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ASTRONOMY IN MEXICO

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Abstract. Mexican astronomy has a long standing tradition of excellence in research. After a brief review of its history, I outline the current profile of the community, the available infrastructure and participating institutions, and give a glimpse into the future through current projects. The development of astronomy can serve as a powerful lever for science, technological development, education and outreach, as well as for improving the much needed link between basic research and industry development.

1. Brief History

Astronomy in Mexico has a long tradition, and the achievements of all the major prehispanic cultures, beginning with the Olmecs are deeply ingrained in the popular culture. The creation of the Long Count Calendar, the orientation of large architectural complexes and observatories, and all the basic timekeeping knowledge creates a heritage of which people are justifiably proud (Aveni 2001, Coe & Koontz 2002). Although the Spanish conquest took place in the context of the less enlightened post-classic, the basic knowledge has remained, and modern scholarship and museum exhibits have easily allowed the population to connect with this more remote past. During the Colonial period, various Spanish expeditions and initiatives led to the study of astronomy, often linked to engineering ventures. After independence, the major thrust for the creation of an official astronomical research body came in the context of observing the transits of venus which ocurred in the late 19th century(Ávila *et al.* 2008).

The Observatorio Astronómico Nacional (OAN) was founded in 1878, and was initially located in downtown Mexico City. It operated as a national facility, without being associated to a particular government body. In 1929, the national university, Universidad Nacional Autónoma de México (UNAM, Moreno Corral & Ávila 2009, Bartolucci 2000)) underwent a major restructuring, gaining autonomy from the government in its bylaws. At that point the OAN was attached to the University and it was charged with its development and maintenance. In 1942, Luis Enrique Erro founded the Observatorio Astrofísico Nacional in Tonantzintla, Puebla, where a large Schmidt camera became the preeminent research instrument. The OAN grew as several renowned directors and faculty members came to work within it, notably Paris Pishmish (1911-1999) and Guillermo Haro (1913-1988), to name but two. During Haro's tenure as Director, in 1967 the OAN was transformed into Instituto de Astronomía (IA[1]) within UNAM, which was at the time undergoing yet another distinctive transformation in its structure, and spawning a number of research institutes on a par with its existing system of undergraduate schools.

Fleeing the city lights, the observing facilities of the OAN itself had moved in 1908 from downtown to what was then the outskirts, in the neighborhood of Tacubaya, and in 1951 relocated to Tonantzintla as well, on the grounds adjacent to to where Erro had moved in 1942. Here the 1m telescope, still in use, was comissioned in 1961. The rapid growth of the city of Puebla, along with that of Mexico City, forced the consideration of an alternative site, and exploration of the mountains of Baja California revealed that the Sierra of San Pedro Mártir (SPM) was a good locale. Development began in the 1960s and continued through the 70s, and what started in Ensenada as a base of operations for the OAN-SPM became a branch of IA in 1974. This culminated in the installation of the 2.1m telescope, dedicated in 1979, which remains today one of the two largest optical telescopes in Mexico.

During the 1990s, a group of faculty members of IA, led by the eminent radioastronomer Luis Felipe Rodríguez, established a new branch of the Institute in the city of Morelia, Michoacán. It thrived over the next few years, and in 2003 separated from IA to become, within the University's structure, a separate center for Astronomy, the Centro de Radioastronomía y Astrofísica (CRyA[2]).

After his term as Director of IA expired, Haro left UNAM and in 1971 founded the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) from the Observatory created by Erro three decades earlier[3]. Over

[1] http://www.astroscu.unam.mx/
[2] http://www.crya.unam.mx/
[3] http://www.inaoep.mx/

the next few years, INAOE grew in size and impact, and began operations of its own 2.1m telescope in Cananea, Sonora, now Observatorio Astrofísico Guillermo Haro (OAGH). It is now a national center operated by the federal Consejo Nacional de Ciencia y Tecnología (CONACyT[4]).

Throughout this era, most of Mexico's astronomers came from Physics majors as undergraduates, who, after learning from the few faculty members at these small institutions, obtained graduate degrees abroad (mainly in the US) and returned to Mexico to further strengthen UNAM and INAOE. In the last 15 years or so this has slightly shifted, as graduate programs within Mexico (again mostly within UNAM and INAOE), have contributed to the pool of researchers, and posdoctoral exchange has increased, adding as well to the number of foreign nationals working in astronomy in the country today (Aretxaga 2008).

2. Community and Institutions

The astronomical community in Mexico is still quite concentrated in a small number of institutes and universities. The bulk resides in Mexico City, and the states of Puebla, Michoacán and Baja California, reflecting the historical role of UNAM and INAOE. Smaller groups have been created more recently, particularly at Universidad de Guanajuato, which currently has 11 researchers, Universidad de Guadalajara, where 9 people are currently dedicated to astronomy, and Universidad de Sonora in Hermosillo, with 4 members. The current distribution is shown in Table 1, and includes both astronomers and technical support staff and instumentation engineers (for INAOE only the Astrophysics division is included).

The number of people thus dedicated to astronomy is close to 200, for a country of 112 million according to the 2010 census, or 1/560,000. For comparison, this number is closer to 1/50,000 in the USA, and 1/80,000 in Spain. The comparison is not exclusive to astronomy, and reflects the low fraction of GNP that in general is dedicated to science and technology, hovering at 0.3-0.4% for the last 25 years at least[5].

Nevertheless, astronomy remains one of the highest ranking disciplines, if not the highest (CNCT 2007), in Mexico in terms of impact, and has international recognition as such in various fields, such as studies of the interstellar medium, chemical abundances, planetary nebuale, radioastronomy and AGN studies, to name a few.

[4]http://www.conacyt.mx/
[5]http://www.amc.mx/recomendaciones_2012.pdf

TABLE 1. Staff per institution

Institution	**Staff**
Instituto de Astronomía, UNAM Mexico City http://www.astroscu.unam.mx/	70
Instituto de Astronomía, UNAM Ensenada, B.C. http://www.astroscu.unam.mx/	52
Centro de Radioastronomía y Astrofísica, Morelia, Mich. http://www.crya.unam.mx/	18
Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Pue. http://www.inaoep.mx/	35
Escuela Superior de Física y Matemáticas, Instituto Politécnico Nacional http://www.esfm.ipn.mx/	3
Departamento de Astronomía, Universidad de Guanajuato, Guanajuato, Gto. http://www.astro.ugto.mx/	11
Departamento de Astronomía y Meteorología, Universidad de Guadalajara, Guadalajara, Jal. http://www.iam.udg.mx/	9
Área de Astronomía, Universidad de Sonora, Hermosillo, Son. http://www.astro.uson.mx/	4

3. Research and Instrumentation

In terms of astronomical research, measured as the output of refereed scientific papers in international journals (ApJ, MNRAS, A&A, AJ, PRD, Phys Rev Lett., Science, Nature), Mexican astronomy contributes about 250-300 papers per year in all disciplines, from observation to theory, from radio to gamma rays and numerical modeling and simulation. Traditionally, most of the observational emphasis has been on optical-infrared, and radio astronomy, although studies at high energies have in the last ten years or so grown substantially, through the use of satellite observatories like Chandra, XMM-Newton, Swift and Fermi and the advent of HAWC (see below Sect. 4). Theory work has likewise covered all areas, and access to powerful computing facilities and networks has been a constant feature of astronomical research (the first node of the internet in Mexico was on the roof of the Instituto de Astronomía at UNAM in the late 1980s). Strictly outside

of large institutions formally dedicated to astronomy, physicists in other locales also pursue research interests with ties to astrophysics. This is notably the case at instituto de Física-UNAM[6], the Centro de Investigación y Estudios Avanzados-Instituto Politécnico Nacional[7], and the Instituto de Física at Universidad Michoacana de San Nicolás de Hidalgo[8].

Considering the highest ranking faculty members at all institutions, through their membership in Mexico's Sistema Nacional de Investigadores (SNI), which has four levels (Candidate, I, II, III), one finds that those with Levels II and III have an average Hirsch Index of h∼18. This indicates a certain maturity of the available human resources. If the restriction is made to those at Level III, this rises to h∼28 or so[9], comparable to those found in high ranking institutions in the US and the UK, for example.

Maintaining observatories (OAN and OAGH in the past, and HAWC and the LMT more recently) has required the large institutes to have their own instrumentation departments, both for maintenance proper and for the development of new astronomical instruments to make available to their communities. This has proven to be a crucial advantage, and allowed participation in large scale international projects such as GTC (see below) and innovate solutions internally, as is the case with a hydrodynamical polishing tool developed at IA-UNAM over the past ten years and which is the object of several international patents, and possible licensing agreements with private companies in the near future.

GRADUATE PROGRAMS

The graduate programs have grown substantially over the last 15 years, both at the MS and PhD level. Currently UNAM has a Graduate Program in Astrophysics, where IA, CRyA, the School of Science and the Institute for Nuclear Science all participate. Each has associated students and contributes advisors to the overall pool, allowing students to choose from a variety of topics in institutes with their own particular emphasis. INAOE has its own program, where students are also in direct contact with the Electronics, Optics and Computer Science divisons of the center[10]. Finally , the department in Guanajuato also has its own graduate program[11]. Altogether, about 20 PhDs are awarded in astronomy every year, still far short of the level required to attain large scale growth of the community through that processs alone. A large number of students still go abroad, mainly to

[6] http://www.fisica.unam.mx/
[7] http://www.cinvestav.mx/
[8] http://www.ifm.umich.mx/
[9] http://www.amc.mx/recomendaciones_2012.pdf
[10] http://www.inaoep.mx/
[11] http://www.astro.ugto.mx/

the US and Europe, to obtain postgraduate degrees and represent potential hires in the mid to long term.

4. Facilities

OBSERVATORIO ASTRONÓMICO NACIONAL-SAN PEDRO MÁRTIR, B.C. (OAN-SPM)

The site at SPM is one of the best in the world for optical-infrared astronomy in terms of sky darkness (V$\sim$21.2mag/arcsec^2 in dark time), atmospheric stability and quality, resulting in superb seeing of about 0.61 arcsec, and number of clear nights (63% photometric, 81% spectroscopic), along with Hawaii, the Canary Islands and Chile (Tapia 2003). It has been continuously operated by IAUNAM since the 1960s, and currently has three telescopes of 0.84m, 1.5m and 2.1m, equipped with optical and infrared instrumentation for imaging and spectroscopy. The site is within the limits of the Parque Nacional San Pedro Mártir, and is thus a protected natural reserve. Within the park, with over 70,000ha, a surface of 3048ha is reserved for astronomical research by grant of the National Comission for Natural Protected Areas (López & Gutierrez 2003). Facilities include a lodge, machine and electronics shops, power generators, with a microwave link for telecommunications. The road from Ensenada to the Observatory is fully paved (completed in 2009), and infrastructure upgrades to the site in terms of energy and telecommunications are in progress.

Long-term monitoring of the site by groups from UNAM (Tapia 2003) and INAOE (Carrasco *et al.* 2012) has characterized the site over a long baseline, and the SPM site was tested extensively for the Large Synoptic Survey Telescope (LSST[12]), and the Thirty Meter Telescope (TMT, Schöck *et al.* 2009), confirming its excellent qualities for astronomical research. Several projects are in process or in planning to further exploit the unique qualities of this site with national and international partners (we detail some below in Sect. 5).

Protecting the sky of SPM is a priority of IAUNAM. The lack of water in Baja California has kept population density at low levels, but the border corridor of Tijuana-Mexicali-San Diego-Yuma grows rapidly, and threatens the site with light pollution. To counter these effects, an ordinance for the Municipality of Ensenada, which covers all the way to the border with Baja California Sur at 28'N, was promoted and went into effect in 2006[13]. It then became state law for Baja California in 2010[14], and the municipality

[12] http://www.lsst.org/

[13] http://www.astroscu.unam.mx/ia/reglamentos/Reglamento-Ensenada-29sep2006.pdf

[14] http://inapramex.com/normatividad/lpabc-decreto339.pdf

of Mexicali enacted its own version in 2011[15]. The ground is set thus for proper protection of the sky darkness for years to come, providing security for further projects at the site.

OBSERVATORIO ASTRONÓMICO NACIONAL-TONANTZINTLA, PUE. (OAN-T)

The IAUNAM still maintains the site of OAN-T and operates the 1m telescope, although light pollution has degraded the science capabilities of the observatory, making it more attractive for teaching and outreach purposes, which are routinely carried out, frequently in collaboration with INAOE[16].

OBSERVATORIO ASTROFíSICO GUILLERMO HARO, CANANEA, SON. (OAGH)

INAOE operates the OAGH in Cananea, Sonora, just 30km south of the border with Arizona. It is equipped with a 2.1m telescope with optical and infrared instrumentation for imaging and spectroscopy which is open to the national community[17].

LARGE MILLIMETER TELESCOPE/GRAN TELESCOPIO MILIMÉTRICO (LMT/GTM)

The LMT[18] is the largest millimeter antenna designed for astronomical observations, at the summit of Sierra Negra (4500m above sea level), and is a collaboration between INAOE and the University of Massachusetts (UMass). With a planned aperture of 50m, the LMT is designed to observe at between 0.85mm and 3mm wavelengths with unprecedented accuracy, and is the largest science project ever undertaken in Mexico. Currently the dish is at 30m aperture, and completion is planned in the next few years. Science observations have succesfully been carried out at 3mm in 2011. The LMT, besides its enormous potential as a research tool for the national community, can also in principle be linked to the VLBI network and further profit from the access of other groups, notably at CRyA-UNAM, to large scale radio astronomy infrastructure.

[15] http://www.bajacalifornia.gob.mx/portal/gobierno/legislacion/periodico/2011/julio/SECC-I-08-07-2011.pdf

[16] http://www.astroscu.unam.mx/Tonantzintla/

[17] http:// www.inaoep.mx/∼astrofi/cananea/

[18] http://www.lmtgtm.org/

HIGH ALTITUDE WATER ČERENKOV OBSERVATORY (HAWC)

HAWC[19] is a collaboration between Mexico and the US involving about a dozen institutions in each country, led by Los Alamos National Laboratory and the University of Maryland in the US, and UNAM and INAOE in Mexico. It is located on the border between Puebla and Veracruz at 4100m just below the LMT/GMT site at Sierra Negra. It will consist when completed of 300 water tanks 4m high and 7m in diameter, and wil observe the entire sky visible from the site between 100GeV and 100TeV, through Čerenkov radiation in water, performing an all-sky map as well as searching for transient sources. The project involves a large community which has brought together astronomers as well as high energy physicists from various research institutes and is currently in the construction stage, with the prototype array, VAMOS, operating in 2011.

GRAN TELESCOPIO CANARIAS (GTC)

Mexico is a 5% partner in the GTC at Observatorio Roque de los Muchachos on La Palma[20]. Spain is the lead partner at 90%, and the University of Florida is also a member at 5%. Besides the associated share of observing time for the Mexican astronomical community, in itself a major benefit, instruments have been developed in Mexico for the telescope. The first was the comissioning instrument, awarded through international competition and built in Mexico through a collaboration between IAUNAM and Centro de Ingeniería y Desarrollo Industrial (CIDESI), a CONACyT center[21]. The second was OSIRIS, and optical imager and spectrograph, partially designed and built at IAUNAM and currently operating at GTC. The third is FRIDA, (in**FR**ared **I**mager and **D**issector for **A**daptive optics), an integral field spectrograph for the near infrared with imaging capability that will make use of the adaptive optics system of the GTC, scheduled for delivery in 2015. FRIDA is led by IAUNAM in collaboration with UF, Instituto de Astrofísico de Canarias, Universidad Complutense de Madrid (UCM), Laboratoire dAstrophysique-Observatoire Midi-Pyrénées, and CIDESI. In addition, MEGARA (Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía) is an optical Integral-Field Unit (IFU) and Multi-Object Spectrograph (MOS) for GTC led by UCM with strong participation from INAOE. All of these projects have substantially contributed to the capabilities for astronomical instrumentation within Mexico, and are key in the development and proposal of national infrastructure projects.

[19] `http://www.hawc.umd.edu/`
[20] `http://www.gtc.iac.es/`
[21] `http://www.cidesi.mx/`

THE EXPANDED VERY LARGE ARRAY (E-VLA)

The Mexican radioastronomy community has been extremely successful in doing research with the VLA, operated by NRAO. Lacking sufficient funds to become a direct partner in ALMA, which has started operations in Chile, the Mexican community obtained access to NRAO facilities, including ALMA[22], through partial financing of the e-VLA with the USA and Canada[23]. The e-VLA gives a ten-fold increase in sensitivity over the VLA, and widens the spectral range from 1GHz to 50GHz. Acces to ALMA ensures that the outstanding radioastronomy tradition, led by the group at CRyA-UNAM will continue to produce high impact results and benefit the community as a whole.

5. The Future

The astronomical community in Mexico is currently participating in several projects, at various stages of development, that seek to promote its growth in quality, number and diversity. A strong emphasis is placed on the development of new observational infrastructure and seeking investment, from national and international partners for mid- and large scale projects. I briefly detail some of the most relevant here. In particular, development of the site of San Pedro Mártir for optical-infrared astronomy into an international, large scale observatory is desired.

TAOS-II

The first stage of the TAOS project, let by Academia Sinica-Institute of Astronomy and Astrophysics of Taiwan (ASIAA) and Smithsonian Astrophysical Observatory (SAO) installed at Lulin Observatory in Taiwan, with participation from Yonsei University in South Korea, sought to detect transneptunian objects through stellar occulations with 50cm telescopes. The second phase, the Trans-Neptunian Automated Occultation Survey-II[24], in which IAUNAM is a partner, will install three 1.3m robotic telescopes at SPM by 2013 to carry out a deeper survey in search of Kuiper Belt objects. The site for installation has been selected, and telescope and building design and construction are under way, as is camera design. This is the first international project to mount telescopes at SPM, and will represent the first telescopes to be built since the inauguration of the 2.1m in 1979. The project represents an investment of approximately 13MUSD.

[22] http://www.almaobservatory.org/
[23] http://www.nrao.edu/index.php/about/facilities/vlaevla
[24] http://taos2.asiaa.sinica.edu.tw/

GROUND FOLLOW-UP TELESCOPE ASSOCIATED TO THE SVOM MISSION (GFT)

The satellite SVOM mission for high energy observations between France and China is nominally scheduled for launch in 2015 (Götz *et al.* 2009). As an integral part of the mission, robotic ground telescopes of 1m class will observe optical-infrared counterparts of transient high-energy events. One such telescope is set to be installed at SPM in collaboration with IAU-NAM, and among other things, will seek to characterize the onset of the afterglow of Gamma-Ray Bursts, and detect distant events through photometric redshift determinations. The associated investment is approximately 3MUSD.

THE SAN PEDRO MÁRTIR TELESCOPE (SPMT)

A wide-field optical-infrared telescope is projected for the site of San Pedro Mártir, in possible collaboration with international partners. Through an agreement between INAOE and the University of Arizona, a 6.5m primary mirror has been cast at the UA and will undergo figuring and polishing over the next two years. The general plan calls for the design, construction and operation of a wide-field telescope that could be equipped with optical-infrared instrumentation, taking advantage of the superb seeing and sky darkness conditions at SPM. A possible project for this telescope is the Synoptic All-Sky InfraRed Survey, aimed at a deep, multi-color NIR characterization of the sky visible from SPM, with particular emphasis on the characterization of the transient sky, in collaboration with the University of California[25].

THE ČERENKOV TELESCOPE ARRAY (CTA)

Mexico has become a member of the CTA collaboration in May 2012[26]. The project considers the construction of two atmospheric Čerenkov arrays, one in each hemisphere. One candidate for CTA North is the site of San Pedro Mártir, and a viable site has been identified with the area available for astronomical research in the national park. Final site selection will take place in 2014. CTA will be the most sensitive instrument for high-energy sources, operating above 100GeV and up to 10TeV, and will allow monitoring of persistent and transient sources, continuing the opening of this electromagnetic window through ground-based observatories like MILAGRO, HAWC, VERITAS, MAGIC and HESS. Groups from five institutions (Instituto de Astronomía-UNAM, Instituto de Física-UNAM, Insti-

[25] http://www.sasir.org/
[26] http://www.cta-observatory.org/

tuto de Ciencias Nucleares-UNAM, Instituto de Geofísica-UNAM, Instituto Nacional de Astrofísica, Óptica y Electrónica) have either committed their participation or expressed their interest in doing so. Given the participation of the Mexican community in HAWC, it is only natural to continue pursuing research at very high energies, and entry into CTA will allow for this in the next generation of observatories.

OTHER SITES FOR OPTICAL INFRARED ASTRONOMY, THE DEVELOPMENT OF NEW CENTERS FOR ASTRONOMY AND GROWTH OF THE COMMUNITY

The Astronomy Department at Universidad de Guanajuato[27] operates its own observatory, "La Luz" close to the city. A 57cm optical telescope, and two radio antennas, are in use for research by department staff, teaching and outreach. Plans for the comissioning of a robotic telescope are in place.

One of the largest public universities in Mexico, Universidad Autónoma de Nuevo Léon, in Monterrey, N.L., has current plans to develop an astronomy group in close connection to its engineering school, and to install modern facilities at its observatory in San Pedro Iturbide, close to Monterrey[28]. The site has been used for outreach, and the University has for a number of years successfully collaborated with amateur astronomers. The possible contributions of UANL to other national astronomical projects at the OAN is desirable and would allow for further decentralization of working groups.

Finally, in Zacatecas, the Observatory founded by José Árbol y Bonilla in the late 19th century, which now bears his name, is being refurbished by Universidad Autónoma de Zacatecas[29] and plans for further growth of the astronomy group will hopefully bear fruit over the next few years.

The above is important in terms of future growth of the astronomical community in Mexico. It is essential that not only the existing institutes grow and enter into new projects, but that the number of centers where astronomy is carried out is increased. Most of the public state universities in Mexico have physics departments, and these are natural starting points for the placement of Astronomy groups, along with some national centers operated by the CONACyT. This would also allow the graduates from the growing Master's and PhD programs to eventually find permanent positions and foster competition, in the best sense of the term, between all centers. In turn, this will enable securing the funding and other resources that are necessary to sustain a healthy, national community that is not dependent on a small number of institutes for its development and growth.

[27] http://www.astro.ugto.mx/
[28] http://www.uanl.edu.mx/
[29] http://www.uaz.edu.mx/

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[30] http://www.revista.unam.mx/vol.10/num10/art64/int64.htm#a