napier et al., 1983) 1.3 cm continuum observations (Rodríguez et al., 1992; 1994a). Although dust was indeed present, it was challenging to study because a large portion of the detected emission was due to free-free radiation from the winds. These works highlighted the need to observe at shorter wavelengths and with higher angular resolutions. By 1990, the VLA started to use new 7 mm detectors that expanded its capabilities to shorter wavelengths. Through Dr. Luis Rodríguez, Mexico had a fundamental role in this development. VLA observations at 7 mm allowed the first clear detections of dust around solar-mass protostars (Wilner et al., 1996; 2000)—see Figure 3. These early works permitted the detection and characterization of the emission, but only

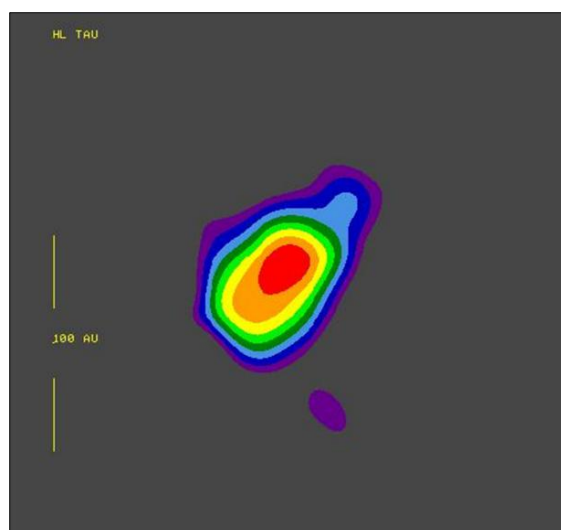


Figure 3: The earliest detection of resolved dust thermal emission in a protoplanetary disk (HL Tau), with VLA observations (cf. Wilner et al., 1996; 2000).

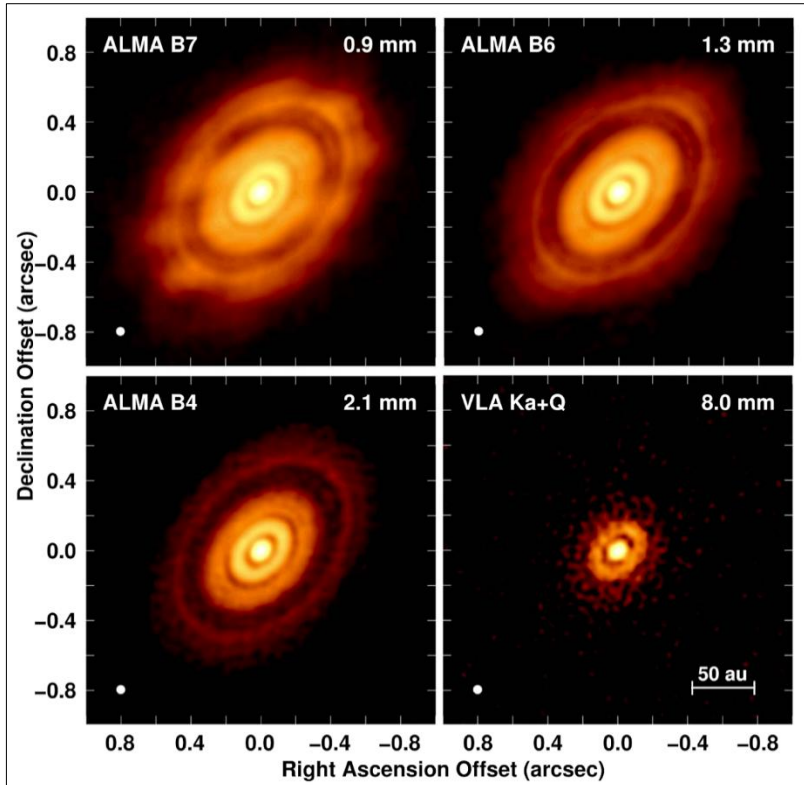
Figure 4: Observations of the dust emission in the protoplanetary disk of HL Tau, using ALMA and VLA data (after Carrasco-González et al., 2019: 4).

marginally resolved the morphology of the disks; the observations lacked sensitivity and, hence, disk sizes could be estimated, but their radial structure could not be studied. However, observations at 7 mm, of which no other instrument in the world was capable at that moment, were fundamental to detecting disks around binaries (Rodríguez et al., 1998). The main finding was that disks in binaries were truncated by gravitational interactions and, therefore, were more compact than in single stars.

In parallel with the observational efforts, the Mexican community was involved in some of the earliest theoretical models of dust emission in protoplanetary disks; the physical properties of the disks could then be obtained from IR and radio observations. Paola D'Alessio led this work in a series of papers that explored the structure of the disks, their dust properties, and dust growth (D'Alessio et al., 1997; 1998; 1999; 2001; 2006). The international community then used these models to characterize the disks' properties from unresolved multiwavelength observations.

During the first decade of the twenty-first century, significant improvements in the observing capabilities at millimeter wavelengths started to take place. First, an upgrade of the VLA receivers finally made it possible to perform high-sensitivity observations at high frequencies, thus allowing dust emission to be observed with the maximum possible resolution. From then on, it was possible with the VLA to resolve the disk structure and to detect sub-structures related to planet formation (Carrasco-González et al., 2009; 2016). At the same time, the Atacama Large Millimeter Array (ALMA; Wootten and Thompson, 2009), a new interferometer working at shorter wavelengths, started to systematically detect substructures, i.e., bright and dark rings, in disks. The Mexican community led works combining ALMA and VLA data in order to study the dust properties in the disks (Carrasco-González et al., 2019; Macías, et al., 2021). These works were of great importance, since they

(1) imposed the first constraints on particle



sizes for disks of different ages, and

(2) demonstrated the association of bright rings with high-density regions and of dark rings with low-density regions. Today, it is believed that planetesimals form in high-density rings.

See Figure 4.

However, because of the lack of short baselines, ALMA was not a good instrument for observing very extended sources. Debris disks are better observed with the Large Millimeter Telescope (LMT; Chávez-Dagostino et al., 2016), which has the highest sensitivity to perform this kind of work and is located in Mexico.

Starting in 2010, the Mexican community has led theoretical developments in the field, related to, among other issues, the influence of magnetic fields on disk structure and evolution (Lizano et al., 2010; 2016; Tapia and Lizano, 2017); the effects on the emission of dust growth, dust segregation, and dust concentration (Sierra et al., 2017; 2019; Tapia et al., 2019); the evolution of the disks' inner regions (Manzo Martínez et al., 2020). There have also been works studying how different phenomena manifested themselves with the higher angular resolution observations then possible: scattering, temperature gradients, and dust settling (Sierra and Lizano, 2020), as well as self-obscuration in very young stars (Galvan-Madrid et al., 2018). These are now all fully taken into account by the international astronomical community.

3.1 Proto-Brown Dwarfs [A.P.]

Brown dwarfs are objects that do not have enough mass to fuse hydrogen in their interiors ($< 0.075 M_{\odot}$). Discovered in 1995 by independent groups, the formation of these intriguing objects posed a problem, with two main scenarios widely debated in the literature: the star-like and the planet-like scenarios (see Palau et al., 2024, and references therein). In the star-like scenario, brown dwarfs would be the natural lower-end outcome of the fragmentation process in molecular clouds, explored by Mexican astronomers in recent years (e.g., Palau et al., 2021, and references therein). In the planet-like scenario, brown dwarfs would be the result of core accretion or disk fragmentation in protostellar disks, which form planetary seeds, but would be ejected after a dynamical interaction.

Almost simultaneously with their discovery, there were pioneering searches for their precursors, which would be very low-mass dense cores undergoing gravitational collapse, if they were formed as scaled-down versions of low-mass stars. However, while these systematic searches did not result in clear candidates (Palau et al., 2024), serendipitous discoveries were carried out by Mexican astronomers that provided convincing cases of brown dwarfs forming as scaled-down versions of low-mass stars, in particular, in their most embedded stages, the so-called proto-brown dwarfs. This is the case of IC348-SMM2E, an object identified about 10" northeast of a solar-type, deeply embedded, object in the IC348 cluster (Palau et al., 2014). This object, for which a rotating structure perpendicular to the outflow was identified, later was confirmed to be driving a thermal radiojet (Rodríguez et al., 2017). Motivated by this detection of a thermal radiojet associated with a proto-brown dwarf, subsequent works searched for thermal radio emission from proto-brown dwarf candidates, and found several thermal centimeter sources (e.g., Rodríguez et al., 2017, and references therein), thus making this a promising way of searching for these elusive objects. Thermal emission has also been found by Mexican astronomers towards the so-called Jupiter Mass Binary Objects, discovered in Orion by the James Webb Space Telescope, whose nature is currently being intensely debated (see Rodríguez et al., 2024).

Very recently, Mexican astronomers have reviewed the main observational strategies used in the literature to search for proto-brown dwarfs; have presented a compilation of promising candidates with ALMA counterparts; and have explored their relationships with several clouds in the solar neighbourhood (Palau et al., 2024). This research shows that proto-brown

dwarfs seem to follow the well-known correlations of protostellar objects, between their bolometric luminosities and their ejection/accretion properties. What is more, it seems that the lower-end of the Initial Mass Function could be affected by the stellar feedback from high-mass stars near molecular clouds. This is based on the detection of a deficit of planetary-mass proto-brown dwarfs (the so-called Free Floating Planets) in clouds bathed in and heated by the energetic photons of nearby OB associations. Overall, this research line has been actively explored by Mexican astronomers for more than 10 years now, and future observing strategies are currently being designed as a preparation for the upcoming new instrumentation, such as the ngVLA.

4 CHEMISTRY IN STAR-FORMING REGIONS [A.P.]

Radio astronomy, in particular millimeter astronomy, has played a crucial role in characterizing the chemistry of star-forming regions. The millimeter range covers the frequencies where many molecules in star-forming regions have most of their detectable rotational transitions. Since the discovery of the first molecule in the interstellar medium, methylidyne (CH), by Swings and Rosenfeld (1937), many works have revealed an increasing complexity in the chemistry of star-forming regions. A crucial discovery was carried out in 1979 by Paul T.P. Ho and collaborators: they found a dense core in the Orion molecular cloud that presented unusually high temperatures, and called it a 'hot core'. In the mid-1990s, R. Cesaroni, C.M. Walmsley, and E. Churchwell found that hot cores in high-mass star-forming regions present a particularly rich chemistry, and that they are characterized by high temperatures (> 100 K), high densities ($> 10^7 \text{ cm}^{-3}$), and compact sizes (< 0.1 pc). These physical conditions are the right ones to release complex organic molecules from dust grains to the gas phase and make them detectable. Also at this time, Stan Kurtz was Edward Churchwell's student, and he took the lead in this research. He led the team that published a chapter in the book *Protostars and Planets IV* (Kurtz et al., 2000), where the main observational results of the earliest phases of high-mass star formation and of hot molecular cores were presented. There, hot molecular cores were proposed to be a stage prior to ultra-compact HII regions. This was later confirmed by many observations, and the chapter has received many citations. In some cases, the molecular emission in massive star-forming regions was found to be masing, mainly in OH, H₂O and CH₃OH (e.g., Kurtz et al., 2004).

Later, other astronomers in Mexico from different institutions continued the research on (complex) chemistry in high-mass star-forming regions, including researchers from the Universidad Nacional Autónoma de México (UNAM, Michoacán, e.g., [Zapata et al., 2007](#); [Franco-Hernández et al., 2009](#)); Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE, Puebla), using the Large Millimeter Telescope (e.g., [Gómez-Ruíz et al., 2017](#)); and the Universidad de Guanajuato (Guanajuato, e.g., [Trinidad and Verbená, 2023](#)), among others. In most cases, the origin of the complex chemistry was assumed to be closely related to the immediate surroundings of high-mass protostars. However, Mexican astronomers proposed that the complex chemistry could also arise from shocks ([Zapata et al., 2011b](#); [Palau et al., 2017](#); [Rojas-García et al., 2024](#)), and this is currently a very active research area.

5 COMPACT RADIO SOURCES IN THE HEARTS OF ULTRACOMPACT HII REGIONS [S.D.]

Ultracompact HII (UCHII) regions represent an early phase in the evolution of HII regions, and are associated with massive star formation. Known UCHII regions are located at distances beyond 1 kpc and, thus, have small angular sizes of only a few arcseconds. One of the earliest Mexican contributions to this field was the detection of compact radio sources at the centers of some UCHII regions ([Carral et al., 2002](#)). This was a great accomplishment, given their small angular size. Because they are located near the center of the ionized material, they were assumed to be associated with the radio emission from the stellar winds of the massive star ionizing the UCHII region. However, these findings remained largely unexplored in the years following their discovery.

Years later, high-angular resolution (0.05") VLA observations, led by then Centro de Radioastronomía y Astrofísica (CRyA, UNAM) graduate student S. Dzib, detected a time-variable radio source near the center of the UCHII region W3(OH), not included in earlier studies. The newly discovered source was proposed to be a fossil photoevaporated disk rather than a simple stellar wind, due to its unexpectedly high flux density. Later, deeper observations showed that this radio source is connected to the brightest part of the region through a narrow structure. Several hypotheses were proposed regarding the nature of this structure, including a proplyd's tail, a photoevaporated filament, or a collimated jet. However, its true nature remains uncertain. These were the first in a series of studies dedicated to observing these intriguing compact radio sources inside the UCHII regions.

As summarized by [Yanza et al. \(2026\)](#), recent results obtained by Mexican radio astronomers show that the origin of compact radio sources is diverse. They can be magnetically active low-mass stars, ionized stellar envelopes, and bow shock structures that can arise from either a wind collision region or a runaway star. In addition to these types of sources, there is the well-known case of the proplyds, protoplanetary disks that are being externally ionized by the OB stars in the region ([O'Dell et al., 1993](#)), and that are compact radio sources. In some cases, multiple compact radio sources with different physical origins coexist within a single UCHII region, as demonstrated in DR 21, where up to 10 radio sources were detected well inside the young HII region.

The discovery of compact radio sources within UCHII regions has opened new avenues for understanding the earliest phases of massive star formation. These studies show pioneering discoveries led by Mexican radio astronomers, which have increased our knowledge of the interplay between massive stars and their surrounding ionized environments. As radio facilities continue to advance, future high-resolution observations will be critical in resolving the mysteries of these compact sources, providing further insights into the complex nature of massive star formation.

6 STELLAR RADIO ASTRONOMY AND ULTRA-HIGH PRECISION ASTROMETRY [L.L. and S.D.]

6.1 The Quest for Radio Stars

Radio emission associated with stars often does not originate in the stars themselves but, rather, from thermal emission from their circumstellar disks, envelopes, or jets. In contrast, magnetically active stars produce radio emission from magnetic reconnection events on their surfaces, a process that generates non-thermal emission, typically through gyrosynchrotron or the electron cyclotron maser mechanism. In this specific case, the radio emission comes from the surface of the stars themselves. There are advantages to studying radio stars. First, the stellar motion can be precisely tracked using interferometric multi-epoch observations. Second, coronal radio emission has brightness temperatures above a million Kelvins; hence, it is detectable with the Very Long Baseline Interferometry (VLBI) technique.

Between the years 2005 and 2010, VLBI studies, many of them conducted in Mexico, demonstrated that magnetically active young stars could be used for high-precision astrometry (e.g., [Loinard et al., 2007](#); [Torres et al., 2007](#); [Dzib et al., 2010](#)), enabling distance de-

terminations to stars with accuracies around 1%. These efforts, led by Laurent Loinard alongside doctoral students Rosa Torres and Sergio Dzib, played a pivotal role in refining distance measurements to star-forming regions. Notably, the accuracies they achieved were not matched by any other instrument until the arrival of the Gaia telescope more than a decade later. However, during these years, very few radio sources were unambiguously associated with magnetically active young stars, prompting a dedicated effort to identify more such sources while continuing to explore the distances to other star-forming regions (Dzib et al., 2011).

During these years, emerging evidence suggested that star-forming regions contain many radio sources associated with stars. However, the available information was insufficient to determine whether these were radio stars or if the emission originated from other phenomena associated with young stars. VLBI observations were strongly limited to distinguish between these possibilities, for two main reasons. First, VLBI observations could only target one star per observation and, second, radio stars are highly variable, meaning that a non-detection does not necessarily rule out a source as a radio star. Therefore, the search had to shift toward using the VLA as the primary detection instrument. While VLA observations do not have the angular resolution achieved with VLBI, they do not have the field-of-view limitations of VLBI and can simultaneously study multiple radio sources. The search focused on prominent nearby star-forming regions from the Gould's Belt: Ophiuchus, Taurus, Orion, Serpens, and Perseus.

The Gould's Belt Very Large Array Survey (GBS-VLA) was an international effort involving Mexican PhD students, aimed at detecting stars displaying non-thermal radio emission (Dzib et al., 2013). This project was launched at the end of 2010, as an aside and precursor to the Gould's Belt VLBA Distance Survey (GOBELINS), which will be discussed later. The launch of the GBS-VLA project coincided with a transformative period for the VLA. In 2010, the VLA was finalizing a major technological upgrade, replacing its old electronic system with a new, state-of-the-art one, while keeping the same antennas. The upgraded facility was named the Karl G. Jansky Very Large Array, maintaining the acronym VLA.² The new VLA generated significantly larger data volumes, with enhanced sensitivity, wider bandwidths, and improved spectral capabilities compared to its predecessor. However, its calibration and imaging procedures were not yet fully established, and its full capabilities were not publicly available until 2012. The National Radio Astron-

omy Observatory (NRAO) introduced the Resident Share Risk Observer (RSRO) program, which allowed early access to the new VLA capabilities. Advanced projects were selected, and one researcher associated with each selected project had to reside in Socorro, New Mexico, to assist in the telescope's commissioning efforts. The GBS-VLA was one of these selected advanced projects. In 2011, S. Dzib spent six months in Socorro (the only Mexican and one of the few PhD students awarded an RSRO residence) and gained early access to new VLA capabilities, amounting to 120 hours of telescope time for the GBS-VLA project. In Socorro, S. Dzib helped with the early development of pipelines to calibrate VLA data in general, and to calibrate and image some test observations in particular. While doing these tasks, he also designed all the GBS-VLA observations and began the data calibration of the recently acquired data.

The idea of the GBS-VLA project was to use the most extended configurations of the VLA (A and B) to observe these regions with high angular resolution in three epochs. The detected sources were characterized by looking into variability, circular polarization, and their in-band spectral indices, a brand-new VLA capability. These parameters helped determine whether the emission originates from thermal or non-thermal processes. Sources were also compared with the results at other wavelengths, which provided ages, spectral types, and evolutionary status for many of the targeted sources. The results were published in a series of papers led by PhD students (see Dzib et al., 2013 and associated papers). Beyond providing a target list for future VLBI experiments, the most significant results of GBS-VLA included:

- (1) a clear tendency for the fraction of non-thermal sources to increase from the younger (Class 0/I or flat spectrum) to the more evolved (Class III or weak line T Tauri) young stars;
- (2) about half of the radio sources associated with stars have properties suggesting that they are related to the stellar magnetic activity;
- (3) a comparison with X-ray results showed that the detected young stars follow the Güdel–Benz relation observed for magnetically active main-sequence stars, although with a lower normalization factor.

The efforts to determine the origin of radio emission from young stars did not conclude with the completion of the GBS-VLA project. Using the full VLA capabilities, significant results were obtained in subsequent years, some led by Mexican students, such as Sac Medina, or for-

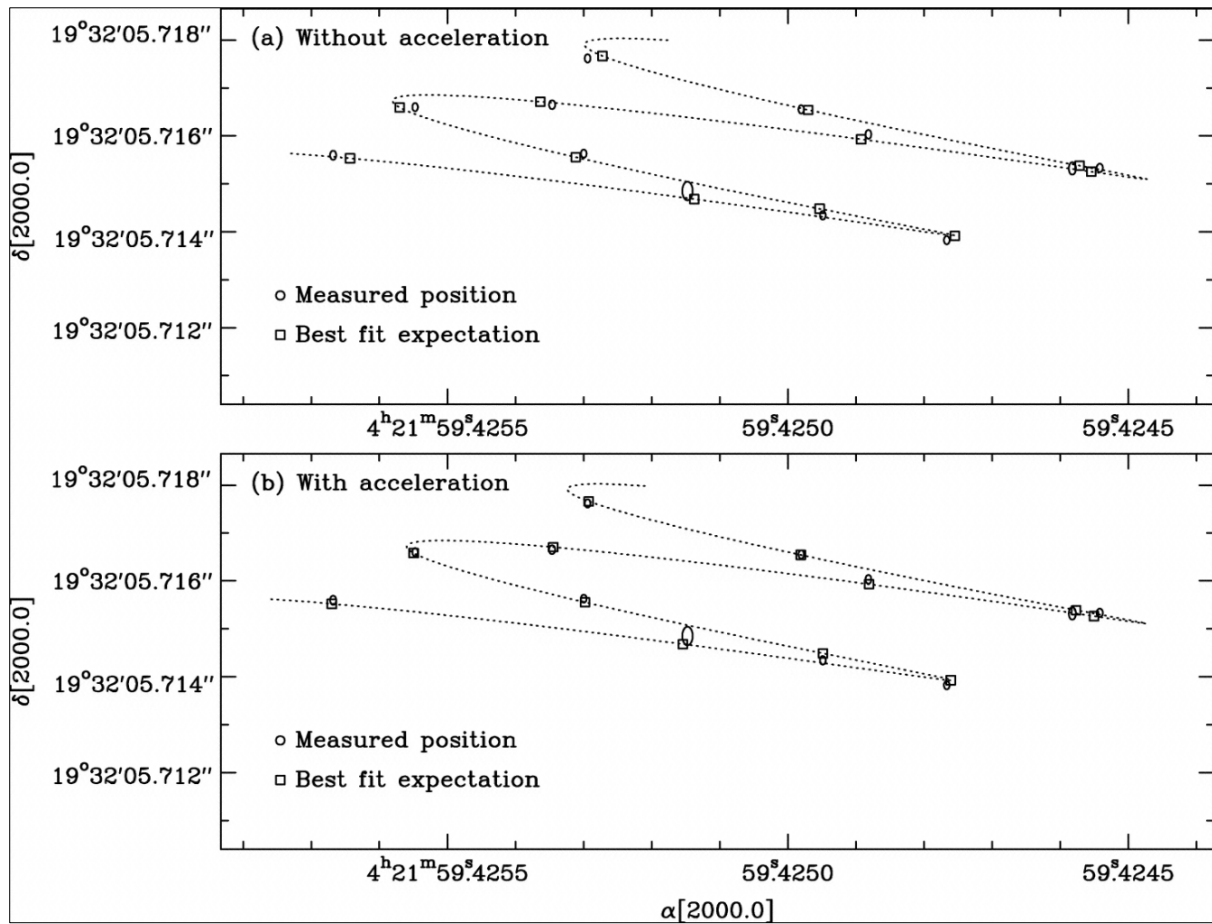


Figure 5: Measured VLBI positions of T Tau Sb and best fits, both (a) without and (b) with acceleration terms. The observed positions are shown as ellipses, the size of which represents the magnitude of the errors. Note the very significant improvement when acceleration terms are included (adapted from Loinard et al., 2007: 549).

eight students affiliated with Mexican universities, like the Colombian Vanessa Yanza. These works extended the search for radio stars, both to other Gould's Belt regions, like Barnard 59 and Lupus 1, and to more distant ones, like HH 124 IRS, NGC 6334, M 17, and DR 21. These endeavors also include the search for radio emission from 'old' pre-main sequence stars unrelated to major star-forming regions but at distances below 100 pc. The search also involved images from extensive VLA surveys, like the Global View of Star formation with the VLA (GLOSTAR-VLA; Medina et al., 2024) and the VLA Sky Survey (VLASS; Loinard et al., in preparation). In general, the results obtained align very well with those from the GBS-VLA.

These results show the importance of characterizing the radio emission from young stars, particularly while preparing for the next revolution in radio astronomy: the next generation Very Large Array (ngVLA). With some antennas located in Mexican territory, Mexican radio astronomers will have privileged early access to the ngVLA. Building on decades of expertise, they are well-positioned to lead groundbreaking

studies of stellar magnetism and radio emission mechanisms in the upcoming era of ultra-high-resolution and ultra-high-sensitivity radio astronomy.

6.2 Ultra-precise Distances

Observations of non-thermal radio sources at centimeter wavelengths with VLBI instruments enable the determination of their position on the celestial sphere with an accuracy of >0.1 milliarcseconds (mas). Thus, by combining at least four observations distributed over a year or more, the parallax and proper motion of sources of interest can be measured with an accuracy of >20 microarcseconds (μ as). This is comparable to the accuracy delivered in the third data release of the Gaia satellite, and corresponds to an accuracy of the order of 1% for sources within a few hundred parsecs. As an example, we show the case of the young star T Tauri Sb in Figure 5. In this case, the distance is found to be $d = 147.6 \pm 0.6$ pc, or an accuracy better than half a percent.

After early results demonstrating the potential of this approach to obtain ultra-precise dis-

tances to young stellar objects (e.g., [Loinard et al., 2007](#)), we embarked on a large project called The Gould's Belt Distances Survey (GOBELINS), which was awarded more than 2,500 hours of observing time in the Very Long Baseline Array. The source selection was based on the results of the GBS-VLA project described earlier, and resulted in the identification of well over 100 potential targets. The main GOBELINS results were published in a series of papers (e.g., [Ortiz-León et al., 2017](#), and associated papers), and yielded about 60 very accurate distances for sources in the best-studied star-forming regions. Comparison with the Gaia satellite results for sources in common demonstrates that the VLBI distances are at least as accurate as Gaia's (e.g., [Ortiz-León et al., 2018](#)). We have also complemented the results of the GOBELINS survey with additional VLBI observations of specific regions where no potential GOBELINS targets were identified (e.g., Serpens South; [Ortiz-León et al., 2023](#)) or not considered in the original project (e.g., Cygnus OB2, LkH α 101 and Mon R2; [Dzib et al., 2018](#)).

One interesting aspect should perhaps be mentioned here: VLBI astrometry is currently the only technique that can provide astrometry with a level of accuracy comparable to Gaia's (and will remain the only one for the foreseeable future). This means that VLBI data are the only way to systematically test Gaia's results. An initial attempt was carried out by [Lindgren \(2020\)](#), on the basis of a few tens of radio stars. This effort needs to be extended by increasing the number of known radio stars with available radio astrometry.

6.3 Precision Radio Astrometry of Young Binary Stars

Gravitationally bound binary stars are common in the Galaxy. Astrometric studies of these systems can lead to the determination of one of the most basic stellar parameters: the stellar mass. This is basically achieved through Kepler's third law. While the concept seems straightforward, doing it is hard, especially for young stars. The stellar mass is a key parameter used to correctly model the evolution of young stellar objects (YSOs). Precise measurements of the dynamical masses of young stars are fundamental, since they are obtained geometrically and do not rely on assumptions about any stellar parameter.

Young stars are often deeply embedded in their natal molecular clouds, where high dust column densities obscure them at optical and even infrared wavelengths. Furthermore, the nearest young stars lie at distances of approxi-

mately 150 pc. Given that standard observational techniques achieve angular resolutions of around one arcsecond, most detected young binary systems at optical and infrared wavelengths have orbital periods spanning from several decades to centuries, i.e., longer than the lives of astrometric missions such as the Gaia space telescope. Moreover, astrometric measurements at these wavelengths are relative, meaning that the motion of one star is traced with respect to its companion. As a result, only the total system mass, rather than individual stellar masses, is derived. Given these challenges, alternative techniques are needed to obtain precise astrometric measurements of young binaries. Radio astrometry provides key advantages over optical and infrared methods.

First, radio observations are not affected by dust obscuration, making it possible to detect deeply embedded young stars that are invisible at shorter wavelengths. Second, radio observations use quasars for phase-referencing calibration. This ties radio astrometric measurements to the International Celestial Reference Frame (ICRF), effectively providing a nearly absolute reference frame. This second advantage has a significant implication for the study of binary stars, as it allows the tracing of the individual motion of each component in the system relative to the mass center, and hence deriving individual stellar masses. Mexican radio astronomers have exploited these advantages of radio astrometry for decades, mainly through the use of two outstanding NRAO instruments, the VLA and the VLBA.

In its most extended configurations, the VLA can achieve angular resolutions of a fraction of an arcsecond, and astrometric accuracies of about 10 mas. It is an ideal instrument for probing YSOs with thermal or nonthermal radio emission and has been used to study very young binary stars. One of the most studied cases is L1551 IRS 5, whose radio emission can be traced to disks and jets (see [Hernández-Garnica et al., 2024](#), and references therein). Earlier astrometric results pointed to orbital periods of about 250 years, and masses in the range 1–2 $M_{\odot}$. A more recent study led by PhD student Ricardo Hernández-Garnica combined VLA and ALMA data spanning nearly 40 years, and determined a precise total system mass of $0.96 \pm 0.17 M_{\odot}$. This study demonstrated that, with an appropriate methodology, radio observations with different interferometric arrays, frequencies, and gain calibrators can be combined to obtain accurate astrometry. Other young systems that have been studied with the VLA by Mexican astronomers are IRAS 04368+2557, IRAS 16293-2422, and T Tauri. However, the

VLA's limited angular resolution only allows the study of wide binaries, and higher angular resolution observations are required when studying tight binary systems.

VLBA observations achieve an angular resolution of about 1 mas and accuracies of 0.1 mas at frequencies between 4 and 10 GHz. Since magnetically active YSOs are nonthermal radio emitters, they can be detected with the VLBA (see discussion above). These observations have been used to determine their distances via trigonometric parallaxes, mainly as part of the GOBELINS project (see Section 6.2). An interesting result from these VLBA observations is that a significant fraction of the detected YSOs are binary systems, with both components detected in the VLBA images (e.g., [Torres et al., 2008](#)). Their typical separations are a few tenths of a mas and, thus, unresolved by astrometric missions like Gaia. Preliminary mass estimates were derived from existing VLBA observations; however, many of these systems require more systematic observations to determine their masses with high precision.

The Dynamical Masses of multiple YSOs using the VLBA (DYNAMO-VLBA; P.I.: S. Dzib) project aims to determine the masses of several binary and triple systems previously observed with the VLBA. The dynamically determined masses will be compared with predictions from pre-main sequence evolutionary models, to assess the validity of the latter. The project has started to deliver substantial results. The PhD student Jazmin Ordoñez-Toro led the studies and obtained the most accurate dynamical masses of young intermediate-mass stars ([Ordoñez-Toro et al., 2025](#), and references therein). Notably, the DYNAMO-VLBA results in the case of the Oph S1 system revealed that the mass of the primary component is $4.1 M_{\odot}$, significantly lower than the $6\text{--}8 M_{\odot}$ predicted by evolutionary models. As the project continues, we expect further exciting discoveries and anticipate involving more Mexican students in leading these studies.

Studying young binary stars through radio astrometry has provided unprecedented insights into stellar masses and evolutionary models, and refined our understanding of early stellar formation. As technology advances, future instruments like the ngVLA and enhancements to VLBI networks will further improve astrometric precision, enabling the study of even tighter binaries and fainter radio sources. With Mexico's increasing involvement in these cutting-edge projects and the active participation of Mexican researchers and students, the country is poised to contribute significantly to the next era of high-precision radio astronomy.

7 EXOPLANETS [S.C.]

Historically, astrometry was the first technique used to study and search for exoplanets. However, insufficient precision and systematic errors have greatly hindered the discovery of exoplanets using this technique. Until recently, astrometry has been generally limited to a ~ 0.1 mas precision, which could only be achieved using large telescopes, due to atmospheric image motion and systematic effects ([Malbet and Sozzetti, 2018](#)). This precision is adequate for studying binary systems, but not for discovering exoplanets. Thus, the contribution of astrometry to the study of exoplanets has been relatively limited although, with the advent of space missions with increased accuracy, such as Gaia, this might change in the near future. The Mexican community is currently actively participating in the development of new methods to search for exoplanets using high-precision radio interferometry. In recent years, the development of new methods to search for exoplanets directly and indirectly, including the use of astrometry, has opened new windows of opportunity. In particular, high-precision astrometric observations with radio interferometers have become a new way to search for exoplanets ([Curiel et al., 2019; 2020; 2022; 2024](#)).

The search for planets associated with young, active stars with strong magnetic fields is challenging with most of the current search techniques (e.g., radial velocity and transit). However, these same stellar characteristics are an advantage for the radio search of exoplanets, because the stronger the star's magnetic activity, the stronger its radio emission is expected to be. Thus, the VLBI technique offers an alternative to conduct astrometric searches of planetary companions at radio frequencies (see [Bower et al., 2009; Forbrich and Berger, 2009; Forbrich et al., 2013; Gawronski et al., 2017; and Curiel et al., 2020, 2022](#)). Thanks to the discovery of radio emission from late M and L dwarfs ([Berger et al., 2002; Berger, 2006](#)), we can now uncover exoplanets or brown dwarf companions to low-mass stars using VLBI. In addition, radio interferometric observations have the advantage of providing absolute parallaxes and proper motions, which are tied to an extragalactic reference frame and facilitate the search for sub-stellar companions.

Recent successful attempts to find sub-stellar companions around T Tauri and other low-mass stars were made with the VLBA, observing in the 6 and 8 cm continuum bands and using absolute radio astrometry (e.g., [Curiel et al., 2019; 2020](#)). The discovery of two intermediate-mass brown dwarfs orbiting the Weak-Line T Tauri star DO Tau, and of a Saturn-like

planet associated with the M9 Ultra-Cool Dwarf (UCD) TVLM 513-46546 demonstrated the great potential of VLBI astrometry in the search of exoplanets. Furthermore, in the early 2020s, the observing capabilities of the VLBA were significantly improved, a project in which Mexico participated. This increased sensitivity has facilitated the search for planetary companions. In the following years, a Jupiter-like planet was discovered orbiting the main star in the low-mass M-dwarf binary system GJ 896AB (Curiel et al., 2022), and it was found that the low-mass binary system LP349-25AB is, actually, formed by a UCD and a high-mass brown dwarf (Curiel et al., 2024). Until now, TVLM 513-46546 b and GJ 896A b are the only planetary-mass companions that have been found with radio astrometric observations. However, these results have demonstrated the ability of VLBI astrometry to make a unique contribution to the field of exoplanet research.

The possible detection of coherent radio emission associated with exoplanetary systems, or with planetary companions directly, has motivated searches from MHz to GHz frequencies, because of such emissions' potential to probe the unknown magnetic properties of exoplanets (e.g., Zarka, 2007; Hallinan et al., 2013; Pineda et al., 2023). Although VLBI observations are the best way to find the origin of the radio emission, radio studies of young and low-mass stars have not provided the direct detection of planetary companions. The closest result so far has been the direct detection of a low-mass brown dwarf (a 35 Jupiter masses companion) orbiting the young WLTT star DoAr21 (Curiel et al., 2019).

The search for interstellar 'rogue planets' (single planets not gravitationally bound to a star), also known as free-floating planets, is an alternative method to find planetary bodies that are not associated with stars. Although an increasing number of free-floating planets have been detected in the optical and near-infrared in the past few decades (e.g., Lucas and Roche, 2000; Zapatero Osorio et al., 2000), very few free-floating, planetary-mass, candidate objects have been discovered using radio observations (e.g., Kao et al., 2018). Recently, a Jupiter-mass binary object (JuMBO), discovered by observations with the James Webb Space Telescope (Pearson and McCaughrean, 2023), was detected at radio wavelengths with the Jansky Very Large Array (JVLA) (Rodríguez et al., 2024). However, due to the low angular resolution of the observations, the radio emission of this binary system was not spatially resolved, and it is not clear if the emission is associated with one or both planetary-mass bodies. In addition, the nature of the radio emission of the

JuMBOs is not clear.

8 IMAGING SUPERMASSIVE BLACK HOLES WITH THE EVENT HORIZON TELESCOPE [L.L.]

The size scale relevant for black holes is their so-called gravitational radius GM/c^2 , where G is the gravitational constant, c is the speed of light, and M is the mass. Even for large nearby black holes, such as the supermassive black hole at the center of our Milky Way galaxy, the angular size corresponding to the gravitational radius is exceedingly small, of order $10 \mu\text{as}$.³ As a consequence, to obtain images of black holes with an angular resolution comparable with their intrinsic size scales, special techniques must be employed. There is currently only one observational strategy that can provide the required level of angular resolution: VLBI at millimeter wavelengths. This technique consists in linking together telescopes across the globe to computationally simulate a single telescope with a size comparable to Earth's. After several decades of steady progress, this was realized by the Event Horizon Telescope (EHT) starting in 2017.

Mexico played a central role in the development of the EHT thanks to the Large Millimeter Telescope Alfonso Serrano (LMT) atop the Sierra Negra extinct volcano in the state of Puebla, and to the efforts of the Mexican radio community. These efforts started around 2012, when Laurent Loinard and several of his students (particularly Sergio Dzib and Gisela Ortiz-León) began to participate in proto-EHT experiments with the CARMA interferometer in California. These observations yielded interesting scientific results of their own (e.g., Akiyama et al., 2015), but also enabled the Mexican community to gain expertise in a highly specialized subfield of radio astronomy. The first attempts at VLBI observations with the LMT were made in 2015, and the first science-grade VLBI observations that included the LMT were secured in 2016. They were reported by then graduate student Gisela Ortiz-León, who used them to obtain a stringent constraint on the size of the radio source associated with the black hole at the center of the Milky Way (Ortiz-León et al., 2016). In that same paper, the technical setup of the VLBI capabilities on the LMT is described in detail.

On 10 April 2019, the EHT collaboration published the first results from the inaugural EHT observations collected in April 2017. These results (The Event Horizon Telescope Collaboration et al., 2019, and references therein) revealed the structure of the supermassive black hole at the center of the nearby giant elliptical galaxy M87 and, remarkably, the expected black

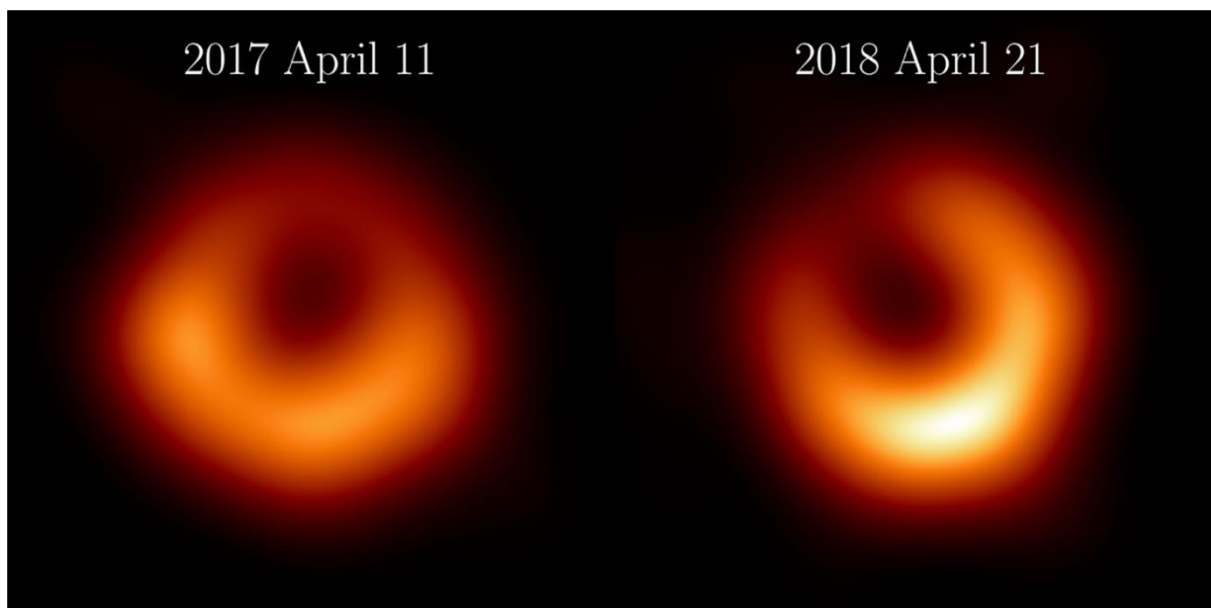


Figure 6: EHT images of the supermassive black hole at the center of M87 (EHT Collaboration et al., 2019; 2024a).

hole shadow, a dark central region expected from theoretical models due to photon capture by the central black hole (Figure 6). This central dark zone is surrounded by a bright ring, whose emission is dominated by the synchrotron emission from the accretion flow onto the supermassive black hole in M87. This emission is gravitationally focused by the black hole and corresponds to the sum of an infinite series of rings (Johnson et al., 2020). Its radius provides a direct measure of the mass of the black hole with only a minor correction due to its spin.

More recently, the EHT collaboration also published images of the black hole at the center of M87 in polarized light (The Event Horizon Telescope Collaboration et al., 2021; 2023), which showed that the plasma surrounding the black hole is threaded by intense magnetic fields. A second EHT image of M87, from data collected in 2018, revealed a similar structure, but with a slight change in the position angle of the brightest part of the ring (The Event Horizon Telescope Collaboration et al., 2024a: Figure 6). Such changes are expected to take place on time-scales of weeks to years in the highly dynamic environments of black holes. Finally, images (in total and polarized light) of the black hole at the center of the Milky Way (known as Sgr A*) were published in The Event Horizon Telescope Collaboration et al. (2022, and references therein; 2024b). These observations revealed a structure very similar to that of M87, i.e., with a central depression caused by the black hole shadow surrounded by a bright ring. One great advantage of Sgr A* relative to M87 is that its mass is known extremely accurately thanks to the work of Andrea Ghez and Rein-

hardt Genzel and their groups (Ghez et al., 2008; Gillessen et al., 2009), who monitored the orbits of several stars around Sgr A* over several decades. This means that the predictions of General Relativity can be directly tested from the measured size of the bright ring in the EHT image. On the other hand, because of its lower mass, Sgr A* varies on timescales of minutes, so its structure likely changes appreciably during a single night of observations. In addition, it is located behind a screen of ionized gas along the line of sight, which induces time-variable scintillation. The combination of these two effects makes the analysis of the Sgr A* observations more complex than for M87.

9 RADIO SURVEYS, CATALOGS, RADIO GALAXIES, AND VLASS [H.A.]

In 1994, the Department of Astronomy of Universidad de Guanajuato (UG) was founded as the third institution (after UNAM and INAOE) in Mexico to pursue professional astronomy (Phillips et al., 2002). In late 1997, H. Andernach (H.A.) joined the UG to continue his research on the large-scale structure of the Universe (e.g., Einasto et al., 1997) and the radio emission of clusters of galaxies, showing for the first time (Slee et al., 2001) the fine structure of so-called cluster relic radio sources; galaxy clusters had previously been assumed to be genuinely diffuse.

Motivated by the original dearth of radio-astronomical information in databases like NED and Simbad, H.A. has been collecting machine-readable catalogs of radio sources since 1989, and has so far recovered many hundreds of these via optical character recognition (OCR),

with the goal to have them included in NED and Simbad (e.g., [Norris et al., 2007](#)). However, only part of this collection (see <http://www.astro.ugto.mx/~heinz/cats.and>) has since been integrated into the CATS database at URL <https://www.sao.ru/cats/> ([Verkhodanov et al., 2000](#)); the above-mentioned, most used, databases still lack more than two-thirds of the radio collection ([Andernach, 2009](#); URL <http://www.astro.ugto.mx/~heinz/cats.sum>).

From 2013 through 2019, H.A. was involved in the first citizen science project on radio surveys, the 'Radio Galaxy Zoo' (RGZ), which aimed to identify the hosts of extended radio galaxies based on radio and infrared survey images, a task that is still challenging for current machine-learning algorithms. Part of the results for the smaller radio galaxies have been published only recently ([Wong et al., 2025](#)), but many volunteers have made extraordinary discoveries that still need to be prepared for publication. The exercise demonstrated not only the enormous motivation of the public to contribute to the advancement of science, but also the necessity to constantly supervise and guide them to guarantee reliable results.

Mexico has various regional and institutional programs that sponsor summer research internships for undergraduate students to become acquainted with research. Between 2005 and 2020, the UG participated in these programs, and H.A. supervised 25 such students for periods of five to eight weeks. One of the projects was related to determining more exact positions for the blue stellar-like sources found with a multi-exposure method invented by Guillermo Haro, which became known as either Palomar-Haro-Luyten (PHL) or 'Tonantzintla' (Ton) objects around 1960. Some of those sources were found to be quasars shortly thereafter. While for some 3000 objects (mostly Ton) exact positions could be identified, for most PHL objects exact positions will remain uncertain, because the original finding charts by Haro and Luyten could not be located ([Andernach et al., 2016](#), and references therein).

However, most of the summer students worked on topics related to finding and identifying radio galaxies. Some of the obligatory research reports were written in English and subsequently uploaded to online conference websites or the arXiv e-print server (e.g., [Andernach et al., 2012](#); [Rentería Macario and Andersnack, 2017](#); [de la Rosa Valdés and Andersnack, 2019](#)). These projects revealed the enormous potential of discovering large radio galaxies by visual inspection of modern large-scale radio survey images, in combination with optical digital sky surveys, much deeper than the photographic

Palomar Observatory Sky Survey that later became the Digitized Sky Survey (DSS). This motivated H.A. to examine a large part of the Rapid ASKAP Continuum Survey (RACS, see [Andernach et al., 2021](#)) and, more recently, to supervise a PhD thesis on the inspection of the LOFAR Two-Metre Sky Survey (LoTSS) Deep Fields ([Simonte et al., 2024](#)). Both projects led to substantial samples of newly found giant radio galaxies.

Since 2017, the Very Large Array Sky Survey (VLASS) has been scanning the entire sky north of declination -40° with a novel 'on-the-fly' mode, using the S-band (2–4 GHz) of the Very Large Array (VLA) in its B configuration. The planned three epochs of observation were finished in late 2024 (see <https://archive-new.nrao.edu/vlass>), and a median stack image atlas is available at <http://archive-new.nrao.edu/vlass/HiPS/MedianStack/Quicklook>. The primary science goal of VLASS is to find transient radio sources. However, it also provides, for the first time, a radio atlas of 82 percent of the sky with 2.5 arcsec angular resolution. This allows the reliable identification of counterparts for the radio sources among even the faintest optical galaxies or more distant objects detected only in the mid-infrared, e.g., with the Wide-field Infrared Survey Explorer (WISE).

VLASS was not designed to detect nor expected to reveal large radio galaxies by their extended emission. Nevertheless, in early 2018, an inspection of 2,000 square degrees of VLASS images around the North Celestial Pole by H.A. unveiled large numbers of extended radio sources, sometimes paired and aligned with each other; upon a thorough comparison with optical and infrared surveys, and with the help of summer student J.U. Guerrero González, the examination resulted in the identification of about 200 new giant radio galaxies with projected linear sizes larger than 1 Mpc in this region (see <https://www.aoc.nrao.edu/events/VLA40th/slides/session9/Heinz-Andernach.pdf>). Before that, another one of H.A.'s summer student projects ([Villarreal Hernández and Andersnack, 2018](#)) presented the very first research results based on the visual inspection of VLASS 'QuickLook' (QL) images of more southerly regions. It became the first paper to describe the VLASS survey, and has since been cited by some authors as a reference for VLASS, even after the publication of its 'official' description by [Lacy et al. \(2020\)](#). The student report also gained H.A. an invitation to become a member of the VLASS Survey Science Group, starting in mid-2019 and continuing up to the present.

The potential of VLASS to reveal large quant-

ities of classical double radio galaxies has also been shown by [Gordon et al. \(2023\)](#) and [Flesch \(2024\)](#), who extracted such symmetric structures based only on the source catalog of the first VLASS epoch. The cutout server at <http://cutouts.cirada.ca/> offers a stack of all three epochs with the 'mosaic' option, providing images with a noise level below 0.1 mJy per beam. H.A. has been using the VLASS (QL) images to identify the hosts of giant radio galaxies, especially in cases where lower-resolution surveys would not distinguish between the members of close pairs of optical hosts. The ultimate capacity of VLASS will only become available after the final data products are released; these include 'Single-Epoch Continuum Images' (SECI) produced with more reliable, but time-consuming, imaging procedures; a stack of all three epochs (plus the last approved epoch 4.1, to be completed in February 2026); as well as images smoothed to a lower angular resolution that would be more sensitive to low surface brightness emission.

H.A. is also a member of the science team conducting the radio survey Evolutionary Map of the Universe (EMU, [Norris et al., 2021](#)) with the Australian Square Kilometre Array Pathfinder (ASKAP) interferometer. The interferometer is currently observing the entire southern sky at 944 MHz, with an angular resolution of 13 arcsec, and to a depth of a 1σ noise level of 0.03 mJy per beam.

10 OBSERVING THE ATOMIC HYDROGEN IN GALAXIES [H.B.A.]

Atomic hydrogen, denoted in astronomy by HI, is by far the largest component of baryonic mass in the Universe. It constitutes the main raw material building stars and galaxies and it is, in addition, the primary fuel of thermonuclear reactions at the core of stars. After several nuclear reactions, hydrogen is transformed into heavier elements that are spread across the Universe through a complex gas-cycling process. During early evolutionary stages, elliptical galaxies have transformed most of their gas reservoir into stars. On the contrary, spirals and irregulars preserved a large fraction of their HI, which constitutes the diffuse interstellar medium (ISM) they show at the present epoch. In these galaxies, the gaseous component fills the space between the stars; it has temperatures in the range 10–200 K, and densities of just a few particles per cubic centimeter. Under such physically calm conditions, the hydrogen atoms, composed of a proton and an electron, only suffer transitions involving the spin of both particles. The spin of the proton and the electron can be in a parallel or antiparallel configuration.

The difference in energy between these two quantum states is tiny, but non-zero. When an atom flips spontaneously from the parallel to the antiparallel configuration, the excess energy is balanced through the emission of a low-frequency photon, through a so-called hyperfine transition. Despite the abundance of atomic hydrogen in the Universe and the interest in studying this component, its detection remained elusive for many years. It was only in the 1940s, still during World War II, that Henrik van de Hulst, an astronomer working at Leiden Observatory under Jan Oort, predicted that atomic hydrogen should be able to produce emission in radio wavelengths. He calculated the energy of the spin transition of atomic hydrogen, now known to be 1420.405 MHz or a wavelength of 21 cm, which is well into the radio domain of the electromagnetic spectrum. After the war, several large radar dishes were modified to be used as radio telescopes. Consequently, astronomers in the Netherlands, the USA, and Australia started a race to achieve the first detection of the 21-cm line. This thrilling history, ending with independent, nearly simultaneous, detections made by the three research groups, is beyond the scope of this contribution.

The impact of detecting the 21-cm line was huge. It allowed astronomers to trace both the distribution and the kinematics of the Milky Way ISM, thanks to the Doppler shifts in the 21-cm line. Modern projects, like the Leiden–Argentina–Bonn Survey ([Kalberla et al., 2005](#)) allowed one of the most accurate estimations of the distance between the Sun and the Galaxy center (25,500 light-years); to trace the Milky Way spiral structure; and to measure the average thickness (between 300 and 1,000 light-years) of the Galactic disk. Furthermore, observing at a wavelength of 21 cm allows the study of regions, like the Galaxy Center, that are invisible through optical methods, due to the presence of interstellar dust. The study of the rotation speed as a function of Galactic radius led to the discovery of the rotation curve problem: the outer regions of most spiral galaxies, including those in the Milky Way, rotate faster than expected. This became one of the strongest pieces of evidence for the existence of dark matter (see the seminal review by [Trimble, 1987](#)).

The problem of galaxy evolution through cosmological timescales is another fundamental issue in modern astrophysics in which HI data play a crucial role. The old debate, nature versus nurture, seeks evidence on the leading physical mechanisms shaping galaxies from early epochs to the present cosmic time. Using several individual antennas, the interferometric

synthesis imaging technique is able to obtain the same angular resolution as a much larger radio telescope, going from a few to thousands of kilometers (e.g., WSRT in the Netherlands, the NRAO-VLA in the USA, and the next generation SKA in Australia and South Africa). During their lifetime, galaxies experience different kinds of environmental effects, either exerted by neighboring galaxies and/or by the groups and clusters in which they are embedded.

The HI component of unperturbed spiral galaxies extends well beyond (two to three times) the stellar disk; the low anchoring force at the galaxy outskirts makes the HI more vulnerable to any kind of interaction. Therefore, mapping the distribution of HI of a large sample of galaxies living under different environmental conditions (with special emphasis on galaxy clusters) has proven to be a powerful tool for studying environmental effects. Until the beginning of the twenty-first century and due to technical limitations, HI-imaging of galaxies had been restricted to the nearby Universe ($z < 0.1$). For this reason, both single-dish and interferometric HI-surveys focused on the nearest clusters, like Virgo, Hydra, and Coma. Some examples are HIPASS, ALFALFA, and the first HI blind surveys carried out with the VLA (see Cayatte et al., 1994; Bravo-Alfaro et al., 2000). Despite the small number of observed clusters, those studies already provided statistical data on the gas content of spirals in different environments, showing that late-type galaxies located in clusters are more HI-deficient. This raised the hypothesis of an evolutionary sequence, where normal spirals infalling to massive clusters are systematically transformed into red, passive objects (mostly S0s). In the end, this could be at the origin of the density–morphology relation, i.e., the fact that ellipticals and S0s are the dominating populations in clusters, in contrast with low-density regions, where spirals are more abundant (Dressler, 1980).

It is in this context that several projects, based on large-volume HI-imaging surveys, were performed with the VLA and WSRT (e.g., van Gorkom et al., 2003). The advantage of synthesis imaging is to measure, not only the gas content/deficiency as a function of cluster position, but to trace disruptions like gas-disk shrinking, asymmetries, and offsets between the gas and the stellar disk (Bravo-Alfaro et al., 2001; Chung et al., 2009; Scott et al., 2010; López-Gutiérrez et al., 2022). In the last decade, the upgraded VLA and WSRT, as well as the new generation of radio facilities like MeerKAT, are pushing the HI-imaging limits up to redshifts in the range 0.2–0.4 (e.g., Fernández et al., 2016; Gogate et al., 2020).

Due to the large variety of environmental physical conditions found in different clusters, increasing the number of studied clusters in HI is as important as observing HI at higher distances. The combination of HI observations with imaging and spectra taken at other frequencies (e.g., X-ray, UV, optical, $H\alpha$ and NIR) enables the study of the effects of diverse physical processes transforming normal spirals into S0s. This strategy unveils the evolutionary stages followed by normal (main sequence) spiral galaxies while infalling/orbiting massive clusters. First, they undergo a short-lived star formation episode accompanied by some HI disruptions, then a quenching phase attested by red colors and high HI deficiency. All this process lasts a few 10^8 yr (López-Gutiérrez et al., 2025). Finally, the HI imaging of galaxy clusters to a few times their virial radii opens the possibility to explore some fundamental correlations, like the dependence of environment effects on stellar mass and the role played by pre-processing in transforming spirals into S0s. Based on recent results obtained by López-Gutiérrez et al. (2022), in three Abell clusters imaged in HI with the VLA (A085, A496, A2670), it is possible to make direct comparisons between predictions made by cosmological simulations (like Illustris-TNG) and observational data. Preliminary results obtained by Núñez-Beltrán (2023), show important disagreements on the predicted effects suffered by low-mass ($< 10^{10}$ solar masses) subhalos infalling to massive ($> 10^{14}$ solar masses) halos. Although these objects should be gas-stripped and quenched, there is a non-negligible number of very low-mass galaxies ($< 10^9$ solar masses) that harbor a normal HI content and a high star formation rate in the three clusters mentioned above.

In summary, mapping galaxies through the 21-cm hydrogen line is a powerful tool for understanding their physical properties, dynamics, and evolution. This window helps the study of environmental effects on galaxy evolution and constitutes a key element in improving our knowledge of intriguing extragalactic objects, such as dark galaxies and star-forming, low-redshift galaxies, analogous to objects at cosmic noon.

11 MILLIMETER-CONTINUUM SURVEYS: FROM AzTEC TO TOITEC [I.A.]

The approval of the Large Millimeter Telescope Alfonso Serrano (LMT) brought a strengthening of the collaborations between the two partner institutions that were leading the project in the USA and Mexico, the University of Massachu-

setts in Amherst (UMass-Amherst) and the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), respectively. The initial suit of instruments for the LMT included a continuum camera to be built at UMass-Amherst, in collaboration with CalTech, JPL, the University of Colorado, and the University of Cardiff (Irvine et al., 2005: 89), that was named the ‘Aztronomical’ Thermal Emission Camera (AzTEC). This was a 144-pixel array camera with bolometer detectors, inspired by the Bolocam instrument in operation at the 10-m Caltech Submillimeter Observatory.

A key element to the success of building and exploiting AzTEC in a collaborative mode was the hiring in 2001 of G.W. Wilson in UMass-Amherst, to become Principal Investigator of AzTEC, and in 1999 of D.H. Hughes at INAOE. Hughes, who was already well known for submillimeter studies carried out in the UK, became, first, LMT’s Project Scientist and, later, Director. He started a millimeter-wavelength instrumentation laboratory with two Mexican students, D. Ferrusca and M. Velázquez, who were partially trained in UMass-Amherst and helped commission AzTEC. At the same time, Hughes hired two Canadian students, E. Chapin and J. Wagg, to work on millimeter-wavelength surveys of the extragalactic sky with data acquired with other facilities, among them, the SCUBA Half-Degree Survey (SHADES). SHADES was a big consortium, mainly of the Canadian, Dutch, and British communities, that ran the 15 m James Clerk Maxwell Telescope (JCMT). I. Aretxaga joined at that time the INAOE group to design quick and effective methods to determine redshifts to the galaxies with the existing far-IR to radio colors, and firmly placed the dusty galaxy population that SHADES was sensitive to a distribution that peaked at $z \sim 2.5$ (when the age of the Universe was ~ 2.6 Gyr). Fate had it that the SCUBA camera failed beyond repair in 2005 without completing SHADES. Negotiations between the JCMT community and the LMT group led by Hughes and Wilson allowed for AzTEC to be installed in 2005 on the JCMT, to acquire its first scientific campaign before the replacement JCMT camera, SCUBA2, was ready. At that point, AzTEC was ready but the LMT was not. It was a good strategy to commission the instrument in a proven telescope, complete SHADES, and train the community in Mexico and UMass-Amherst.

The first campaign of AzTEC was very successful: it completed SHADES at 1.1 mm and a small section of the COSMOS field (Scott et al., 2012, and references therein), among other projects, to uncover a few hundred robust dusty galaxy candidates. Follow-up of the brightest sample with interferometers gave rise to the

concept of compact starburst galaxies at high redshift, like AzTEC1, forming stars at a rate 1000 times faster than the Milky Way. The surveys required the presence of 2–3 members of the AzTEC team at the JCMT site in Mauna Kea, Hawaii, to support the observations and to maintain the camera at the required cold temperatures by supplying cryogenics.

Negotiations of the AzTEC/LMT team with the Japanese community allowed for AzTEC to be installed during the winters of 2007 and 2008 on the 10-m Atacama Submillimeter Telescope Experiment (ASTE), where surveys of the Galactic and extragalactic sky continued through remote operations from the Japanese institutions, UMass-Amherst, and INAOE. A small group of AzTEC team members was also deployed to San Pedro de Atacama, Chile, to maintain the camera cold and take over observations whenever long-distance communications failed. These campaigns allowed the acquisition of thesis data and the training of a new generation of Mexican students, including E. Aguilar, A. Montaña, D. Sánchez-Argüelles and M. Zeballos. Among other impactful results, the extragalactic surveys uncovered overdensities of galaxies around bright dusty starbursts (Tamura et al., 2009); alignments of the dusty galaxy overdensities with the putative accretion disks of radio galaxies (Zeballos et al., 2018), revealing the possible feeding paths of galaxies; and correlations of background and foreground large-scale structures due to lensing (Aretxaga et al., 2011), indicative of the massive nature of the dusty galaxies and their role in the large scale structure of the Universe. AzTEC produced catalogs of more than 2,000 sources, mostly dusty galaxies, and it became a brand name in the literature: a search in the Astrophysics Data System on papers that mention AzTEC in their abstracts yields 277 results.

By the time AzTEC was to return to Mexico, in 2011, it was evident that a new camera was needed at the LMT in order to surpass the mapping capacity of SCUBA2 on the JCMT. The new camera could use the advantage of the 50-m diameter of the telescope to detect faint sources that SCUBA2/JCMT could not reach, but it needed to be much faster than AzTEC to compete with the best survey facilities. Meanwhile, AzTEC studies at the LMT focused on targeted observations of objects of interest (e.g., Chávez-Dagostino et al., 2016).

The fruitful collaboration between UMass-Amherst and INAOE researchers made the partnership on a new instrument a natural result. The consortium was completed with Northwestern University, Arizona State University, the University of Michigan, the National Institute of

Standards and Technology (NIST), and Cardiff University. The new project to build a continuum camera that could simultaneously image the sky at 1.1, 1.4, and 2.1 mm was led by Wilson and funded by the National Science Foundation of USA with 6.9 million USD. The Mexican Consejo Nacional de Humanidades, Ciencia y Tecnología awarded one of its Fronteras de la Ciencia big projects of 3.2 million Mexican pesos to a team led by Aretxaga, as Project Scientist of TolTEC, to integrate the Mexican community into the science definition and verification teams of TolTEC, which include over 30 Mexican scientists. The TolTEC instrument gets its name from the indigenous civilization that predated the Aztecs, which the latter considered superior.

The light reception of TolTEC (Wilson et al., 2020) is based on the new generation of Kinetic Inductance Detectors designed and built at NIST. TolTEC has 7718 such detectors, integrated into three arrays sensitive to 1.1, 1.4, and 2.1 mm light. Every point of the sky is covered in each band by two detectors sensitive to orthogonal polarizations, with a resolution, measured as the full-width at half-maximum of the beam, of 5, 7, and 11 arcsec, respectively. The arrays are designed to cover the telescope's focal plane, which has a 5 arcsec diameter, making it a very efficient mapping machine. The considerable mapping speed predicted for TolTEC is a factor of 1500 to 9000 faster than the AzTEC camera on the LMT, and also faster than other millimeter-wavelength telescopes.

TolTEC was fully integrated and tested at UMass-Amherst, with instrumentation contributions from the partner institutes in the consortium, including INAOE. In 2021, after an almost two-year hiatus in operations due to the COVID-19 pandemic, all pieces of TolTEC were sent to the LMT, and the TolTEC team reassembled the instrument and mounted it in its final position in the receiver cabin. The instrument's first light happened in mid-2022, and commissioning continued to the last months of 2022. In 2024, a second commissioning campaign was scheduled.

The main objective of TolTEC is to perform ten open-access legacy surveys of 100 hours each. The first four surveys have been designed by a community of more than 300 interested researchers worldwide. These are the Galactic surveys 'Clouds to Cores' and 'Fields in Filaments', that target the origin of the distribution of stellar masses in the Milky Way, and the role of magnetic fields in the collapse of molecular clouds to form new generations of stars. The 'Large Scale Structure' survey and the 'Ultra

Deep Survey' are designed to look for dusty star-forming galaxies that trace the obscured star formation history, and the metal enrichment history of the Universe.

A cosmologically-motivated mock catalog of the dusty galaxies predicts that the TolTEC extragalactic surveys will yield catalogs of tens to hundreds of thousands of galaxies, that will accurately reproduce the contribution of dusty galaxies to the star formation history of the Universe. It is predicted that, from galaxies forming stars at a rate ten times faster than the Milky Way to galaxies forming stars 100 or more times faster, the intrinsically brightest galaxies are the furthest away.

12 EVOLVED STARS [D.T. and L.U.]

The study of evolved stars in Mexico began with the pioneering surveys of planetary nebulae (PNe) in optical bands, conducted using the Schmidt Camera at the National Astronomical Observatory in Tonantzintla, Puebla (Haro, 1951; Peimbert and Batiz, 1960; Peimbert and Costero, 1961). These early investigations significantly advanced our understanding of the PNe population in our Galaxy, offering indirect estimates of the duration of this evolutionary phase. Additionally, analyses of the spatial distribution of PNe within the Milky Way provided valuable insights into the structure of our Galaxy.

Momentum in the study of PNe in Mexico grew significantly due to the dedicated work of Manuel Peimbert and Silvia Torres-Peimbert. Initially, their research focused on determining the chemical abundances of elements in PNe. However, in the early 1980s, the scientific community developed a growing interest in the complex problem of bipolar planetary nebula (PN) formation. Notably, Peimbert and Torres-Peimbert (1983) observed that a large fraction of PNe, classified as Type I by Peimbert (1978) displayed a clear bipolar or hourglass structure. Calvet and Peimbert (1983) further investigated the connections between the morphology of planetary nebulae, the mass of their progenitor stars, and their chemical compositions. Despite significant progress in understanding the origin of bipolar PNe, it soon became evident that fully unraveling the mechanisms behind their development required examining objects with massive neutral envelopes, which are often opaque at optical wavelengths. Consequently, observations at longer wavelengths, particularly in the radio spectrum, became essential for advancing this area of research.

Luis Felipe Rodríguez pioneered the systematic study of PNe in Mexico using radio techniques. Rodríguez and Moran (1982) used the



Figure 7 (left to right): Lizette Guzmán-Ramírez, the late Yolanda Gómez, and Lucero Uscanga, at Roque de los Muchachos National Park, La Palma, Canary Islands in 2007 (photograph: Lucero Uscanga).

then recently constructed Very Large Array (VLA) to observe the PN NGC 6302, achieving the first-ever detection of HI absorption associated with a PN. These observations were crucial in developing a detailed morphological model of NGC 6302, providing key insights into the formation mechanisms of bipolar structures in PNe. Rodríguez's work soon inspired a new generation of young astronomers, including José Antonio García-Barreto and Yolanda Gómez Castellanos. Using higher angular resolution observations with the VLA, they confirmed the association of HI absorption with NGC 6302 (Rodríguez et al., 1985a; 1985b, 1985c).

Yolanda Gómez (Figure 7) became a leading figure in the study of PNe and other evolved stars at radio wavelengths, dedicating the next couple of decades to advancing our understanding of these objects. Her radio astronomical observations yielded accurate measurements of the helium abundance in NGC 6302 (Gómez et al., 1987). She and her colleagues also determined upper limits for the mass-loss rates of PNe central stars (Gómez et al., 1992). They likewise found candidate PNe near the Galactic Center, and evidence for a binary system at the core of the bipolar proto-planetary

nebula OH 231.8+4.2 (Gómez et al., 1997; 2001). One of Yolanda's most influential contributions is her statistical analysis of SiO and water masers in OH/IR stars. This research revealed that the fraction of objects exhibiting detectable water and SiO maser emission declines as the [25 micron–12 micron] color index, which is thought to be correlated with the age of the star, increases. This finding led to the conclusion that maser emission significantly diminishes or disappears when mass-loss ceases at the tip of the Asymptotic Giant Branch (AGB) phase, thus providing a reliable method for assessing the evolutionary state of post-AGB stars. In another important contribution, Yolanda and her colleagues conducted observations of anomalous water masers in OH/IR stars (Gómez et al., 1994), laying the groundwork for the study of another intriguing class of evolved stars known as 'water fountains'.

Perhaps Yolanda Gómez's most significant breakthrough was the discovery of water vapor maser emission in the planetary nebula K 3-35, made in collaboration with her colleagues (Miranda et al., 2001). This finding was groundbreaking because the presence of water maser emission indicates that the ionization of the

nebula commenced only recently. Investigating a PN as young as K 3-35 offers critical insights into the early stages of bipolar morphology development. Motivated by this discovery, Yolanda dedicated herself to an in-depth study of K 3-35, to enhance our understanding of the mechanisms that shape bipolar structures in PNe. Her research placed particular emphasis on the emission of OH masers, which can be employed to measure the magnetic field in the circumstellar envelopes of astronomical sources (e.g., [Gómez et al., 2005; 2009](#)).

Much like Luis Felipe Rodríguez, Yolanda Gómez inspired and mentored a new generation of young astronomers, with a particular emphasis on radio observations of evolved stars. The discovery of water masers in K 3-35 raised several intriguing questions, one of which concerned the survival of water molecules in the ionized regions of the PN. To address this mystery, Yolanda and her students, including Daniel Tafoya, searched for dense molecular clouds that could shield the water molecules in K 3-35. Using the Nobeyama 45-m, IRAM 30-m, and Onsala Space Observatory 20-m radio telescopes, they detected significant amounts of carbon monoxide (CO) and of the high-density tracer molecule HCO^+ ([Tafoya et al., 2007](#)). Another parameter crucial for understanding the physical properties of K 3-35's circumstellar environment is its distance from the Sun. [Tafoya et al. \(2011\)](#) obtained an exceptionally accurate distance measurement to K 3-35 through the proper motions and parallaxes of water masers, using observations from VLBI.

As with other cosmic sources, obtaining accurate distances to PNe is challenging, and radio observations have played a pivotal role in refining their measurements. Yolanda, for instance, measured the distance to NGC 6302 using radio continuum observations ([Gómez et al., 1989; 1993](#)). This technique involves comparing radio continuum images taken at two different epochs to observe the angular expansion of ionized gas. By either measuring or assuming the expansion velocity of this gas, one can derive the distance to the nebula. Using this method, Lizette Guzmán, another one of Yolanda's students ([Figure 7](#)), successfully measured the distances to several PNe ([Guzmán-Ramírez, 2011a; 2011b](#)).

As mentioned above, Yolanda's research into anomalous water masers in OH/IR stars laid the groundwork for studying an entirely new class of fascinating, evolved, stars known as water fountains. Water fountains are a rare and intriguing type of evolved star system, characterized by high-velocity, collimated, outflows

traced by water maser emission. These outflows are believed to signal a transitional stage between the AGB phase and the formation of a PN, providing a unique window into the early processes that shape complex nebular morphologies ([Imai, 2007](#)). With the arrival of new generation mm and sub-mm radio telescopes, such as the Atacama Pathfinder Experiment (APEX) and the Atacama Large Millimeter Array (ALMA), Daniel Tafoya has been able to detect for the first time sub-mm water masers, and to image with unprecedented high-angular resolution the collimated outflows of water fountains ([Tafoya et al., 2014; 2019; 2020](#)). Moreover, by investigating isotopic abundances in the circumstellar material of water fountains, Daniel and his collaborators have concluded that water fountains are likely systems undergoing common envelope evolution ([Khoury et al., 2021](#)). This finding represents a significant advancement in our understanding of the development of bipolar morphologies and of the progenitor stars of PNe exhibiting such structures, bringing us closer to resolving the mysteries that the Mexican astronomers have sought to unravel for several decades.

The study of PN exhibiting water masers and water fountains continues to be a vibrant area of research in Mexico, with Lucero Uscanga, one of Yolanda Gómez's former mentees ([Figure 7](#)), emerging as one of the leading figures. Lucero has not only dedicated herself to increasing the number of known water fountains in our Galaxy; she has also taken on the important role of training the next generation of radio astronomers focused on evolved stars ([Uscanga et al., 2014; 2022; 2023](#)). Notably, she has used the Mexican Large Millimeter Telescope (LMT) to search for high-density tracers, such as HCN and HCO^+ , in water maser-emitting PNe and water fountains ([Uscanga et al., 2019](#)). These tracers may originate from dense clumps that provide a shielding mechanism for the molecules, akin to the case of K 3-35. Another project using the LMT to investigate molecular emission in water fountains was led by Arturo Ivan Gómez-Ruiz and Lizette Guzmán, who detected SiO, HCN, SO, and ^{13}CO ([Gómez-Ruiz et al., 2017](#)).

Related to the exploration of bipolar morphologies in evolved stars, Mexican astronomers have also focused their research at radio wavelengths on 'born-again' stars. These unique objects are white dwarfs that undergo a late thermal pulse, temporarily re-igniting helium burning beneath their surfaces and causing them to revert briefly to a phase reminiscent of the AGB ([Iben et al., 1983](#)). For decades, astronomers searched in vain for molecular mil-

limeter and submillimeter emission resulting from the material ejected during the born-again event. With the advent of the Atacama Large Millimeter/submillimeter Array (ALMA), Daniel Tafoya, Jesús Toalá, and their collaborators have conducted high-resolution radio observations that reveal, for the first time, the spatial distribution of various molecules in the ejecta of these events. Their findings provide invaluable insights into the elemental abundances in the ejected material, and substantial evidence for the presence of binary systems that may be responsible for the observed bipolar morphologies (Tafoya et al., 2022; 2023).

In summary, radio astronomy in Mexico has been marked by groundbreaking research that has significantly advanced our understanding of evolved stars, particularly PNe and their complex morphologies. Beginning with the early surveys and pioneering work by astronomers like Manuel Peimbert and Silvia Torres-Peimbert, the field has grown to encompass sophisticated radio observations that reveal intricate details about stellar evolution. Key contributions from such figures as Yolanda Gómez and Luis Felipe Rodríguez laid the foundation for subsequent discoveries.

The arrival of advanced radio telescopes like the Very Large Array (VLA), ALMA, and the Mexican Large Millimeter Telescope (LMT) has further propelled research efforts, allowing for high-resolution studies that have illuminated the physical processes underlying the formation of bipolar nebulae and the chemical compositions of stellar ejecta. The collaborative efforts of both established astronomers and emerging scientists, such as Lucero Uscanga, ensure that the vibrant tradition of radio astronomy in Mexico continues to flourish. This ongoing research not only addresses longstanding questions about stellar evolution and nebular structures; it also places Mexican astronomy at the forefront of global efforts to unravel the complexities of the Universe.

12.1 Evolved Massive Stars [S.D.]

The life cycle of massive stars is shorter and more violent than that of low-mass stars. After the main sequence, they go through different phases characterized by strong winds and significant loss of their initial mass. These changes culminate in a supernova (SN) explosion, and the remnants of these stars can be either neutron stars or stellar-mass black holes.

Before, the most massive stars ($M \sim 50 M_{\odot}$) evolve into Wolf-Rayet (WR) stars. WR stars have the most powerful stellar winds and complex circumstellar environments, making them key contributors to the enrichment of the inter

stellar medium. After leaving the main-sequence, WR stars shed their outer hydrogen layers, exposing their hot, dense cores. Radio observations have played an essential role in understanding WR stars, and Mexican astronomers have significantly contributed to this field.

Mexican astronomers have conducted several key studies using the VLA to investigate the radio properties, kinematics, and wind structures of WR stars. Early works focused on detailed VLA observations of WR 6 and WR 147, searching for anisotropies in their winds and analyzing the interactions between the WR winds and their environments (see, e.g., Contreras and Rodríguez, 1999). Studying interacting wind binary systems, such as WR 147, provided valuable insights into colliding wind regions and revealed complex shock structures. The recent work on WR 147 identified a radio pinwheel structure (Rodríguez et al., 2020), confirming the presence of a tight colliding-wind binary and further characterizing its emission mechanisms.

Subsequent research explored the proper motions and variability of WR stars, with radio interferometry offering precise measurements of their movements within the Galaxy. Studies of WR 112 and other massive stars demonstrated how radio emission varied over time, potentially influenced by wind collisions or episodic mass ejections (e.g., Dzib and Rodríguez, 2009). These astrometric studies also provided insights into the history of these stars. In the case of WR 145a (Cyg X3), a known microquasar (see Section 12), the lack of high proper motions and SN remnants (SNRs) in its surroundings suggests that the black hole in this binary system formed by direct core-collapse and without a (or with a weak) SN explosion.

Pulsars, a unique subclass of neutron stars, have received relatively little attention in Mexico. A notable exception is PSR J1813-1749, studies of which at radio frequencies have been summarized by Dzib and Rodríguez (2021). This pulsar was first found as an X-ray pulsar and subsequently identified as the second most energetic pulsar, just after the Crab pulsar. However, initial searches for radio pulses were unsuccessful, creating a conundrum given the extreme energy of the source. Besides this enigma, the pulsar was interesting because it was near the projected center of the SNR G12.82-0.02 and the γ -ray source HESS J1813-178. In early 2010, L.F. Rodríguez and his Master's student S. Dzib reported a variable, non-thermal, radio continuum source coincident with the position of the X-ray pulsar. They suggested that it may be a variable radio pulsar, which could explain the failure to detect the radio

pulses in dedicated observations. Follow-up VLA observations confirmed the radio continuum source. However, quasi-simultaneous pulse-search radio observations at 1.4 GHz with the Effelsberg 100-m telescope again failed to identify the pulsar, deepening the mystery surrounding this source. The puzzle was solved by [Camilo et al. \(2021\)](#), who detected the radio pulses with observations at higher frequencies (4.4–10.2 GHz). They revealed that this is the most scattered pulsar in the Galaxy, explaining why it cannot be detected at low frequencies, where pulsars are typically observed. In addition, X-ray observations suggested that PSR J1813-1749 is a hypervelocity neutron star moving at approximately $1,500 \text{ km s}^{-1}$ and, thus, with a kinematic age of only 300 years. These findings indicated that this neutron star may be one of the youngest known pulsars. However, an astrometric analysis of VLA observations confirmed its high motions, albeit with lower velocities of 500 km s^{-1} , and thus a larger kinematic age of 1,500 years. This kinematic age matches the estimated age of the associated SNR of $\sim 2,000$ years.

Mexican radio astronomy has been increasingly involved in studies of extreme astrophysical objects, particularly in understanding the final stages of massive stars. This role is expected to increase with Mexico's participation in next-generation arrays. The formation and training of students in these areas will be essential to fully leverage these opportunities, and further solidify Mexico's contributions to high-impact astrophysical research.

13 QUASARS AND MICROQUASARS [L.F.R.]

13.1 Quasars

By 1990, there was already a clear idea of what quasars are. Most, probably all, galaxies have a supermassive (millions to billions of solar masses) black hole at their centers. If this black hole were surrounded by an accretion disk, the friction between adjacent radii of the disk would heat it to significant temperatures, producing copious amounts of electromagnetic radiation. Finally, magnetohydrodynamic processes accelerate and collimate a small fraction of the gas in the disk to produce relativistic jets ([Blandford and Payne, 1982](#)).

These three dominant components (black hole, disk, and jets) became the key ingredients in the unified models of active galactic nuclei ([Antonucci, 1993](#)). At the same time, it was being understood that black holes come in two varieties: the supermassive black holes already mentioned, which exist at the centers of gal-

axies, and the stellar black holes (with masses from several solar masses to tens of solar masses) that result from the death of massive stars and are widespread across a given galaxy.

While there is usually only one supermassive black hole per galaxy, millions of stellar black holes are expected. This estimate comes from assuming that in a galaxy like ours, about one massive star dies every 100 years and that the galaxy is about 10 billion years old.

It has always been difficult to detect these stellar black holes. The reason seems to be that a black hole is a dark object unless it is actively accreting and has a hot disk surrounding it. It is important to note that, while the disks around supermassive black holes emit mostly in the optical and ultraviolet, the disks around stellar mass black holes emit strongly in the X-ray region of the spectrum. For accretion to be present, the black hole must be one of the two components of a binary system. When X-ray emission is detected, these systems are known as X-ray binaries ([Forman et al., 1978](#)).

While supermassive and stellar black holes shared the presence of a black hole and an accretion disk, relativistic jets appeared to be absent in stellar black holes. In 1979 the X-ray binary SS433 was found to have associated jets. However, these jets were dissimilar to those found in quasars. Their velocity was 'only' 26% percent of the speed of light, and it is still debated whether the binary's collapsed component is a black hole or a neutron star ([Han and Li, 2020](#)).

13.2 Microquasars

In 1992 the GRANAT space observatory, a collaboration between Russia, France, Denmark and Bulgaria, detected a bright transient X-ray source that came to be known as GRS 1915+105 ([Castro-Tirado et al., 1992](#)). As part of a radio monitoring program with the VLA, [Mirabel and Rodríguez \(1994\)](#) reported the detection of repeated ejections that presented a superluminal illusion. The illusion had been observed previously only in quasars. It is produced because the radio emission from the approaching ejections has to travel progressively shorter distances to the observer (see [Figure 8](#)). Approximately 20 microquasars are known in the Milky Way.

What have we learned from microquasars? The discovery of microquasars has provided important astrophysical information, which we list below.

- (1) Microquasars consolidated the quasar–microquasar analogy, since both types of objects are now known to have three main

- components: a black hole, an accretion disk, and relativistic radio jets (Figure 9).
- (2) Microquasars were among the first sources to reveal the expected presence of a receding lobe. With this result, it was possible to corroborate that, even when both lobes are most likely very similar, in the sky the receding lobe seems fainter and slower than the approaching lobe. These effects are well understood in terms of special relativity (Mirabel and Rodríguez, 1994). When the proper motions of both lobes can be determined, it is possible to derive an upper limit to the distance (Mirabel and Rodríguez, 1999).
 - (3) The fastest time variability in these systems is expected to be of the order of the light crossing-time for the disk. Since dimensions in quasars are millions of times larger than in microquasars, variations that take years in quasars only take minutes in microquasars. This makes microquasars ideal for searching correlations between jet ejections and disk accretion flows (Choudhury et al., 2003; Fender and Belloni, 2004), offering insights into universal jet-launching mechanisms. The study of microquasars is also relevant to the study of the spin of stellar black holes.
 - (4) Because of their proximity, microquasars have been helpful in searching for interactions between their jets and the surrounding medium (Gallo et al., 2005; Tetarenko et al., 2020). In particular, it has been proposed that the southeast jet of GRS1915+105 has triggered star formation in the HII region complex IRAS 19132+1035 (Rodríguez and Mirabel, 1998; Tetarenko et al., 2018).
 - (5) The study of quasars and microquasars will help establish the expected properties of the elusive intermediate black holes, which could turn out to be mini-quasars. These comparative studies will also help predict the characteristics and effects of black holes in the early Universe (Mirabel and Rodríguez, 2022).
 - (6) Finally, some microquasars have turned out to be sources of ultra-high-energy γ -ray emission, up to TeV energies (Alfaro et al., 2024). Future studies are underway to determine if microquasars could be an important source of TeV γ rays and even energetic cosmic rays.

13.3 The Radio–Gamma-Ray Connection of Blazars [S.D. and V.P.A.]

Active Galactic Nuclei (AGN) are among the most energetic objects in the Universe. They are powered by supermassive black holes

(SMBHs) that actively accrete surrounding matter. As material spirals into the black hole, it forms a hot accretion disk and generates immense radiation detectable across the entire electromagnetic spectrum, often outshining their host galaxies. Blazars are an extreme subset of AGN, whose relativistic jets are pointing nearly directly at Earth. Because of the low angular resolution of γ -ray observations, it is uncertain where and how they produce γ -ray emission.

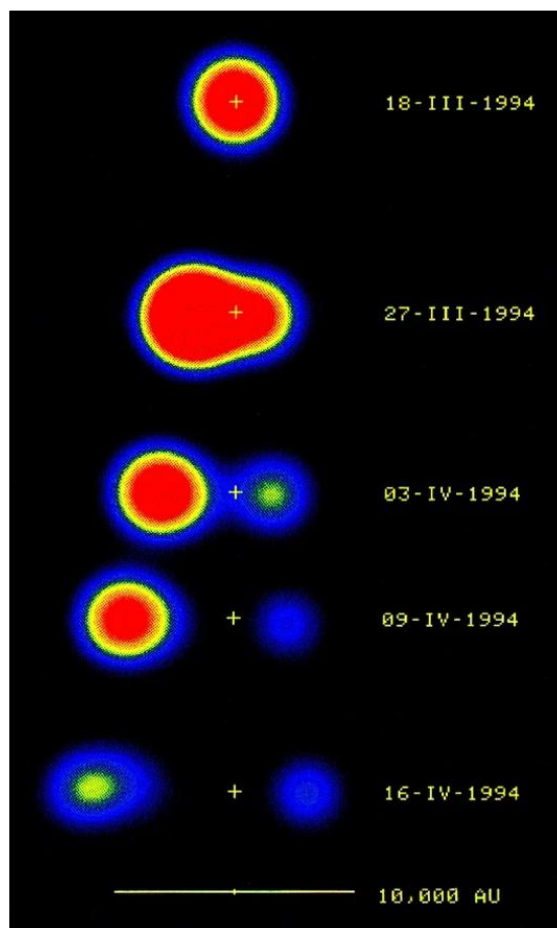


Figure 8: This sequence of observations made in 1994 exhibits the special relativity illusion discussed by Mirabel and Rodríguez (1994). Although the two moving lobes are very similar, the one to the left appears to move faster and be brighter than the one to the right (after Mirabel and Rodríguez, 1998: 675).

To address this issue, two young Mexican postdocs at the Max-Planck-Institute for Radio Astronomy (MPIfR) in Bonn, Germany, Víctor M. Patiño-Alvarez and Sergio Dzib, initiated a study combining VLBI data and Fermi-LAT γ -ray observations. They aimed to identify the origin of the γ -ray emission in blazars. As a starting point, the study extracted information, such as flux and source positions, from existing VLBI observations. The extracted flux densities were then used to construct the light curves of

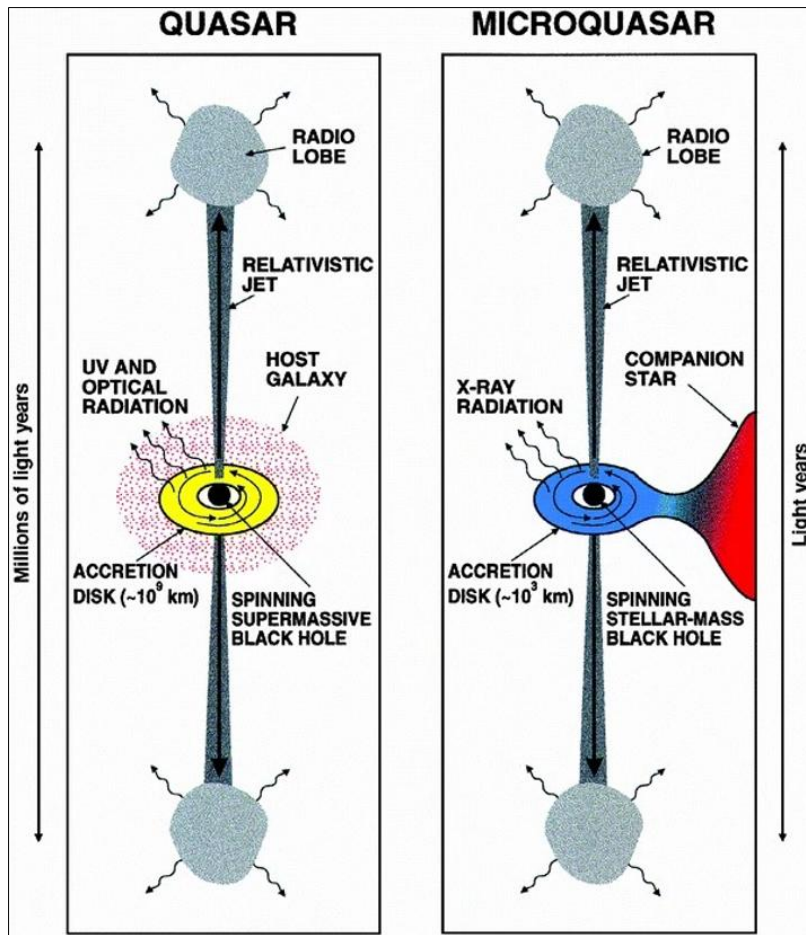


Figure 9: Artistic diagram of the quasar–microquasar analogy. In the case of quasars, the black hole accretes from surrounding gas in the center of a galaxy. The disk emits mostly optical and ultraviolet radiation. In the case of micro-quasars, the black hole accretes from a companion star. The disk is hotter than in the quasar case and emits mainly in X-rays. Both types of sources produce relativistic synchrotron jets that are better studied in the radio (after Mirabel and Rodríguez, 1998: 673).

14 HIGH REDSHIFT [E.J. and J.Z.]

14.1 Meter and Centimeter Radio Astronomy in Mexico

A pioneering study of high- z radio sources was published by Irene Cruz-González and René Carrillo (Cruz-González and Carrillo, 1991) in 1991. They presented a compilation of 33 radio sources with radio jets and superluminal motions at redshifts $0.0 < z < 2.4$, to explore the relation between the jets

and their central radio sources. One of their main results was that the observed velocity of the jets, inferred from proper motions, did not depend on the redshift, suggesting that such a jet property was not linked to evolutionary effects. To put this result in perspective, in 1991 the community was still discussing whether the characteristic epoch of galaxy formation was at redshifts larger or lower than $z = 2$. Hence, Cruz-González and Carrillo were peering into the evolution of extragalactic jets up to some of the highest redshift values reported by 1991. A decade later, in 2002, Vahram Chavushyan, Raúl Mújica, José Ramón Valdés, and collaborators (Chavushyan et al., 2002) presented the classification of the optical counterparts and radio spectra of nine radio sources, of which three had $2 < z < 3$. Radio data were taken with the RATAN-600 radio telescope at 0.97–21.7 GHz, while the optical spectra were obtained with the 2.1-meter telescope of the Guillermo Haro Observatory (Cananea, Mexico), operated by INAOE, highlighting the role of national astronomical facilities in studies of high- z radio sources. The decade of the 2000s also witnessed the development in Mexico of studies about jet–gas interactions in $z \sim 2.5$ radio galaxies. Albeit the first studies focused on the theoretical aspects of the Ly α -emitting gas with extended radio emission (Binette et al., 1998; 2006),

the core and jet components, while positions allowed proper motion determinations. Meanwhile, γ -ray light curves of blazars were also constructed from Fermi LAT data.

The first results were obtained for the famous blazar 3C 279, and show that γ -ray emission can be produced near the SMBH and also in a relativistic moving jet component 42 pc away from it (Patiño-Alvarez et al., 2019). These findings support the idea of multiple γ -ray emission sites, suggesting a complex interplay between the base of the jet and downstream shock regions. Moreover, they also show that the γ rays produced in the moving component are due to a process called synchrotron self-Compton, whereby the synchrotron photons are scattered by the same electrons that produced them in the first place.

Víctor moved back to Mexico as a Professor in INAOE, and was also offered the position of lead of a Max-Planck partner group (MPPG) to continue multi-wavelength studies of blazars. Until today, this is the only MPPG in astronomy active in Mexico. Víctor and his students are now pursuing complementary radio and γ -ray investigations in other blazars (e.g., 3C 454.3; Palafox et al., 2025), while continuing to collaborate with Sergio and other colleagues at the MPIfR.

subsequent analyses heavily relied on multi-band radio continuum imaging with the VLA to study the radio morphology, radio spectrum, and polarization properties of $z > 2$ radio galaxies harboring an extended Ly α halo (e.g., [Humphrey et al., 2007](#), and references therein).

At the beginning of the 2010 decade, Janet Torrealba and Vahram Chavushyan ([Torrealba et al., 2011](#)) co-led a major study of the VLBA radio emission at 15 GHz, and optical nuclear emission of 135 compact jets with redshifts out to $z = 3.4$. They found a positive correlation between the VLBA and optical nuclear luminosities, suggesting that—as with the 15GHz VLBA radiation—optical emission is non-thermal and originates in the innermost part of the jet at sub-parsec/parsec scales. It was also in the 2010s when studies of magnetic fields and polarization properties of intermediate/ high-redshift radio galaxies were set in motion by the Mexican community. In 2015, Shane P. O'Sullivan and collaborators ([O'Sullivan et al., 2015](#)) used the NRAO VLA Sky Survey to compare the degree of polarization at 1.4GHz of $z < 0.7$ radio galaxies in different accretion states. They found that low-excitation radio galaxies can achieve a higher degree of polarization at 1.4 GHz than their high-excitation counterparts. Later, in 2017, Shane P. O'Sullivan and collaborators ([O'Sullivan et al., 2017](#)) pushed their analysis to radio galaxies out to $z = 2.8$. Their 1.4 GHz observations, taken with the Australia Telescope Compact Array (ATCA), indicate no redshift evolution of the magneto-ionic properties of the 100 radio galaxies at $0 < z < 2.8$ included in their sample.

Evidently, until the 2010s, studies of high- z radio sources focused on radio-loud AGNs, given their high brightness and the shallow depths of the available radio observations. One of the exceptions was the work led by Itziar Aretxaga and David Hughes in 2007 ([Aretxaga et al., 2007](#)). They primarily used 1.4 GHz Very Large Array photometry, and 850 and 450 μ m SCUBA data, to determine the radio-mm-FIR photometric redshifts of 120 submillimeter-selected galaxies (SMGs) in the Lockman Hole East and the Subaru XMM-Newton Deep Field. Itziar Aretxaga and her team used such photometric redshifts (with a median $z \sim 2.4$) to derive one of the first measurements of the contribution of SMGs to the cosmic star formation rate density of the Universe across cosmic time.

While [Aretxaga et al. \(2007\)](#) laid the foundations for the study of star formation processes in high- z galaxies in Mexico, the authors were limited to only exploring the most luminous systems: SMGs with star formation rates

larger than one hundred solar masses per year. Recently, Eric F. Jiménez-Andrade led the production of the deepest radio survey ever obtained in an entire extragalactic field: the 10 GHz map of GOODS-N ([Jiménez-Andrade et al., 2024](#)), which is five times more sensitive than the pioneering data set used by [Aretxaga et al. \(2007\)](#). The 10 GHz map of GOODS-N resulted from a VLA Large Program to explore the radio emission of star-forming galaxies detected in the sub-micro Jy regime out to $z \sim 5$. Eric F. Jiménez-Andrade and his team are also producing the 3 GHz map of the GOODS-N and CEERS fields, with similar depths to the 10 GHz map; this work will lead to the most complete and deepest radio data set of the high- z Universe.

14.2 Submillimeter and Millimeter Studies at High Redshifts

As mentioned in Sections 11 and 15, the first decade of the new millennium saw a surge in submillimeter and millimeter studies of high-redshift objects. These efforts were primarily driven by the start of the construction of the Large Millimeter Telescope (LMT) and the arrival of astronomers in Mexico who were involved with this project, such as David Hughes and Itziar Aretxaga (along with their first group of students mentioned above). However, despite the magnitude of the LMT project, the fraction of professional astronomers in Mexico working in submillimeter and millimeter wavelengths remained relatively small—and continues to be a minority to this day.⁴

The earliest of these studies focused on the physical characterization of submillimeter-selected galaxies, which typically have redshifts in the range of $z = 2-4$ (e.g., [Hughes et al., 2002](#); [Aretxaga et al., 2003; 2007](#); [Chapin et al., 2008](#); [Austermann et al., 2009](#); [Wilson et al., 2008](#); [Yun et al., 2008](#)). The involvement of Mexican astronomers (or astronomers based at Mexican institutions) in submillimeter/millimeter studies of high-redshift galaxies grew significantly during the second half of the 2000s, mainly due to the AzTEC campaigns on the JCMT and ASTE telescopes (2005–2008; see Section 15) and their participation in other projects, such as the Balloon-borne Large Aperture Submillimeter Telescope (BLAST) and the James Clerk Maxwell Telescope. These efforts expanded Mexico's engagement in international collaborations with numerous foreign institutions, resulting in several joint publications (e.g., [Devlin et al., 2004](#); [Takagi et al., 2007](#); [Clements et al., 2008](#); [Coppin et al., 2006; 2008](#); [Ezawa et al., 2008](#); [Scott et al., 2008](#); [Chapin et al., 2009a; 2009b](#); [Tamura et al., 2009](#)). At the same time, these

collaborations and observing campaigns were crucial to training a new generation of Mexican students (see Section 15 for more details).

During the second decade of the millennium, the LMT began the commissioning phase of several instruments and started its ‘Early Science’ observations. The 1.1-mm AzTEC camera and the 3-mm Redshift Search Receiver (RSR) became the ‘workhorse’ instruments for high-redshift studies. The first publication with LMT data in the field of high-redshift galaxies saw the light in 2015 and was led by Jorge Zavala, at the time a PhD student at INAOE under the supervision of Itziar Aretxaga and David Hughes. This work presented AzTEC continuum observations and detections of CO emission lines in a small sample of gravitationally lensed submillimeter galaxies at $z = 2.0\text{--}4.7$ (Zavala et al., 2015b). Subsequent studies by the LMT community successfully detected dust continuum emission and/or gas emission lines in various galaxy samples spanning a wide redshift range (e.g., Geach et al., 2015; Yun et al., 2015; Harrington et al., 2016; Pope et al., 2017; Montaña et al., 2021; Berman et al., 2022). These studies demonstrated the LMT’s capabilities in providing spectroscopic redshifts and characterizing the physical properties of submillimeter-bright galaxies, yielding breakthrough insights into the nature of these extreme objects. They were also crucial in understanding the prevalence of dusty galaxies in the early universe, as Zavala et al. (2018b) demonstrated. This study exploited ALMA, LMT, and SMA observations to spectroscopically confirm a submillimeter galaxy at $z = 6.23$, at the time the second most distant galaxy of its kind, and one of the highest-redshift submillimeter-selected galaxies known to date.

Beyond studies of bright submillimeter-selected galaxies, LMT observations have also contributed to other research areas, always involving Mexican astronomers. For example, Caliendo et al. (2021) placed constraints on the gas fraction of a quiescent galaxy at $z = 1.9$, while Zavala et al. (2015a) provided constraints on the dust mass of an ultra-high-redshift galaxy at $z \sim 9.6$ (both studies based on non-detections).

In recent years, Mexican-led studies of high-redshift sources using submillimeter and millimeter observatories have expanded beyond LMT data to include observations from other cutting-edge facilities, such as ALMA and NOEMA. An example of this is the study led by Eric F. Jiménez-Andrade (then a PhD student at the University of Bonn), who combined ALMA and NOEMA observations to investigate the properties of a pair of massive, dusty, star-

forming galaxies initially discovered with the AzTEC camera (Jiménez-Andrade et al., 2020). Several other ALMA studies of high-redshift objects have been led by Mexican astronomers or researchers affiliated with Mexican institutions (e.g., Zavala et al., 2018a; 2019; 2021; Quirós-Rojas et al., 2024). Notably, ALMA recently broke the $z = 10$ barrier with the detection of the [OIII] $88\mu\text{m}$ transition in a JWST-selected galaxy at $z = 12.33$ (Zavala et al., 2024), a work led by Mexican astronomer Jorge Zavala, who was at the time working at the National Astronomical Observatory of Japan.

It is thus clear that, despite the relatively small number of submillimeter/millimeter astronomers in Mexico working on high-redshift galaxies, their contributions have had a significant impact. This progress has been primarily driven by the advent of the Large Millimeter Telescope, which holds the promise of even greater achievements once it operates at full capacity.

14.3 SCI-HI: the Search for the First Stars and Galaxies in the Universe [O.L.C.]

Pushing the search for the first stars and galaxies in the Universe leaves us with only a few tracers. Hydrogen is the ubiquitous and most abundant element in the Universe, and its 21 cm line is the tracer of choice (e.g., Loeb, 2010; Loeb and Furlanetto, 2013; Mesinger, 2020; Mirabel and Rodríguez, 2022). However, detecting this hyperfine transition (the splitting of the hydrogen ground state $1^2S_{1/2}$) is challenging (see the earlier review by Bravo-Alfaro) due to its weakness. At high redshift, the 21 cm line excitation sources are (a) the absorption of cosmic microwave background (CMB) photons, (b) collisions with other particles, and (c) resonant scattering of Ly α photons, known as the Wouthuysen–Field Effect. The excitation temperature of the 21 cm line is known as the spin temperature (T_S) and depends on the ratio of H atoms in the two hyperfine levels. If T_S differs from the CMB temperature, T_{CMB} , the 21 cm line is observable. This difference is known as the brightness temperature contrast δT_b :

$$\begin{aligned}\delta T_b(\mathbf{x}, \nu) &\equiv T_S(\mathbf{x}, \nu) - T_{CMB,0} \\ &\equiv \frac{T_S(\mathbf{x}, \nu) - T_{CMB}(z)}{1+z} \left(1 - \exp^{-\tau_{\nu 0}(\mathbf{x}, \nu)}\right),\end{aligned}$$

where $\mathbf{x}$ gives the spatial dependence, ν is redshifted frequency, and $\tau_{\nu 0}$ is the optical depth of the 21 cm line. Pritchard and Loeb (2012) generated the expected evolution of the global 21 cm brightness with redshift, shown in Figure 10; they highlight the following main evolutionary phases (e.g., Greig, 2020): (A) a local minimum during the Dark Ages, where collisional

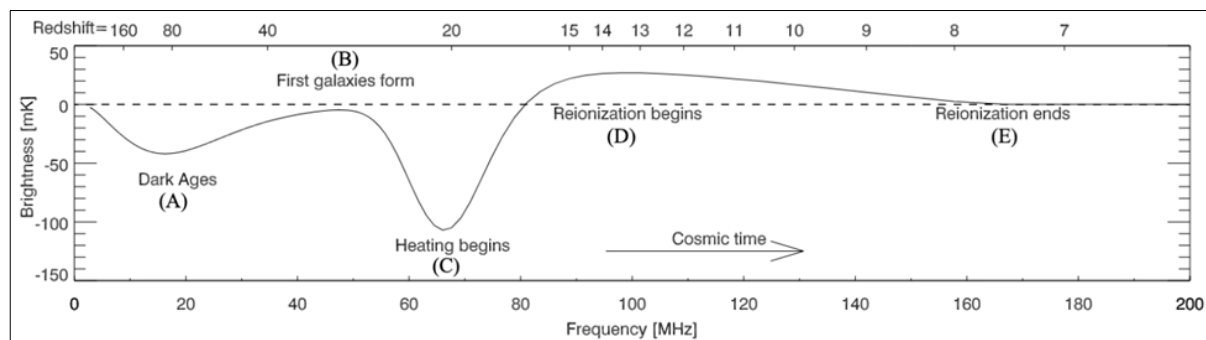


Figure 10: An early example of the 21 cm global (all-sky-average) brightness temperature signal, showing the major cosmological transitions from the Dark Ages ($z \sim 50$) to the end of the EoR ($z \geq 6$). The spectrum's shape and the epochs of the cosmological transitions depend strongly on the model (e.g., [Cohen et al., 2017](#)) (figure after [Greig, 2020: 4-3](#), who adapted it from [Pritchard and Loeb, 2012](#)).

coupling is no longer effective; (B) a local maximum when the Ly α pumping due to first sources becomes relevant, marking a transition from the Dark Ages; (C) a minimum when the X-ray heating that eventually brings the signal back to emission initiates; (D) a maximum during the Epoch of Reionization (EoR), when the 21 cm signal becomes saturated. Finally, (E) marks the end of the EoR. However, the shape and epoch of these transitions are model-dependent (e.g., [Cohen et al., 2017](#)). For further details, see [Greig \(2020\)](#).

The 21 cm global signal is a new cosmological test promising to provide fine details on dark matter, black holes, and other exotic Universe components (e.g., [Loeb and Furlanetto, 2013](#); [Mesinger, 2020](#)). Among the first attempts at detecting the 21 cm global signal were the projects Experiment to Detect the Global EoR Signature (EDGES; [Rogers and Bowman, 2012](#)), the second generation Shaped Antenna Measurement of the Background Spectrum (SARAS 2; [Patra et al., 2013](#)), and the Large-Aperture Experiment to Detect the Dark Ages (LEDA; [Greenhill and Bernardi, 2012](#)).

Terrestrial radio frequency interference (RFI), in particular the commercial FM band (87.5 to 108.0 MHz), is the primary noise contributor within the 40–130 MHz band. Hence, to avoid the introduction of complex RFI detection and removal techniques (e.g., [Offringa, 2012](#)), in 2010 a group of astronomers from Carnegie Mellon University and INAOE started a collaboration called Sonda Cosmológica de las Islas para la Detección de Hidrógeno Neutro (i.e., Cosmological Probe of the Islands for the Detection of HI, SCI-HI for its acronym in Spanish). The goal was to identify the best radio-quiet zones in Mexico, and to design and construct sensitive portable radiometers capable of detecting the trough (C) in the 21 cm global brightness temperature signal (see [Figure 10](#)), from

the selected radio-quiet zones. The Mapimí Biosphere Reserve was explored in 2010, arriving at encouraging results. Unfortunately, the heart of the Silent Zone (the Zona del Silencio in Spanish) was unsafe. Looking for safer conditions and after some testing, the group found the best radio-quiet zone, on Guadalupe Island (Lat 28° 58' 24" N, Long 118° 18' 04" W), located about 300 km off the coast of Baja California, home to a population of only 40 fishermen and Mexican Navy personnel. The first SCI-HI run was conducted from Guadalupe Island's West Side (Punta Oeste) on 1–5 June 2013. Data were processed and calibrated using a trifold approach (see [Voytek et al., 2014; 2015](#); [Peterson et al., 2014](#); [Jáuregui-García, 2016](#)). The first results of the SCI-HI experiment reached residuals of about 5–10 K in 4.4 hours of integration, providing an upper limit (<1% of the foreground signal) but also a clear proof of concept.

SCI-HI is a single antenna experiment covering the 40–130 MHz range. Different designs of dipole antennas were tried as the experiment evolved. The first measurements were carried out with Hlbiscus, a wide-angle (55°) broadband antenna with matching impedance and uniform radiation pattern, centered at 70 and 100 MHz ([Voytek et al., 2014](#); [Jáuregui-García et al., 2017](#)). The newest Mango Peel design ([Jáuregui-García, 2016](#); [Palillero-Pérez, 2020](#)) has a more uniform radiation pattern. The SCI-HI receiver has a standard design (see [Greenhill and Subrahmanyam, 2020](#), for a review) and operates with a 12 V battery. After sampling (500 MSamples s⁻¹ with a 12-bit resolution), the signal is Fourier-transformed to generate a power spectrum from 0 to 250 MHz ([Voytek et al., 2014; 2015](#); [Jáuregui-García, 2016](#)).

The collaboration has been working on an improved version of SCI-HI to eliminate the self-generated RFI and reduce the calibration errors.

The goal is to bring the residuals below 40–130 mK in the 40–130 MHz range. For this purpose, the project is switching to ROACH boards (Ulloa-Velázquez, 2020), and aiming to carry out coordinated observations with longer integration times from multiple sites (i.e., the Socorro and Clarion islands in the Mexican Revillagigedo Archipelago, Lat 18° 49' 17" N, Long 112° 45' 50" W), to account for the effects of the ionosphere (e.g., Shen et al., 2022). In parallel, the experiment Probing Radio Intensity at High z from Marion Island (PRIZM), which adopted the SCI-HI observing strategy, set forth its first results (Philip et al., 2019), while EDGES (Bowman et al., 2018) reported a first detection of the trough (C). Nevertheless, a recent rejection of EDGES's result by SARAS 3 (Singh et al., 2022) shows that the search for the detection of the 21 cm background is still open.

SCI-HI has introduced 21 cm cosmology in the Mexican astronomical community and has increased the scientific activities in the Mexican Exclusive Economic Zone (EEZ). Some of the islands in the EEZ are radio quiet and have dark skies; they are excellent sites to set up robotic astronomical observatories.

15 THE LARGE MILLIMETER TELESCOPE AND THE STUDY OF DEBRIS DISKS [M.C.D. and E.B.]

15.1 The Origin of the Large Millimeter Telescope (LMT)

In the early 1990s, a group of astronomers from the University of Massachusetts at Amherst (UMASS) and Mexico discussed the possibility of starting a binational collaboration to build an astronomical infrastructure that would be highly competitive in the concert of the great ideas and projects of the period. They concluded that this effort should focus on a telescope with instrumentation sensitive to millimeter radiation, since the largest single-antenna radio telescopes working in those wavelengths at the time were relatively small. Although such facilities had already provided critical scientific results, including some that were revolutionary, a larger telescope in a privileged location could yield even more impressive findings in multiple branches of contemporary astrophysics.

Having decided on the path to follow, the colleagues joined forces to develop financing proposals and prepare a conceptual design that established the series of technical requirements to carry out the project. After this design, the site where it would be built had to be defined: it should be located in a high and dry place, since water vapor in the Earth's atmosphere is the main impediment to millimeter radiation being collected by ground-based telescopes. Finally,

the resources granted by the Mexican National Council of Science and Technology (CONACyT), the United States Congress, and the state of Massachusetts would allow the construction of the antenna to begin at a site still to be selected.

15.2 The LMT Site

The search for the site required a great effort that lasted more than four years. Instruments sensitive to the amount of water vapor in the atmosphere (radiometers) and meteorological stations were placed at each proposed location. The initial list consisted of 12 promising sites, such as the peaks of Malinche, Cofre de Perote, and Sierra de San Pedro Mártir, among others. The decision to place the telescope on Mexican soil was mainly because such a location would give access to a large part of the sky in the Southern Hemisphere. It was an enormous challenge, since most of these sites did not have—even partially-made—roads to their summits, so sometimes people had to climb under adverse geographical and climatic conditions. The extinct volcano Sierra Negra, on the border between the Mexican states of Puebla and Veracruz and approximately seven km from the top of the colossal Pico de Orizaba (Citlaltepetl), turned out to be the ideal site. With an altitude of almost 4,600 m (~15,000 ft) above sea level and at a latitude of +19°, it met the established requirements. In the end, constant monitoring of the conditions of the site would show that it was indeed an exceptional place to carry out the intended observations (see Figure 11).

15.3 The LMT Construction

The financing proposal had been accepted and construction began in the late 1990s. The first stage of construction consisted of providing access to the summit by building a dirt road, for the thousands of trucks that would eventually transport materials required for the civil works, and later, the telescope itself. Once the ground where the telescope would be built had been leveled, work was done on drilling the sites where concrete would be poured for the 36 piles, each one meter in diameter and 18 m deep; they would serve as foundations for the base of the enormous telescope and would support the LMT to withstand hurricane winds of up to 250 km h⁻¹. This task took more than a year, due to the volcanic nature of the soil. Three milestones were identified during the first phase of the telescope construction. The first was the conclusion of the civil engineering works in 2006, which allowed the construction and assembly of the large antenna to begin. The second, due to the risk it represented, was lifting the base structure of the antenna itself. The weight of



Figure 11: Map of the LMT site (map: the authors).

the framework of 700 tons required the use of two huge tower cranes with sufficient capacity to guarantee the procedure without risks. With the structure in place, the 180 panels that make up the main reflective surface could be inserted, some of them provisionally at the time. The third crucial moment corresponded to the 'first-light' observations, in which both the telescope and its instrumentation were tested. Two

instruments were built by the UMASS for the beginning of the LMT scientific operations: the spectrometer Redshift Search Receiver (RSR), which observes in the 3 mm atmospheric window (73–111 GHz), and the AzTEC camera, now decommissioned, destined to map the sky at a wavelength of 1.1 mm (see the LMT official web page for more details: www.lmtgtm.org).

15.4 First Light

In December 2010, a cryogenic radiometer, operating at 7 mm, arrived at the LMT from Carnegie–Mellon. Dr. Alfonso Serrano had directed a group of astronomers and engineers to design and construct a three-mirror camera to couple the radiometer to the Cassegrain focus. After aligning the setup, the first drift-scan observations of M42 at 7 mm were obtained with the LMT on 24 December 2010. Although 7 mm was not an expected working band for the LMT, the telescope's superb pointing accuracy was on full display.

The first-light observations took place at the beginning of June 2011. Previously, it was necessary to carry out the exhaustive task of aligning the surface, that is, adjusting the primary surface to a parabola as perfectly as possible, so that the collected radiation could be optimally sent to the secondary mirror and, subsequently, to the instruments. This task was accomplished with a holography method that consists in pointing the telescope at artificial satellites, which usually have beacons that emit radio waves (12 GHz in frequency or 2.5 cm in wavelength), and characterizing this radiation before and after it was reflected by the large antenna. It was a long process, mainly because there still was no automated method to move the 84 panels of the antenna's three inner rings.

Although these initial tests and corrections did not reach the desired surface precision, they were considered sufficient to answer some crucial questions: Does the telescope work? Do the instruments provide the expected information? The telescope, equipped with the RSR, was pointed at two already known sources. The first was a relatively nearby galaxy, about 12 million light-years away, Messier 82 (M82), known for having prominent star formation, that is, with enormous amounts of molecular gas and dust. Through multiple observations with other millimeter telescopes, it was known that this galaxy presents notable transitions of molecules in the 3 mm band and, consequently, represented the ideal celestial object to test the capabilities of the telescope and the instrument. At the end of the night of 1 June, work was done on the collected image and, with great joy, it was confirmed that the array was capable of detecting numerous molecules, among which those of carbon monoxide (CO), hydrogen cyanide acid (HCN) and the formyl cation (HCO^+) stand out. A more complex molecule, methyl-acetylene, composed of seven atoms ($\text{CH}_3\text{C}_2\text{H}$), was also detected.

After this successful observation, the telescope was pointed at other celestial objects that posed a greater challenge, such as the so-

called Cosmic Eyelash, a galaxy that also has abundant formation of new stars, but is about a thousand times more distant than M82. That is, the millimeter light emanated from that object when the Universe was only 20% of its current age, which is around 13.7 billion years. With these examples and subsequent observations, obtained with the other first-light instrument, the AzTEC continuum camera, it became clear that the scientific objectives of the LMT were realistic.

15.5 The First Scientific Results

Since 2014, the LMT has operated scientifically. That year, the project partners (the Mexican scientific community and colleagues from the UMSS) were invited to develop astronomical observation proposals that could lead to scientific results of the highest impact. Since that time, six additional calls have been released, attracting submissions of nearly 500 research projects, all crafted by the combined efforts of over ~800 scientists worldwide (from countries on the five continents). From Mexico, researchers and students from institutions located nation-wide, from Baja California to Chiapas, have participated. The proposed projects range from studies of objects in our Solar System (comets, planets, and satellites of the gas giants Saturn and Jupiter) and in the Milky Way, to galaxies in the distant Universe, when it was just a small fraction of its current age. Numerous investigations have been performed with the LMT; for reasons of space they are omitted here, but they constitute significant contributions to the understanding of the formation and evolution of structures at all cosmic scales. The papers published with LMT data can be consulted on the LMT website. In what follows, we focus on the study of the so-called debris disks (DDs), which will undoubtedly be one of the major contributions of the LMT to contemporary astrophysics.

15.6 Debris Disks at Millimeter Wavelengths

Cool DDs, surrounding main sequence (MS) stars, are remnants from the planet formation process (Hughes et al., 2018; Matthews et al., 2014; Wyatt, 2008), similar to the Solar System's Edgeworth–Kuiper Belt. These disks are composed of solid particles varying widely in size, ranging from tiny micron-sized dust grains to larger planetary bodies. Correlations identified between stars and their planetary systems suggest that DDs and exoplanets are inextricably linked (e.g., Bryden et al., 2013). Continuum emission from micron-sized dust grains dominates the observed flux from DDs: this radiation peaks at far-infrared wavelengths.

These structures exhibit typical temperatures of about 30–80 K and radial size scales of 10s–100s au, with narrow annular architectures. Far-infrared studies identify 20–30% of nearby stars with infrared excesses (Eiroa et al., 2013), a fingerprint of the presence of dusty disks. In the sub-mm regime, data from the James Clerk Maxwell Telescope (JCMT) DD legacy survey SONS (SCUBA-2 Observations of Nearby Stars) detected excesses at 850 microns in 49 out of 100 stars (Holland et al., 2017). The presence of extended emission from a circumstellar disk is a meaningful factor in the modeling process, as it directly constrains the orbital radius of the dust responsible for the observed emission, weakening inherent degeneracies between grain size and radial distance in the models reliant solely on the disk integrated thermal emission (e.g., Marshall et al., 2014). At longer, (sub-)mm, wavelengths, the emission from larger millimeter-sized dust grains begins to dominate the observed flux, reducing the measured flux commensurately, due to the lower ratio of surface area to mass of the larger grains. These wavelengths trace the coldest and largest dust grains, which do not drift as far from their parent planetesimal belt under the action of radiation forces as the micron-sized grains, which are more visible at far-infrared wavelengths. Therefore, the measured disk extent will closely match that of the original dust-producing bodies in each system. Since these disks are optically thin, we observe the radiation emitted from the whole volume of the disk, making the flux a proxy for the dust mass (Williams and Andrews, 2006).

Virtually all telescopes, both from space (e.g., IRAS, Spitzer, WISE, Herschel) and from the ground (for instance, the JCMT and currently ALMA), have devoted a significant time to the observations of circumstellar material around mature stars, mainly through legacy surveys that attempt to observe as many targets as possible, optimizing the target lists on the basis of the results of previous observations. The same should be valid for the LMT, so we are constructing an ambitious proposal aimed at studying the properties of cold dust around some 200 stars in the solar vicinity. The proposal, called TUPURI (which means ‘dust’ in the Purépecha⁵ language), is briefly described in Chávez-Dagostino et al. (2004). An important note is worth mentioning: every single disk represents an individually important science case. We describe below one of our LMT results.

15.7 Epsilon Eridani and its Cold Environment

One of the most illustrative results of the LMT capabilities, even operating only with a 32-m

aperture (until 2017), concerns the study of the dust ring that surrounds our neighboring star, just 10 light-years away, ϵ Eridani (EE). EE is slightly smaller (in radius, mass, and temperature) than our Sun, and just a quarter its age (our Sun has an estimated age of about 4.5 billion years). In 1983, the Infrared Astronomical Satellite (IRAS) space mission detected prominent infrared emission in the EE environment, which was later explained as light coming from very cold circumstellar dust (about 40 K), the product of collisions between planetesimals (e.g., comets and asteroids), even at planetary scales. Motivated by this discovery, numerous exhaustive investigations of EE were carried out based on data collected by a great diversity of (sub)millimeter telescopes. Among other results, these studies determined that this circumstellar material is located at a distance com-

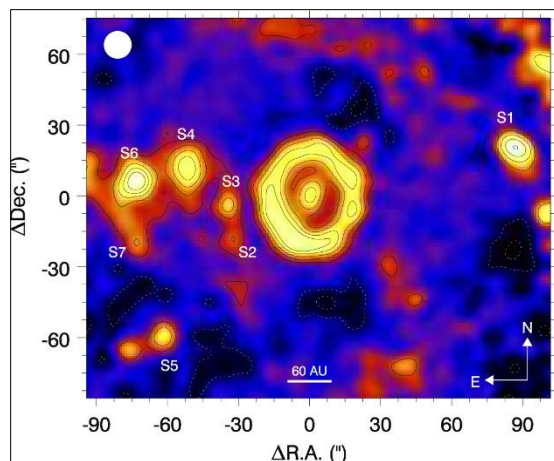


Figure 12: Map of the ϵ Eridani face-on debris disk at 1.1 mm, obtained with the AzTEC camera on the LMT. Seven other sources are seen on the map; they are labeled as S1-S7 and are possibly dusty distant galaxies (Chávez-Dagostino et al., 2016: 2287).

parable to the tenuous ring of material that revolves around our Sun, beyond the orbit of Neptune, i.e., the Kuiper or Edgeworth–Kuiper Belt. So why study it with the LMT? The answer lies in the debate over whether the disk of material was evidence of the disturbance of a planet the size of Neptune orbiting EE at about 40 times the Earth–Sun distance. Previous spectacular images, particularly submillimeter maps obtained with the JCMT, showed that the disk appeared to contain brighter regions, which were attributed to the effects of the potential planet’s gravity. The image we obtained with the AzTEC camera attached to the LMT (Figure 12), undoubtedly even more spectacular than previous observations, showed for the first time the complete ring and the emission from the star EE; it is, to date, the only detection of the stellar EE emission with a single antenna

telescope (Chávez-Dagostino et al., 2016). It was possible to show that the ring has a homogeneous structure, within the uncertainties associated with the observation. Furthermore, it was demonstrated that the brightening detected with other, less sensitive, telescopes could well be due to background objects, most likely very distant invisible galaxies, with prominent formation of new generations of stars. Recently, Booth et al. (2023) reported deep high-spatial resolution observations with ALMA at band 6 (1.29 mm), and suggested that the observed brightening could be caused by a migrating planet, and also that multi-epoch observations are required to assess the potential orbital motion of the dust clumps.

15.8 The LMT with 50 Meters in Diameter

At the end of 2017, the antenna was completed with panels of excellent quality. With the conclusion of the LMT completion plan, since 2018 the LMT has been operating at full capacity with a 50-m diameter active antenna. With this increase in its collecting capacity of almost two and a half times, and the new generation of instruments, the scientific future of the LMT looks very promising. At the time of writing this contribution, the TolTEC continuum camera (Wilson et al., 2020) is in the commissioning phase. A proposal has been made to observe the DDs of the prototypical stars Vega and EE during this process; we expect to report on these observations soon.

16 RADIO INSTRUMENTATION [S.K.]

The early years of radio astronomy in Mexico were marked by the use of internationally accessible radio telescopes. In the early 1980s, L.F. Rodríguez, J. Canto, and various collaborators published results using the Kitt Peak 11-m telescope and the Texas (Millimeter Wave Observatory) 4.9-m telescope. These single-dish observations soon gave way to aperture synthesis ones with the NRAO VLA in New Mexico, which, for nearly 30 years, was the 'workhorse' radio telescope for much of Mexican radio astronomy. Despite this tendency to depend on foreign radio telescopes, several radio instrumentation projects have been developed in Mexico. The Large Millimeter Telescope and the TolTEC camera, described in previous sections, are notable examples of substantial Mexican participation.

The first 'high-impact' instrumentation project initiated in Mexico was the development of the Q-band (7 mm) receivers for the VLA. This project was proposed by Luis Rodríguez and funded by CONACyT in the mid-1990s, with the

astronomical goal of detecting dusty circumstellar disks, where the cold dust has substantial emission even at longer mm-wavelengths. Although an effort was made to involve Mexican industry and academia in the project, in the end it was more effective to simply pass the funds to NRAO and have them develop the receivers. The project funded 13 receivers (for the 27 VLA antennas); an additional 14 receivers for the full complement of 27 were funded independently several years later. The initial results with the receivers were perhaps not as impressive as hoped for, mainly because the VLA was never designed to observe at such high frequencies. Extensive work by the VLA staff over the following years—to improve the antenna performance and to develop new observing procedures for use at high-frequency—largely resolved these issues, and Q-band VLA observations have had an enormous impact in the past two decades, with thousands of hours of observing time and hundreds of published articles.

A similar situation developed in the second decade of the twenty-first century, when additional CONACyT support, in a project led by Laurent Loinard, Luis Rodríguez, and Susana Lizano, obtained funding for hardware to install on the NRAO VLBA interferometer. This upgrade, carried out by NRAO with the CONACyT funds, substantially increased the VLBA's sensitivity and permitted the ultra-high-precision astrometry results discussed in Section 6.

A number of Mexican researchers have carried out smaller-scale instrumentation projects. Particularly noteworthy are David Hirrat's water vapor radiometer and atmospheric phase interferometers at the Institute of Astronomy in Ensenada, Eduardo Mendoza's and Abraham Luna's multiple projects at INAOE, and the Millimeter-wave Laboratory at INAOE, led by Daniel Ferrusca and Miguel Velazquez.

Worthy of mention too is MEXART—the Mexican Array Radio Telescope—developed by the Geophysics Institute of the UNAM. MEXART is a 4096-element dipole array operating at 139.65 MHz, located in the state of Michoacan, and is the longest-operating radio telescope in the country. Somewhat unfortunately, its design was so highly optimized for the geophysicists' goal of interplanetary scintillation studies of the solar wind that the array is nearly useless for general radio astronomy. Nevertheless, it has proven a useful test bed, and has trained a small cadre of technicians in the fine art of VHF radio electronics.

More recently, an inter-institutional radio instrumentation collaboration has developed, formed by researchers at the Institute for Radioastronomy and Astrophysics in Morelia, the

Institute of Astronomy in Ensenada, and the Millimeter-wave Laboratory at INAOE. The collaboration began as a CONACyT-funded collaboration with South African researchers, with the expressed goal of developing hardware and data analysis algorithms for water vapor radiometry (WVR). The team has deployed two radiometers in Namibia to conduct site-testing for the proposed African Millimeter Telescope which, if deployed, would participate in Event Horizon Telescope observations of black holes as described in Section 8. The collaboration, led by Daniel Ferrusca at INAOE, David Hiriart in Ensenada and Stan Kurtz in Morelia, has also taken on several additional projects. Building on the site-testing ideas of water vapor radiometers, the group is deploying a site-testing trailer to study potential sites for ngVLA antennas in northern Mexico. The trailer has multiple weather station modules, lightning detection equipment, RFI monitoring systems, solar radiation detectors and water vapor radiometers. System integration is currently underway, with deployment planned for late 2025.

The collaboration also assists in a project to provide Mexico with its own centimeter-wave radio telescope, in Tulancingo, Hidalgo. This project was funded in 2018 with equal contributions from the state government of Hidalgo and the Newton Fund of the United Kingdom. Tulancingo was home to the original Mexican Earth Station for geostationary satellite communications, which was built in time to broadcast the 1968 Olympic Games to the world. As in other countries, advances in technology have rendered these 30-meter class antennas obsolete for telecommunications, and the two 32-meter dishes in Tulancingo had not been in use since the early 2000s.

Prompted by the availability of funding from the Newton Fund, Stan Kurtz of the IRyA initiated a project, in collaboration with researchers at the Universities of Oxford and Leeds, to convert one of these telecommunications antennas into a radio telescope. Drawing heavily on the expertise of the metrology group at the LMT, led by David Gale, the Tulancingo-I antenna was characterized with a surface rms of just over 1 mm. A warm L-band receiver was built at the IRyA to begin the commissioning process, while a cryogenic C-band receiver was built at Oxford. The collaboration developed through the South African–Mexican project later proved invaluable, as it opened the door to participation by technicians from the National Astronomical Observatory in San Pedro Martir. Led by David Hiriart and Enrique Colorado, with support from Felix Diaz, Tomas Calvario and Hazael Serrano, the SPM technicians reprogrammed the motion controls of the telescope,

which had been upgraded by an Hidalgo-supplied contractor, thereby allowing antenna tracking of astronomical objects.

The Tulancingo-I telescope has already seen first light at L-band and should be fully operable at the C-band by late 2026. Although such telescopes were in common use by the radio astronomy community 50 years ago, they still have a place today, for example, in monitoring studies of periodic methanol maser flares, and searching for pulsar glitches, among many others. The system is also being designed for compatibility with the European VLBI Network, with the goal of eventual incorporation into the array, providing a much-needed East-West baseline after the collapse of the Arecibo telescope. And, of course, the Tulancingo-I telescope will provide an ideal environment to prepare the next generation of Mexican radio astronomers and engineers, with hands-on training experience.

17 CONCLUDING REMARKS [L.F.R.]

While optical astronomy in Mexico can be traced back to pre-Hispanic times, radio astronomy is only five decades old. During this period it was possible to develop international collaborations, as well as radio telescopes and instrumentation located in Mexico itself. At present, there are around 25 radio astronomers in Mexico, and more than a dozen graduate students who are starting to do research in this field.

The major project on Mexican soil today is the consolidation of the operation of the Large Millimeter Telescope Alfonso Serrano, located in the Sierra La Negra, Puebla. This instrument has produced significant research results and is part of the Event Horizon Telescope, the international millimeter interferometer that produced the first images of the surroundings of super-massive black holes.

There is also great interest in participating in the ngVLA, expected to be the dominant centimeter interferometer in the world for the twenty-first century. The proposed ngVLA represents a natural extension of the long-standing involvement of Mexican radio astronomers with the VLA and the VLBA. Mexican participation in the scientific planning of the ngVLA builds upon decades of experience in radio instrumentation, interferometry, and high-impact science, particularly in areas such as star and planet formation, astrometry, and the study of compact objects. Within this historical context, Mexican engagement with the ngVLA reflects the maturation of a nationally based radio astronomy community whose expertise has been shaped through sustained international collaboration. In particular, Mexico has engaged in successful collabor-

ations with the US NRAO, and the ngVLA will broaden this partnership. The important successes of Mexican science achieved with the VLA and the VLBA let us anticipate future exciting results.

In this review, we have presented the above projects as well as several others, both in radio telescopes and instrumentation, with which the radio astronomical community has diversified the range of topics pursued in Mexico. We have also presented accomplished contributions that form part of the rich astronomical lore of the present day. We look forward to the future.

18 NOTES

1. New Spain was a kingdom and not a colony; its Spanish settlers rejected the label ‘colonists’, which meant laborers working on rented land; they preferred ‘vecinos’, i.e., citizens with the rights granted by Castilian law. Similarly, they identified their homeland as a ‘kingdom’ and not a ‘colony’ (Burkholder, 2016: 125). In Mexico, the expression ‘Colonial period’ started to be used in the nineteenth century, following the Anglophone tradition (*ibid.*; Martínez Baracs, 2022:16).
2. Some researchers still use other acronyms like EVLA or JVLA, which were coined during the transition period. However, the NRAO suggests the use of the VLA acronym.

3. A microarcsecond is a millionth of an arcsecond, which is itself 3,600 times smaller than a degree.
4. It is said that Alfonso Serrano once mentioned that every astronomer in Mexico should work in, or at least show interest in, millimeter astronomy. In response, Vahram Chavushyan began doing his calculations on millimeter graph paper. He then visited Alfonso Serrano’s office to proudly demonstrate that he was now, indeed, following the recommendation.
5. A group of indigenous people today living mostly in the Mexican State of Michoacán. During the fifteenth and sixteenth centuries, they were a great power, and they also occupied the southern part of Guanajuato and the northern part of Guerrero. They were never conquered by the Aztecs.

19 ACKNOWLEDGEMENTS

RAGL acknowledges the financial support of DGAPA, UNAM, projects IN106124 and PASPA. LFR is thankful for support from grant CBF-2025-I-2471 of SECIHTI, Mexico. IA’s work is supported by Milgatz Grant ATR2024-154316 funded by MICIU/AEI/10.13039/501100011033. SAD acknowledges the M2FINDERS project from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant No 101018682).

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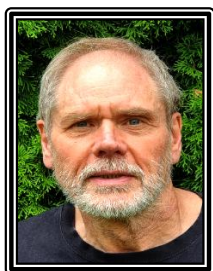
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Starting in 1989, Heinz felt the need to complement astronomical databases with information on radio sources, and he then collected source lists from many hundreds of publications, often converting them from printed to electronic form using optical character recognition (OCR) software. A list of the assembled catalogs is available at http://www.astro.ugto.mx/~heinz/cats_ but only about one third of these lists have made it into databases like NED, Simbad or Vizier.

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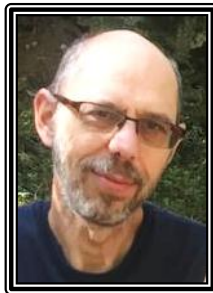
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Itziar has published several book chapters on the demographics of Mexican astronomy, in particular, about the growth of the radio astronomical community. These include: Aretxaga, I., 2014, "Hacia dónde va la ciencia en México: Astronomía y Astrofísica" in A. Carramiñana and W. Lee (Co-ords.), *Demografía de la Investigación Astronómica en México* (Academia Mexicana de Ciencias), and Peimbert, M., Poveda, A., Rodríguez, L.F., and Aretxaga, I., 2010, "Los dos últimos siglos de la astronomía mexicana" in E. Matos Moctezuma (Co-ord.), *El Pasado del Presente: Miradas y Perspectivas* (El Colegio Nacional).



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Dr. Emanuele Bertone, born in Italy in 1968, earned a PhD in Astronomy from the University of Milan.

He is currently a full-time researcher at the National Institute for Astrophysics, Optics, and Electronics in Puebla, Mexico. He focuses on the study of stars and their circumstellar environments. He has forayed into millimeter-wave astronomy with the study of debris disks and the mm emission of main sequence stars in the Solar Neighborhood.

Associate Professor Carlos Carrasco-González was born in Algeciras (Spain), in 1978. He is a radio astronomer renowned for his contributions to our understanding of star and planet formation. He earned his degree in Physics with a focus on Astrophysics from the University of La Laguna (Spain) in 2004, and completed his PhD at the University of Granada in 2010, conducting research at the Instituto de Astrofísica de Andalucía. During his years as a PhD student, he established a close collaboration with Mexican astronomers working at the Universidad Nacional Autónoma de México (UNAM). From 2010 to 2013, he was a postdoctoral researcher at the Max-Planck Institut für Radioastronomie in Germany. In 2013, he obtained a tenure-track position as an Assistant Professor at the Instituto de Radioastronomía y Astrofísica at the UNAM. He is currently a permanent researcher at UNAM, holding the position of Senior Associate Professor.



His primary research focuses on two key phenomena in the early stages of star and planet formation: protostellar jets and protoplanetary disks. He has made important contributions to the understanding of the launching and collimation mechanisms of protostellar jets, their relationship with accretion processes, the early evolution of protostars, and the evolution of dust in protoplanetary disks to form new planetary systems.

Most of his research employs high sensitivity, high angular resolution observations using some of the world's most powerful radio interferometers, including the Very Large Array, the Atacama Large Millimeter/Submillimeter Array, and others, such as the Australia Telescope Compact Array, the Combined Array for Research in Millimeter-wave Astronomy, Giant Metrewave Radio Telescope, the Submillimeter Array, and eMERLIN. He has also been actively involved in radio instrumentation projects, such as the TolTEC camera for the Large Millimeter Telescope and the Next Generation Very Large Array, of which Executive Science Advisory Council he is a member. He is an expert on the analysis and interpretation of continuum emission produced by different mechanisms, including free-free, dust-thermal, and synchrotron radiation, as well as its polarization in the centimeter to millimeter wavelength range. His most notable achievements to date include

the first detection of magnetic fields in protostellar jets, observations of the earliest stages of jet collimation, and the detailed study of dust properties in disks around young, Sun-like, stars.

Carlos has authored more than 100 publications, with more than 3,000 citations, and has an h-index of 33. His work has appeared in high-impact journals, garnering widespread attention from the astronomical community and the general public alike. He has supervised 11 young researchers pursuing their master's, PhD, or postdoctoral degrees.

Dr. Miguel Chavez Dagostino has a degree in Physics from the University of Guadalajara, Mexico, and a PhD in Astrophysics from the International School for Advanced Studies, Trieste, Italy. He is a Senior Researcher at the National Institute for Astrophysics, Optics, and Electronics (INAOE) in Mexico, where he has taught a course on stellar physics since 1996.

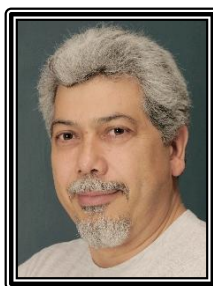


He is a member of the Mexican Academy of Sciences since 2004, and a member of the Latino Lunar Lobby, based in Madrid, Spain. Among several managerial positions, he has been Coordinator of Astrophysics at the INAOE, Scientific Director of the Large Millimeter Telescope, and President of the Mexico node of the International Astronomical Union.

Miguel's line of research is stellar physics, with a recent emphasis on the study of exoplanetary systems, including debris disks around mature stars. He is the author of several chapters in popular astronomy books, and has directed (or co-directed) more than 30 theses

at all levels.

Dr. Salvador Curiel Ramírez was born in Mexico City (México) in 1957, where he obtained Masters and Doctoral degrees at the Universidad Nacional Autónoma de México (UNAM). He completed his doctoral thesis at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, United States, where he was also a postdoctoral researcher. He joined the Institute of Astronomy at the UNAM in 1995 as a full-time Junior Research Fellow. He is still there, currently as a full-time Senior Research Fellow and a member of the SNII (Mexico's National System of Researchers). He is also a member of various scientific associations, including the International Astronomical Union, the Mexican Academy of Sciences, and the Mexican Society of Physics.



Over the past two decades, Salvador has supervised five theses, three of them at the doctoral level. He has also been a principal advisor and member of various tutorial committees for several graduate and undergraduate students, and has participated in numerous degree and candidacy examinations.

Salvador conducts research primarily on the birth and adolescence of low- and high-mass stars, a long-standing field of study in Mexico, in which he and other Mexican astronomers have made fundamental contributions. He has also conducted studies of supernova remnants, evolved stars, and extragalactic jets. For his research, he uses or has used various telescopes, including the Atacama Large Millimeter/Submillimeter Millimeter Array, the Very Large Array, the Very Long Baseline Array, as well as other types of telescopes, such as the

Hubble Space Telescope, the ROSAT X-ray satellite, and optical and infrared facilities.

In recent years, he has promoted the formation of a group dedicated to the search and characterization of exoplanets, using various techniques, in particular, astrometry with radio observations. This group recently detected the first exoplanets using the radio astrometry technique. Furthermore, they were able to establish the three-dimensional orbital structure of a low-mass binary system, including a Jovian planet associated with the main star.

Dr. Sergio A. Dzib was born in Chetumal, Mexico, and obtained his PhD in Astronomy from the Universidad Nacional Autónoma de México in 2013. He has developed a career in radio astronomy, with particular emphasis on radio interferometry and very long baseline interferometry. After holding postdoctoral positions at the Max-Planck Institut für Radioastronomie (MPIfR) in Bonn, Germany, and at the Institut de Radioastronomie Millimétrique in Grenoble, France, he became an Assistant Researcher at the MPIfR.



His work has contributed to the modern development and technical heritage of radio astronomy, particularly in advancing astrometric Very Long Baseline Interferometry (VLBI) methods for stellar and Galactic studies. He has participated in several long-term international VLBI programs, in particular those aimed at tracing the orbits and dynamical masses of young stars, as well as in calibration and observational campaigns that have influenced current standards of radio interferometric data analysis.

Dr. Dzib has collaborated on projects at the cutting edge of centimeter, millimeter, and submillimeter VLBI, including participating in the Event Horizon Telescope (EHT) earlier campaigns, involving stations such as CARMA, the LMT, and NOEMA. These efforts have linked contemporary astrophysical research with the broader historical development of high-frequency radio astronomy. His current research interests include VLBI astrometry of young stellar objects, massive star-forming regions, and active galactic nuclei. He is also a member of the EHT Collaboration.

Professor Rosa A. González-Lópezlira obtained a PhD in Astrophysics at the University of California, Berkeley. She is a Professor of Astronomy at the Universidad Nacional Autónoma de México (UNAM).

She has made important contributions to the field of observational extragalactic astronomy, in particular related to stellar populations, large scale star formation, and galaxy dynamics, formation, and evolution. She confirmed observationally the existence of azimuthal age gradients across the arms of spiral galaxies, as predicted by the density-wave theory of spiral structure, and which had eluded detection for more than 30 years. In the process, her work reignited observational and theoretical interest in such theory, and its consequences for star formation.



Rosa was also the first person to observe that the maximum masses of star clusters increase with decreasing radius in a spiral galaxy, with important implications for the initial stellar mass function. She discovered that the globular cluster system of another spiral galaxy rotates in phase and as fast as the disk of neutral gas, and hence may be a relic from star formation at high redshift, barely perturbed by interactions. Rosa has also found correlations between the globular cluster systems, black hole masses, and total stellar masses in spiral galaxies, which have been much less studied than their elliptical counterparts. Professor

González-Lópezlira has authored or co-authored 55 papers in peer-reviewed journals, which have received more than 2400 citations.

Before becoming a physicist, Rosa completed the course work for a degree in Latin American Studies at the Faculty of Philosophy and Letters, also at UNAM. In 2024, she co-authored a paper published in this journal about Novohispanic observers of the comet of 1652. One of them, Diego Rodríguez, may have been the first person to observe the comet, whose discovery has been attributed to the Dutch navigator Jan van Riebeeck.

Dr. Eric Faustino Jiménez-Andrade was born in Tecamachalco, Puebla, Mexico, in 1990. He obtained his Bachelor's degree in Physics from the Meritorious Autonomous University of Puebla, and his Master's degree in Astrophysics from the National Institute for Astrophysics, Optics, and Electronics, also in the state of Puebla, Mexico. He earned his PhD in 2019 from the University of Bonn, Germany, under the framework of the Max Planck Research School for Astronomy and Astrophysics. Subsequently, he held a postdoctoral fellowship at the National Radio Astronomy Observatory in the USA. Since 2022, he has served as an Assistant Professor at the Instituto de Radioastronomía y Astrofísica at the Universidad Nacional Autónoma de México.



Dr. Jiménez-Andrade's research focuses on the formation and evolution of galaxies. He primarily employs observations from the Very Large Array to investigate how star formation and black hole activity shape galaxies across cosmic time. One of his key contributions to radio astronomy is the production of some of the deepest and sharpest radio maps ever obtained of the extragalactic sky, paving the way for future radio surveys with the Square Kilometre Array and the new Generation Very Large Array (ngVLA), which will include radio antennas located on Mexican territory. Dr. Jiménez-Andrade has been a leading advocate for the ngVLA in Mexico, and currently coordinates efforts to establish a national consortium of universities and research institutions to participate in the project.

His academic and outreach achievements have been recognized with the National Award for Scientific Journalism and Communication from the Government of Mexico (2014), and the Vicente Suárez Youth Achievement Award from the Government of the State of Puebla (2018). In 2025, he was elected as a Young Affiliate of The World Academy of Sciences in the field of Physics, Astronomy, and Space Sciences.



Professor Stan Kurtz received his doctorate in Physics from the University of Wisconsin, with a specialization in Astrophysics and Radio Astronomy. In 1993 he went to Mexico for a postdoctoral appointment at the Instituto de Astronomía at the Universidad Nacional Autónoma de México (UNAM). In 1997, he left Mexico City to form part of the new Instituto de Radioastronomía y Astrofísica (then CRyA) in the state of Michoacán. He is presently a full Professor at this Institute.

Stan's research is in the area of massive star formation and the effects of these stars on the interstellar medium. He has served the National Radio Astronomy Observatory in the USA as a proposal referee, as a member of its Time Allocation Committee, its Users Committee, the Science Advisory Panel of the Jansky Very Large Array, and the Technical Advisory Committee of the New Generation Very Large Array.

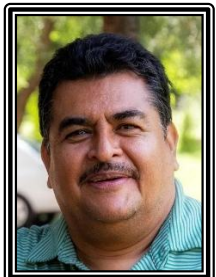
Professor Laurent Loinard is a Professor of Astronomy at the Universidad Nacional Autónoma de México in Morelia, Michoacán. His research focuses on the formation and youth of stellar systems, the interstellar medium and its chemistry, and the environment of supermassive black holes. He is a member of the Event Horizon Telescope consortium, which recently published the first images of the black holes at the centers of the galaxy Messier 87 and our own Milky Way.

He has published more than 200 research papers which have received 18,000 citations in the specialized literature. He has directed nearly 30 theses, one of which won the 2017 IAU PhD Prize for the best doctoral thesis in fundamental astronomy.



Laurant has received numerous accolades, including a fellowship from the Guggenheim Memorial Foundation in 2010, the Bessel Prize from the von Humboldt Foundation in 2011, and the 2022 Prize of The World Academy of Science. As a member of the EHT group he is a co-recipient of the Breakthrough 2020 Prize in fundamental physics, the 2020 Einstein Medal, and the 2021 Group Award from the Royal Astronomical Society of the United Kingdom. In 2024, he was named Robert F. Kennedy Visiting Professor at Harvard University and, in 2025, Director of the Event Horizon Telescope Collaboration.

Professor Omar López-Cruz was born in La Paz, Baja California Sur, Mexico, in 1964. He holds a BSc from the School of Physics and Mathematics at the National Polytechnic Institute (ESFM-IPN) in Mexico City, and an MSc and a PhD from the Department of Astronomy and Astrophysics at the University of Toronto in Canada.



He is full Professor and National Researcher level III (SNII III, the highest level) at the Instituto Nacional de Astrofísica, Óptica y Electrónica. He has been a Visiting Professor at the University of Bristol in the UK and the University of North Dakota in the USA. He is the current cosmology Editor of the *Revista Mexicana de Astronomía y Astrofísica*.

Omar is interested in the role of black holes in the evolution of galaxies across the cosmic web, from the dark ages through the nearby Universe. He is also interested in multimessenger astronomy and observational cosmology.

Dr. Aina Palau obtained her PhD from the University of Barcelona, in collaboration with the Harvard-Smithsonian Center for Astrophysics, in 2006, under the supervision of Drs. Robert Estalella and Paul Tsang Pop Ho. Her thesis focused on the observational characterization of the fragmentation of massive dense cores, the precursors of stellar clusters, mainly using millimeter/submillimeter interferometers.



Aina was a postdoctoral researcher at the Centro de Astrobiología in Madrid, where she concentrated her efforts on the search for the least massive outcomes of molecular cloud fragmentation, potentially deeply embedded brown dwarfs. After a second postdoc at the Spanish National Research Council, she got a permanent position in the Instituto de Radioastronomía y Astrofísica at the Universidad Nacional Autónoma de México.

Associate Professor Víctor M. Patiño Álvarez was born in Poza Rica, Veracruz, Mexico, in 1988, and has MSc and PhD degrees in Astrophysics from the National Institute for Astrophysics, Optics, and Electronics (INAOE) in Puebla. After getting his PhD in 2016, he earned a postdoctoral position at the Max-Planck Institut für Radioastronomie in Bonn, Germany. He returned to Mexico in 2019 as an Associate Professor at the INAOE, his current position, and he is also the leader of the only Max Planck Partner Group in astronomy in Mexico.



So far, Victor has supervised two BSc, four MSc, and one PhD theses. He has co-authored 45 papers in peer-reviewed journals. His main research interests are the study of multifrequency variability of astronomical sources, mainly blazars; spectroscopy; and Very Long Baseline Interferometry studies.

Professor Emeritus Luis F. Rodríguez is at the Instituto de Radioastronomía y Astrofísica at the Universidad Nacional Autónoma de México (UNAM). He obtained a Bachelor's degree in Physics from the UNAM and a PhD in Astronomy from Harvard University. He is a specialist in radio astronomy, a technique that he pioneered in Mexico, and with which he studies the birth and youth of stars and planets, as well as X-ray binaries.



His work and that of other Mexican researchers constitute a core part of the modern conception of how stars and planets are formed. He has received the National (Mexico) Science Award and the Bruno Rossi Award from the High Energy Division of the American Astronomical Society, among other recognitions. Luis is a member of El Colegio Nacional, the institution whose 40 members bring together the most distinguished representatives of the sciences, arts, and humanities in Mexico. In 2021 he received the Jansky Lectureship, an honor established by the National Radio Astronomy Observatory to recognize every year outstanding contributions to the advancement of radio astronomy.

Dr. Daniel Tafuya is a radio astronomer specialising in the physics of circumstellar envelopes, jets, and molecular outflows, from evolved stars and related late stellar evolutionary phases. His research combines high-resolution interferometry and spectral-line diagnostics, using facilities such as Atacama Large Millimeter/Submillimeter Array

(ALMA), Atacama Pathfinder Experiment, and the Jansky Very Large Array, and benefits from more than 20 years of experience working across Europe, Japan, and Mexico.

He currently serves as Staff Scientist at the Onsala Space Observatory, and as Deputy Manager of the Nordic ALMA Regional Center node, where he leads advanced interferometric data-analysis tool development, provides proposal and data-reduction support to the Nordic community, and contributes to European ALMA Regional Center activities and user training. His prior appointments include faculty and postdoctoral roles at the East Asian ALMA Regional Center at the National Astronomical Observatory of Japan, Onsala Space Observatory, the Universidad Nacional Autónoma de México (UNAM), and Kagoshima University, where he worked on leading ALMA software development and research on maser astrophysics using Very Long Baseline Interferometry techniques.



Dr. Tafoya holds a PhD in Astronomy from the UNAM, and has authored over 80 refereed publications, spanning evolved stars, maser astrophysics, planetary nebulae, and massive-star formation. He has received competitive research grants, serves on international telescope review panels, and is an active member of the International Astronomical Union. His teaching experience includes graduate-level courses, conference schools, and supervision of postgraduate and undergraduate research projects.

Beyond research, he maintains a strong commitment to outreach, contributing to public astronomy programs in Mexico and Sweden, and authoring science communication articles and radio content in Spanish.

Professor Lucero Uscanga Aguilera was born in Veracruz. She studied Physics at the Universidad Veracruzana before attending the Universidad Nacional Autónoma de México (UNAM) in Mexico City for her graduate studies. She got her PhD in Astronomy in 2006 with the thesis “Maser emission in star-forming regions,” under the supervision of Dr. Jorge Cantó Illa, which was awarded the Weizmann and Guillermo Haro Prizes in 2007 and 2008, respectively.



She carried out postdoctoral research in the former Centro de Radioastronomía y Astrofísica of UNAM, in Morelia, Mexico; the Instituto de Astrofísica de Andalucía, CSIC, in Granada, Spain; and the Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, in Greece. She has done research stays at the CSIRO Astronomy and Space Science unit (Australia), and the Observatorio Astronómico Nacional (Spain). In 2015 she became an Associate Professor at the Department of Astronomy of the Universidad de Guanajuato (Mexico), where she is a full Professor since 2025.

Lucero is leading her institution's research on low-mass evolved stars with high angular resolution (radio interferometry). She is a member of the Mexican National System of Researchers, known as SNII, and of the International Astronomical Union. She is an active member of the Galactic ASKAP Spectral Line Survey (HI and OH), and the Maser Monitoring Organization (M2O). She is also a member of the VLBI & Our Galaxy Science Working Groups of the Square Kilometre Array, and of Science Working Group 1 of the New Generation Very Large Array.

Assistant Professor Jorge Zavala is a Mexican astronomer specializing in galaxy formation and evolution, with extensive experience in observational astronomy. After completing his PhD studies in Mexico, he worked as a postdoctoral researcher at The University of Texas at Austin, and later as a Staff Astronomer at the National Astronomical Observatory of Japan in the East-Asian ALMA Regional Center. Currently, he is an Assistant Professor at the University of Massachusetts Amherst.



His research harnesses cutting-edge observational tools and techniques to address fundamental questions about how galaxies form and evolve, particularly in the early Universe, and to understand the role of dust and gas in these processes. Over the years, Jorge has led several surveys using some of the most advanced telescopes on Earth and in space, including the Atacama Large Millimeter/Submillimeter Array, and the James Webb Space Telescope.

His work spans a wide range of topics, from studying dusty star-forming galaxies and tracing the formation and evolution of massive galaxies across cosmic time, to probing the dust and gas properties of galaxies, mapping galaxy proto-clusters, and investigating ultra-high-redshift galaxies. To date, he has published around 100 papers with more than 5,000 citations.