Astronomy in Spain

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Spanish astronomy has grown in a spectacular way over the last few decades. Spain hosts world-class astronomical facilities, and its astronomers publish over 5 % of all papers in this discipline. As an ESO member, Spain joins forces to pursue the most ambitious projects in European ground-based astronomy.

Some history

What best defines the current state of astronomy in Spain is its rapid development over the last three decades. By the end of the 1970s, there were only a handful of astronomers in Spain who were active in research, and only a few places with some activity in astronomy. The Jesuits had some observatories in Spain: the Carthusian Observatory in Granada; the Ebro Observatory; and the Fabra Observatory in Barcelona which combined, and still continues, studies in meteorology, geophysics and astronomy. These observatories were founded at the beginning of the twentieth century. The Naval Astronomical Observatory in San Fernando (Cádiz) was created over 250 years ago to train naval officers in navigation techniques. One of their driving tasks was to prepare the Nautical Almanac and, together with the National Astronomical Observatory, they provided the official time in Spain. Today, the Navy's Royal Institute and Observatory in San Fernando runs, among other projects, the Carlsberg meridian telescope. Finally, the National Astronomical Observatory (OAN) in Madrid, which is part of the National Geographical Institute (founded in 1786 by King Charles III) was also active in optical astronomy. Today, OAN is a reference for Spanish, European and world-wide radio astronomy. In addition to these institutes, a few universities (Madrid, Barcelona, Santiago de Compostela, Zaragoza, Valencia) had astronomy professorships, often engaged in the more mathematical branches of astronomy and in charge of teaching positional astronomy to scientists and engineers.

The big leap forward

The late 1970s were the key period for the large and spectacular development of astronomy in Spain. Beyond doubt, the international agreements promoting and regulating the use of the observatories in the Canary Islands were the main driver. This enabled internationally competitive facilities to be installed on Spanish land, with a reward of observing time to Spanish astronomers. In addition, the fact that Spain was a founding member of the European Space Agency (ESA) triggered early on the involvement of Spanish scientists in the construction, use and scientific exploitation of space-borne astronomical observatories and exploratory missions in the Solar System. The creation of the Spanish-German Astronomical Centre, with its observatory in Calar Alto (near Almería, in the south-east of Spain), the deployment of the 30-m IRAM dish in Pico Veleta, the establishment of ESA's Villafranca Satellite Tracking Station near Madrid (now converted to the European Space Astronomy Centre – ESAC) and specifically the founding of ESA's International Ultraviolet Explorer Science Operations Centre there, were all of them instrumental in forming new generations of astronomers in regular contact with international partners. Soon afterwards, in the 1980s and 1990s, the universities began to create new permanent positions in the field of astronomy and astrophysics. Many of those posts, as well as those in the Research Centres, were filled with young and talented people who had often entered astronomy through these international enterprises and had then followed their professional career in internationally recognised research institutions abroad.

The current workforce

The Spanish R&D system now contains over 500 professional astronomers, including PhD students. Of these, well over 350 have their PhDs completed and conduct independent research. About one half of these PhD astronomers have permanent positions in universities and research centres. They are assisted by about 150 technical people totally devoted to astronomy. They work in about 30 different places spread around all over Spain. University departments, where research is conducted along with teaching, and research centres share the astronomical workforce in approximately equal halves.

In recent years the training of new PhD students in astronomy has proceeded vigorously. About 25 new PhDs in astronomy are obtained every year, and this number may be growing. At the moment, the Ministry of Education and Science alone is funding 20–25 PhD fellowships in astronomy and space science, to which other fellowships provided by the regional governments, universities and research centres can be added.

Astronomical research in all fields is pursued to some degree. A study conducted in 2002[1] for the Spanish Astronomical Society (SEA)[2] showed that relative to other European countries, Spain is fractionally stronger in studies of stars and the Galaxy, and fractionally weaker in extragalactic astronomy and cosmology as well as in Solar System science (planets and interplanetary medium). Concerning the tools used by Spanish astronomers, not surprisingly, the use of optical observations is fractionally stronger than in other European countries. A counterpart to this is the relative weakness of high-energy (X-ray and Gamma-ray) and laboratory astrophysics.

Overall Spain has about 12 professional astronomers per million inhabitants, a number which is smaller than the one claimed for countries like France and Germany (about 16 to 18) and a factor of two lower than that claimed for the United Kingdom. The expectations recently raised by a very substantial yearly increase of the budget dedicated to R&D by the Spanish government are that, in the following decade, Spain should grow much closer to average European numbers.

[1] This document can be accessed through *http://sea.am.ub.es/TWiki/pub/Main/InformacionSea/Informe2002.zip* (in Spanish only).

[2] The Spanish Astronomical Society (*http://sea.am.ub.es*) was constituted in 1992 as a society of professional astronomers. It is associated to the European Astronomical Society (EAS) and was the main promoter of the Confederation of Scientific Societies (COSCE, *http://www.cosce.org*) in Spain.

Astronomical centres

The largest astronomy centre is the Instituto de Astrofísica de Canarias (IAC). Formally founded in 1975, the IAC is a consortium with participation by the Spanish Government through the Ministry of Education and Science (MEC) and the Spanish Council for Scientific Research (CSIC), the local government (*cabildo*) of Tenerife and the University of La Laguna, one of the oldest in Spain. About 25 % of all researchers in astronomy in Spain work at the IAC, but this share is indeed much higher when technical staff are included. The IAC owns the observatories of Roque de Los Muchachos in the island of La Palma and Teide in Tenerife, where national and international facilities are based.

Whilst there is activity in all fields of astronomy at the IAC (cosmology, extragalactic astronomy, interstellar medium, stars and their evolution), it is in solar physics and optical and infrared astronomy (including instrumentation in both cases) where IAC is clearly a reference both nationally and internationally.

In 1975 the CSIC also founded the Instituto de Astrofísica de Andalucía (IAA) in Granada. The IAA has largely expanded from its moderate initial size to a truly multi-disciplinary research centre. Astronomers at the IAA conduct investigations on radio astronomy and Galactic structure, Solar System, stars and extragalactic astrophysics. IAA is the flagship of CSIC in the astronomy domain and a reference for the development of instrumentation aboard Solar System space missions and its scientific exploitation. The IAA owns the Observatorio de Sierra Nevada and the Spanish-German Astronomical Centre of Calar Alto in conjunction with the Max-Planck-Gesellschaft.

The CSIC also has other astronomical research units in other places in Spain. A very active Department of Molecular and Infrared Astrophysics is now operational in Madrid, where important R&D activities around ALMA, Herschel and the James Webb Space Telescope instrument MIRI take place. The Instituto de Física de Cantabria, a joint venture of CSIC with the University of Cantabria, is the reference centre for X-ray astronomy in Spain and for microwave background experiments in space, through participation in the ESA missions Planck and XMM-Newton. The Institute for Space Science (ICE), located in Barcelona, is very active in theoretical and observational astrophysics of stars, cosmology (for example, through participation in the Dark Energy Survey (DES) project) and gravitational waves.

The Department of Astronomy and Meteorology of the University of Barcelona is one of the largest and with the longest tradition among astronomy departments in Spain. The research topics covered include galaxy formation, astrometry and the Milky Way, micro-quasars, star formation, supernovae, robotic astronomy and space weather. Similarly, the University of Valencia (UV) also hosts an ample set of astronomers, working on numerical astrophysics, theoretical and observational cosmology and radio interferometry. A further group heavily dedicated to space activities is also very active in Gamma-ray astronomy both from the scientific and instrumental point of view.

The National Astronomical Observatory (OAN), belonging to the National Geographical Institute, one of the classical sites of astronomy in Spain, is now dedicated almost in full to radio-astronomy. Its headquarters are in Alcalá de Henares, near Madrid, and its own observatory is in the Centro Astronómico de Yebes (CAY), province of Guadalajara. Besides its research in star formation, evolved stars and galaxies, the OAN technological work in High Electron Mobility Transistor (HEMT) amplifiers is internationally recognised.

The Universities Complutense (UCM) and Autonomous (UAM) of Madrid encompass also an important number of active researchers. The projects cover a wide range of topics such as observational, theoretical and numerical cosmology, extragalactic astrophysics, star formation, active stars and exo-planets. The two universities, along with other research centres in the area, are collectively engaged in the training of new researchers through a joint PhD programme.

Madrid also hosts the Laboratory of Space Astrophysics and Fundamental Physics (LAEFF), belonging to the National Institute of Aerospace Technologies (INTA), which hosts a number of astronomers conducting research in many topics. Thanks to the INTA premises and support, LAEFF has led an instrument on-board ESA's INTEGRAL mission (the Optical Monitor Camera, shown in Figure 1). LAEFF is the chief node of the Spanish Virtual Observatory and will host the Gran Telescopio Canarias data centre. INTA also shares with CSIC the newly-created Centre for Astrobiology, with growing activity in the fields of exoplanets and exobiology. INTA hosts one of the most important teams of technicians dedicated to building instrumentation for space science payloads.

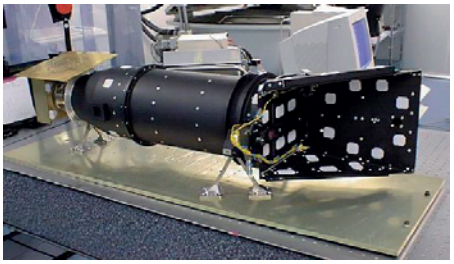

Figure 1: The Optical Monitor Camera (OMC), an instrument led by Spain now on-board ESA's INTEGRAL mission. See *http://www.laeff.inta.es* for details.

Many other places are important for their unique contributions to astronomy. To mention a few (and the list is not complete): the University of the Basque Country hosts a very active group in Planetary Atmospheres; the University of Granada has a group in galactic magnetism and stellar astrophysics; the Polytechnical University of Catalonia group works on white dwarfs and supernovae; the University of Alicante on the physics of collapsed objects and active stars; the historical naval Royal Institute and Observatory is dedicated to astrometric surveys; the University of Santiago de Compostela conducts studies on binary stars; and the University of Alcalá de Henares hosts a group working on solar-terrestrial physics.

Astroparticle physics is another field with growing impact in Spain. In terms of infrastructure (for example, in the construction and operation of the MAGIC Cerenkov

telescope), groups traditionally engaged in high energy physics have taken the lead. The exploitation of these facilities benefits a much wider community, including some active groups in high energy astrophysics. A similar scheme applies to the growing field of gravity waves, where much of the initial effort is being provided by groups traditionally working on relativity theory.

Observatories and facilities

Owing to its privileged geographical situation and to a number of other factors, Spain is home to a number of astronomical observatories where both Spain and other international partners operate their facilities. A list of the most prominent observational facilities is given in Table 1.

The Canary Islands are amongst the best sites around the world for optical ground-based observing. Through international agreements, around 60 institutions from

Table 1: Main observing facilities at Spanish observatories. Those marked with an asterisk are joint national participations with Spain.

Observatory	Facility
ORM	10.4-m Gran Telescopio Canarias*
ORM	4.2-m William Herschel Telescope*
ORM	3.5-m Telescopio Nazionale Galileo
ORM	2.6-m Nordic Optical Telescope
ORM	2.5-m Isaac Newton Telescope*
ORM	2.0-m Liverpool JMU Telescope
ORM	1.2-m Mercator Telescope
ORM	0.18-m Carlsberg Meridian Telescope*
ORM	1.0-m Swedish Solar Tower
ORM	0.45-m Dutch Open Telescope (Solar)
ORM	MAGIC, Gamma-Ray Cerenkov*
OT	1.5-m Telescopio Carlos Sánchez*
OT	0.8-m IAC80*
OT	0.9-m THEMIS (Solar)
OT	0.7-m Vacuum Tower Telescope (Solar)
OT	1.5-m GREGOR
OT	Solar Laboratory*
CAHA	3.5-m Telescope*
CAHA	2.2-m Telescope*
CAHA	1.23-m Telescope*
CAHA	1.52-m Telescope* (OAN)
OSN	1.5-m Telescope*
OSN	0.9-m Telescope*
Yebes	14-m Antenna*
Yebes	40-m Antenna*
Pico Veleta	30-m IRAM Antenna*

Figure 2: Panoramic view of the Observatorio del Roque de los Muchachos (ORM) in the island of La Palma.

Figure 3: The Observatorio del Teide (OT) with the Solar Telescopes THEMIS (right) and VTT (centre) in the foreground.

17 different countries operate their facilities either in the Observatorio del Roque de los Muchachos (ORM) on the island of La Palma (see Figure 2) or at the Observatorio del Teide (OT) on the island of Tenerife (Figure 3). These agreements have been instrumental in the development of astronomy in Spain, since a fraction of the observing time is reserved for Spanish astronomers and a further 5 % is devoted to international cooperative programmes.

The ORM has been, and continues to be, a primary destination for international observational facilities in Europe. The ORM hosts a number of night-time facilities operated by several countries, often through international consortia or ad-hoc agreements. The Very High Energy Gamma-ray Cerenkov facility (MAGIC) is also operational in the ORM (see Figure 4). The Teide Observatory is mostly dedicated to solar observations, but also hosts two experiments to observe the structure of the Cosmic Microwave Background from the ground. A support sea-level facility, the CCALP (Common Centre for Astrophysics in La Palma) has recently opened in La Palma.

The ORM is also the home of Spain's top national astronomical facility, and biggest challenge, the Gran Telescopio Canarias (GTC), shown in Figure 5. This is a 10.4-m segmented telescope being built by a public enterprise called GRANTECAN, S.A. (co-sponsored by the Spanish and Canarian governments) on behalf of Spain and its partners: Mexico (through the Instituto Nacional de Astronomía Óptica y Electrónica and Universidad Nacional Autónoma de México) and the University of Florida. The construction of the GTC is at present in its final stages. GTC is preparing for the first pointing on the sky (first light) with the first six segments of the primary mirror (Figure 6); the secondary (shown in Figure 7) and

Figure 4: The MAGIC Cerenkov ultra-high energy gamma-ray telescope in the ORM. See *http://magic.ifae.es* for more details.

Figure 5: External view of the Gran Telescopio Canarias (GTC) dome.

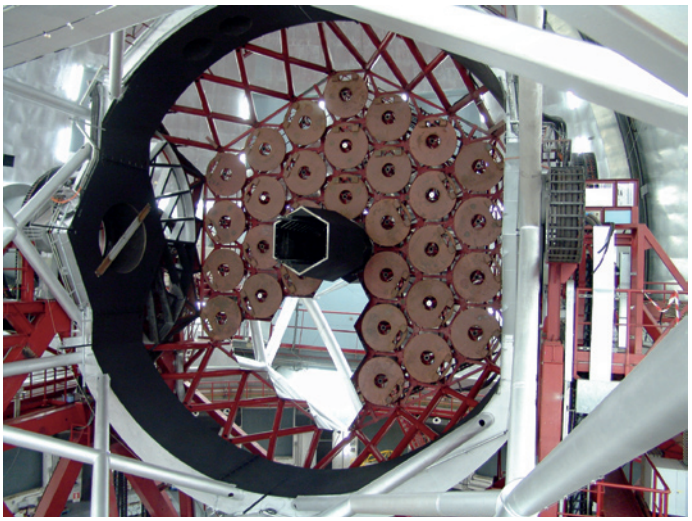

Figure 6: The primary mirror of the GTC with the first six segments already mounted.

Figure 7: The secondary mirror of the GTC, fully aluminised and mounted.

Figure 8: The Centro Astronómico Hispano-Alemán (CAHA) in Calar Alto, jointly owned and operated by the MPG and the CSIC. From left to right: the 2.2-m, 1.23-m (no longer offered), the 3.5-m and the Schmidt (not offered) telescopes. See *http://www.caha.es* for details.

tertiary mirrors are already mounted. First light will be followed by a one-year commissioning of the telescope and the two Day 1 instruments – OSIRIS, an optical instrument led by Spain, and CanariCam a thermal infrared instrument built by the University of Florida – before the start of normal science operations.

The GTC is the first segmented telescope built in Europe. Important high-technology components have been contracted to Spanish and other European industries. This has placed Spain and Europe at the forefront in the capacity to build large segmented telescopes, specifically in some key technologies. Spain is proud that part of the in-kind contribution for the accession to ESO has been agreed in the area of scientific and technological programmes at the GTC. From the technological viewpoint, this will be an important tool for the design and eventual construction of a European Extremely Large Telescope.

The Spanish-German Astronomy Centre (CAHA) is another major asset in terms of infrastructure for Spanish astronomy, and is shown in Figure 8. The agreement for the installation of German telescopes in Calar Alto was signed in 1972, with the first operations carried out in 1976. After years of development from the German side and modest participation by Spain, a new agreement was signed in 2004 between the Max-Planck-Gesellschaft (Germany) and the CSIC (Spain) to share costs, responsibilities and property of the CAHA on a fifty-fifty basis. There are currently two fully operational telescopes with apertures of 2.2 m and 3.5 m,

along with other instrumentation. Nearby the IAA also operates an observatory in Sierra Nevada (OSN) where 0.9-m and 1.5-m telescopes are located.

The Centro Astronómico de Yebes (CAY), near Guadalajara, is the home for the OAN's radio telescopes. The currently operating 14-m antenna will soon be joined by a fully Spanish designed and built 40-m antenna (Figure 9). Operations of this new facility are expected to start early in 2007. OAN is also the Spanish partner in IRAM (along with France and Germany). Besides the millimetric interferometer in Plateau de Bure, IRAM also operates a 30-m antenna in Pico Veleta, not far from Calar Alto and Sierra Nevada, shown in Figure 10.

There are other facilities that have played a very important role in the development of Spanish astronomy. Among others are, the Deep Space Network antennas of NASA at Robledo de Chavela near Madrid (partly used for VLBI radio observations, and available to Spain in a small fraction) and ESA's Villafranca Satellite Tracking Station (popularly VILSPA, now renamed ESAC), which will host the Science Operations Centres of all the new ESA astronomy and Solar System missions.

Computing is also another pressing need in modern astronomy and astrophysics, for which the Barcelona Supercomputing Centre (hosting the Mare Nostrum super computer) is an important asset that devotes a part of its scientific service to astronomy projects. This and other smaller facilities have lent support to increasing activity in numerical astrophysics.

Figure 9: The 40-m antenna being installed in the Centro Atronómico de Yebes (CAY), near Guadalajara. See *http://www.oan.es*.

Figure 10: The IRAM 30-m millimetre antenna in Pico Veleta. *http://www.iram.fr/IRAMES/index.htm*

Funding

The main national funding resource for research teams in Spain stems from the National Plan for Research, Development and Innovation, a four-year plan whose current version will expire in 2007[3]. There are a number of programmes devoted to specific R&D areas. The Astronomy & Astrophysics Programme was created in 2000, its main objectives being:

– Basic research in astronomy and astrophysics
– Design and development of astronomical instrumentation
– Exploitation of available facilities
– R&D in astronomy-related technologies

This Programme is complemented by the Space Programme, where an important ingredient is the development of scientific payloads for astronomy and Solar System missions, and their scientific exploitation.

The National Plan has a number of tools, which range from provision of funding for direct research costs, provision of PhD fellowships and technical trainee contracts, postdoctoral contracts at various levels, and many others. An important tool is funding to 3–5 year projects, which often provides the largest financial contribution to astronomy groups. Project funding is assigned following strict peer-review evaluation and an overall rank decided by a national programme board.

Infrastructures, and particularly what are currently called 'singular scientific infrastructures' (which for astronomy means telescopes or similar), are funded through independent channels and budgeted separately. An Advisory Committee on Singular Infrastructures proposes, evaluates and oversees these at national level.

[3] More information under *http://www.mec.es/ciencia/jsp/plantilla.jsp?area=plan_idi&id=3*.

Productivity

Scientific productivity[4] in astronomy in Spain reflects very closely the development of the discipline. In the 1970s, before the big leap forward, less than 10 papers per year were published in the field. In the first half of the 1980s, the publication rate stabilised at some 40–60 papers per year. It is instructive to see that many of today's main centres of Spanish astronomy are contributing to this success (Calar Alto, Yebes, and several universities), but most remarkable is the contribution from the ESA Villafranca station (and specifically the International Ultraviolet Explorer data). The IAC and the IAA started to dominate the scene in that epoch.

In the second half of the 1980s the publication rate started to increase dramatically. This rise has not stopped and if anything, is growing even faster since 2000. In 2005 the number of publications in astronomy and astrophysics exceeded 600, which is well above 5 % of the total number of publications in this field from around the world. Astronomy and astrophysics is the discipline where Spanish scientists have made their largest contribution, which is on average around 3 %. A direct count of all papers shows that the fraction of papers in the field of astronomy and astrophysics among all scientific production in Spain has gone up from well below 0.1 % in the 1970s to close to 0.2 % in the last decade or so.

Another important product of astronomical research is technological development, through contributions to instrumentation. There is a long tradition in Spain of contributions to ESA's space science missions, in part due to full ESA membership since its foundation and to the existence of a Space Programme, which dates back longer than the Astronomy & Astrophysics Programme. Indeed, a variety of research centres and university departments have contributed, and are contributing, to virtually all important ESA astronomy and Solar System science missions. These are complemented by participation in ESA's Earth observation programme, as well as the Exploration programme, along with some contributions to NASA and other agencies.

In terms of ground-based astronomical activities, the Gran Telescopio Canarias is indeed the greatest technological challenge faced by Spain. Besides the construction and operations of the whole facility, Spain is leading two of the main instruments: OSIRIS, a Day 1 optical multi-object spectrometer equipped with tunable filters; EMIR, a second-generation multi-object near-infrared spectrometer. In addition, ELMER, a back-up first-light optical instrument, has also been built by GRANTECAN. Vigorous activity is now building up to secure a full second-generation instrument complement for GTC.

On a more modest scale, other optical and infrared instruments have been built and are operational in some other facilities. The optical spectrometers ALBIREO on the 1.5-m telescope in IAA's Sierra Nevada Observatory, ALFOSC on the 2.5-m NOT and the infrared instrument LIRIS on the 4.2-m WHT are examples of these developments.

Radio astronomy has also been an active field of instrumental development in Spain. The OAN is currently finishing the 40-m antenna at its Yebes observatory (Figure 9), which is fully designed and built in Spain and will start operations by early 2007. The antenna will be part of the European VLBI Network, where Spanish astronomers had an active role even before this important instrumental contribution was planned. In a collaborative effort between CSIC and OAN, along with other partners, Spain is providing some important items to ALMA, a project that Spain joined prior to the accession to ESO.

The future

Spain has a glowing future in astronomy which is fostered by its accession to ESO. Activity does not appear to stop growing, and, if anything, is growing faster. The most important asset of Spanish astronomy – its human resources – appears to be in good shape, as new generations of highly skilled and enthusiastic astronomers are being recruited. Consolidating these new generations in the R&D system is now one of the major challenges.

Operating, maintaining and exploiting the GTC will continue to be a top priority in Spain. There are plenty of ideas for second-generation scientific instruments accompanying EMIR, which will be the first operational near-infrared multi-object spectrometer. Among them, FRIDA, making full use of the adaptive-optics facility to be implemented at the GTC, is high on the list. We will make sure that GTC stands up as a top-class facility well within the era of the ELTs.

In parallel to the GTC, smaller aperture optical telescopes will play a crucial role in a balanced development. These facilities are far more efficient than larger aperture telescopes in conducting some types of observing programmes and will need to be equipped with the correct instrumentation. Fortunately, Spain shares, or has access to, a number of these 2–4-m-class telescopes (particularly in Calar Alto and La Palma).

The frontier infrastructures for ground-based astronomy after the current epoch are clearly on the scale of a billion Euros. In joining ESO, Spain confirms its full participation in the ALMA project and will work vigorously towards making the European ELT a reality. Spain brings experience from the construction of the GTC and other facilities to this enterprise. It also brings the possibility of placing this E-ELT in our best observatory – the ORM in La Palma. The other key international facility under study, the Square Kilometre Array (SKA), is also a target for Spain.

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[4] All data related to publications has been obtained through ISI's Web of Science, thanks to a subscription funded by the Spanish Ministry of Education and Science and the Spanish Foundation for Science and Technology.

The VLTI AMBER instrument undergoing adjustment.

Photo: H. H. Heyer, ESO