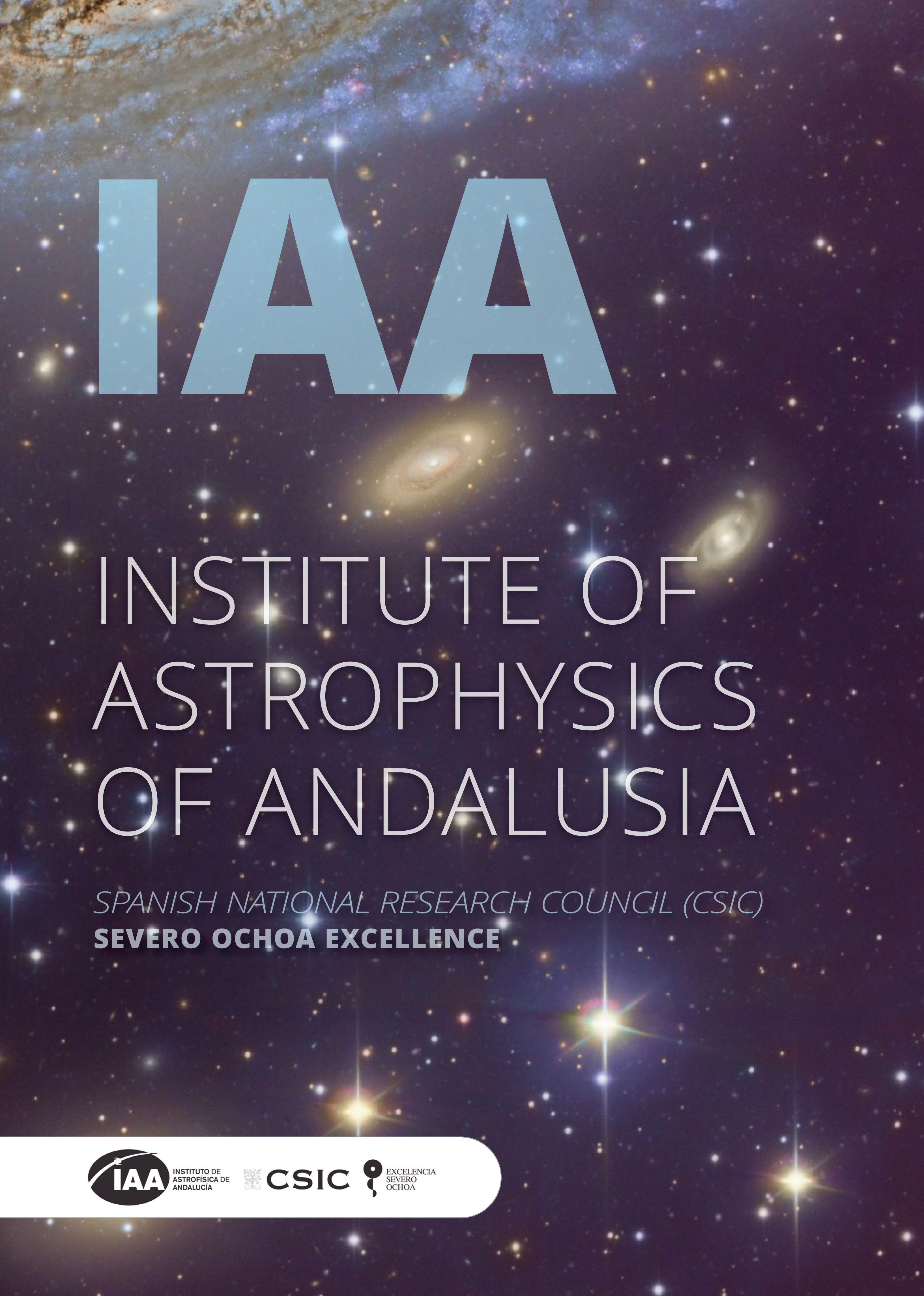


IAA

INSTITUTE OF ASTROPHYSICS OF ANDALUSIA

SPANISH NATIONAL RESEARCH COUNCIL (CSIC)

SEVERO OCHOA EXCELLENCE

IAA INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA   CSIC   EXCELENCIA SEVERO OCHOA

From Granada to the far reaches of outer space

THE IAA'S ACTIVITY COVERS THE MAIN AREAS OF ASTROPHYSICS, RELYING ON THE THREE FUNDAMENTAL PILLARS OF MODERN SCIENCE: OBSERVATION OF ASTROPHYSICAL PHENOMENA, DEVELOPMENT OF NEW INSTRUMENTATION AND THEORETICAL RESEARCH AND DEVELOPMENT OF NUMERICAL SIMULATIONS

Space sciences comprise the study of a great variety of objects and move among blistering distances that go from our own atmosphere, literally hanging over us, to billions of light years away. And even if the first source of information regarding the universe is indeed light, it represents no more than a messenger with many faces. Depending on the different wavelengths we are observing, it is possible to explore different objects: for example, gamma and X-rays reveal information on very energetic objects, such as supernovas or active galactic nuclei (AGN), while infrared takes us to cold regions, like the gas clouds where stars are formed; not to mention a new kind of messenger, that had been predicted for decades but was spotted just four years ago: gravitational waves. Therefore, to obtain a complete overview of the cosmos, it is not only necessary to cover many objects and distances, but also different types of light, and even to design and develop the needed instrumentation to approach the object of investigation. With more than forty years of history and hard work, that started with stellar physics and

Extract from the ALHAMBRA sky map, a survey of more than five hundred thousand galaxies.

an energetic impulse towards technology, IAA is capable today of delivering in all those areas and participating in revolutionary international projects. The Severo Ochoa Centre of Excellence accreditation confirms the outstanding position of the IAA in the national and international astrophysical field; so, in the following pages we will try to disclose some of our work. As it is known, brevity is key in written texts and we cannot list every single project and line of our centre. Despite this, we will try to draft the most comprehensive approach possible.

ATMOSPHERES

In our first stop, we will not move far: it is actually close enough to be breathing it. In the last decade we have experienced a golden age of observation of the Earth's atmosphere, with several space missions that have provided global data for more than one solar cycle, as well as a great advance in the models, which face the climate system as a whole. At the IAA, we work with data from missions such as TIMED (NASA) or ENVISAT (ESA), as well as with Earth instrumentation, paying special attention to the study of the effects of the Sun over the atmosphere: the Sun shows an eleven year cycle with ups and downs on its activity, causing changes on the amount of energy emitted. Known as solar forcing, it is a factor to be taken into account when it comes to climate model simulations. Some studies coordinated by the University of Kiev and the IAA showed in 2017 a higher influence of solar activity on the atmosphere of the Earth, particularly on the stratosphere. This set of data, which also includes the effects of particles and a new estimation of the solar constant (or the amount of the average Sun radiation) was possible thanks to the work of an interdisciplinary team and it can be seen nowadays as the best possible evaluation of the past, present and future solar variability. This will help improve our understanding regarding climate variability on a decade scale and to clearly distinguish the natural processes from the anthropogenic[*1] ones, serving as the base for the next climate report from the Intergovernmental Panel on Climate Change (IPCC).
Earth's atmosphere presents a variety of electrical phenomena known already for some time, such as lightning[*2]. But there are also some others recently discovered, known as transient luminous events (TLEs), a series

LIGHT AS A SOURCE OF POLLUTION

1

NIGHT LIGHTS: A GLOBAL PROBLEM

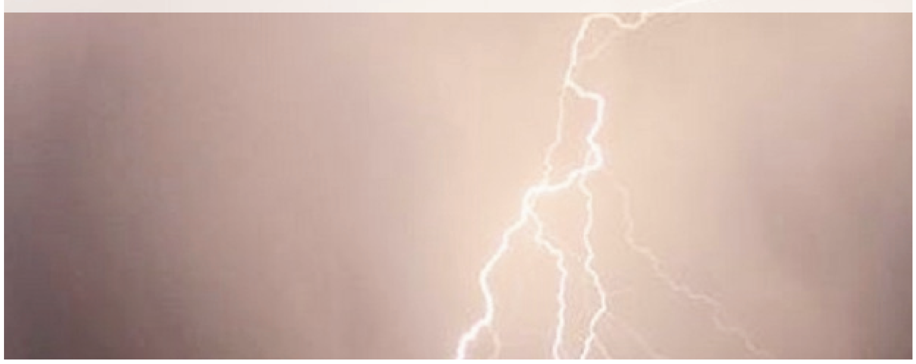
Climate change is one of the factors that shows how human activity is affecting life in the planet. There is another one though: light pollution, and we have just started to acknowledge it. Produced by an excess in night lighting or a wrong lightning, its effects over the astronomic observations have been known since the middle of the 20th century. However, it was not until the beginning of this century when its risks for ecosystems and human health due to the alteration in night and day cycles have been documented: half of Europe suffers from a generalized "night loss".
The IAA has participated in two pioneering studies that analyse the evolution and effects of light pollution. In 2017, a study showed that illuminated surfaces in the planet have an average growth of around 2% a year, despite the launching of more efficient lighting systems, while in 2018 another one proved that the exposure to blue light during the night increases the risk of suffering breast and prostate cancer. This research area came along with the opening of the Sky Quality Office in the IAA, in order to claim the night sky as a scientific, cultural and environmental resource.

E-LIGHTNING

2

AN ERC PROJECT TO UNDERSTAND ATMOSPHERIC ELECTRICITY

Three centuries ago, the electrical nature of lightning was discovered. Although we know that lightning affects the composition of our atmosphere and that it exists in Jupiter and Saturn –also maybe in Venus, Uranus and Neptune– they are one of the most unknown phenomena in planetary science.
It is estimated that, every second, around fifty lightning flashes occur. As they are descending, lightning advances in a series of discontinuous jumps of unknown origin. The reason why lightning flashes emit high energy pulses when propagating has not been understood yet, nor the origin of the phenomenon known as "terrestrial gamma-ray flashes", connected to electrical storms.
With the existing instrumentation it is not possible to solve the space scales that are necessary to investigate these processes. However, the project called eLightning (H2020), coordinated by the IAA, is using advanced computational techniques to reveal the physical processes involved in the advance of a lightning strike with microscopic detailing.

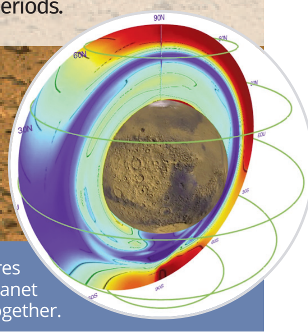


The IAA has participated in a variety of missions, both on a scientific and technological level

3 UPWARDS: UNDERSTANDING PLANET MARS

THE PROJECT HAS REVIEWED AND UPDATED ALL DATA OBTAINED BY MARS EXPRESS AND OTHER MARTIAN MISSIONS

The main goal of H2020 UPWARDS project (2015-2018) was to develop new mathematical techniques in order to collect more information from the available data about Mars, enabling, for example, the combination of a variety of instruments' and missions' data.
Data analysis methods have been designed for the planet's limbo, resulting in vertical profiles of water vapour –a very scarce gas in Mars, although very important– and carbon dioxide –the most abundant gas in the planet. Five years ago, achieving these data was not even imaginable.
At the same time, the project could also look into dust storms. For the first time, an anti-correlation between the atmospheric dust and water vapour amounts inside the storm was found and quantified. Furthermore, a complete mapping including the distribution and the annual cycle of water-ice clouds has been created, which points how important can the role of these clouds be over the annual water cycle. Hydrogen emissions have been measured in the highest layers of the atmosphere when water molecules escape towards the space, and they could be explained thanks to a recent result: high amounts of water vapour could reach great altitudes in the atmosphere of Mars during the dust storms periods.



Crop of a 3D Mars atmosphere image, from the surface up to 200 kilometres (dimensions have been expanded). In the absence of wind, the solid planet and its atmosphere rotate together.

4 THE GIGANTIC "Y" IN THE SKY OF VENUS

"Y" SHAPED DARK CLOUDS IN THE SKIES OF VENUS WHOSE SHAPE AND EVOLUTION WERE INEXPLICABLE

When it was discovered, astronomers thought at first that the Y was a cluster of clouds that had been dragged to its position by the wind. However, in 1973, the data from Mariner 10 mission (NASA) revealed that the structure was travelling as a unit, and that its speed was different compared to its surroundings.
In the end, it was said to be a wave, or a periodic disturbance in the atmospheric variables, but its typology was remained unknown. A study led by the IAA described the underlying mechanism supporting it and even got to reproduce, for the first time, its evolution throughout a month.
The study showed that the Y shape was due to wind distortion, and refuted the hypothesis accepted during decades (which assumed that this wave had similarities with the atmospheric equatorial waves on Earth).

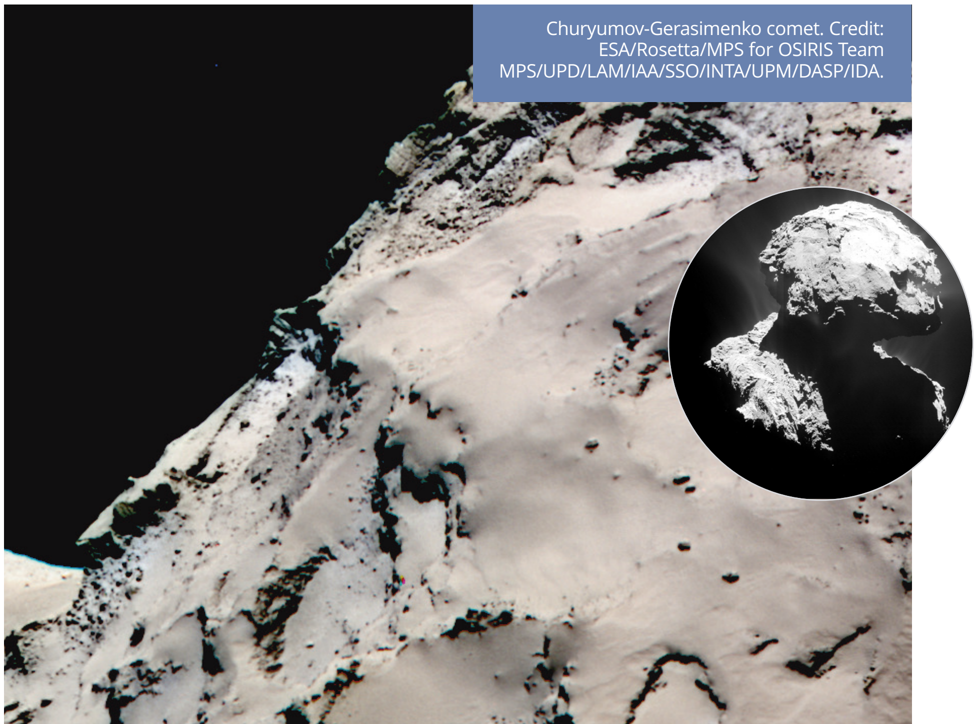
Venus. Credit: NASA

of electrical events related to storm lightning which occur dozens of kilometres above the clouds. It is known that these phenomena have an influence on the chemical composition of the atmosphere, but there are still a lot of unknowns about them. Earth and space investigations are being held at the IAA regarding these phenomena, with the development of our own instrumentation and through our participation in missions such as ASIM, which is carrying out a research on TLEs from the International Space Station (ISS).
Studying our atmosphere naturally leads us to the atmospheres of other Solar System planets, like Mars*3 and Venus*4. But also, to other planets' moons: in 2016, researchers from the IAA participated in the discovery of a unique phenomenon in the Solar System. It showed that the atmosphere of Io, one of Jupiter's biggest moons, practically fades away every time the planet´s shade looms over the satellite. We even reach atmospheres from planets outside the Solar System, that is, extrasolar planets, a recent and very promising field of study that brings researchers of the IAA from different groups together.

TO THE LIMITS OF THE SOLAR SYSTEM

Our Solar System does not have a uniform distribution. The Sun, our star, agglutinates more than 99% of the system's total mass; but there are also four considerably small sized rocky planets (Mercury, Venus, Earth and Mars), four giant gas planets (Jupiter, Saturn, Uranus and Neptune), several

confirmed dwarf planets (Pluto among them), hundreds of thousands of asteroids, more than six thousand identified comets and more than two thousand frozen objects beyond Neptune. Despite the variety, we know our vicinity quite well: the Solar System is 4600 million years old; it was formed from a single gas and dust cloud that started to congregate and rotate until it became a flat disc. In its core, the densest and hottest region, the birth of the Sun occurred. Around it, small gas and dust lumps were created, known as planetesimals, that slowly gathered enough matter to grow as planets; they are rocky in inner and warm regions and gaseous in outer and cold regions. We find an example of this process in what we know today as the asteroid belt, a group of rocky bodies located between Mars and Jupiter that constitute the remains of a planet that could not be formed because of Jupiter's gravitational force. Some other "debris" stayed in the most outer regions of the System, forming the Kuiper belt of trans-Neptunian objects, and much further away, in the Oort cloud, a bubble that surrounds the entire Solar System and may contain millions of comets.
Given its proximity, the study of this complex neighbourhood is approached in a variety of ways at the IAA: for instance, we have participated in Mars Express and Venus Express, ESA space missions that have respectively flown over Mars and Venus; also in Cassini-Huygens (NASA/ESA), where besides flying over Saturn, a lander was released to descend upon Titan, one of its moons; and Rosetta[*5], a pioneer mission that accompanied 67P/Churyumov-Gerasimenko



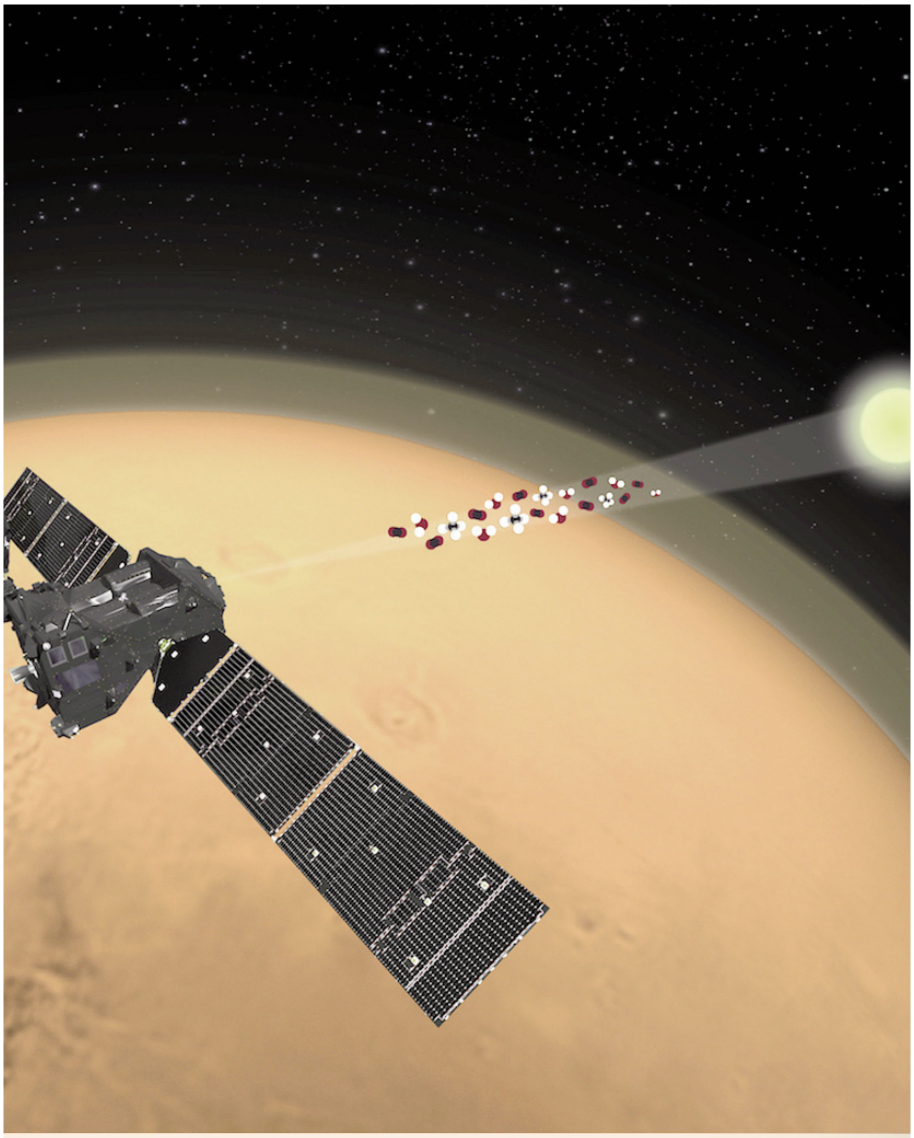
Churyumov-Gerasimenko comet. Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA.

5

67P COMET, CRYSTAL-CLEAR

ROSETTA MISSION ALLOWED US TO GET TO KNOW A COMET IN DETAIL AS NEVER BEFORE

After travelling almost six thousand four hundred million kilometres through the Solar System, Rosetta space probe reached the orbit of its target, 67P comet, in August 2014. For the first time, it was possible to observe in situ how a comet nucleus unleashed its activity and developed the coma –the central nebulous envelope– and the tails, which provide the comets with their characteristic appearance.
This manoeuvre marked a breakthrough in space exploration, but there was more: apart from accompanying 67P on its journey to the inner regions of the Solar System, the spacecraft released the Philae probe that landed on the comet nucleus. It had a rough landing and could not get fixed in the surface, but it did have time to collect samples and send the data before hibernating.
Rosetta's mission became an endless source of surprises: images did not show an irregular and spherical rock, but a bi-lobed shape that reminded us of a rubber duck. Also, the comet awakened –or showed activity– earlier than expected; Philae lander verified that its surface was harder than it was thought –there were concerns about the lander drowning in the loose dust; its seasons were examined, also its ice-water and carbon dioxide cycles, and the comet also showed a surprising variety of structures and textures if we consider its small size.
Thanks to Rosetta, today we know that key components like molecular oxygen and nitrogen, xenon or water are present in comets. This study points out that comets did affect the atmosphere but not terrestrial oceans –or, at least, not much. The mission also revealed a clear sign of glycine existence in a comet (glycine is the only amino acid that does not require a watery environment to be formed) as well as many organic molecules like phosphorus, one of the key elements in living beings. With this, the theory that states that comets nourished the early Earth with crucial molecules that made possible prebiotic chemistry can be supported.
The observations carried by Rosetta indicate that 67P was formed in very cold conditions and that its processing was minimum, confirming its pristine interior and, therefore, becoming an example of how was the nebula material during the Solar System formation.
The IAA participated in two out of the eleven instruments that were on board at the spacecraft: OSIRIS camera and dust analyser GIADA. It also actively participates in the gathering of scientific results from the mission.



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FIRST RESULTS OF EXOMARS (TGO) MISSION: NO METHANE IN MARS

Results were obtained with the ACS and NOMAD instruments

Methane can be of great interest because it can suggest a sign of life existence –on Earth, 95% of atmospheric methane comes from biological processes– or geological processes. It is known that solar radiation destroys methane molecules in a few hundred years, therefore every detection of methane today would mean a recent release, even if it was produced millions or billions years ago and remained trapped in the underground. Besides, global wind circulatory models indicate that methane would be mixed uniformly in the whole planet in just a few months.
The results regarding methane in the Martian atmosphere have been intensely discussed, because detections have been very sporadic in terms of time and location. Actually, many of them have been found very close to the instrument detection limits.
The newest ExoMars results provide the most detailed global analysis so far. They show an upper limit of 0.05 parts per billion volume (ppbv), between ten and a hundred times lower than all previous detections. As an upper limit, 0.05 ppbv still means up to five hundred tons of methane emitted during the three hundred years of useful life-cycle predicted for methane. However, it is a very low value that suggests a global absence of methane in the Martian atmosphere.

Future holds exciting news with BepiColombo and ExoMars missions, travelling to Mercury and Mars

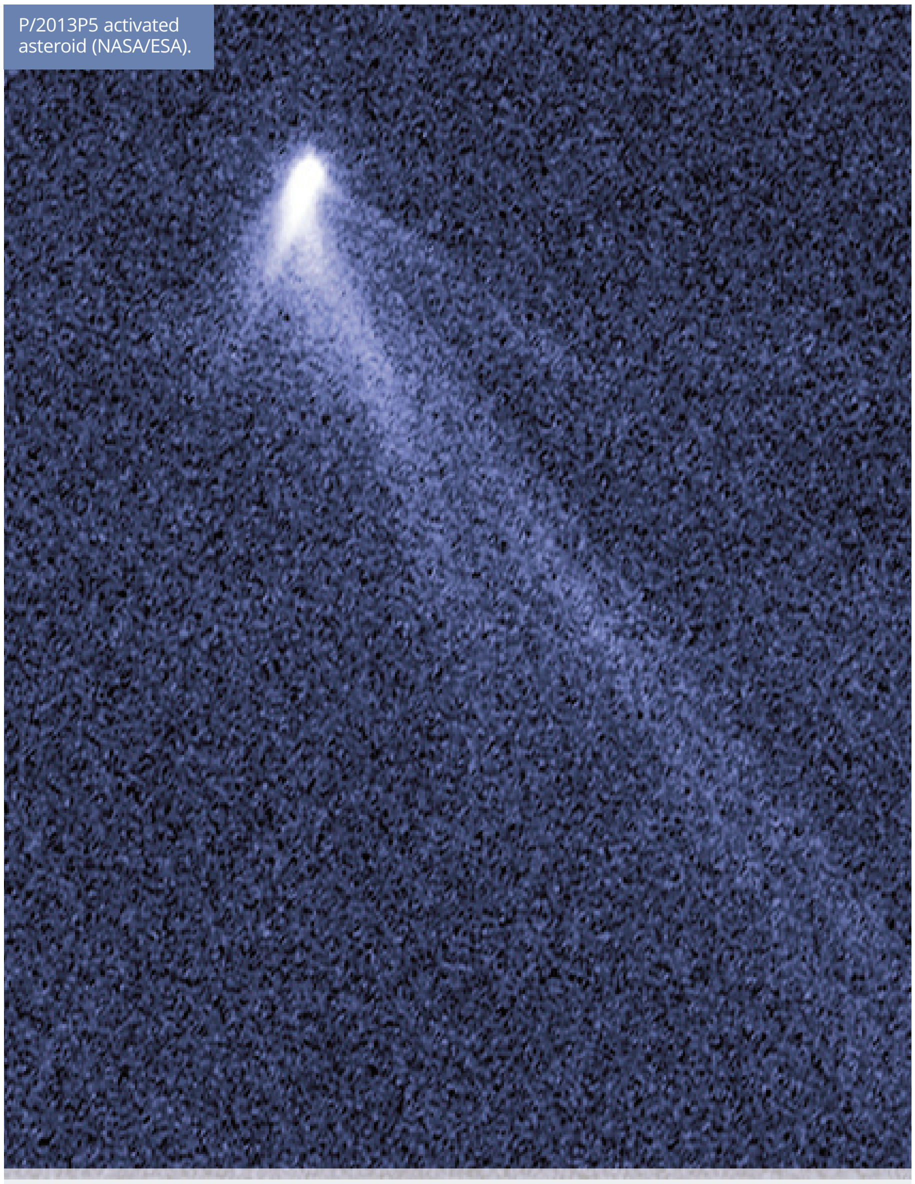
comet on its journey to the inner regions of the Solar System.
The IAA has taken part in them both in their technical dimension and regarding the scientific use of the obtained data. The future upholds exciting news with the BepiColombo and ExoMars, missions that departed in 2016 and 2018 to Mercury and Mars respectively with instrumentation developed at the IAA. As for BepiColombo (ESA/JAXA), which will study Mercury's composition, geophysics, magnetosphere and even the history of one of the least explored planets, the contribution of IAA has focused on the BeLa laser altimeter; and regarding ExoMars, we have participated in the development of NOMAD, a key piece from ExoMars orbital specifically designed for studying methane, a gas produced on Earth mainly by living beings and surprisingly found on Mars in 2004*6.
In a more distant future, we will reach Jupiter's frozen moons: the IAA is the only Spanish institution technologically and scientifically contributing to JUICE mission (Jupiter ICy moons Explorer, ESA), which will be departing to Jupiter on 2022 to study its features and the ones from their main moons in order to analyse the possibilities of life development conditions around the gas giants.
Data provided by these missions are combined with research held in Granada: the IAA has an experimental laboratory dedicated to exploring how dust particles scatter light, an essential aspect for studying both the

planetary atmospheres and the gas and dust cocoon that surrounds cometary nuclei (known as the coma).
The study of the latter, along with asteroids*7 and the frozen bodies beyond Neptune*8 is a research area here at our centre that seeks to understand the history of the Solar System: these objects are the original blocks that, after a great transformation, we see today as so different entities as our solid planet or the airy Saturn, with such a low density that it would float in the sea.
And the Sun, our star, is also being investigated at the IAA: we know about sunspots (or colder regions), we also know that it suffers from violent phenomena –which, besides from being the cause of aurorae , they can interrupt terrestrial communications and even provoke outages– and which have an eleven-year cycle. We are aware that this is caused by its magnetic field, but the way it actually works is still unknown. IAA researchers are studying this solar activity engine and actively participate in missions such as Sunrise or Solar Orbiter (ESA)*9, and also, in the construction of the European Solar Telescope (EST).

STARS: CORE, PULSATIONS AND PLANETS

In 1825, Auguste Comte assured that we would never get to know the stars but as unreachable light points in the sky due to the huge distance that separates us from them. Clearly, he was wrong.
Stars are massive gas spheres –the Sun´s radius is one hundred and nine times the Earth's, given the fact that it is considered an intermediate-mass star– mainly composed by hydrogen and helium. A star generates

P/2013P5 activated asteroid (NASA/ESA).



THE ASTEROID THAT SPLIT IN TWO AND GREW TAILS

7

UNLIKE COMETS, ASTEROIDS ARE NOT CHARACTERISED BY HAVING TAILS, ALTHOUGH THERE ARE EXCEPTIONS

Asteroids from the main belt rotate around the Sun in orbits that are almost circular, so they do not experience the temperature changes that produce comet tails. However, around twenty documented cases in which an asteroid increases its brightness and deploys a dust tail have been documented. Such is the case of P/2016 J1, a peculiar pair of asteroids.
Asteroid pairs are produced when a parent asteroid splits in two smaller ones or when a destabilisation of binary systems occurs. Asteroids that form pairs are not gravitationally bound to each other; they progressively drift away from one another, but they follow similar orbits around the Sun.
A study led by IAA showed that six years ago, the asteroid P/2016 J1 fragmented. The two remaining pieces became the youngest asteroid pair of the Solar System. Additionally, both fragments have been found active, meaning that they show dust structures that resemble comets. It is the first time that a pair of asteroids has been observed with a simultaneous activity. Data suggest that the asteroid fragmentation was produced in the perihelion of the previous orbit.

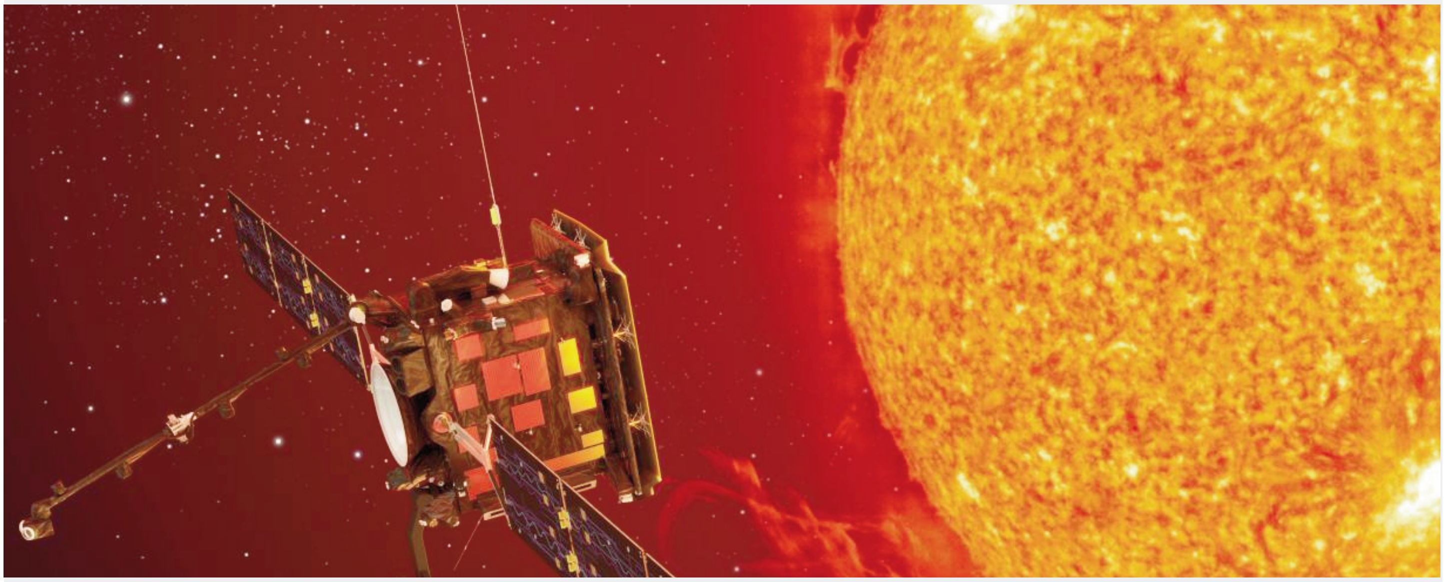
8

THE MINIATURE RINGS OF THE SOLAR SYSTEM

Ring systems: stronger presence than it was thought

Only until around five years ago, it was thought that rings were exclusive features of giant gas planets, like Saturn and Uranus. But finding rings around Solar System bodies other than planets, a study in which IAA notably participated, made necessary reviewing these structures, apparently more common than it was initially thought. In 2013 and 2017, respectively, two bodies from the Solar System joined the list of bodies with rings: Chariklo, the largest object from a group known as centaurs, that can be found between Jupiter and Neptune and have common characteristics with both comets and asteroids; and Haumea, a dwarf planet located beyond Neptune with a similar size –in its largest side– to Pluto. They both have narrow and confined rings, which suggests the existence of shepherd moons, whose gravity would be responsible for keeping them confined like the ones observed around Saturn and Uranus. However, an important difference exists between giant planets and non-planetary objects, as that the latter can show very irregular shapes: they can present reliefs, such as craters or mountains, inexistent in gas planets, or they can show an elongated shape (for example, Haumea's shape is a flattened sphere like a rugby ball). Therefore, these miniature ring system dynamics can be more complex than the ones from giant planets.

Artist's impression of Haumea and its ring. Credit: IAA.



9

AN INSTRUMENT TO MAP THE SOLAR MAGNETIC FIELD

SO/PHI: Solar Orbiter biggest and probably most complex instrument

Solar Orbiter mission (ESA), launched in February 2020, will be rotating around the Sun in an orbit that has a minimum distance similar to Mercury's. This will enable a brand new and unique perspective that will make possible to examine the Sun's poles.

Co-led by the IAA-CSIC, the instrument SO/PHI will accurately map the solar magnetic field, which is responsible for almost all phenomena that we observe in the Sun: sunspots, solar storms or solar wind (a continuous flow of electrically charged particles emanating from the Sun and travelling around the interplanetary space). SO/PHI will also measure plasma speed in the photosphere, the most internal layer of the Sun's atmosphere responsible for solar wind.

SO/PHI is heir to IMaX instrument, which was created in Spain for SUNRISE mission. SO/PHI has been designed for taking images and also for polarimetry and spectroscopy. Furthermore, instead of sending original data, it will do science on board: a device designed at the IAA, with a speed that is equivalent to more or less fifty computers working in parallel, will convert the measurements taken into maps with solar physical magnitudes. Measurements will be erased to release memory and the maps will be sent to Earth.

IAA gathers several recent scientific milestones on exoplanets

energy thanks to the thermonuclear reactions that are produced in its core: hydrogen, its fuel, becomes helium in a process that produces energy. This energy rises to the surface of the star and travels long distances until reaching our eyes.
At the IAA, stars are studied from very different points of view and through different techniques: with photometry, we can measure quite precisely the daily light emission of a star and its possible variations; spectroscopy is a technique that decomposes the light and allows us to study the composition, temperature or rotation speed of stars; and last but not least, with asteroseismology we can calculate the oscillations that take place in the surface of stars, a phenomenon that is similar to earthquakes, but caused in this case by the gas movement in their cores. CoRoT international mission, in which IAA was involved, used this technique, making possible the study of the stars´ inner structure. A pioneer in asteroseismology studies, CoRoT also focused on seeking planets beyond our Solar System. In this field, CARMENES[*10] and PLATO[*11] took over in the IAA, obtaining several scientific breakthroughs: in 2016, a rocky planet was found around the closest star from the Sun, Proxima Centauri. Located in the star's habitable zone, that is, the region where conditions allow the existence of liquid water, the planet Proxima Centauri b has a minimum mass equivalent to 1.3 times the Earth's, and the orbit around its star lasts 11.2 days at a seven million kilometres distance. This distance only represents 5% of the one existing between the Earth and the Sun, but Proxima is colder than the Sun, so its habitable zone can be found much closer in

CARMENES: DETECTING EXOPLANETS AND STUDYING ATMOSPHERES

Terrestrial planets from Calar Alto Observatory

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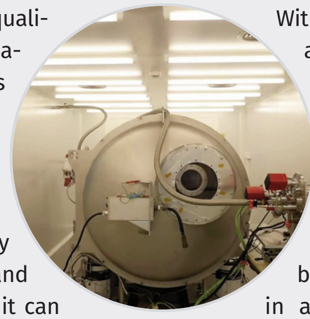
CARMENES, a high-resolution spectrograph co-led by the IAA and installed in Calar Alto Observatory (Almeria), is a unique instrument in terms of stability and precision: essential qualities if the objective is to measure small speed variations provoked by a planet on the stars.
Actually, it consists of two instruments in one, because it simultaneously observes in the visible and the infrared. By doing so, it can perform direct planet detections avoiding false positives. The effectiveness of this method has already been proven, allowing a collaboration with TESS mission (MIT-NASA), one of the most important projects nowadays in terms of exoplanet search.



With more than three thousand and eight hundred extrasolar planets spotted so far, the next step will be focused on describing their characteristics and getting to know these worlds in detail. And CARMENES is becoming a leader instrument in atmospheric studies, partly because of its infrared channel (CARMENES-NIR), a reference across the world that was developed at the IAA.

Artist's impression of a planet around Proxima Centauri, the closest star to the Sun. Credit: ESO/M. Kornmesser.

PLATO, A MISSION LOOKING FOR HABITABLE EARTH ANALOGUES

Planetary transits and stellar oscillations

11

Plato (ESA) will be focused mainly on the search for planets of the size of the Earth or larger (what is known as "super-Earths") which orbit stars similar to the Sun in the habitable zone. It will also go through stellar oscillations, which are produced by the gas movement inside the stars and allow us to know their internal structure. Also, they help determine essential parameters like their density, composition or inner dynamics.
The mission will consist of a group of twenty-six telescopes bringing enough precision to find planets that are smaller than Earth, located at a similar distance than the one between our planet and the Sun. These telescopes could be combined in a variety of ways, working as a unique eye or divided in groups. PLATO will be equipped with the biggest camera equipment ever sent to space: eighty million pixels altogether.
This mission will mark a milestone in Spanish technological participation when it comes to European space missions. Particularly, the IAA will be responsible –along with the University of Granada– of designing and building the main electronic unit of the mission.

comparison to our star. Also, in 2018, a cold Super-Earth was discovered orbiting Barnard's star, the second closest star system. Both discoveries have been spotted in low mass red stars and in the Sun's vicinity, which constitutes an impulse to continue the search for exoplanets around our stellar neighbours.
In the IAA, theoretical tools are also developed to help understand the observations, focusing on specific aspects such as the star rotation, its oscillations, evolutionary state or even the characteristics of its atmosphere*12.

INTERSTELLAR MEDIUM AND BIRTH OF STARS

What happens in the gap among stars? One may tend to think that it is an empty space. Even if it can be an extremely tenuous environment, the interstellar medium –constituted by gas and a small percentage of dust– is key to understand how galaxies work. Its importance is such that it would be hard to imagine the life cycle of the stars without it.
Stars are formed in molecular clouds, highly dense regions found in the interstellar medium, and are actually responsible of enriching it. By means of the nuclear reactions that are produced in their core, stars generate increasingly heavier elements, and when they die most of their mass is released. This process enriches the medium and generations of stars emerge. From the very beginning, and the same occurs with the Sun, they already feature heavier elements than hydrogen and helium, components of the first generations. At the IAA, we study the life cycle of stars, paying special attention to the first and last stages, during which their interaction with the environment is especially significant.
First stages usually take us to those periods in which stars are not shiny yet: protostars. They grow by accreting gas from the parent molecular cloud through a surrounding rotating disk. At the same time, these stellar embryos release the spare material via two jets that emerge from the poles. According to a recent study coordinated by IAA, these jets could induce the birth of a star in the neighbourhood: the impact of the jet material travelling at high speed could generate instability in other molecular cloud regions and trigger the birth of another star.
Star formation necessarily makes us think about planet formation. During recent decades, thousands of planets around other stars have been discovered, showing the great diversity in planetary systems*13 and challenging our understanding of how a

12

LANDMARK STUDY: THE ATMOSPHERE OF AN EXTRASOLAR PLANET

It triggers the detailed study of chemistry in exoplanetary atmospheres

WASP-19b can be considered very exotic considering it has a slightly higher mass than Jupiter's, but it is 40% bigger –which places it almost in the range of low mass stars. It is the giant planet with the shortest orbit period we know: it rotates around its star in less than nineteen hours and it is estimated that its atmosphere temperature reaches a thousand and seven hundred degrees Celsius.
When WASP-19b passes in front of its star, the light of the star goes through the planet's atmosphere, causing small changes. An accurate analysis of that light makes possible to isolate the trace of the chemical elements that compose the planet's atmosphere. By doing so, small quantities of titanium oxide, water and sodium could be found, as well as a sort of haze that covers the planet. The presence of titanium oxide in the atmosphere of WASP-19b may have substantial effects over the structure and circulation of the atmospheric temperature. This study, in which IAA took part, opens up the detailed analysis of atmospheric chemistry in extrasolar planets.

Artist's impression of WASP-19b. Credit: ESO/M. Kornmesser.

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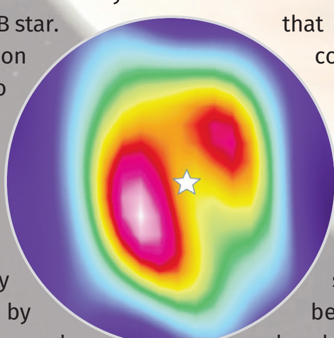
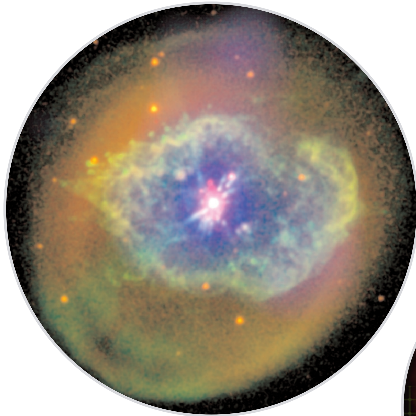
A MINIATURE PLANETARY FORMATION DISK

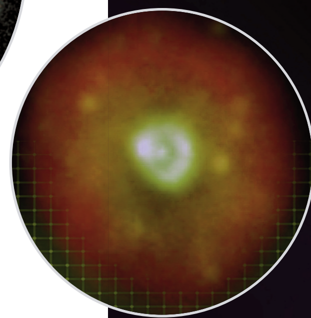
It could reveal real-time planet formation

Led by IAA researchers, this discovery took place around XZ Tau B star. With less than five million years of age, it is still so young that it has not finished its contraction process yet. This young star is surrounded by a gas and dust disk which presents a central cavity that seems to be created by protoplanets orbiting around the star. With a size dozens of times smaller than our Solar System, the disk around XZ Taub B confirms the models that indicated that dwarf disks could be formed. It also fits with the finding of Kepler satellite of extremely compact planetary systems.



Due to its small size, the evolution of the disk surrounding XZ Tau B will be between fifty and five hundred times faster than in bigger systems, that is why it can be studied as it evolves.





Below, HuBi1. Left, Abell 78 (XMM-Newton and NOT telescopes).

planet is formed. Searching for gas and dust disks around young stars, which represents the origin of planetary systems, is of great importance to explain the observed new worlds. As a relatively recent research field, at the IAA its approach is interdisciplinary, meaning that it includes experts in protoplanetary disk formation, stellar physics and Solar System. This collaboration has found one of its key objectives in Proxima Centauri: observations performed with ALMA interferometer, located in Atacama Desert (Chile), revealed in 2017 the emission of cold dust clouds around the star. Part of this material is distributed in a belt few hundred million kilometres away from it, and some signs were found with regards to the existence of a second belt ten times further and much colder than the first one. It is the first evidence of an existing complex planetary system around the Sun's closest star, with a substantial history on interactions that led to the formation of one or several dust belts. Deeper research will provide more information to spot the location of possible unidentified planets.

DEATH OF STARS

During their formation, stars take the material they need from the interstellar medium until the core reaches the optimal temperature to trigger nuclear reactions. Then, they start shining. This is considered the beginning of their adult stage, whose duration depends on the time spent until the star consumes all the hydrogen. Eventually, this depends on its mass: a intermediate-mass star like the Sun would live around ten thousand million years on this stage, while a star with a mass ten times bigger than the Sun would only last a hundred million years. When hydrogen is consumed, the star begins to collapse by its own weight, a process that warms up the external layers, which become expanded. Thus, the star increases its radius and the red giant stage starts, a moment in which their stories diverge.

When it comes to intermediate mass stars, helium starts to burn in the core, while the envelope dilation continues until the core loses control over it and it expands freely in space. The core, a very hot white dwarf star, produces ultraviolet radiation and a stellar wind. When these elements interact with the envelope material, light is emitted. This is how an astrophysical phenomenon of great beauty is created: a planetary nebulae (PNe). All stars that have less than ten solar masses (including the Sun) end their lives as planetary nebulae. However, we still do not know many details of this brief but relevant final stage: in 2015, a research coordinated by IAA showed that this scenario, conceived as a smooth process, could present explosive components. At the same time, IAA researches have brought to light some processes in the death of intermediate mass stars that imply their "rebirth"[*14].

But what happens with massive stars? We now reach an explosive field that implies an enormous release of energy: supernovae. Stars with more than eight solar masses do burn heavier elements after consuming hydrogen, creating a structure that can be compared to an onion: the most external layers hold hydrogen and helium, and as it gets closer to the star core, carbon, nitrogen, oxygen and increasingly heavier elements

REBORN STARS

14

Some planetary nebulae follow different evolutionary paths

Abell 78 was formed like any other planetary nebulae. However, at a certain point, the helium fusion at one of its layers turned on, provoking the ejection of part of the material and such a great expansion that the star came back to the red giant stage. After this second phase of red giant, it came back to contraction and started to emit a stellar wind traveling at great speed. The material ejected during the "first death" was then swept away by this wind and ionized by its UV radiation. Also, some lumps with radial shape have been observed emerging from the central star.

As for HuBi1, it may look like a typical double-shell planetary nebula, with a diffuse outer gas envelope and a bright inner shell. However, a study led by the IAA revealed an inverted ionization structure whose inner region –colder than the external one– defied basic thermodynamic laws. It actually pointed to a peculiar episode in its evolution: HuBi1 central star, instead of progressively turning off, was brought back to life thanks to a late thermal pulse that burned the helium from its surface.

HuBi1 has been caught at the exact moment when its central star underwent a born-again event, becoming a hydrogen-poor [WC] star. About 15% of planetary nebulae so far discovered have [WC] central stars, but their evolutionary path had remained unidentified until now. This brief born-again process ejected large amounts of fast-moving highly processed material, which now interacts and shocks the outer nebula to produce the observed double-shell morphology.

are found. Even iron. The stellar core will not burn any iron, therefore the star stops producing energy and the external layers collapse, provoking an explosion so bright that it may compete with the light intensity of its own galaxy. This generates two equally extreme objects: a neutron star or a black hole. They both represent posthumous versions of the stellar core and show extreme densities – when it comes to black holes, density is so high that not even light can escape from their gravitational attraction.

At the IAA, we study these explosive phenomena individually[*15], along with their collective influence in the environment[*16]. But we also deal with another phenomenon that is associated to the most intense versions of supernovae: gamma-ray bursts (GRBs). They consist of intense gamma-ray flashes that can last from a hundredth of a second to several minutes, and they are as unpredictable as sneaky. However, the combination of observing with big ground-based telescopes, satellites and robotic telescopes -such as the ones from BOOTES network, managed by IAA-, is starting to shed light to a phenomenon that was one of the biggest astrophysical enigmas fifteen years ago.

We know now that short GRBs are produced most likely by the merging of two neutron stars[*17], while the long ones are due to the collapse of massive stars: when the core collapses, it generates a black hole or a neutron star. At that time, two polar jets are ejected, drilling the external layers of the stars. When they get to the surface they produce the GRBs. Hereafter, the hypernova explosion takes place, and it is dozens of times more intense than a supernova. Published in 2019, a research coordinated at the IAA contributed with a key piece to complete the

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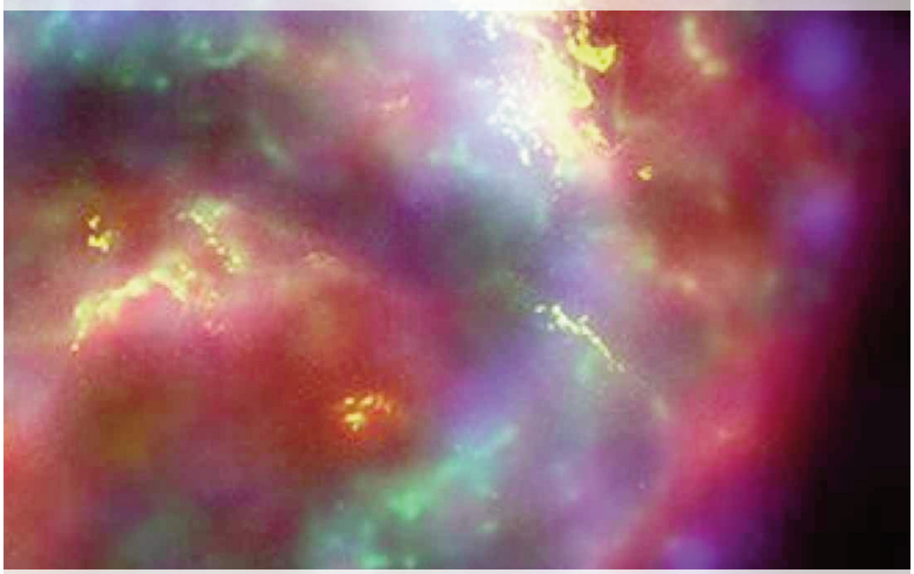
SN2015BH: AN "IMPOSTOR" SUPERNOVA?

An explosive event could refer to a supernova or a giant eruption anticipating an evolutionary change

Luminous blue variable stars show two different kinds of eruptions: regular outbursts after which the star returns to its original state and giant eruptions which alter the star permanently. A prominent example is Eta Carinae, a star which has already lost mass equivalent to 40 times the mass of our Sun through winds and eruptions.

Some stars suffer even larger outbursts that very much resemble real supernova explosions. The dividing line between those impostor supernovae and real ones is still a matter of debate. The case of SN 2015bh is a good example for this difficult decision about whether the explosion has ended the life of the star or not. In fact, the evolution of SN 2015bh turns out to be basically a carbon copy of SN 2009ip, a famous example of a supernova impostor that took place in 2012 whose fate is still highly debated.

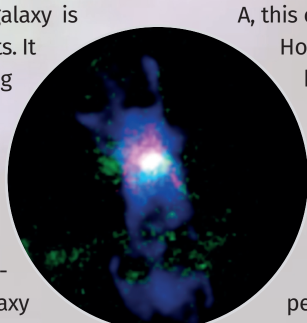


16

GIGANTIC GAS FLOW GENERATED BY SUPERNOVAE

Arp 299-A galaxy, which is in the process of merging with another galaxy, is notable for its intense starbursts and its high rate of supernova production

At the IAA, we have been researching this galaxy for years, which due to the interaction with the companion galaxy is generating intense starbursts. It is, therefore, very interesting because it allows us to study almost in real time how stars are born, die and interact with the surrounding environment.



In fact, one of the most interesting features of this galaxy is, precisely, its high rate of supernova production, the result of the death of stars with more than eight times the mass of the Sun: if in a galaxy such as the Milky Way a supernova is expected every fifty years, it is estimated that in Arp 299-A, this occurs around one per year.

However, the discovery of a huge material outflow has come as a surprise: it extends over 9000 light years and releases a minimum of ten solar masses per year at a speed of between 370 and 890 kilometres per second. The research team discovered that it is the activity generated by stars –mainly by supernova explosions– the responsible for this structure.

At the IAA we study these explosive phenomena individually and also their collective influence in the environment

narrative that connects hypernovas to GRBs, when observing a hot cocoon formed around the jet: the jet transfers a considerable amount of its energy to the cocoon, and if it gets to drill through the progenitor star the gamma-ray emission will take place. However, the jet can fail to pierce the external layers of the star and never emerge into the circumstellar medium if it lacks the necessary energy. In this particular circumstance, a hypernova and not a GRB is produced.

TO THE CORE OF GALAXIES

So far, we have examined stars as individual entities, but if any context should be added it would have to be focused on how stars gather together. Besides the formation of binary or multiple systems, two types of basic stellar groupings exist: on the one hand, open clusters are filled with young and hot stars; on the other hand, globular clusters can gather millions of stars together, though cold and old in this case. Additionally, a look on even bigger stellar societies would take us to galaxies, bound systems of stars, gas and dust that remain together thanks to gravity (it should be clarified that this stands for a very, very brief definition; if we would go into specifics, there is also dark matter, magnetic fields, supermassive black holes, different types of

FIRST SIMULTANEOUS STUDY IN LIGHT AND GRAVITATIONAL WAVES

17

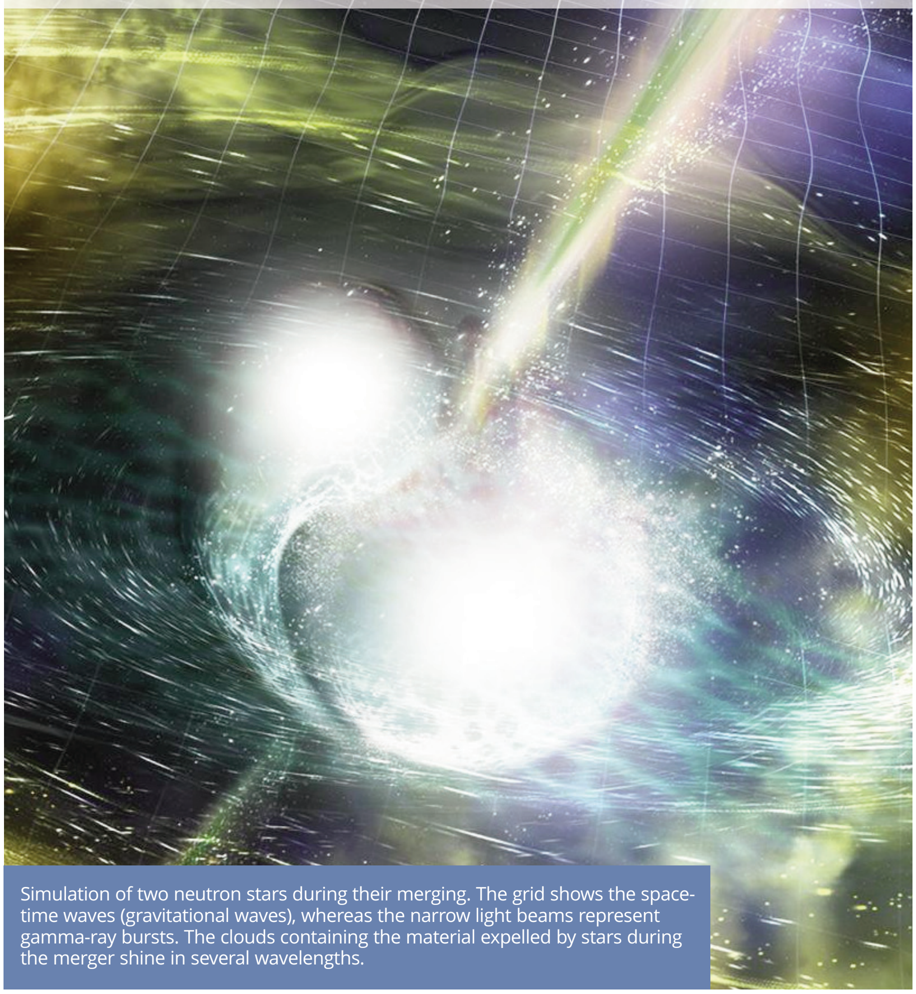
The fifth detection of gravitational waves, but the first in which the counterpart in electromagnetic waves is located and studied

After centuries of studying the universe in electromagnetic waves –what we call light–, the detection in 2015 of gravitational waves opened a new window to the cosmos. The origin of this new emission was found in the merging of two black holes, objects that do not emit light and can only be studied through their gravitational force.

In 2017, an international study in which IAA took part allowed for the first time to observe an object in light and gravitational waves: a merging of two neutron stars that inaugurated a new era in the observation of the universe.

The discovery and study of both the gravitational waves and light of this phenomenon has revealed many of the physical processes involved and established a unique body of knowledge of a celestial object: gravitational waves have revealed the mass, rotation, distance and position in the sky, while electromagnetic waves have allowed to study its surroundings (an aging galaxy that possibly merged with another in its recent past), as well as the hydrodynamics and the formation of elements in the ejected material.

Another group of researchers, also with the participation of the IAA, followed this phenomenon during two hundred days. They confirmed that, after the fusion, a jet of particles drilled the cocoon and travelled at almost the speed of light. This jet showed as much energy as the one produced by all the stars of our Galaxy in an entire year. The study suggests that more than 10% of these mergers should produce similar jets.



Simulation of two neutron stars during their merging. The grid shows the space-time waves (gravitational waves), whereas the narrow light beams represent gamma-ray bursts. The clouds containing the material expelled by stars during the merger shine in several wavelengths.

galaxies –spiral, elliptical or irregular, each one with very specific features–, which can be young or old, or disturbed due to the interaction with other galaxies, etc.).
Our Milky Way is a spiral galaxy that contains between a hundred billion and four hundred billion stars. It is part of the galaxy group called Local Group, which also includes Andromeda and thirty other smaller galaxies. Its interaction with nearby galaxies provided the undeniable clue to clarify its origin: the Milky Way was formed by the merging of several dwarf galaxies; and it is not on a stable and isolated stage, it is still "under construction". The big evidence was found in 1994, hidden behind the dense central regions of the Milky Way: it is the Sagittarius dwarf galaxy, which revolves around the Milky Way and, it is believed, will not survive another orbit and will merge with it in about 750 million years.
Astronomers from the IAA are studying the stellar populations of the Milky Way and they take part, for instance, in Gaia (ESA), a satellite that will conclude its mission gathering data from a billion stars to create the most complete Milky Way 3D map ever done.
Gaia will shed light to the history of our Galaxy from its origins to its stage today. But in order to obtain a full image of it, it will be necessary to also study what cannot be seen: 26000 light years away from Earth, at the centre of the Milky Way, we can find Sagittarius A* (SgrA*), a supermassive black hole whose existence was proposed thirty years ago but which was not confirmed until the end of last century[*18]. Astronomers observed that there were stars orbiting the galactic centre at a speed of 1500 kilometres per second (fifty times faster than the speed of Earth orbiting the Sun), and only the gravitational force of a black hole could retain these stars in their accelerated orbits.
It is estimated that, during its life, SgrA* has absorbed an amount of matter equivalent to more than two million Suns. Despite this fact, it is considered a dormant black hole, which leads us to a type of objects that changed the way of understanding galaxies: active galactic nuclei (AGNs). Here, we are speaking about galaxies whose energy –much higher than the one their stars can produce–, is concentrated in the central region or nucleus.
Our knowledge about AGNs represents a nice example of the advances in scientific understanding. Throughout the last century, there were many discoveries of "peculiar" galaxies. In the 1940s, Seyfert galaxies were found, presenting a very bright and compact

At the background, central regions of the Milky Way (NASA/ESA). On the right, the position of the closest stars to Sagittarius A* -central star- (Keck/UCLA Galactic Center Group).

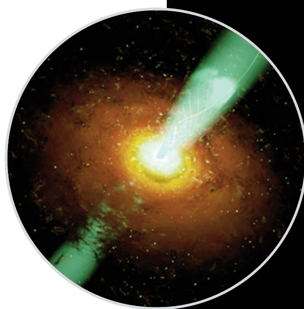
18

GALACTICNUCLEUS: CUTTING-EDGE STUDY AT THE IAA ABOUT THE GALACTIC CENTRE

The environment of SgrA*: an astonishing Astrophysics lab

The centre of the Milky Way is the only galactic nucleus and the most extreme astronomic environment that we can observe in a milliparsec scale (more or less twice the radius of influence of the Sun, a very short distance in astronomy). This precision allows the individual study of stars at the galactic centre. This would be impossible in the case of other galactic nuclei: we can only analyse the diffuse light of thousands of sources not resolved individually.
Therefore, the central region of our galaxy constitutes an essential laboratory to investigate galactic nuclei and their role in the evolution of galaxies. However, we still do not have enough data to examine the stellar composition of the galactic centre: it barely covers one percent of the projected area. Almost every study has been focused on the closest environment to Sagittarius A*, the densest and most energetic region and the one that has the highest rate in terms of star formation.
GALACTICNUCLEUS project (ERC) seeks to resolve open questions by increasing in more than a hundred times our current knowledge about the star population surrounding Sagittarius A* in a radius of between one and a hundred parsecs (a parsec is equivalent to 3.26 light years). has allowed to unravel the history of star formation in the galactic center and detect what was possibly its most energetic episode: a burst of star formation that produced more than one hundred thousand supernova explosions.

Decades of investigation led to a model that grouped these peculiar galaxies, implying the existence of a black hole of hundreds of thousands million suns



core and signs of gas moving at great speeds. From the 1950s onwards, radio galaxies were studied for the first time; apparently normal galaxies, they show a very intense emission in radio on both sides of the core. In 1960, the first quasar was spotted, an object previously seen as a "faint blue star" but that turned out to be a monstrous energy source located three thousand light years away. Finally, at the end of the 70s, it was found that some objects that had been previously categorized as variable stars were instead very luminous and distant active galaxies: BL Lacertae[*19].

Decades of investigation led to a model that grouped all these objects, involving that a black hole of hundreds or thousands of million suns does exist at the centre of the galaxy. It is the matter found around the black hole the one that, in its downfall, releases large amounts of energy. Beyond that, we can find gas clouds moving very fast and a dust and gas structure with the shape of a toroid (or a doughnut) surrounding the object. In some cases, around 10% of AGNs, two jets emerge from the core and travel close to the speed of light, in a direction more or less perpendicular to the toroid plane.

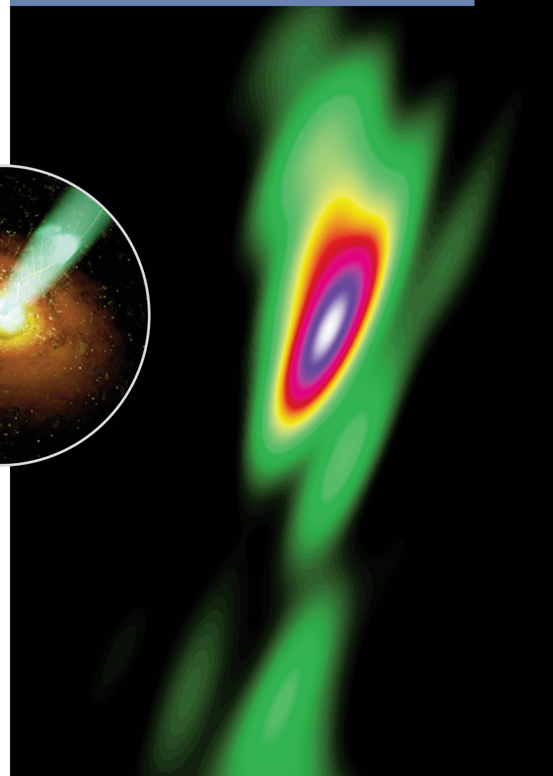
At the beginning of the 21st century, it was confirmed that all galaxies with similar masses to that of the Milky Way or larger host a supermassive black hole at their centre[*20]. Furthermore, even though the sizes we are speaking about may be completely different, the mass of this tremendous black hole is related to the central mass of the host galaxy. This points to a connection between the formation process of a galaxy and the black hole, and seems to have a lot in common with the evolution of the universe, given that the most active period of stellar formation coincides with the peak level in terms of universe activity.

However, it is important to understand which are the conditions for a galaxy to be active (or not, like the Milky Way and many others). We know that the galaxy merging processes can feed the black hole and generate very intense bursts of star formation. Also, we know that those processes generated by the black hole can affect its own galaxy through winds altering the regions they cross, whether inhibiting or increasing the star formation. Hence, the study of active galaxies allows us to discover an important aspect of the evolution of galaxies.

But why do we observe one kind or another of active galaxies? To a large extent, it is due to orientation: depending on its position towards us, the toroid will show or hide the central part of the galaxy, where energy is produced. The jets, likewise, can appear to us in an amplified or weakened way depending on whether they point at us or at somewhere else. In general, it is a scheme that offers good results, but the need to add other factors in each individual case cannot be ignored. For instance, features like the toroid specific characteristics, the mass of the black hole or its matter accretion efficiency should be taken into account, since they will determine how active an AGN can be.

From the most powerful active nuclei, quasars, to the ones showing a lower brightness, at the IAA we are dealing with all sorts of them. As for the first ones, we have found that in addition to distant and very energetic quasars, which evolve rapidly and are associated with large galaxy mergers, there is a quasar population that evolves at a

At the background, an image from the galactic nucleus (MPIfR/A. Lobanov). On the left, artist impression of an AGN (Wolfgang Steffen, UNAM).



THE HIGHEST ANGULAR RESOLUTION IMAGE IN ASTRONOMY

19

IT REVEALS THE INSIDES OF AN ACTIVE GALACTIC NUCLEUS

Since 1974, the technique known as very-long-baseline interferometry (VLBI) allows many geographically spread radiotelescopes to work at the same time. They act like a telescope whose size is equivalent to the largest separation between them. This technique has provided images that deliver a resolution that was unconceivable some time ago. They are one thousand times better than images from the Hubble space telescope.

In 2016, an international collaboration broke all records by combining fifteen radiotelescopes on Earth and the radio dish of the RadioAstron mission (Russian Space Agency), in orbit around Earth. The work, led by the IAA-CSIC, provides new insights into the nature of active galaxies, where an extremely massive black hole swallows surrounding matter while simultaneously shooting out a pair of jets of high-energy particles at nearly light speed.

much slower rhythm. As for the less powerful active nuclei, which are most of them, our multi-frequency study brings us the possibility of analysing whether the scheme generally used for the most powerful active nuclei (including supermassive black holes, accretion disks and toroids) should be modified, since the toroid disappears on these low brightness conditions. We also investigate, in all sorts of active galaxies, the conditions needed to turn on the activity in galactic nuclei (or the factors provoking that supermassive black holes leave their dormant stage), as well as the role played by nuclear activity and the surroundings in the evolution of galaxies.

BILLIONS OF GALAXIES

We have just finished the previous section with a key concept in astronomy: the evolution of galaxies. At the IAA, our approach comprises several perspectives. One is designing projects that enable large-scale research: at the IAA, two large galaxy surveys were conceived, both of them developed from Calar Alto Observatory. ALHAMBRA survey has identified, classified and calculated the distance of more than half a million galaxies distributed in eight sky regions, making possible to outline the evolution of the universe in the last ten thousand million years (J-PAS project, heir of ALHAMBRA, will continue in this line studying tens of millions of galaxies). In parallel, in CALIFA, a 3D spectroscopy method was used to obtain the complete history of stellar formation in each one of the regions out of six hundred galaxies. With this, it could be proved that galaxies grow inside out and that the massive ones grow faster. Also, the way in which the chemical elements needed for life existence are produced inside the galaxies was analysed. Conceived as a legacy project, CALIFA data have accumulated more than thirty thousand downloads that have led to many scientific articles and PhD theses.
Although we may have an idea on how galaxies were in past times –the IAA has actually participated in milestone findings in distant galaxies, meaning very young ones– it

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FIRST EVER PICTURE OF A BLACK HOLE

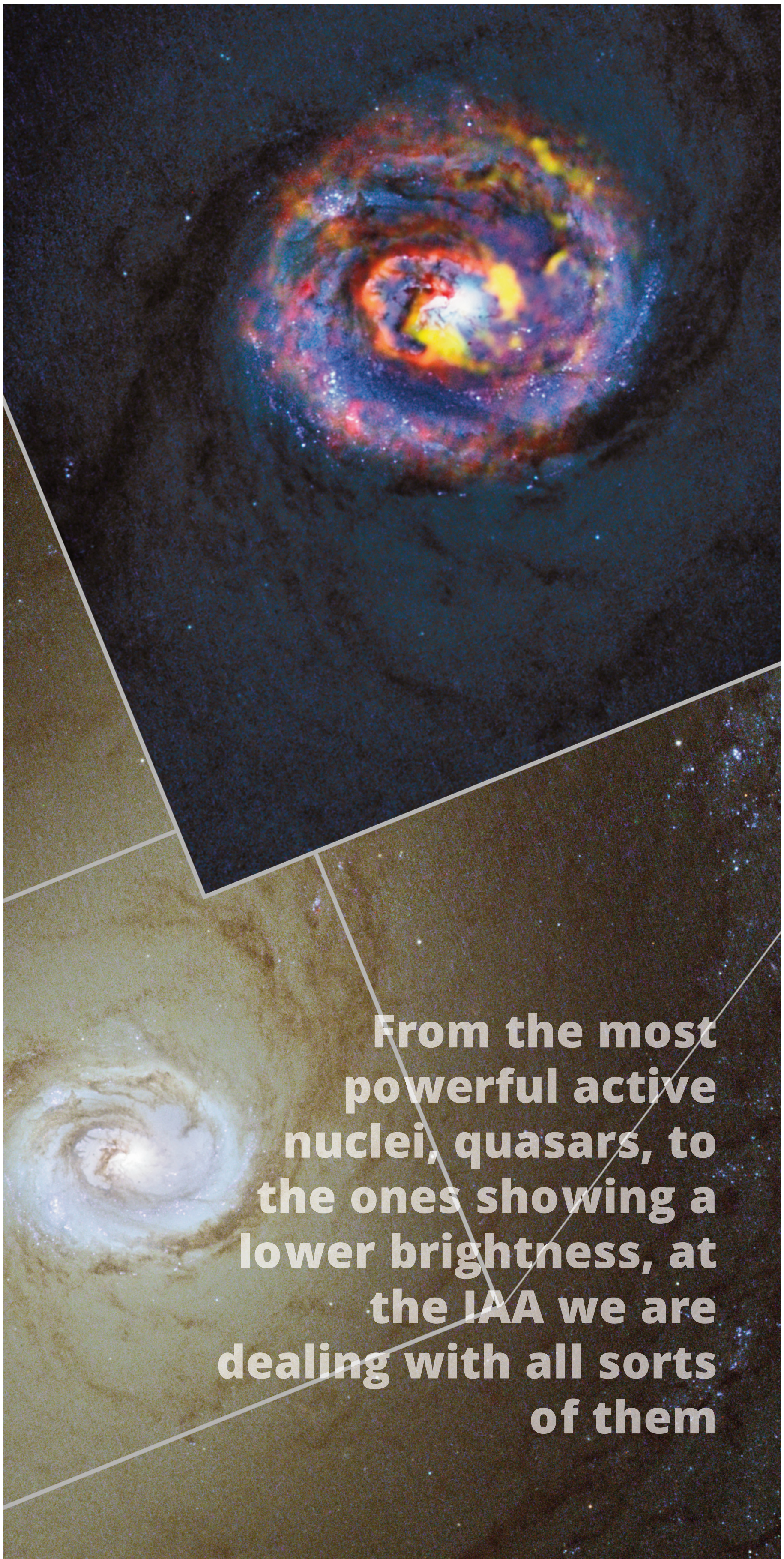
It implies a paradigm shift in the observations of the supermassive black hole located in the centre of the Messier 87 galaxy

The Event Horizon Telescope (EHT) is a planet-scale array of eight ground-based radio telescopes forged through an international collaboration. In April 2019, it provided the first direct visual evidence of a supermassive black hole and its shadow. More than two hundred investigators have participated in obtaining this image, some of them from the IAA. The image shows the black hole in the centre of the galaxy known as Messier 87 (M87), having a mass equivalent to 6.5 billion Suns.
Black holes are extraordinary cosmic objects with enormous masses but extremely compact sizes. The presence of these objects affects their environment in extreme ways, warping spacetime and super-heating any surrounding material. If immersed in a bright region, like a disc of glowing gas, we expect a black hole to create a dark region similar to a shadow — something predicted by Einstein's general relativity that we've never seen before. Several independent observations from EHT, each one analysed with different image reconstruction techniques, revealed a ring structure with a dark central region: the shadow of the black hole.
The EHT observations use very-long-baseline interferometry (VLBI), which synchronises telescope facilities around the world and exploits the rotation of our planet to form one huge, Earth-size telescope observing at a wavelength of 1.3mm. VLBI allows the EHT to achieve an angular resolution of 20 micro-arcseconds — enough to read a newspaper in New York from a sidewalk café in Paris.

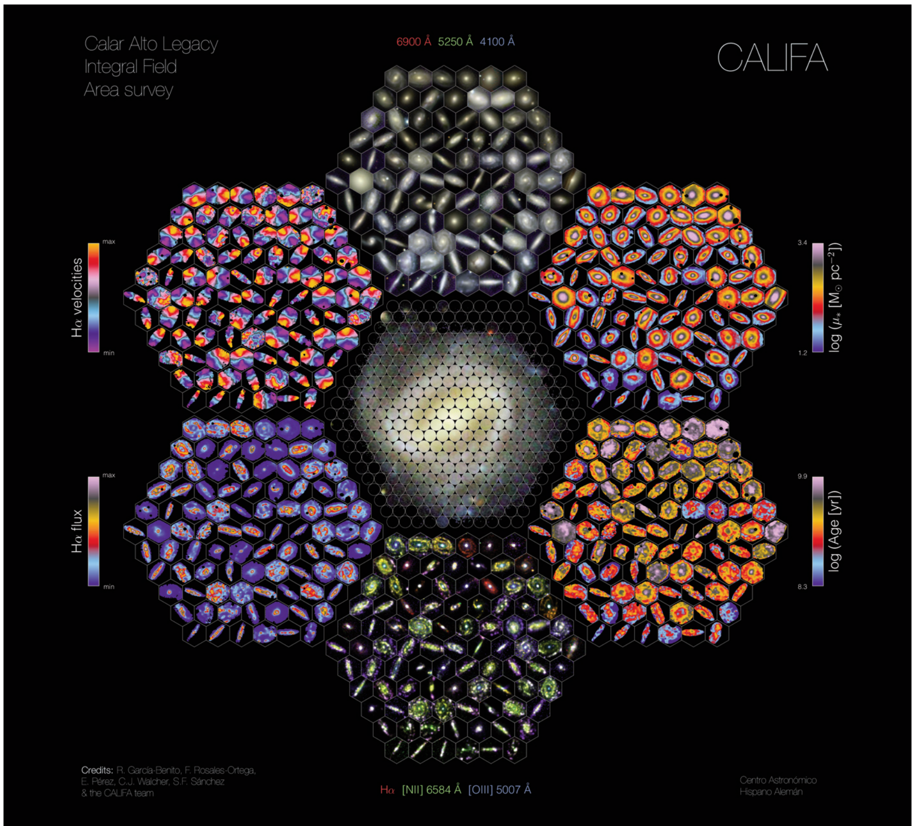
is technically impossible to study them in detail because of the distance. To come up with a solution, we study similar objects in closer environments*21 and participate in technological developments that improve our observation ability. This is the case of MEGARA, an instrument conceived for the Gran Telescopio Canarias (GTC) which makes possible to study the gas between distant galaxies, capture the light of individual stars in other galaxies or examine how stars and gas moved in galaxies more than ten thousand million years ago.

THE UNIVERSE...

The Local Group of galaxies in which the Milky Way is included represents a tiny entity within the universe, composed by thousands of millions of galaxies associated in galaxy pairs, in dozens, clusters of hundreds and superclusters. If the impossible could be made, that is, taking a picture from outside the universe, it could be seen that the distribution of galaxies in space is shown as a collection of giant voids with bubble shape. They would be separated by filaments constituted by galaxies, while clusters would appear occasionally as relatively dense nodes.
However, it is not a static distribution. In 1929, Edwin Hubble proved that galaxies recede from one another and that this movement increases with distance: the more distant they are, the quicker they step away from each other. It is known as universe expansion, a process that, by rewinding, shows galaxies coming closer. This points to the origin of everything: 13 800 million years ago, there was an instant in which all matter and energy were contained in an infinitely dense and small point that experienced a violent expansion. It is the origin of time, space and all matter associations. Known as the Big Bang, it has become the theoretical skeleton that best explains the origin of the universe we live in.
Nevertheless, there are still many questions without answer: to understand the universe and be able to anticipate its evolution, it is necessary to take into account all the matter and energy composing it, and there is a large percentage of it that remains invisible or



NGC 1433, an active galaxy that presents a complex ring, bar and spiral system that guides the gas towards the central supermassive black hole.
Credit: ALMA (ESO/NAOJ/NRAO)/NASA/ESA/F. Combes



With CALIFA, it is possible to study gas and star features: age, movements, mass or metallic composition –elements that are heavier than hydrogen and helium. From the compiled data, thirteen thousand million years of history of each galaxy can be followed to search for common patterns. In the image (clockwise): 1) broadband images; 2) star mass density; 3) average age of the stars; 4) diagnostic emission lines; 5) emission in H-alpha; 6) cinematics.

At the IAA, two big galaxy surveys were conceived, both of them developed from Calar Alto Observatory: ALHAMBRA and CALIFA

completely unknown. Latest researches indicate that 68.3% of the universe is dark energy, a repulsive force that provokes the progressive (and accelerated) detachment of galaxies. 26.8% would be dark matter, a component that does not reflect light neither emits it, and that can only be detected by its gravitational influence. And a frugal 4.9% would be the ordinary matter, that is, the type of matter that forms galaxies, stars, planets and also ourselves.

At the IAA, we are carrying out an approach to cosmological problems that includes theoretical models, observational data (mainly through large scale galaxy surveys, like J-PAS project, which will establish restrictions on dark energy properties) and instrumentation development*22. The objective is to deepen in the nature, distribution and dynamics of galaxies and groups of galaxies to be able to understand their evolution, to detect and get to know dark matter and to figure out the nature of dark matter along with the implications of its existence.

We are also participating in large cross-

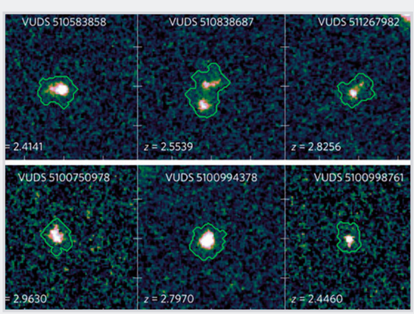
21

THE "TWINS" OF EARLY GALAXIES

With them, it is possible to study the initial stages of galaxy formation

Astronomers have been able to penetrate into what are known as "dark ages," a period corresponding to the first 700 million years after the Big Bang and in which the first, very weak galaxies were cocooned in neutral hydrogen, a gas that increases the opacity of the medium. Precisely that gas cocoon has prevented detailed studies of these galaxies from current observatories and, as a result, the birth and early stages of galaxy growth have not been studied in detail. With the participation of the IAA, a team of astronomers has taken a different approach. The team presents the discovery of nascent galaxies observed at a later cosmic moment, only one billion years after the end of the dark ages, when the universe was 5% of its current age.

Thus, this study, which has analyzed more than 2,000 galaxies and found ten of these primordial galaxies, has captured what appears to be one of the first massive episodes of star formation in the universe. These galaxies are about thirty times smaller and about a hundred times less massive than the Milky Way, with compact and irregular shapes.



cutting projects, like the Cherenkov Telescope Array (CTA), which will be the main very high energy gamma-ray observatory the next few decades. Its scientific potential is extremely vast: from understanding the role of relativistic cosmic particles to searching for dark matter. CTA will explore the extreme universe from both hemispheres (Paranal, Chile and La Palma, in the Canary Islands) and study from the closest black hole environment to the universe low density regions at a large scale.

... AND ITS LAWS

In its relativity theory, Einstein showed that time and space, always considered differentiated entities, were actually a unique one: spacetime. Spacetime is the scenario in which all physical events from the universe take place; it is a ductile tissue that can be curved in the presence of matter. Gravity scenarios in extreme situations, such as black holes or the origin of the universe itself, are a research field at the IAA that includes a variety of objectives. Among them, building bridges between the macroscopic (gravity) and the microscopic universe (quantum physics); deepening in the understanding of gravitational waves, “wrinkles” in spacetime produced by the movement of massive objects; also figuring out why some elementary particles do have mass when, based on theory, should not have it.

BACK TO GRANADA

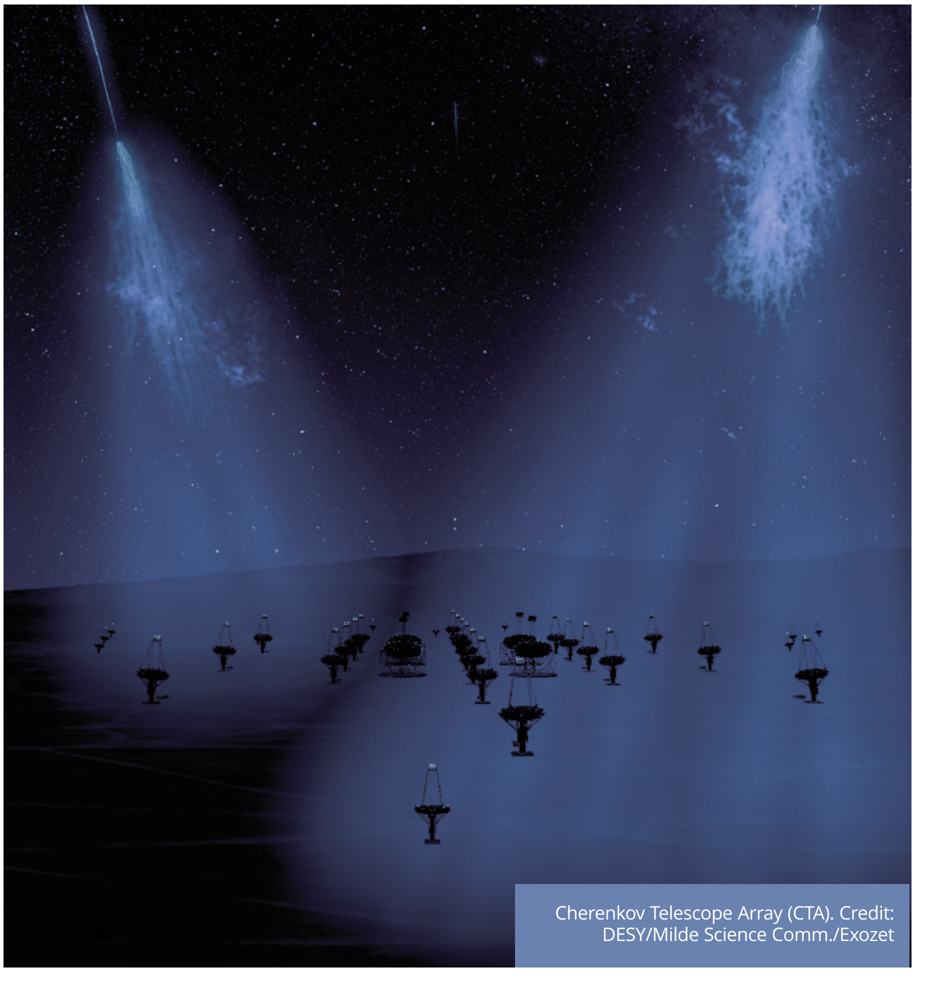
Here concludes our rocket journey through the scientific and technological activity of the IAA. Severo Ochoa’s accreditation marks a milestone on a solid and cross-cutting work path. But it is also an opportunity to make IAA one of the referential astrophysics and space science institute in Europe as well as to improve its research work and its structure to a privileged position level for the next generation of advanced and cutting-edge experiments.
Next years will be vibrant for the Institute of Astrophysics of Andalusia. And we are looking forward to telling you all about it. ■

Silbia López de Lacalle (IAA-CSIC)

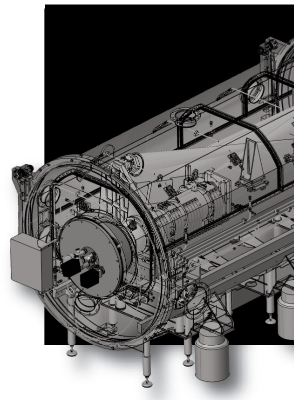
NEW ASSIGNMENT FOR A 45-YEAR-OLD TELESCOPE

MAYALL TELESCOPE IS GETTING READY TO INVESTIGATE DARK ENERGY

Located in Kitt Peak Observatory (Arizona), Mayall telescope hosts DESI, an instrument designed for studying dark matter and the large scale universe. The Institute of Astrophysics of Andalusia participates in the project.
DESI will use an array of 5,000 positioning robots, each carefully choreographed to point a fiber-optic cable at a preprogrammed sequence of deep-space objects, including millions of galaxies and quasars (galaxies that harbor actively feeding, massive black holes).
The fiber-optic cables will carry the light from these objects to 10 spectrographs, which are tools that will measure the properties of this light and help to pinpoint the objects’ distance and the rate at which they are moving away from us. DESI’s observations will provide a deep look into the early universe, up to about 11 billion years ago.



Cherenkov Telescope Array (CTA). Credit: DESY/Milde Science Comm./Exozet



INSTRUMENTAL AND TECHNOLOGICAL DEVELOPMENT UNIT

UDIT

UDIT DEVELOPS TECHNOLOGY FOR SCIENTIFIC INSTRUMENTATION AND OFFERS TECHNICAL SUPPORT TO ALL RESEARCH DEPARTMENTS FROM THE IAA. IT HAS A MECHANICS WORKSHOP, OPTIC, ELECTRONICS AND SOFTWARE LABORATORIES AND TWO ISO 8 TYPE CLEAN ROOMS

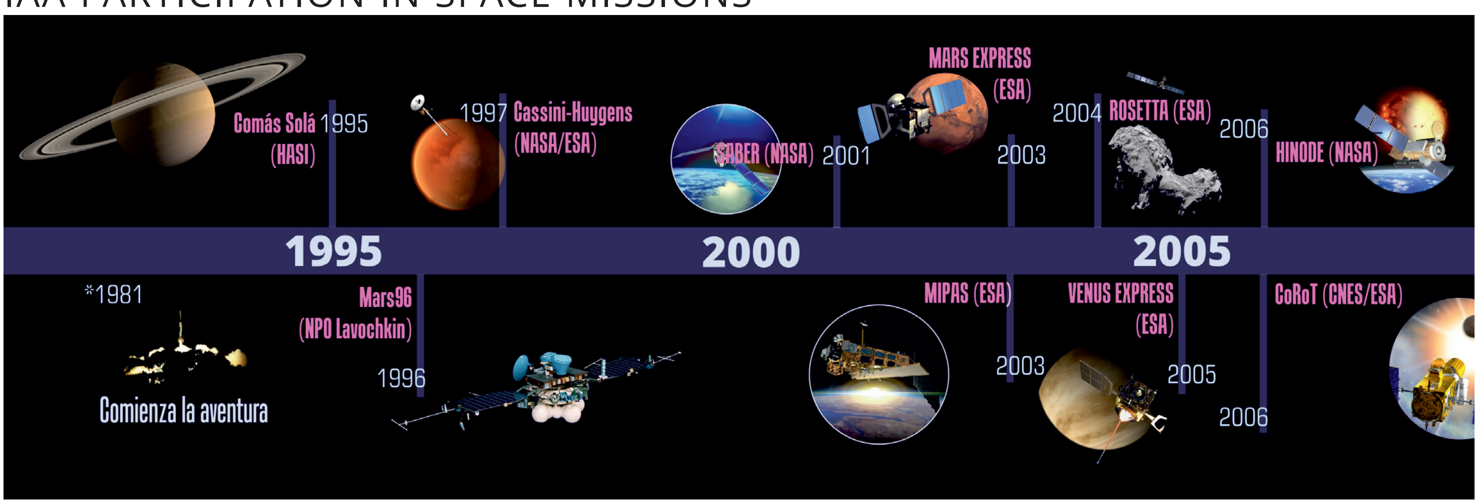
software

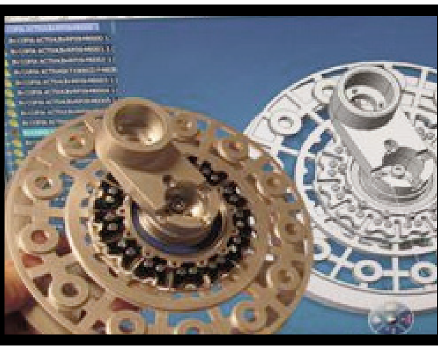
It offers comprehensive solutions (analysis, design, integration and verification) for instrumentation control software. They are based on reprogrammable devices (FPGA), microcontrollers, DSP, embedded systems with light operative systems and last generation processors. It also covers the complete development of processing software and data analysis obtained during space missions and ground-based observations, based on data processing environments with high performances (HPC).

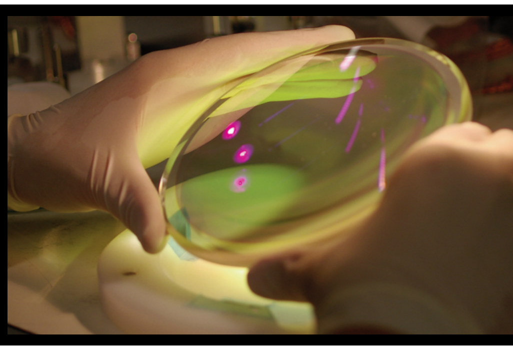
optics

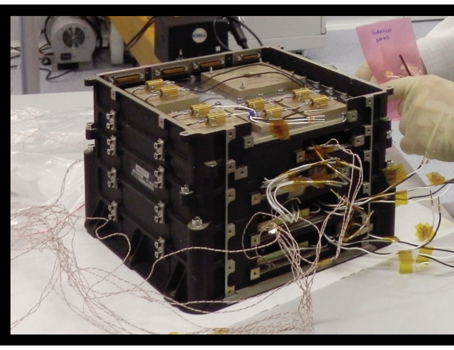
It produces the optical design of astronomical instrumentation in the visible and infrared spectral range (image, spectroscopy, photometry and polarimetry). The laboratory also assembles, integrates and verifies the instrumentation in the clean room (ISO 8) when such instrumentation requires it. It also calibrates the variety of elements that compose the astronomical instrumentation (detectors, spectral lamps, system alignment, etc.). It also has an international benchmark laboratory in polarimetry and optical engineering.

IAA PARTICIPATION IN SPACE MISSIONS









mechanics

It works on the development of cryogenic and vacuum systems, as well as high performance mechanical structures for space and ground-based instrumentation. The optomechanics field includes all aspects of engineering regarding optical component frames and supports. High precision positioner systems are also being developed.

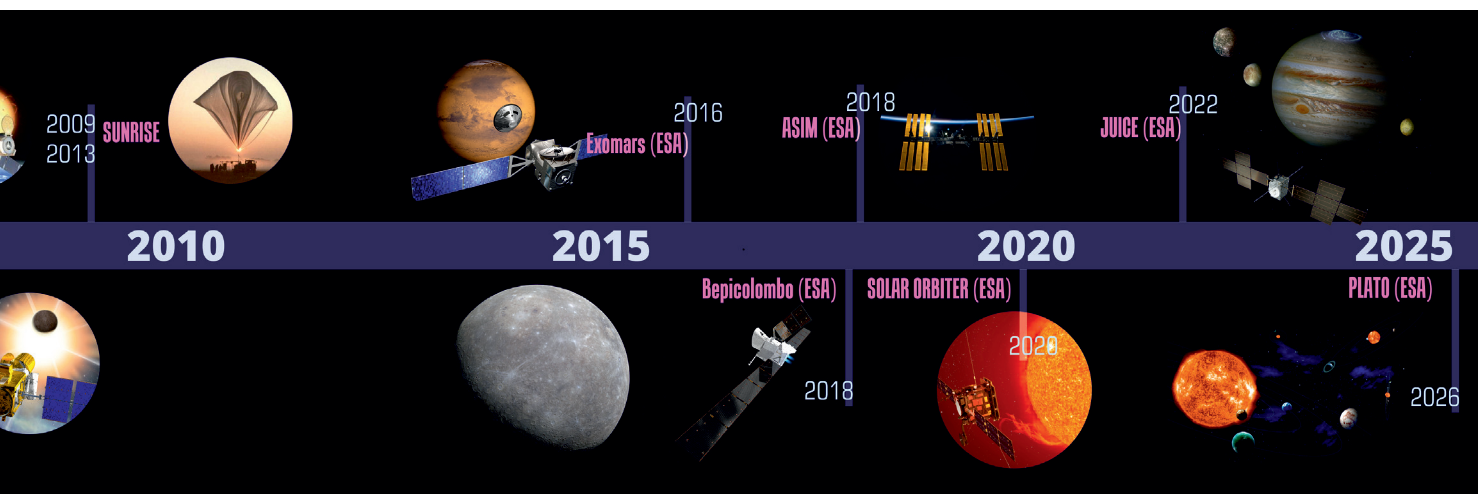
Structural analyses are being carried out by finite element analysis (FEA) tools that enable to face integrally any problem related to structural mechanics.
We have a mechanics workshop for manufacturing complex geometric pieces that offer excellent surface finishes defined by strict dimensional tolerances.

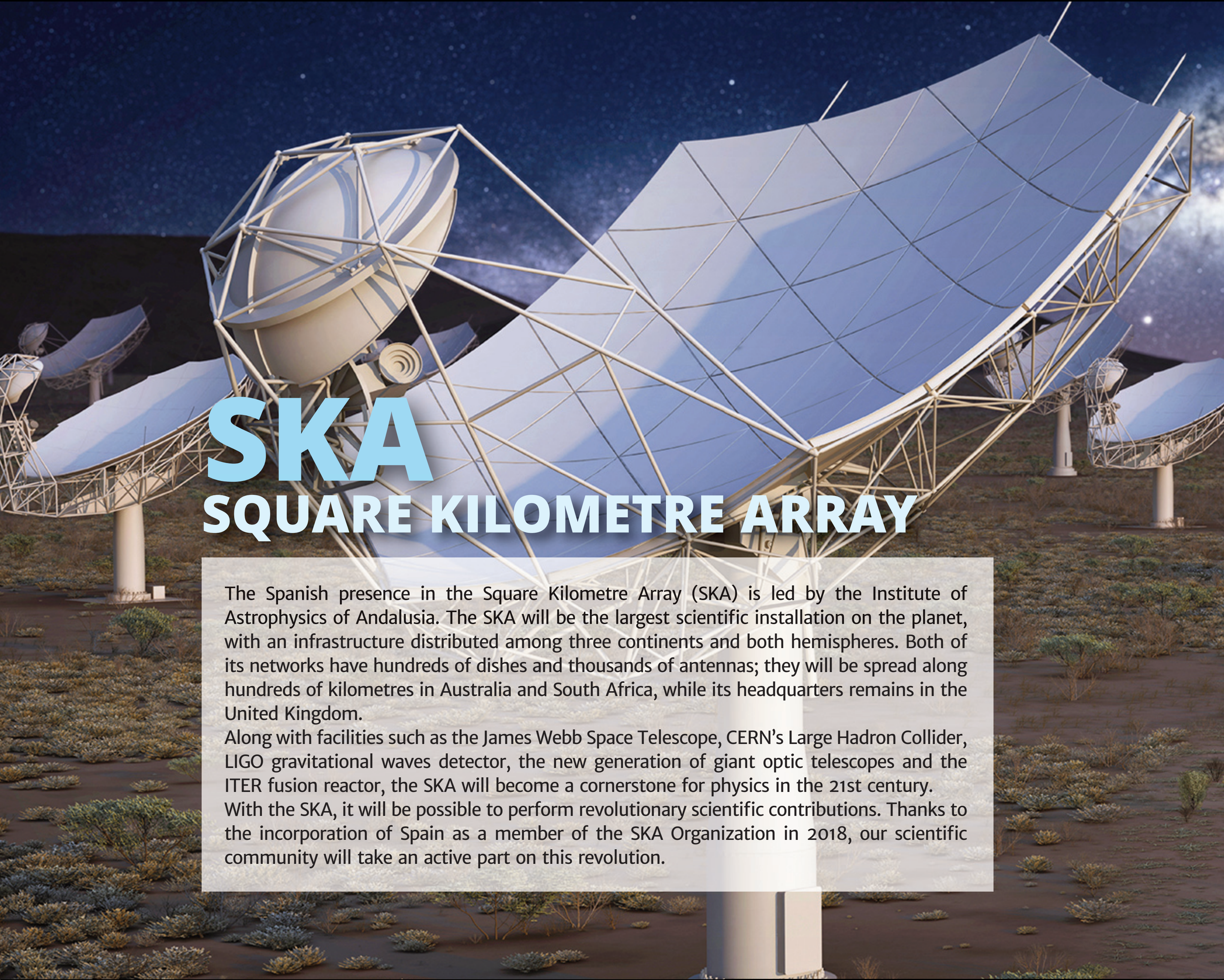
electronics

It develops control and power electronic systems. This includes high density printed circuit boards, which, after the design phase, are manufactured in related companies. Afterwards, they are evaluated with strict testing at the IAA to obtain the quality accreditation for space flights.
We work with high-performance programmable integrated circuits (FPGAs) for complex applications: mechanism control systems and data acquisition, monitoring and processing.
We perform advanced project consulting in hardware and software development, for both ground-based and space missions instrumentation. We have a broad experience in low consumption, redundancy and high reliability systems.

international projects

As it can be seen in the timeline below, the IAA participation in space projects is wide and deals with a variety of objects and fields. For ground-based observation, the visible and infrared spectrograph CARMENES and the PANIC camera for Calar Alto Observatory (Almeria) are the most standout pieces. They are respectively dedicated to the search of terrestrial exoplanets and broad-spectrum observation. Also, the IAA has participated in the development of the MEGARA multi-object spectrograph for the Gran Telescopio Canarias (Roque de los Muchachos Observatory), which studies with an unprecedented detail the chemical composition and the dynamics of galaxies in different ages of the universe.



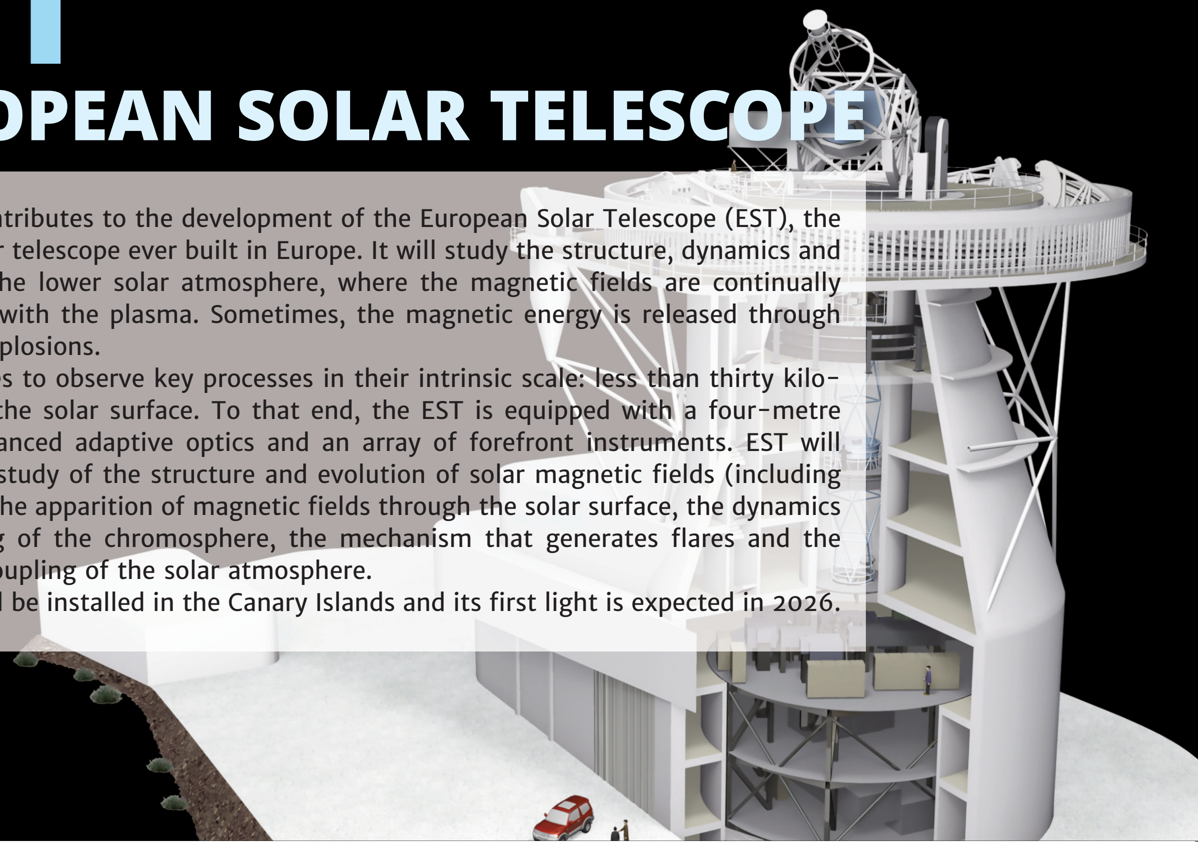


SKA
SQUARE KILOMETRE ARRAY

The Spanish presence in the Square Kilometre Array (SKA) is led by the Institute of Astrophysics of Andalusia. The SKA will be the largest scientific installation on the planet, with an infrastructure distributed among three continents and both hemispheres. Both of its networks have hundreds of dishes and thousands of antennas; they will be spread along hundreds of kilometres in Australia and South Africa, while its headquarters remains in the United Kingdom.

Along with facilities such as the James Webb Space Telescope, CERN's Large Hadron Collider, LIGO gravitational waves detector, the new generation of giant optic telescopes and the ITER fusion reactor, the SKA will become a cornerstone for physics in the 21st century.

With the SKA, it will be possible to perform revolutionary scientific contributions. Thanks to the incorporation of Spain as a member of the SKA Organization in 2018, our scientific community will take an active part on this revolution.



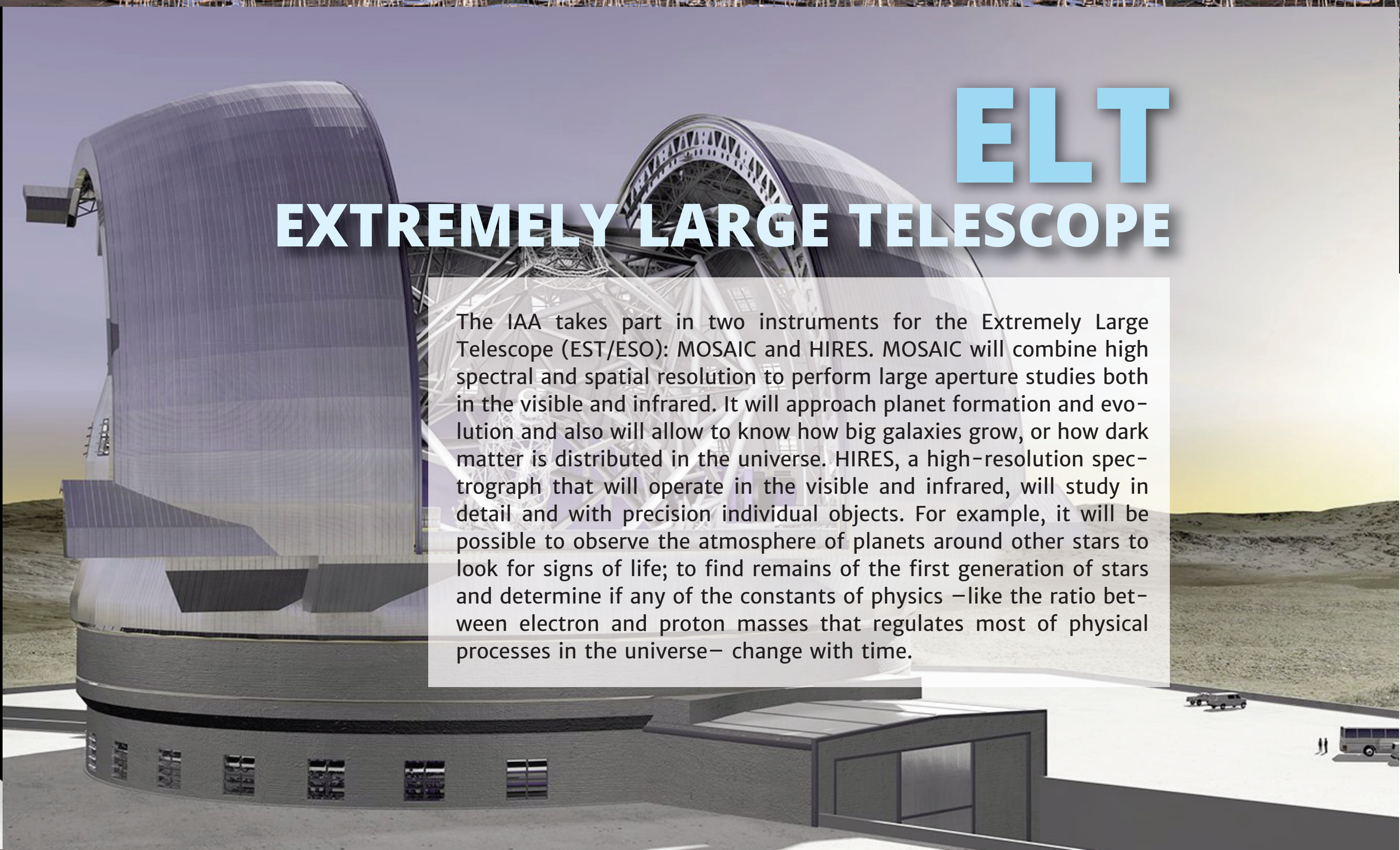
EST
EUROPEAN SOLAR TELESCOPE

The IAA contributes to the development of the European Solar Telescope (EST), the largest solar telescope ever built in Europe. It will study the structure, dynamics and energy of the lower solar atmosphere, where the magnetic fields are continually interacting with the plasma. Sometimes, the magnetic energy is released through powerful explosions.

This requires to observe key processes in their intrinsic scale: less than thirty kilometres on the solar surface. To that end, the EST is equipped with a four-metre mirror, advanced adaptive optics and an array of forefront instruments. EST will enable the study of the structure and evolution of solar magnetic fields (including sunspots), the apparition of magnetic fields through the solar surface, the dynamics and heating of the chromosphere, the mechanism that generates flares and the magnetic coupling of the solar atmosphere.

The EST will be installed in the Canary Islands and its first light is expected in 2026.

GREAT UPCOMING PROJECTS



ELT

EXTREMELY LARGE TELESCOPE

The IAA takes part in two instruments for the Extremely Large Telescope (EST/ESO): MOSAIC and HIRES. MOSAIC will combine high spectral and spatial resolution to perform large aperture studies both in the visible and infrared. It will approach planet formation and evolution and also will allow to know how big galaxies grow, or how dark matter is distributed in the universe. HIRES, a high-resolution spectrograph that will operate in the visible and infrared, will study in detail and with precision individual objects. For example, it will be possible to observe the atmosphere of planets around other stars to look for signs of life; to find remains of the first generation of stars and determine if any of the constants of physics –like the ratio between electron and proton masses that regulates most of physical processes in the universe– change with time.

CAHA

Calar Alto Observatory

The largest observatory in Continental Europe

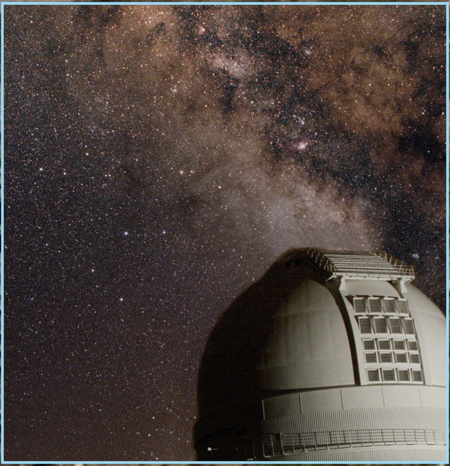
Calar Alto Observatory is located at the Sierra de Los Filabres (Almeria). Until 2018, it was jointly managed by the Max Planck Institute for Astronomy (MPIA-MPG) in Heidelberg (Germany) and the Institute of Astrophysics of Andalusia (IAA-CSIC) in Granada. In 2019, the regional government of Andalusia, Junta de Andalucía, has joined the scientific facility, replacing the German partner.

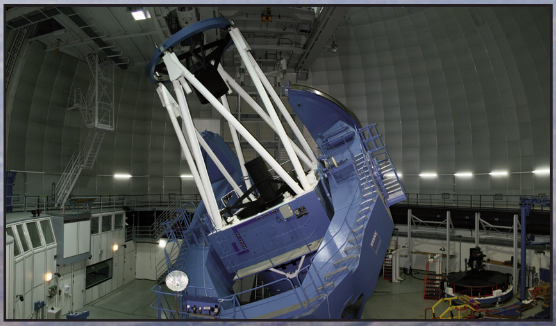
Calar Alto has become the most relevant astronomical facility in the continental European territory. Since 1975, it has been one of the pillars for German and Spanish astronomical developments. With telescopes with an opening of 3.5 and 2.2 meters (and two more telescopes of 1.23 and 0.8 meters), the observatory is now considered a singular scientific and technical infrastructure (ICTS). The continuous renewing of the instruments that are attached to the telescopes keeps Calar Alto at the forefront of astronomy. Spanish engineering, science and business sectors are also participating in this development.

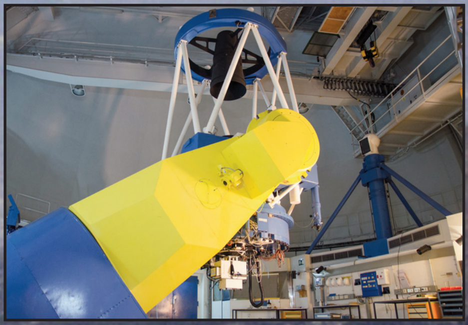
With around 70% of useful observing time, the inherent natural quality of the night sky in Calar Alto makes of it the best place in Europe for astronomical observation.

From the closest environment, the Solar System, to the edges of the observable universe, the studies carried out at the observatory cover a wide range. Since modern astrophysics is characterized by an interdisciplinary and collaborative nature, many of these projects consist on supporting observations for space missions. In this field, Calar Alto has contributed to researches regarding satellites such as CoRoT, Herschel, Deep Impact, Gaia or Rosetta, among others, with additional data.

Calar Alto is one of the most productive observatories when it comes to published scientific articles in international magazines with an independent peer review system.







Part of the observing time is dedicated to special projects that have a long-term development, which means a guaranteed access to telescopes and instruments during several years. In this area we can highlight ALHAMBRA and CALIFA surveys. ALHAMBRA, finished in 2010, was oriented to the analysis of the properties of the universe from the closest environment to great distances. CALIFA, a legacy project, applied integral field spectroscopy techniques to six hundred selected galaxies from the local universe. This provided unprecedented information about the structure, evolution and history of the star formation in these big star systems, similar and different at the same time to our own Galaxy.

Currently, observations for the cutting-edge project known as CARMENES are in progress, focused on the research about habitable planets in the universe.

OSN
Sierra Nevada Observatory

The atmosphere at the top of the Sierra Nevada mountains, in Granada, has extraordinary properties for astronomy. The pureness and stability of the skies stand out for their great quality.
Besides, the atmospheric water vapour level in Sierra Nevada is so low that it allows the passing of millimetric and infrared radiations, which are normally trapped in the atmosphere. Along with the abundant clear nights, Sierra Nevada becomes an exceptional spot for observation.
Belonging to the IAA, the observatory is fitted with a telescope with an aperture of 1.5 meters, another of 0.9 meters and several others with smaller measurements. Close to three thousand meters high, it is the highest permanent scientific installation in Europe.

The IAA: towards an equal centre

IN SPAIN, ASTROPHYSICS IS ONE OF THE SCIENTIFIC FIELDS IN WHICH WOMEN HAVE THE LEAST REPRESENTATION. INITIATIVES TO ACHIEVE REAL EQUALITY ARE ESPECIALLY NECESSARY

Nowadays, only 29% of women occupy employments related to astronomy and astrophysics (compared with 39% of female researches generally speaking), and only 34% are women with a permanent position. And, as with other sciences and engineering, the glass ceiling is still present: the percentage of women with a university chair represents the 15%, a number that goes down to 4% when it comes to public research organisations (OPIS).

Since its creation in 1977, the IAA has had one female director and five female associate directors. Currently, in the IAA both deputy directors, in science and technology ,are women, as well as the management in Observatorio de Sierra Nevada and in Unidad de Desarrollo Instrumental y Tecnológico.

From the 90s to our days, the Instituto de Astrofísica de Andalucía has been characterised for supporting inclusive gender equality initiatives. Some of them have been developed personally by our researchers, launching seminars, publications and reports. Also, they participated in the CSIC Woman and Science Comission and organized activities for March 8th (International Women's Day) and February 11th (International Day of Women and Girls in Science).

The role carried out by our female scientists in promoting equality in science has led to institutional initiatives, such as WITEC (Women in TECnology), one of the first European initiatives to help the inclusion of women in STEM areas; the development of dissemination activities to highlight the role of women in science; the implementation of initiatives related to family conciliation –like a breastfeeding room; or the treatment of personal data and report generation with the gender variable, in order for the segregated information to be permanently updated.

The most recent milestone in the IAA has been the creation of the first plan in gender equality, approved on March 8th 2018. It is important to bring into consideration that in this plan, the creation of a commission with representatives from all Institute areas was approved. The objective is to create a discussion and analysis forum regarding the implementation of equality policies in the centre.

Besides, the commission is keen to collect and answer all requests coming from the youngest female workers and to listen the most experienced women. By these means, we will keep an eye on the gender balance and recommend it, so opportunities are the same for all the staff in our centre.

Josefa Masegosa (IAA-CSIC)

Institute of Astrophysics of Andalusia.
February 11th, International Day of Women and Girls in Science.

The IAA: a centre of excellence

THE NEAR FUTURE OF IAA WILL BRING GREAT CHALLENGES AND OPPORTUNITIES

The Institute of Astrophysics of Andalusia (IAA) was founded in 1975. It was created by a handful of brave specialists in astronomy and engineering who knew how to position the project in an international and competitive scientific stage. Throughout the years, IAA has evolved from their very first photometers, which are photon counters and that we now look at as museum pieces, to create first line instrumentation for both ground-based and space observatories. Back then, the IAA was starting to establish contact with the international astrophysical research field. Nowadays, it holds a predominant position spot among the elite research centres in the country as a Severo Ochoa Centre of Excellence. And all this was possible due to the intelligence, initiative, competence and determination, along with the effort and loyalty to the IAA from all who have been part of its history.

Science, knowledge and technology have greatly evolved in recent years, transforming challenges in unquestionable achievements, where the IAA contribution has been very significant. To mention some of them:

> Planets, moons and comets have been explored, with an active involvement of the IAA practically in all space missions from the European Space Agency (ESA) devoted to the study of our Solar System. A prominent example has been the mission known as Rosetta, which orbited the comet 67P/Churyumov-Gerasimenko. But, in the meantime, the IAA has also participated in Cassini-Huyggens, Mars Express, Venus Express, ExoMars, Sunrise, BepiColombo and Solar Orbiter missions.

> Since the discovery of the first exoplanet in 1995, many other planets beyond our Solar System have been found. Now the challenge lies in detecting rocky planets in the habitable zone of stars. On this matter, the IAA has had a relevant role with the development and operation of CARMENES, an instrument located in Calar Alto observatory dedicated to the detection of exoplanets in M-type stars and the study of their atmospheres.

> Launched in 1997, the Hipparcos satellite provided the first astrometric results for a hundred thousand stars. Today, the GAIA satellite can study a billion stars. GAIA will perform an eight-dimension survey of our Galaxy, including the position, speed, metallicity and photometry of stellar objects, a project in which a research team from IAA is actively involved.

> From studying in detail a quite modest number of individual galaxies in the past, we have moved on to lead CALIFA project, consisting of a tridimensional spectroscopic mapping that includes more than five hundred galaxies with different morphologies (the most extensive one so far); all of them studied from Calar Alto, a legacy and a reference for the international astronomic alcommunity.

> Going through the theoretical study of black holes, along with the observational research of active galaxies and relativistic jets emanating from their core, we have been involved in the collection of the first direct image of a black hole with the Event Horizon Telescope (EHT). The IAA actively participates in its scientific team.

> The institute has grown from the initial detection of gamma-ray bursts (GRBs) to the focus on a great variety of transients in the sky and many advances have been made in the understanding of their nature. In this period, the first gravitational waves have been discovered, our newest cosmic messenger that we have just started to meet. Back in 2017, the IAA also took part in the first and historic detection of the electromagnetic counterpart of these events.

The near future holds for our centre great challenges and opportunities. The involvement in ESA missions flying in the next years, like JUICE or Plato 2.0; the contribution to the instrumental developments in Calar Alto Observatory; the national lead of IAA in the Spanish participation in the Square Kilometre Array (SKA); the exploitation of European Southern Observatory (ESO) telescopes, along with the newest scientific results that will be published by our scientific staff, will enable the impact and leadership of the IAA to be reinforced on an international level. The achievement of Severo Ochoa Centre of Excellence accreditation, provided by the Spanish Ministry of Science to those highly competitive centres with frontier research programs which are positioned among the best worldwide in their specific areas, along with the associated external funding, have become a pertinent impulse as well as a source of enthusiasm and commitment. Based on a solid and cross-disciplinary strategy, we now face the challenge to reach an exceptional position in the operation of frontier astrophysical experiments for the next generation.

Antxon Alberdi, Director of IAA-CSIC
Isabel Márquez, Vice Director of the Severo Ochoa project in IAA