THE STATE OF ASTRONOMY IN MEXICO

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1. Background

1.1. Astronomy

Astronomy is one of the first sciences practiced by humankind. Its aim is to explain the evolutionary history of all celestial bodies and of the cosmos itself. Our eagerness for understanding where we come from and where we are heading is so universal that it could be said to be part of the human condition. All cultures in the world have developed some theory about the origin of the universe, the creation of Earth and the role of mankind in the cosmos. Since the earliest times, humans have looked at the sky and sought answers in the stars to the origin of Earth and life itself. Nowadays, this search is a scientific rather than a mythical endeavour.

Astronomy captures our imagination and curiosity, and this provides a powerful incentive for introducing the scientific methodology to citizens. Modern astronomy goes beyond the limitations of the descriptive knowledge of the past. It is based on scientific reasoning and the principles of empirical verification and deduction. Astronomy is such an attractive science that it may be the only one with organized groups of amateurs, without rigorous academic training, that practice it. Amateur astronomers observe the skies purely for the pleasure of doing so, but they also constitute a valuable group for the discovery and follow-up of transitory phenomena that can be used professionally. Despite being apparently accessible to the general public, astronomy is a complex science with tight links to related sciences. It is based on the development and accumulation of knowledge produced mainly in the fields of physics, mathematics, chemistry, biology and geology, to the extent that nowadays we speak of astrophysics, in which most modern astronomers are engaged, but also of astrochemistry, astrobiology and planetology. As a result of its links with related sciences, tangible examples of basic abstract concepts are often produced: phenomena such as the movement of the planets or the amplification of distant galaxies by nearby galaxy clusters are mere expressions of the force of gravity, while the internal structure of a star can be described by a simple differential equation that can be solved by advanced high school students. This is only a brief sample of how astronomy benefits from the growth of other sciences and offers attractive visual applications for science students and even for ordinary citizens curious about the universe.

Astronomy also offers pathways of progress and new challenges to related sciences. Sometimes, these include discoveries that need to be fit into the framework of the basic elements and forces of nature, such as the proposal that dark matter and dark energy exist, revealed by the rotational curves of nearby galaxies and the brightness of supernovae at enormous cosmological distances. It also highlights technical gaps, such as new computational methods that can solve the laws governing radiative transfer in the extreme physical conditions of shock fronts in the interstellar medium. The field in which the greatest challenges are raised, however, is that of technology. In order to go beyond the limits of our present knowledge of nature, it is often necessary to build large-scale facilities equipped with sophisticated instruments. These involve specific challenges in state-of-the-art engineering. This new technology, developed to meet the needs of a new demanding scientific case, often spontaneously finds applications in the civil or business world, although it sometimes takes several decades for it to be translated into consumer technology, by which time it may have been implemented by other academic groups. In this respect, the development of charge-coupled devices (producing digital images) and their image analysis tools, serve as an example of technology originally developed in the basic sciences before commercialization and finding applications in everyday life. In Mexico, machines for printing national currency and the new sensors and positioners for the Navy have also been designed and built by instrumentalists in astronomy.

Apart from the possible economic applications, astronomy is a basic science that must be cultivated in the 21st century. This is as relevant in developing countries because it is a part of the human development and the basis for a critical vision of our place in the cosmic order. It is only by accepting and solving abstract intellectual challenges that the quality of research will improve, together with the country's capacity for innovation. The most relevant value of scientific research in basic sciences, including astronomy, to society, however, is the increased quality of education at all levels.

1.2 Brief History of Astronomy in Mexico

Astronomy in Mexico has been practiced since the Mesoamerican era, when chronology and the design of an accurate calendar were one of the basic motivations behind its study, which in turn were probably linked to the need to predict the seasons for sowing crops. The ancient Mesoamerican astronomers observed and accurately predicted eclipses and planetary positions, full and new moons and the arrival of equinoxes and solstices. The famous Aztec calendar developed by this civilization is actually more accurate than the Gregorian calendar we use today[(1)].

Although there were illustrious Mexicans that engaged in astronomical studies throughout history[(2,3,4)], it was not until 1878 that the first national professional observatory equipped with telescopes was inaugurated in Mexico City: the National Astronomical Observatory (NAO). Originally the observatory was housed in Chapultepec Castle, and was moved twelve years later to Tacubaya. The main astronomical activities undertaken by this observatory included determining positions, creating ephemerides and obtaining optical images to derive the photometry of astronomical sources. The images were part of an international project known as *Carte du Ciel* ("The Map of the Sky"). By the time the Mexican contribution had been completed, the project had already been surpassed by the Sky Survey produced at Mount Palomar[(3)], California, in the USA. In 1929, the NAO was taken over and operated by the National Autonomous University of Mexico (UNAM).

In Mexico, the start of modern astronomy, understood as the predictive and interpretative study of the evolving mechanisms of celestial bodies, dates from 1942, when the National Astrophysical Observatory of Tonantzintla (NAOT) was set up on the outskirts of Puebla[(5,6,3)]. In its time, the NAOT housed one of the largest Schmidt cameras in the world, which led to the discovery of the Haro-Herbig protostellar objects, flare stars and blue galaxies with emission lines. In the early 1940s, there was only one Doctor of Philosophy (PhD) in astronomy in the country[(7)], Dr. Pişmiş, but the ground for the development of astrophysics had been laid even before her arrival in Mexico by the clash between two key figures, Joaquín Gallo and Luis Enrique Erro, and the subsequent arrival of Guillermo Haro.

The 1950s saw the early growth of the national astronomical community. The few astronomers at the time began to teach optional courses in physics and to supervise the undergraduate theses of interested students who, once motivated to work in the area, were sent abroad to obtain Master of Sciences (MSc) and PhD degrees at leading international institutions in astronomy. Once they graduated, most of these students returned to Mexico, mainly to the UNAM Institute of Astronomy (IA-UNAM), created in 1967 and, to a lesser extent, the National Institute of Astrophysics, Optics and Electronics (INAOE), the new center developed as an offshoot of the NOAT in 1971. This was the first research center built outside Mexico City, and marked the start of the decentralization of research in astronomy, although the observatories had already left the capital decades earlier[(7)]. In the 1980s, astronomers who had recently obtained their PhDs abroad joined the IA-UNAM campus in Ensenada, originally founded to support the new National Astronomical Observatory (NAO) in the Sierra de San Pedro Mártir, Baja California. In the 1990s, INAOE reinforced its faculty with young and established researchers, partly attracted by the Large Millimeter Telescope and the Guillermo Haro International Program of Advanced Astrophysics which organized annual workshops and conferences. In 1996 UNAM continued its decentralization process, creating the Morelia Unit of the IA-UNAM , to which some of its leading researchers transferred from the Federal District. In 2003, this unit became the UNAM Center for Radioastronomy and Astrophysics (CRyA-UNAM). Other groups of astronomers were also established in the provinces during this period, particularly in Guanajuato, Jalisco and Sonora.

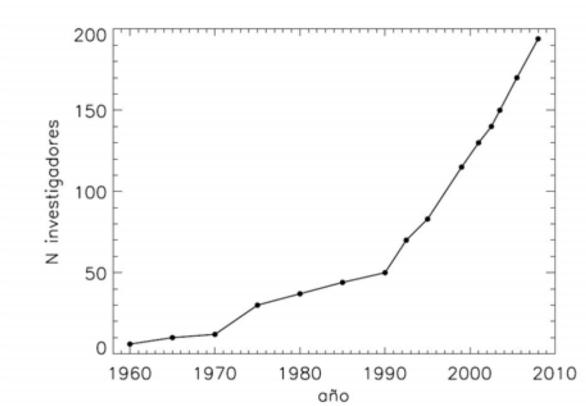

Figure 1: Growth of the number of astronomy researchers in Mexico from 1960 to 2008 (adapted from Peimbert & Rodríguez[(3)], and updated to January 1st, 2008).

The number of Mexican astronomers has grown steadily over the last 5 decades. Attempts have been made to increase the density of astronomers in the country without sacrificing the quality of research undertaken. The new generations of astronomers are mainly composed of those who have obtained their PhDs in Mexico, many of whom have returned to the country after taking post-doctoral positions abroad, and, as at the beginning, of Mexican PhD graduates trained abroad. In the 1990s, Mexican astronomy began to attract foreign scientists to join the national community and thereby contribute to the development of human resources and state-of-the-art research in Mexico[(2)].

2. Current Situation

2.1 Demography of Mexican Astronomy

The 2008 list of professional astronomers includes 194 researchers and professors, distributed between PhDs (93%) and MSc's (7%), supported by and additional 70 ancillary engineers and academic technicians. The researchers' census includes members of the National System of Researchers (SNI) registered under the discipline of Astronomy and Astrophysics, and other members of astronomy research centers or university departments. It also includes astronomers that graduated over the past 10 years and remain engaged in academic work at national centers. Finally, the list also includes a small number of individuals who in the last 5 years have published at least one research result in indexed astronomy journals and do not declare that their main activity is anything other than astronomy. Table 1 and Figure 2 show the distribution of the geographic densities of astronomers by state and institution. In addition to these researchers, there are approximately twenty scientists registered under the disciplines of physics, chemistry, biology and geology in the SNI who also conduct research in astronomy and have not been included in this list.

Astronomers are mainly concentrated in two UNAM centers, the IA-UNAM, with campuses in the Federal District and Baja California, and the CRyA-UNAM in Michoacán, and in a Conacyt center, the INAOE in Puebla. Each of these centers has 20 to 50 astronomy researchers. Moreover, during this decade, the Universities of Guanajuato, Guadalajara and Sonora have consolidated their astronomy groups by forming departments or departmental groups with 5 to 10 researchers. Other universities also have small groups of astronomers established within their departments or institutes of physical sciences. The remaining 13% of astronomers, particularly researchers who obtained their PhDs in the last 10 years, are scattered throughout the country in private and state universities, without yet having created departments or research groups in this discipline within their institutions.

The number of professional astronomers in Mexico is still very small compared with the size of the population: approximately 1 out of every 550,000 inhabitants is working as a research astronomer, compared with one in every 50,000 in the USA and 1 in every 80,000 in Spain. Although Mexico City is home to a large percentage of the total number of researchers in the field (37%), astronomy is a relatively decentralized science. Even in Mexico City, the traditional concentration of astronomers in the IA-UNAM has been diluted by a growing number of astronomers hired at other UNAM departments and other research institutes and public and private universities in the capital. If the state concentration index is defined as the percentage of astronomers within a state that are affiliated to the largest institute in that state, we find that the Federal District has the lowest concentration index in the country, of 72%. The remaining 28% are divided among 9 centers. By comparison, other states have concentration indices ranging from 86% to 100%.

Table 1: Distribution of astronomy researchers in Mexico. This chart contains the number of researchers and academic technicians or engineers affiliated to each center and the percentage of SNI members in each category on January 1st, 2008. For those institutes with several campuses, the SNI percentages refer to the combination of all campuses. The columns are: (1) the name of the institution, (2) the state in which it is located, (3) the number of established researchers/professors, (4) the number of associated or post-doctoral researchers, called young researchers, (5) the number of engineers or academic engineers who are either experienced or associates, (6) the percentage of experienced and young researchers in the SNI, (7) the percentage of engineers and technicians in the SNI, (8-11) the percentage of SNI members at levels III, II, I and C.

Center	State	No. res./ prof.	No. young res. / prof	No. eng. / tech.	% SNI res.	% SNI. eng. / tech.	% SNI III	% SNI II	% SNI I	% SNI C
IA-UNAM (*)	Federal District	37	13	29	80%	4%	20%	44%	36%	0%
	Baja California	22	6	27	82%	7%	--	--	--	--
	Puebla	0	0	1	--	0%	--	--	--	--
INAOE(*)	Puebla	27	7	6	88%	17%	16%	38%	34%	12%
	Sonora	0	0	7	--	0%	--	--	--	--
CRyA-UNAM(*)	Michoacán	16	3	4	89%	0%	12%	53%	35%	0%
Univ. Guanajuato	Guanajuato	6	4	2	100%	0%	0%	20%	50%	30%
Other groups with fewer than 10 professors or researchers (**)	Baja California (1), Campeche (1), Federal District (20), Mexico State (1), Guanajuato (1), Jalisco (4), Michoacán (3), Morelos (1) Nuevo León (1), Oaxaca (1), Puebla (3), Quintana Roo (1), San Luis Potosí (2), Sonora (5) Veracruz (1), Yucatán (1), Zacatecas (1)	49	(No information is available on whether they are established researchers or associates and if they were, they are included as established researchers.	(N.A.)	84%	--	5%	17%	46%	32%

(*) IA-UNAM is the acronym for the Institute of Astronomy of the National Autonomous University of Mexico (UNAM), INAOE the acronym for the National Institute of Astrophysics, Optics and Electronics, CRyA-UNAM the acronym for the UNAM Center of Radioastronomy and Astrophysics. (**) Other groups include: other UNAM departments, the Autonomous University of Baja California, the Autonomous University of El Carmen, the National Polytechnic Institute, the Metropolitan Autonomous University, the Ibero-American University, the National Institute of Nuclear Research, the University of Guadalajara, the Michoacán University of San Nicolás de Hidalgo, the Intercultural Indigenous University of Michoacán, the Government of Michoacán, the University of Monterrey, the University of the Isthmus, the Autonomous University of Puebla, the University of Quintana Roo, the Autonomous University of San Luis Potosí, the University of Sonora, the University of Veracruz, the University of Yucatán and the University of Zacatecas.

Figure 2: Percentage of astronomy researchers by state.

Figure 3: Percentage of astronomy researchers affiliated to the SNI by state.

The percentage of SNI members among the astronomy researchers based in Mexico before 2006 is 92% (166 members). If we also include astronomers who have returned to Mexico in the last two years, the percentage of astronomers belonging to the SNI is 86%. The reason for this reduction is due to the rapid increase in the number of researchers in the period 2006-2008, whilst recognizing that some of these new positions are temporary (i.e. postdocs and long-term visitors) and, furthermore, that there is only a single opportunity per year to join the SNI. Most of these scientists who have recently come to Mexico have a level equivalent to SNI-C, I and II. This corrective factor of the percentage of SNI members is clear in the IA-UNAM, which, over the past few years, has embarked on an ambitious policy to hire Mexican and foreign postdocs, following the example of other large international research centers. Excluding postdocs, 93% of IA-UNAM researchers are affiliated to the SNI. This correction also applies to the other large national astronomy research centers with new hires. The geographical distribution of the density of SNI astronomers by state can be seen in Figure 3. The decentralization of SNI members is comparable to that of astronomers in Mexico as a whole. Figure 4 shows the division of SNI members into the 4 categories of increasing seniority: candidate (C), I, II, and III (including emeritus): 48% of SNI members have levels II and III.

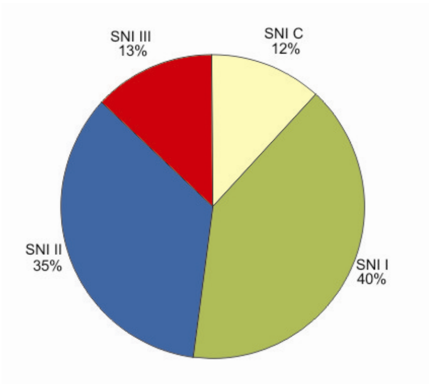

Figure 4: Percentage of SNI members by level.

The gender division, with 23% of women among SNI members, is similar to the 28% of recent physics bachelor (BSc) graduates[8], still a long way from achieving gender equity. This discipline constitutes the main source for the new generation of researchers in astronomy. A considerable number of female astronomers occupy senior positions of responsibility with decision-making authority, and engage in top-level research and teaching: 33% of SNI III members are women. All of them are UNAM scientists. The proportion of women among SNI members affiliated to UNAM is also higher (28%) than that of other national research centers (16%). This difference, despite the small numbers of women involved, only has a 3.6% probability of being produced by chance.

2.2 Productivity and Research Impact

During the period 2002-2006 astronomy in Mexico has been described by Conacyt[9] as the scientific area with the largest productivity (2% of the world's published research articles in astronomy) and immediate research impact (6.4 citations/article). Nationwide, astronomy has the second largest immediate relative impact, 16% lower than the world average impact, which is dominated by the US production. During the period 1998-2002[10] this difference was 9%: 7.05 citations/article compared with the world average of 7.72. In 1981-1985 it was 17% above the world average, with 5.56 citations/article[11]. A detailed analysis of these data is now presented using a number of international benchmarks.

The current productivity level of the largest national research centers is between 1.9 and 3.1 research articles/researcher/year (of which, 0.7 to 2.4 are peer reviewed) – see Table 2. By comparison, during the period 1999-2001 the mode of the distribution of articles/researcher/year in Spain[12] was 0.7, with 68% of the research centers producing between 0.3 and 1.1 articles/researcher/year and a total interval of 0.3-4.3.

Mexican researchers publish 88% of their scientific production in international peer-reviewed journals. Since 1974, national astronomers also can publish in an indexed Mexican journal: the *Revista Mexicana de Astronomía y Astrofísica* (RevMexAA), edited by UNAM. This journal currently has the ninth highest impact of all the specialized journals in the area. During the period 2003-2007, RevMexAA has remained at the same level as journals such as *Acta Astronomica, Publications of the Astronomical Society of Japan and New Astronomy*, with an average 2.5 citations/article. RevMexAA publishes articles from the national and international community in English and can therefore be genuinely considered an international journal. In the breakdown of published national and international research articles mentioned in this section, the RevMexAA has, however, been treated as a national journal. In addition to the main edition of peer-reviewed articles, the journal also publishes a series of conference proceedings, where many of the international conferences organized in Ibero-America can be found. The RevMexAA is the scientific journal with the highest impact produced in Mexico in any research discipline[9]. Until late 2006, RevMexAA also had the highest impact of all the scientific journals published in

Latin America.

Table 2: Summary of research and dissemination productivity of the largest institutes and departments of astronomy in Mexico during the period 2003-2007. Since researchers at different institutes can be collaborators, some articles are included in the productivity of two or more centers.

Institute	Research: Peer-reviewed articles	Research: Non peer-reviewed articles	Dissemination books and articles
IA-UNAM	437	365	200
INAOE	243	189	14
CRyA-UNAM	228	72	40
U. Guanajuato	36	59	2

Productivity is considerably higher in large astronomy centers than among the group of astronomers affiliated to smaller centers. Their research staffs are also usually more experienced, particularly if one takes the distribution of SNI levels into account. In bibliometric studies published by UNAM(13) about all centers in its Sub-system of Scientific Research, during the period 1997-2006, CRyA had the second highest productivity (~2.4 peer-reviewed articles/researcher/year) and the highest impact (~60 "citations received during the period on any article authored by the center's researchers"/ "articles published during the period"). In studies conducted by Conacyt(9) about its research centers, INAOE has been classified in successive five-year periods, from 2001 to 2006, as having the highest productivity and impact, although this statistic reflects all the disciplines practiced at INAOE, not just astronomy.

The situation is, however, critical in centers in the provinces with isolated astronomers, where a significant number of researchers are unable to produce the minimum number of publications (~1 article/year) required to remain in the SNI in the long term. The probable reasons why they have reduced their amount of research include a substantial administrative and teaching workload, local apathy towards research and geographical isolation. Under these circumstances, it is extremely difficult to maintain links with the country's large astronomy centers or other centers abroad or to feel motivated to undertake research. Reversing this trend and enabling university professors in the provinces to continue research is crucial in Mexico. Teaching standards must indeed be raised at all levels, given the results regarding Mexican teenagers' application of scientific knowledge revealed by the Program for International Student Assessment (PISA) in 2006(14), where 50% of young people are below the minimum competence level established by the Organization for Economic Cooperation and Development (OECD) and only 0.3% are within the two top levels. Teaching standards at these universities are compromised if their professors do not continue researching at a high level, thereby keeping up to date with current developments and passing on high standards of analysis and critical reasoning to their own students, who will be the future teachers of the upcoming generations about to join the national education system. On the other hand, there are encouraging examples of universities in the provinces determined to support, strengthen and increase the density of active researchers among their teaching professors. Examples are the highly successful cases of the Universities of Guanajuato and Guadalajara, among others, which maintain higher rates of SNI membership than larger centers, and notable productivity levels. Other encouraging examples, such as the Ibero-American University, a private university, links financial incentives and the funding of its professors' research to both the quantity and quality of the research undertaken and the evaluations to which researchers are subjected within the SNI; and the university calls for research projects, reviewed by Conacyt.

The level of the astronomy research conducted in Mexico is acknowledged both inside and outside the country. A high percentage of astronomers affiliated to Mexican research institutes belong not only to the SNI (92%) but also to other prestigious national scientific associations such as the Academia Mexicana de Ciencias (AMC, 50 members) and El Colegio Nacional (3 members). Various Mexican astronomers have received major awards from Mexican and foreign scientific associations, such as the National Science and Arts Awards, awards from the AMC, the Mexican Physics Society, the Third World Academy of Sciences (TWAS) and the American Astronomical Society. Several researchers are also members of exclusive associations of scientists such as the National Academy of Sciences of the US and the American Philosophical Society. Many are also continuously invited to give reviews at international conferences and graduate schools, and Mexican astronomers are often to be found on international decision-making and management committees(11). One female Mexican astronomer is a member of the Executive Committee of the most prestigious union of professional astronomers worldwide, the

International Astronomical Union.

There is a high international recognition of the research undertaken by SNI astronomers, which can be estimated through the distribution of citations to their work. The Hirsch index[14], *h*, which measures the number of articles *h* that have accumulated an independent number of citations $n \geq h$ is useful for this purpose. It is rapidly being implemented internationally as an indicator of the maturity, expertise and impact of researchers or groups of researchers. The index highly correlates with the total number of citations received by researchers throughout their career, particularly for those who have a variety of articles which are widely used by the community. Like any bibliometric index, it must be calibrated for each area with an international average or with specific examples that will serve as recognized benchmarks. Since it is a consolidation index it fails to reflect the development of researchers with short careers. This is why the analysis of impact that we present here uses only the indices of the researchers in the more senior SNI levels (II and III).

Figure 5 shows the distribution of the *h* indices of level II and III SNI astronomers, constructed with the Astrophysics Data System database, which is available to the public and maintained by the Harvard-Smithsonian Center of Astrophysics (USA). Since this database only contains citations from astronomy journals and not from others in related fields, the study sample only includes SNI members registered under the discipline of Astronomy and Astrophysics. For comparison, we represent the *h* indices of established researchers at the astronomy departments of 6 prestigious international centers: the *Instituto Astrofísico de Canarias* (IAC, Spain), the University of Oxford and Edinburgh (United Kingdom), the California Institute of Tecnology (Caltech) and the Universities of Arizona in Tucson and of Texas in Austin (USA). These comparison distributions have been smoothed to improve their visualization. Temporarily-hired researchers, and visiting or retired researchers are excluded in all cases. The average index for the combination of SNI II and III researchers, $\langle h \rangle = 18.1$, is similar to that of Spanish researchers. The distribution of indices is also similar, with a long tail produced by those that have obtained the highest international recognition $h \geq 20$, which usually corresponds to a total number of >1000 citations. Therefore, one can infer that the set of SNI astronomers with levels II and III have similar consolidation and impact indicators to those of their Spanish counterparts affiliated to one of the most prestigious institutions in their country. The Spanish community, like the Mexican one, has a relatively short tradition in modern astronomy: approximately 40 years. The Spanish community has, however, had the benefit of continuous investment in state-of-the-art infrastructure since the 1970s, particularly as a result of the participation of European partners attracted by the exceptional optical quality of the sky above the Canary Islands, which has given Spain a fraction of guaranteed time for national use.

A comparison of the Mexican distribution with that of institutions found among the top astronomy research centers in the United Kingdom and the United States also provides interesting insights. The average SNI III index $\langle h \rangle = 28.8$ is comparable to the maximum of the distribution of indices of researchers at these British and American institutions. Most of the index interval covered by SNI II and IIIs is included in these international distributions. One should recall that these centers not only benefit from a long tradition of national investment in the development of new applied technologies and astronomy infrastructure, but in many cases, they themselves also take part in technological leaps and in the creation of new niches for scientific exploitation. Centers such as Caltech also invest in infrastructure for the preferential or exclusive use of their institution, as in the case of the first years of use of the Keck 10-m telescopes. Both the United Kingdom and the United States consistently invest in astronomy research and development of state-of-the-art astronomy infrastructure, amounting to $7 to $10 USD per capita per year at the beginning of the decade [16], which far exceeds the Mexican national research budget for all basic sciences. Despite this, the Mexican community has performed well in the international sphere, on a par with first-world countries with a young tradition in astronomy. There is a group of outstanding Mexican researchers who enjoy an extraordinary level of recognition, comparable to that of leading British and American researchers, at least through bibliometric indicators. This appreciation is, however, also reflected in the international recognition and participation in international decision-making bodies mentioned earlier.

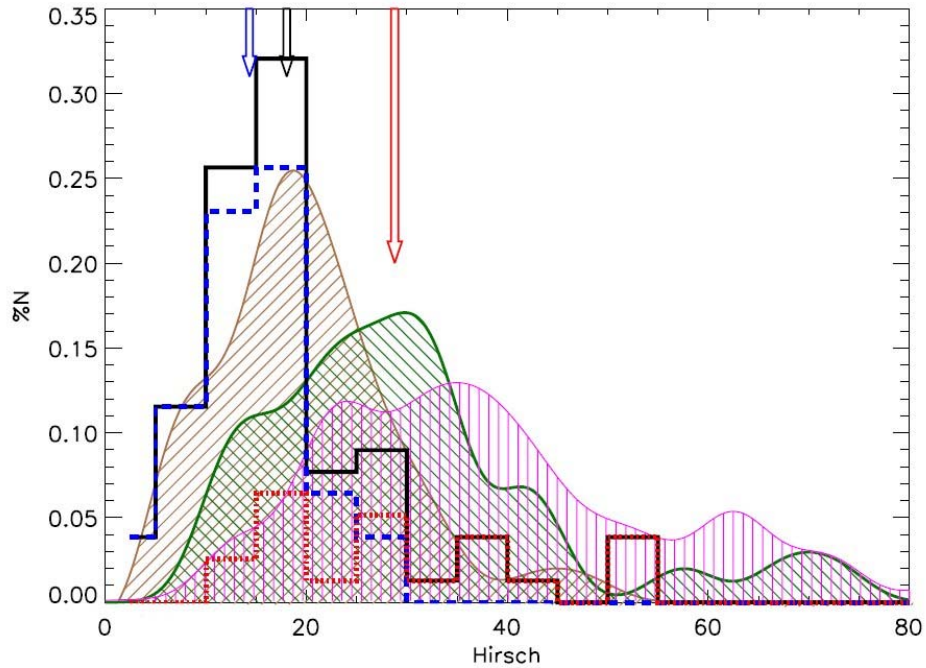

Figure 5: Combined distribution of Hirsch indices, *h,* in June 2008, of SNI II and III members (black histogram) registered under the discipline of Astronomy and Astrophysics. The indices for level II members are shown in blue, while those for level III members are shown in red. The average indices are shown with black, blue and red arrows respectively, at the top of the graph. For comparison, the distribution of indices for the faculty of prestigious astronomy research centers in other countries is also shown: the *Instituto Astrofísico de Canarias*, Spain (in brown), the combined astronomy departments of the University of Oxford and Edinburgh in the United Kingdom (in green) and the astronomy departments of Caltech, the University of Texas in Austin and the University of Arizona in Tucson, USA (in magenta). The tails of the magenta and green distributions continue to *h*~90.

In addition to producing research publications in specialized journals and teaching undergraduate and graduate classes at various centers of higher education, Mexican astronomers play an active role in disseminating this science. Table 2 includes the publication of articles and books in various printed media. All the country's research centers also organize talks for the general public, high schools and higher education institutes. Many professional astronomers are frequent collaborators with regular TV and radio programmes, and most are interviewed by the same audiovisual media. All the national observatories receive thousands of visitors a year while astronomers regularly organize well-attended observation sessions for the public in crowded places such as public squares. They also collaborate with planetaria and local amateur astronomers' associations. Astronomy has outstanding public-speakers, some of whom are also SNI members who have received the highest national and international awards solely for their work in the area of public outreach.

2.3 Lines of Research

Mexican astronomers undertake both observational and theoretical work, covering the entire electromagnetic spectrum, from radio waves to gamma and cosmic rays. The country's theoretical astronomers use a wide-range of analytical and computational techniques. The community has broad scientific interests that include both planetary and exoplanetary sciences, stellar and solar astronomy, diffuse (circumstellar, interstellar, interplanetary, and intergalactic) media, galactic and extragalactic astrophysics, cosmology and astronomical instrumentation. Figures 6 and 7 show the number of researchers working on these sub-disciplines and the techniques used.

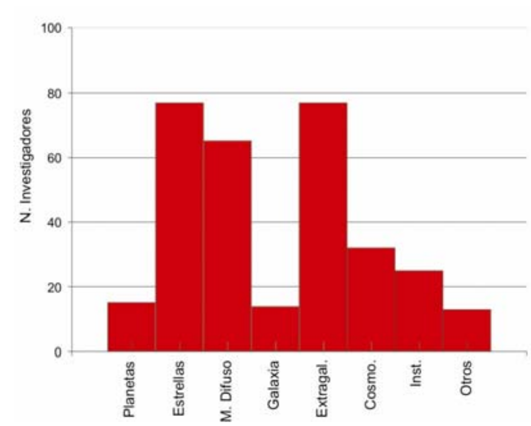

Figure 6. Number of national researchers who, during the period 2003-2007, have published results on the sub-disciplines of planetary systems, stellar and solar astronomy, diffuse mediums, galactic and extragalactic astronomy, cosmology, instrumentation and other sub-disciplines such as archaeoastronomy and the characterization of astronomical sites. It should be noted that it is common for a researcher to work in several sub-disciplines of astronomy and astrophysics.

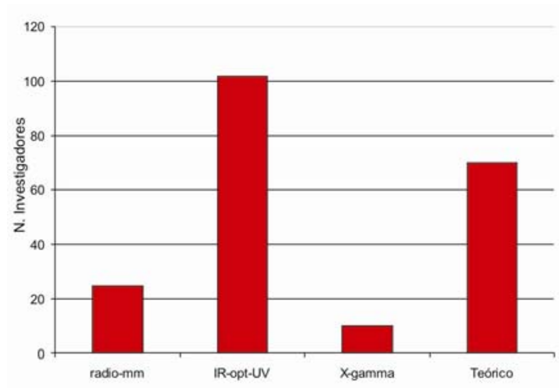

Figure 7. Number of national researchers which, during the period 2003-2007, who have mainly published empirical results based on observations at millimeter or radio wavelengths, infrared, optical and ultraviolet wavelengths, X-rays, gamma-rays and cosmic rays, and theoretical results. The same researcher may be included in several of these categories.

The two most common sub-disciplines, each practiced by 39% of the national community, are stellar and solar astronomy, and extragalactic astrophysics. The percentage dedicated to stellar astronomy is similar to that of European countries, where 22% to 42% of researchers were engaged in this area at the beginning of this decade[12,*]. The number of Mexican researchers in extragalactic astrophysics is above the European average of 17% to 22%, and 8% of the astronomy research in Mexico is related to the study of planetary systems, which is slightly lower than the European standard of 10 to 18%. As for research techniques, 36% of Mexican astronomers engage predominantly in theoretical work, compared with 34% to 54% of Europeans. The wavelength-regimes most commonly exploited by 52% of Mexican astronomers are those in the near infrared, optical and ultraviolet, compared with 33% and 52% in the United Kingdom and Spain. The radio-mm regime, rapidly expanding worldwide, is currently only used by 13% of astronomers in Mexico, which is lower than the European percentage of 19% and 21% in Spain and the United Kingdom at the beginning of the decade. These countries have increased their number of users of these frequencies due to the upgrades to their national facilities, including both the telescopes and the commissioning of new instruments that involve state-of-the-art technologies. Since there are only 25 researchers working on these wavelengths in Mexico, this observational area must expand considerably in the future to make the best use of the new world-class infrastructure available to the national community.

(*) in European statistics, researchers are accounted for in only one subdiscipline or research technique, implying that only the percentages in which Mexico appears below the European standard are meaningful.

If we examine astronomers with the highest impact research, *h*-index≥*20,* which reflects a high degree of international recognition (with over 1000 total citations to their work), we find that 24% use observations in the radio-mm interval, 43% in the IR-optical-UV, and 5% in the X-ray to gamma-ray regime. Also 43% of these successful researchers undertake theoretical work, both analytical and involving simulation. If we restrict this analysis further to those with *h≥30* (which usually corresponds to a total number of citations of >3,000 and in some cases over 10,000), we find very similar proportions, within the errors. Considering the topics of research, 10% of astronomers with *h≥20* conduct research on planetary systems, 50% on stellar systems, 57% on diffuse mediums, 29% on Galactic astronomy, 52% on extragalactic astronomy and 24% on cosmology. Instrumentation involves only 10% of researchers, but not as their main activity. It is worth noting that the blend of new generations of astronomers among the *h≥20* researchers is naturally larger than among the *h≥30* ones*,* since the index can only increase in the course of a researcher's lifetime and it is increasingly difficult to surpass it. Therefore, all subdisciplines practiced in Mexico produce research with large international impact.

2.4 Operational Facilities and Infrastructure

The national astronomical infrastructure currently open to observing time proposals is concentrated in the National Astronomical Observatory (OAN), located in San Pedro Mártir (Baja California) and Tonantzintla (Puebla) and in the Guillermo Haro Astrophysics Observatory, located in Cananea (Sonora). These professional observatories have optical telescopes of 0.84 to 2.1m in diameter. Both observatories were built using national resources in the 1970s, and were supported by the formation of the first groups of instrument builders in Mexico. Although national researchers still publish international, peer-reviewed articles based on observations from these optical/IR telescopes, the topics in which they can make a large international impact are increasingly restricted. This highlights the lag in infrastructure at optical/IR wavelengths and its insufficiency to meet the needs of the growing national astronomical community.

In addition to the use of national telescopes, which were already considered small compared to the international standard a decade ago[(7,11)], Mexican astronomers successfully compete for the extremely small fraction of international time or the open time of international radio to X-ray facilities, such as the Hubble, Spitzer, Chandra, Newton-XMM satellite telescopes (USA/Europe), the *Very Large Array* (VLA, USA), and *Sub-Millimeter Array* (SMA, USA) interferometers, the 15m Submillimeter James C. Maxwell Telescope (JCMT, United Kingdom, Canada and Holland), the 8m Gemini IR/optical telescopes and the *Very Large Telescope* (several countries), to cite just a few examples.

In the last decade, Mexico finally committed an investment in large-scale observational facilities that are expected to start operations shortly. Table 3 presents a summary of the main national observing facilities that are also described further in section 3.

Table 3. Observatories open to national proposals that are either in operation, under construction, or have approved funding. The institution responsible for channeling the national access, through the organization of time allocation committees, is also listed. The table includes the US observatories in which the Mexican community can compete for the US fraction of time.

Main observatories	Location	Wavelength Regime	National Access Manager	Situation
OAN 0.84 – 2.1m	Baja California (Mexico)	optical to IR	IA-UNAM	Operational
OAN 1m	Puebla (Mexico)	optical	IA-UNAM	Operational
Guillermo Haro AO 2.1m	Sonora (Mexico)	optical to IR	INAOE	Operational
e-VLA 27 x 25m	New Mexico (USA)	radio	NRAO (USA)	Operational/ Under construction
LMT 50m	Puebla (Mexico)	mm	INAOE	Commissioning
GTC 10.4m	La Palma (Spain)	optical to IR	IA-UNAM/ INAOE	Commissioning
ALMA 64? X 12m	Atacama (Chile)	(sub-)mm	NRAO (USA)	Under construction
HAWC (~ 900 tanks)	Puebla (Mexico)	gamma-rays	INAOE/ UNAM/ others	Partially funded

Mexico has two national supercomputer centers for research: one in the UNAM Headquarters for Academic Computing Services (DGSCA) and the other in the National Supercomputer Center (CNS) of the Potosí Institute of Scientific Research. The DGSCA, whose incursion into supercomputing for research dates from 1991, has the KanBalam computer with 1368 processors, 3TB of RAM memory, and 160 TB of disk storage. It also has other computers which total over 1,500 processors. The CNS, inaugurated in 2006, is a new center with three modern pieces of equipment comprising nearly 4,000 processors and 12TB of disk storage. Its main resource is a Cluster IBM E-1350, with 2736 processors, 696 GB RAM memory, and 7 TB of disk space.

Although none of these centers are actually considered astronomical infrastructure, it is worth noting that there is a large group of theoretical astrophysicists who carry out high-level modelling using the large computing infrastructure mentioned above. The areas that potentially benefit the most from access to extremely fast calculation time at these centers are those studies of the formation of stars and planetary systems, the hydrodynamics of the interstellar and circumstellar medium, galactic dynamics and cosmological studies for the formation of galaxies and other large-scale structures. Astronomers at UNAM, which is where most theoreticians are concentrated, and their collaborators, routinely use the DGSCA supercomputers. However, the amount of calculation time is not enough to meet their needs. Therefore the CNS is an important high-yield computing alternative for national astronomers. The demand for astronomy calculations is expected to increase as soon as the effectiveness for implementing programs for users outside the center has been proved.

In addition to the national computing centers, some groups of theoretical astrophysicists also have their own computer farms optimized for the particular type of calculations they undertake. These computers are mainly financed through Conacyt. This subset of theoreticians have chosen to solve problems of a smaller scale, which are not any less important, in order not to have to deal with the long queues at the supercomputer centers.

2.5 Formation of Top-Level Human Resources

Since 1989, it has been possible to undertake MSc and PhD studies in astronomy in the country. The first graduate program in astronomy was created at IA-UNAM. There are now 3 astronomy graduate schools that have been incorporated into Conacyt's National Quality Graduate Program: The UNAM joint program of IA, CRyA, the Institute for Nuclear Sciences and the Science Faculty, the program of INAOE and the program of the Department of Astronomy at the University of Guanajuato. Only the UNAM graduate school has Conacyt's top marking of quality, which places a strong focus on student recruitment and graduation efficiency within established time limits, rather than on the quality of the research produced by the students or their performance once they have graduated. However, these three schools train very high level students, as can be seen from their active role in national and international peer-reviewed articles, their contributions to national and international conferences and the number of subsequent contracts at national and foreign research centers. As an illustration, in the recently created prize for the best national thesis in astronomy, awarded during the first half of 2008, the winners at the PhD, MSc and BSc levels were all graduates from these three national programs. The finalists for the best PhD dissertation already had 3 to 7 peer-reviewed publications in high-impact journals as a result of their work as students and all of them had already taken post-doctoral positions at prestigious national and international research centers (in Europe and the USA)

The astronomy groups at the Universities of Guadalajara and Sonora also train astronomy students in their physics MSc and PhD programs. Therefore, new top-level PhDs in astronomy are trained in at least 6 Mexican states.

The initial trend, whereby astronomy students left the country to train, has now been complemented by a generation of students who obtain their PhDs in Mexico. The average of 5 new PhD graduates per year in the previous five-year-period(17) has risen to the current average of 6.6 – see Table 4 – in other words, the number of new PhD graduates trained in Mexico has risen by 28%. In addition to the supervision of nationally-registered students within their own institutes, Mexican researchers also supervise the PhD, MSc and BSc theses of visiting students from other national and international universities. Thus, the impact on the academic training of new scientists goes beyond the borders of their own graduate programs and impacts other centers around the world.

If we consider the 2008 census of 194 astronomers in Mexico, the training rate of new PhD graduates is 0.033 theses/researcher/year. This is similar to the Spanish rate at the beginning of the decade, of 0.033, and below the rates in Germany, France and the United Kingdom, of 0.043 to 0.068 PhD dissertations/researcher/year(12). The Mexican rate has remained virtually constant over the past 10 years(17). This mean is linked to the number of new graduates interested in astronomy but also to the number of top-level researchers hired in the country. If we restrict the term "researcher" to SNI members of any level (although level C members do not usually supervise PhD theses), the Mexican training rate would be 0.0434 dissertations/researcher/year, on a par with rates in countries like Germany.

Table 4: Number of PhD and MSc students graduated in Mexico in 2003-2007 in the discipline of astronomy and astrophysics. The last column lists the number of Mexican BSc students that have graduated with theses supervised by national astronomy researchers. The number of PhD and MSc graduated students in astronomy in the country is the total of the corresponding columns.

Institute	PhD graduates	MSc graduates	BSc graduates
UNAM (*) Federal District + Baja California	11	34	(N.A.)
CRyA-UNAM(*) Michoacán	5	20	18
INAOE Puebla	16	24	14
U. Guanajuato	0 (**)	3	6

(*) These centers operate within a single joint graduate program.
(**) This is a recently created program, from which the first generation of PhD students has yet to graduate.

Recently graduated Mexican PhDs tend to go abroad to take postdoctoral positions before returning to enrich national research centers, public and private universities and industry. The largest research institutes do not hire new researchers unless they have at least one year's work experience abroad. In some cases, this experience may extend to 5 years of temporary contracts, regarded as a typical duration for post-doctoral studies in both Europe and the USA. The funds for postdoctoral contracts are provided by either Conacyt or, in many cases, by the host institutions abroad.

In addition to the supervision of BSc, MSc and PhD theses, researchers also lecture at these three levels, and teach university extension courses at both their own and other centers of higher education. They also often lecture at national and international graduate schools open to other national and foreign students. The country's research centers have a strong interest in reinforcing BSc degree and secondary-school education programs, organize summer schools, and host high-school and BSc-degree students carrying out compulsory work-experience to complement their studies. Mexican astronomers present the possibilities of research to the future scientists of both Mexico and neighbouring countries, regardless of the discipline they will eventually choose. INAOE organizes annual training workshops for secondary-school teachers, science workshops to steer high-school students towards exact sciences and supports junior high-school science clubs. Since 2007 INAOE organizes the "Central American School of Observational Astronomy" for BSc-degree students, and over the past 5 years, it has been home to 3 advanced international schools for Mexican and international students from BSc to PhD degree programs. IA-UNAM organizes the “Summer in the Observatory" school in Baja California while CRyA-UNAM organizes the biannual "Summer School in Morelia", both for BSc-degree students.

3. Astronomical Infrastructure in Mexico for the Next Decade

In the late 1980s, it was quite clear that Mexico's observational infrastructure was far below the capacity and capability required by the scientific community to make ground-breaking advances in astronomy and astrophysics(11). Equally obvious was the fact that the task of building new world-class telescopes with state-of-the-art technology could only be achieved in conjunction with other countries, given the complexity of the projects and the resources required. The cost of the new generation of telescopes significantly exceeds the current investment in astronomy in nearly all world countries. Consequently, most of the new projects involving large-scale astronomical infrastructure are international. A change in mentality has therefore been necessary: to trust that cultural barriers and legal regulations will be overcome; and, to understand that this infrastructure does not necessarily have to be located in Mexico to accomplish the dual goals of developing and strengthening the national scientific and technological communities.

The new facilities that are already funded or approved are summarized below. These will begin commissioning and operation in the near future and will, therefore, be shortly available to the national community. In addition to these national projects, a number of Mexican astronomers, either as individuals, groups, or members of an institution, have access to other international telescopes and, in some cases, specific instruments or dedicated experiments. These smaller facilities are not open to all national scientists and require membership (as co-investigators) of consortia. Examples of such projects include the Pierre Auger Experiment and the Atacama Cosmology Telescope, among others.

3.1 The Large MillimetrerTelescope (LMT)

The LMT (www.lmtgtm.org) is a binational Mexico-US project led by INAOE in Mexico and the University of Massachusetts (UMass) in the USA. This is the largest scientific project undertaken in Mexico in any field of knowledge to date, with a total budget of $120 million dollars, in which Mexico has more than a 50% share. The LMT is the largest national astronomy initiative for the new decade.

Research at millimetre-wavelengths was only conducted by a very small group of astronomers in Mexico before the LMT was approved by Conacyt as the first of its megaprojects. However, since this wavelength regime is relatively new worldwide and has attracted the attention of countries that have heavily invested in new scientific technology (USA, Europe and Japan), it has an enormous potential to place the Mexican scientific and technological community at the forefront of this area.

Figure 8: The LMT antenna, located at 4580m on the summit of Tliltepetl (Sierra Negra), Pue., Mexico. Citlaltepetl (Pico de Orizaba), the highest peak of Mexico, can be seen in the right-hand corner (Courtesy of J. Reyes).

The development and transfer of new technologies was one of the requirements established by the Mexican financing organizations for the project's approval. In response to this challenge, the foundations, the alidade and the structure supporting the antenna have been constructed by Mexican firms, according to the specifications established by the German company that designed the antenna. INAOE has fabricated the secondary reflector using carbon fiber technology, assembled and measured the primary reflecting surface panels and is beginning to develop microwave instrumentation. The broader scope of the LMT project, in particular the opportunity for technological transfer to Mexico, is already encouraging Mexico's development of high-frequency microwave antennae and receivers.

The LMT was formally dedicated in November 2006, with the detection of astronomical sources at 12 GHz. The telescope has not yet been tested at the operational frequencies, 85-375 GHz (0.85-3mm), for which the antenna was designed, since it is still at the commissioning stage of the mechanical engineering and optical systems. The next stage of scientific tests will identify the path to increase the efficiency of observations. The telescope is expected to begin with limited scientific operations in 2008-2009 using the inner 30-m diameter of the surface. The LMT instrumentation has, however, already been installed on smaller (sub-)mm telescopes for commissioning and scientific purposes. This has provided the opportunity to train a growing population of graduate students interested in writing their dissertations on millimeter astronomy. Before 2008, Mexican astronomers and students have published approximately ten articles in peer-reviewed international journals using this instrumentation.

The Mexican community is developing a strong interest in this observational area of astronomy, and it includes astronomers in the country's large astronomy centers that conduct research based on millimeter-wavelength data obtained from foreign facilities. An increasingly large number of graduate students are being trained in this discipline, although the number of astronomers using these wavelengths is still insufficient. As an example, by 2004, INAOE had produced 34 graduate theses in the disciplines of astronomy, optics and electronics, with application in the development of LMT technology, the planning of the scientific programmes it will conduct, the design and construction of instrumentation operating in millimeter wavelengths and research using other millimeter telescopes complementary to the LMT(18). Once the LMT begins scientific operations, a significant increase in new astronomers and experimentalists working at millimetre wavelengths is expected throughout the country. This collective experience will contribute to state-of-the-art training at academic and educational institutes and to the country's industry.

3.2 The Expanded Very Large Array (e-VLA) and Access to the US Radio-mm Infrastructure.

The 1980s saw the early development of a small community of Mexican astronomers exploiting the techniques of radio interferometry, who use open-access international time, mainly from the VLA of the US National Radio Astronomy Observatory (NRAO). There are currently about twenty interferometrists working in Mexico, affiliated to UNAM, the University of Guanajuato and INAOE. These astronomers have high productivity rates as a result of their access to this unique world-class installation.

Figure 9: The cm-wavelength interferometer VLA on the Plains of San Agustin (New Mexico, USA), where the Mexican e-VLA receivers are already installed.

Just over a decade ago, the next large interferometer, the Atacama Large Millimeter Array (ALMA), began to be planned by the NRAO in the USA, in consortium with Europe and Japan. The new project is under construction, and although it has yet to define a specific user policy, it will probably operate on the basis of the European and Japanese quota model, based on the contribution of each country to its construction, maintenance and operation. This new policy poses a potential threat to the Mexican community, which lacks a fraction of time due to contribution, which should initially be $20 million USD and $2 million USD annually for operations and maintenance.

Negotiations between groups of users in Mexico and the NRAO found a way of guaranteeing access through competition for US NRAO time, including ALMA, if Mexico formally contributed to the project for expanding VLA: the e-VLA (http://www.aoc.nrao.edu/evla/), located on the Plains of San Agustin, New Mexico (USA). This upgrade improves the VLA sensitivity and spectral capabilities by a factor of 10, in addition to providing continuous coverage from 330 MHz to 50 GHz. The $72.3 million USD expansion project is financed by the countries in North America: USA 80%, Canada 17% and Mexico 3% (with $2 million USD drawn from the Conacyt initiative for New Fields).

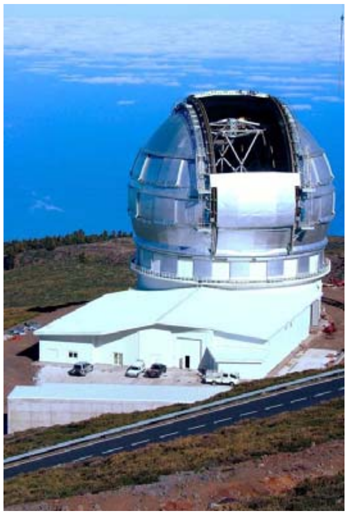
Figure 10: Dome of the 10.4m GTC

The Mexican funding was originally planned to be open for bidding, so that a Mexican institution could compete and thereby create investment in national technological development. However, no Mexican institution submitted a proposal, and the contract was eventually awarded to NRAO. The equipment built using Mexican funds, and comprising the electronics for two antennas and 12 receivers for the18.0 to 26.5 GHz and 40.0 to 50.5 GHz bands, has been installed since 2005 and has already been used in several dozens of peer-reviewed articles by Mexican astronomers and in the BSc, MSc and PhD theses of their students.

The e-VLA expansion is expected to complete the stage of improving receivers in 2010 and the instrument is expected to be working at full capacity in 2012. ALMA is expected to begin restricted operations in test mode in 2009 to 2010, with 14 antennas and 2 receivers.

3.3 The *Gran Telescopio Canarias* (GTC)

The GTC (www.gtc.iac.es) is a segmented optical telescope of 10.4m aperture. It is located at the Northern European Observatory, in Roque de los Muchahos, La Palma, in the Canary Islands (Spain).

The 120 million Euro investment is primarily financed by the Spanish government and the autonomous Canary Islands government. From the outset, GTC sought international partners for this project, a search that eventually materialized into 5% participation by Mexico through institutional IA-UNAM and INAOE contributions. The University of Florida (USA) also contributes another 5%.

Negotiations between the directors of the participating Mexican institutes and the GTC created opportunities for Mexico to play an important role in the construction of the instrumentation of the new telescope, taking advantage of the country's experience in equipping smaller telescopes. The country's community of optical and IR astronomers is eagerly awaiting the telescope's scientific first-light and the first shared risk science, projected for late 2008 or early 2009.

The Mexican contributing institutes have also announced that Mexican time will be available to the entire national community, under peer-evaluated projects, as usually happens in other observatories. Thus, for the first time in the history of national astronomy, a telescope will have a time allocation committee composed of national representatives, which may also include people not affiliated to the country's major centers.

3.4 The High Altitude Water Cherenkov Experiment (Hawc)

High energy astrophysicists and physicists from various national centers have forged an alliance to attract the international project Hawc to Mexico. Hawc is expected to become the new generation of Cherenkov panoramic observatory in water, after the success and completion of the Milagro mission, dismantled in June 2008 so that its electronics and photomultiplying tubes could be incorporated into Hawc. The new generation telescope, expected to have a useful lifetime of approximately 10 years, must be located at a height of over 4000m in order to detect TeV radiation. The telescope must be located in a flat area with access to enough water to fill a series of tanks in which the detectors are submerged.

Of all the potential locations in the world under consideration where Hawc could be installed, Pico de Orizaba National Park was chosen in 2007 by the Hawc consortium because it is only 4 hours' drive from Mexico City International Airport, and because of its proximity to other international scientific installations (LMT) which in turn guarantees access to a modern communications network and other existing infrastructure.

Hawc is a telescope that will simultaneously record high-energy gamma-rays (100GeV to 100TeV) within its instantaneous field-of-view which covers 12% of the available sky. After a year of operations, it will have mapped two thirds of the sky, with 15 times more sensitivity than Milagro, enabling the detection of signals equivalent to 50 mili-Crab nebulae. This sensitivity will permit the detection of previously unknown gamma-ray emitters. Hawc's scientific objectives include a census of gamma-ray emitters in the Milky Way and monitoring the outbursts of variable objects. The experiment is expected to influence the study of supernova remnants, gamma-ray bursts, blazars, and the activity of the central black hole in the Galaxy.

With a joint installation and operating budget of $7 million USD for 2 years, Hawc is an attractive project that capitalizes on Mexican participation through the exploitation of its natural geographical resources. Although the international part of the project has already decided to locate it in Mexico, Mexican high energy astronomers and physicists require an additional national contribution for the installation of the electronics and detectors of Milagro, which will enable them to participate in this experiment as full partners.

3.5 Other initiatives

The projects described below are initiatives that are being seriously considered by sections of the national community, and for which attempts are being made to raise support from the largest possible section of national researchers.

3.5.1 A New Optical/IR Telescope for San Pedro Mártir

San Pedro Mártir National Park (SPM) in Baja California has an area of 3,055 protected hectares reserved for astronomical exploitation, in which most of the NAO infrastructure is located. It possesses extraordinary conditions for optical astronomy, with an image resolution limited by atmospheric turbulence, or seeing, of an average of 0.61", 63% of photometric nights, 81% of spectroscopic nights and a sky darkness in moonless nights of V≈21.2 mag, characteristics that are comparable to those of the world's best ground-based observatories[19]. This sky quality is a powerful attraction for the international astronomical community, which periodically explores the possibility of installing new optical telescopes in SPM. This gives the national community the hope that it will be able to attract new resources to the area of optical and IR observational astronomy, which lags behind due to the lack of investment over the past 30 years.

Although the GTC is expected to reduce this deficiency in access to world-class optical/IR telescopes, the Mexican observational community in the optical/IR is extremely numerous (see Figure 6) and 5% of GTC time is only equivalent to 15 available nights a year, while a typical research project on a small sample of faint objects requires at least 2-3 nights of observation.

A group of Mexican institutions, led by IA-UNAM and INAOE, is attempting to define a large-scale project for SPM by attracting foreign capital, in a model that has been successfully tested in other countries with excellent sky quality such as Chile and Spain. At a time when extremely large optical/IR telescopes with a diameter of over 30 m are beginning to be designed, finding a niche in which smaller, yet powerfully optimized telescopes can achieve a large impact is an essential requirement for launching a new optical/IR astronomy initiative. Maximizing the synergies that can be obtained from joint exploitation with the rest of the national access infrastructure is another aspect that must be taken into account to achieve the support of the national astronomers' community. A project to install two twin complementary optical/IR 6.5m telescopes was ready in 2006[20], but the initiative failed to materialize. The national optical community is still interested in a large optical/IR telescope with strong Mexican participation, and it is re-organizing to promote a new optimized 6-8m optical/IR telescope project.

3.4.2 The Very Long Baseline Array (VLBA)

The VLBA comprises 10 antennae scattered throughout the American continent, Hawaii and the Virgin Islands. The project is seeking international partners. Half a million USD would guarantee Mexican participation. Among other projects, it would be possible to draw up a catalogue of distances and proper motions of star forming regions which would be used for decades as the most accurate reference of its kind. CRyA radioastronomers are experts in this area, although the interferometer can obviously be used for other scientific purposes.

3.4.3 The Square Kilometer Array (SKA)

The most important centimetric radiotelescope planned for this century, SKA, will be an international interferometer with a collecting area of one square kilometer. Its location has yet to be decided, although it will probably be in either Australia or South Africa. One of the main objectives of the interferometer is to detect the collapse of the first stars and use high spatial resolution to trace the evolution of hydrogen clouds from the early universe to the present time. Participating in SKA would be very important for Mexico, since it would enable to maintain its international impact in radioastronomy in the long-term. A possible national participation is being promoted by CRyA, which would require a $20 million USD investment distributed over a period of 10 years. The immediate objective would be to contribute to one of the pathfinders, single-dish telescopes that locate the candidates to be followed using the interferometer, since these are being designed in various countries and could be built in Mexico.

3.4.4 The World Space Observatory (WSO)

WSO is a project to construct an ultraviolet space observatory. The satellite project is being developed by Russia and China and the instruments will be designed by a consortium of European countries. This observatory has yet to raise the necessary funds, but it has already been supported by the United Nations Organization (UN) and is contemplating the participation of countries that do not have their own space projects. Mexico is considering a collaboration with Russia in the fine-guiding telescope instrument. A launch date for the WSO has yet to be defined.

4 Outstanding Challenges

4.1 Maximization of the Scientific/Technological Return from the New Infrastructure

Mexico is looking forward to the future with optimism. Within the modest level of operative infrastructure, beyond 2010, Mexican astronomers will have access to a large fraction of the 50-m LMT, a small participation in the 10.4m GTC, access to US e-VLA and ALMA time, national supercomputer centers, the possibility that Hawc will already be installed, and the hope that it will be possible to obtain national support for other large-scale initiatives. A strong component of the development of national astronomy for the next few decades will be the scientific exploitation of these large facilities, through which a high scientific impact is expected. These telescopes must be operating at the cutting edge of astronomy for several decades, through constant upgrades. Their success and the international impact will also depend on the efficiency with which major changes in scientific investment policy can be identified and implemented to exploit future scientific niches of opportunity.

The instrumentation for nearly all the projects described in section 3 has already been built or is about to be delivered. A second generation of instrumentation is already being planned to keep them at the forefront of science. The cost of building first-generation LMT or GTC instruments varies from 1 to 10 million USD and has been included in the initial cost of construction of the telescopes. All the first-generation instrumentation for LMT and much of that for GTC is being constructed outside Mexico, although there is a great deal of interest to not only participate in the construction of components but also to lead second-generation state-of-the-art projects.

The achievement of significant scientific discoveries with any infrastructure requires that important scientific questions are first raised and subsequently that the necessary scientific instrumentation to address them is coupled with existing facilities. This new instrumentation must be designed, manufactured and tested before being installed in any telescope. The teams in charge of these tasks are highly trained experimental researchers, instrument builders, engineers and technicians who are part of the scientific community. The national investment in large-scale astronomical infrastructure, and hence the guaranteed access to those facilities, is the only way to ensure the scientific independence of the national community.

4.1.1 GTC

Until the 1990s, neither IA-UNAM nor INAOE, the two institutes in Mexico that run professional optical telescopes had the experience to develop complete instrumentation packages for large-scale telescopes, although both had teams of instrumentalists dedicated to the national 2.1 m telescopes. Both had also successfully bidded for and won contracts to manufacture components of instruments for larger foreign telescopes. Mexico's entry into the GTC consortium opened up the possibility of participating in the construction of its scientific instrumentation and winning competitive contracts to produce it. These projects must be developed according to strict schedules, periodic progress reviews and international quality standards. This activity implies renovating lab spaces and equipment and establishing quality-control procedures for the local manufacture of parts and those outsourced to other research institutes or national companies.

IA-UNAM decided to exploit this opportunity through a series of increasingly complex stages: participation in OSIRIS, led by IAC in Spain, and the construction of a camera to verify the telescope's optical quality. This has led to the consolidation of a team of instrument builders capable of leading one of the second-generation GTC instruments, FRIDA, the adaptative-optics camera. The verification camera and the Mexican OSIRIS packages have already been handed over to GTC and FRIDA is currently under construction.

This is an example of a successful strategy to develop: astronomical instrumentation for large national-access infrastructure. The future challenge is the development, construction and commissioning of a complex world-class instrument in Mexico.

4.1.1 LMT

In the past decade INAOE has contributed to the construction and characterization of the LMT antenna, without simultaneously investing heavily in instrumentation development. Due to its greater experience, it was agreed that UMass had the responsibility to provide first light instrumentation for the project. INAOE has constructed the Laboratory of Aspherical Surfaces to measure the quality of the surface panels that constitute the primary reflector of the telescope. This experience in large-piece metrology is now being applied to industry. However, Mexico should make a greater commitment to the development of millimeter instrumentation if it wishes to maximize its leadership and independence in the use of its telescope. This will help guarantee that the LMT is a long-term competitive infrastructure, regardless of any considerations concerning international collaboration. As part of this early effort, two laboratories have also been created which are designing components and collaborating with UMass partners in the characterization tests for these millimetre-wavelength instruments.

Microwave instrumentation permits the development of technological capacities whose applications go beyond astronomical instrumentation but an investment policy has not yet been implemented in this area, probably due to the high costs involved. INAOE is, however, now attracting a new generation of students, mainly engineers, interested in developing instrumentation for the LMT.

4.1.2 Participation in Decision-Making Boards

All national observational and computational facilities have independent governing boards that control and optimize their operation. It is common in leading countries for prestigious scientists and expert users of similar facilities, to serve on these governing boards and determine the policies for use and the strategies for updates of the infrastructure. This guarantees that the decisions these boards take are guided by the search for academic excellence and the highest scientific returns. The governing boards of large-scale infrastructure must make sensitive, informed decisions about their future, such as the division of time dedicated to large or small projects, provide guidance and approve the future generations of instrumentation, or the opportunities to coordinate and collaborate with other complementary facilities at the national and international levels. They are also responsible for the appointments of directors and the regular assessment of their performance, ensuring that important science is produced, and for approving top-level policies that affect the operation. There is little tradition in Mexico of appointing highly specialized governing boards with members that have both academic prestige and expertise in the relevant field, and direct accountability to the national community. Probably the greatest challenge Mexico faces in this decade for dealing with its national infrastructure is to guarantee that the best scientists in Mexico are part of the decision-making process. In line with common international standards, the membership of these boards should be made public and limited to a fixed term, and decisions made must be reported with justification to the community. A mechanism should also be in place to allow the community to submit ideas and recommendations about the development and future use of its national infrastructure to the governing boards.

Moreover, these governing boards and the infrastructures themselves must consider that a growing fraction of the national community is not affiliated to the two largest institutes that have led the policies of astronomy development in Mexico over the past decade. Astronomers at smaller centers, who have achieved international recognition, must also join the decision-making and advisory bodies.

The membership of time allocation committees and users' committees that report directly to directors and governing boards must also be urgently defined in our community.

4.2 Structuring of Human Capital

The mechanisms to control and reward the development of research careers in basic sciences are well-established in Mexico. The creation of SNI and the system of financial incentives in large research centers effectively encourage the productivity of astronomers dedicated to generating basic knowledge and, as one can see in Section 2.2., these research products have an international impact. The new era of national-access large-infrastructure raises the need to find how to shift from a level of international recognition representative of countries with a short astronomical tradition to that of countries with a long tradition and thereby increase the average level of national competence.

Having built the basic physical infrastructure, further gains in efficiency and scientific productivity require a continuous search for new state-of-the-art technology that can be incorporated in next generation instruments. Typically and order of magnitude, or more, gain in performance is expected every decade. This gain is usually due to new instruments rather than the upgrade of the technological infrastructure. It is therefore essential that there exists secure opportunities for instrumentalists to develop their skills and broaden their experience in new technologies and techniques. Instrumentalists, and their “brain-trust”, are a valuable resource that must be encouraged and their career development protected. It is common to find that most of those experimentalists that built instruments, but who not necessarily use them, fail to find ways of effectively advancing in their professional careers. Their activity, in contrast with that of classical observational or theoretical astronomers, is not reflected in a large number of peer-reviewed publications. Ten years usually elapse between the time a large-scale instrument is planned to that when it is commissioned and scientifically productive. This often results in only a few peer-reviewed publications signed by the team of instrumentalists. In the meantime, the project produces countless documents and technical reports that reflect the progress achieved, but the instrument takes much longer than the standard period of evaluation to materialize, to be tested and eventually to be used by the much larger astronomical community than the initial team that developed the instrument.

The SNI includes an engineering section (section VII), which contains some of the most prestigious dedicated instrumentalists in Mexico. Thus the SNI could in principle include those that build astronomical instruments, accepting within their rules of evaluation the long time required to produce astronomical instrumentation. Instrument builders themselves are, however, often unwilling to enter the engineering section. It is also common to find that only those that lead instruments or obtain patents manage to enter this section, and not those that have recently obtained their PhD degrees, engineers or academic technicians who have the responsibility to lead the design and produce specific packages within these large-scale projects. These groups only produce patents occasionally[(13)], since the product is neither commercial nor marketable, and the academic arena within which they work is characterized by the same altruistic spirit regarding the advance of knowledge as exists in the rest of the astronomical community. The lack of patents may mean that progress in section VII of SNI for astronomical instrument builders is not optimal. In fact, many of those that join this section soon move to section I of physical and mathematical sciences, where they find more universally acknowledged criteria for permanence and promotion within the astronomy community, albeit somewhat removed from their main activity. Thus, they embark on a hybrid career midway between basic science and astronomical engineering, dividing their time between the two. The specialty of Scientific Instrumentation in Section VII of SNI could perhaps become a subdiscipline within this section, while a list of permanence and promotion criteria could be drawn up that would be able to absorb the astronomy instrumentalists better.

Apart from the SNI, research institutions have yet to design a control mechanism for the activity of instrument builders that seeks to promote and achieve excellence in this discipline, and to encourage and reward them, particularly in the early years of their career. Restructuring the evaluation methods for the instrumentation groups dedicated to technological development for astronomical use is still a pending issue at the country's research centers that have shown interest in embarking on large-scale instrumental development. Without this restructuring, it is difficult to imagine that the country could take full advantage in this promising area of technological development, on the boundary between basic science and application to industry.

Young Mexican researchers who have recently obtained their PhDs find it difficult to continue with a high-level of research once they get appointed as professors in provincial universities. With an annual rate of 6.6 new PhDs per year, positions should be created in both provincial universities and larger institutes, in order to maintain sufficient growth, however modest, to guarantee the best students of the new generations find post-doctoral and tenure-track positions on their way to become full faculty members. The policy of attracting PhDs to the provinces must also be reformed. In order to maintain these new scientists in research, these universities without a long astronomy tradition might consider attracting small groups of young PhD graduates simultaneously and/or more experienced researchers, and thus provide peer pressure to be more productive and scientifically independent. Annual research visits, lasting from one to three months at other national or international centers, in order to create and reinforce collaborations that will give rise to training, learning new skills and publications, would be beneficial. Establishing links between these small centers and the PhD programs already open in the country, through cooperation or membership agreements, would also encourage research nationwide.

4.3 Structuring National Academic Discussion and Advisory Bodies

Although the national astronomical community could exceed 250 members in the next decade, it is still poorly structured. For years, scientific policy regarding astronomy has been led by IA-UNAM and over the past 15 years also influenced by INAOE. Although these two institutions currently comprise 70% of Mexico's astronomy researchers and have dominated the community in the past, it is clear from the maps and tables in Section 2.1 that there are strong developing groups at other research centers and higher education institutes. It is at these centers that there is the potential for a large expansion of the community. In order to reach a density of researchers comparable with that of countries with high levels of competence in the evaluations of high school education, such as PISA, the community should be at least five times the current size (See Box 2.3 on PISA report[(14)]). It is therefore important for the new places of astronomical expansion to begin to participate in the decisions on the future of astronomy in Mexico.

A Mexican Astronomy Society was created in 2005 but it has yet to make headway as an organization of liaison and national debate. To date, it consists of its founding members only. There have been a series of attempts to revive it. Although astronomers located at small and medium-sized centers and recent PhD graduates are those who are most interested in ensuring that this organization is a success, in the long run, this type of organization would benefit the entire community.

A timid attempt by the AMC to coordinate a debate on strategic policies for scientific development was given a tepid reception by the national astronomy community in 2007. There is a lack of a tradition and experience in collegiate or consensual decision-making by considering the opinions from a broad spectrum of the community. The community is, however, receptive to the idea that commissions of highly respected astronomers, covering the country's entire range of geographical regions, generations and specialization will be able to make important strategic recommendations that will lead to the orderly growth of astronomy in Mexico over the next few decades and maximize the productivity, impact and quality of this scientific area.

At a time when there is a shortage of financing for science, having a united, organized community aware of the priorities for development and links with society is essential. Communities, such as the US and Canadian communities engage in this type of reflection periodically and publish the very influential decadal reviews that prioritize key questions in astronomy research and those facilities to be supported by government funding that will strongly contribute to their resolution. Astronomers are capable of implementing mechanisms and issuing enlightened recommendations, guided by scientific quality. It is probably time for Mexico to engage in a similar debate.

A method[21,22] of arriving at consensual recommendations has been successfully used in various US decadal reports, which affect a community of 5000 astronomers. The process begins by electing a president of the survey commission, a renowned researcher highly respected by a broad spectrum of the community. The president of the commission then chooses 15 prestigious researchers to comprise the survey commission. The president talks to senior administrators and politicians to determine what aspects they are most interested in and obtain potential issues on which surveys could be conducted. These areas of administrative interest are not binding, since the study deals with the generation of top-quality knowledge, yet these conversations permit the identification of scientific areas of opportunity and debate. The survey commission elects presidents of panels for the topics to be discussed (such as education, optical, radio, high-energy infrastructure, professional development, etc.) The panels' presidents and vice-presidents, the latter being members of the survey commission, set up working-groups with the community covering the wide range of disciplines in astronomy, and geographical and generational distribution required to deal with each topic. Between 100 and 300 astronomers are involved in the working-groups. After an exhaustive discussion, the consultive panels prepare non-binding reports identifying the most important issues for helping their field advance during the next decade and prioritize the areas of development. They also collect documents and presentations from individual members of the community that can be analyzed before they make their recommendations. The survey commission combines the reports into a single list of recommendations and priorities. This strategic document is submitted for review (~20 reviewers) and published by the US agency that finances science, the National Science Foundation or the National Research Foundation. The entire process takes 14 months.

The Canadian model[16] is based on similar commissions established within the Canadian Society of Astronomy (CASCA) and involves the community in drafting the reports for this debate on strategies. Canada has a modestly-sized community of approximately 400 astronomers, twice the size of that of Mexico's. The entire community participates with ideas through open discussions at various universities throughout Canada and the collection of documents and letters of intent. A survey committee examines the CASCA committees' recommendations and prioritizes the areas of development. The results of the survey are published by the agencies that finance Canadian science. The process also takes approximately one year.

If these types of debate in other North American countries are adapted to the size of the Mexican community, then a commission of 15-20 national researchers could be set up. As representatives of the national spectrum, they could collect the community's documents and proposals for new initiatives. It is essential to prioritize these proposals according to a judgement on the impact value and quality of the expected scientific results. Without prioritization, these exercises simply become lists of unachievable goals. Unless the constant improvement of the quality of knowledge is cited as an objective, it would be easy to succumb to passing fashions dictated by current policy or the incumbent administration. It would be useful to have commissions, at the very least, on infrastructure, education and dissemination and the progress of a career in research. National recommendations on these issues are vital for keeping the astronomy community at the international level, increasing the density of astronomers in Mexico without sacrificing the quality of research, and increasing impact, high-level human resource formation and strengthening our links with society.

4.4 Necessary Change of the Scientific Policy Environment

The funding assigned to basic science in Mexico is increasingly reduced. Although the level of assistance for training new personnel has been maintained, the level of financing for research projects is still very low. The largest individual or group-sized Conacyt research projects in astronomy obtain amounts of 0.03 to 0.3 million USD for three to five years, with an average amount in the area of physical and mathematical sciences of 0.06 million dollars/project[9]. Mexican astronomy is internationally competitive, but it will be threatened if the resources assigned to projects are not maintained. Not only is there a need for salaries but also for increased investment in basic science through more generous financing of research projects, as well as an increased number of researchers that can obtain funding for peer-reviewed projects.

Moreover, large-scale astronomy instrumentation does not have a traditional source of funding in Mexico. The largest sums assigned for physical, mathematical or engineering projects are too small to enable the country's instrument builders to embark on a new generation of state-of-the-art technology applied to astronomy or to produce cutting-edge instruments in the large, national-access observatories over the coming decade. Maintaining instrumentation laboratories also requires significant commitment to the continuous running costs and expenses for consumables, materials and equipment for those institutes that pursue this line of research. Consequently, instrumentalists also have to fight to obtain resources at the institutional level. Hence, in order to develop world-class instruments in Mexico, advantage must be taken of the collaborative opportunities provided by foreign associates. Furthermore, to enable fast-track development, and new initiatives, including seed-money for speculative ideas, it is necessary to make regular announcements of large, mid-sized and small research grants to support advanced technology projects.

In order to have an effective discussion on the priorities for the development of science, it is helpful if the government specifies the budget for the future investment in all scientific fields to ensure orderly prioritized growth on the basis of decisions taken after the necessary consultation. Investment in basic science in Mexico has traditionally been erratic and identifying strategies for the future involves careful planning.

The search for academic excellence based on previous results or secure evidence to support new innovative ideas should determine which projects deserve this funding.

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