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2023

Observatoire royal de Belgique

Koninklijke Sterrenwacht van België

Royal Observatory of Belgium

ORB - KSB

Cover illustration: The public visiting the radioastronomy station at Humain (Belgium) and its science exhibition. Credit: L.B.S Pham.

Foreword

Dear readers,

I am happy to present you with the annual summary report of the Royal Observatory of Belgium (ORB-KSB). As in the previous years, we have decided to only present the highlights of our scientific activities and public services, rather than providing a full, detailed and lengthy overview of all of our work during the year. We hope to provide you, in doing so, with a report that is more interesting to read and gives a taste of life at the ORB-KSB. If you need more or other information on ORB-KSB and/or its activities, contact rob_info@oma.be or visit our website http://www.observatory.be.

A list of publications and staff statistics are included at the end. To also suit our international readers & collaborators and to give it an as wide visibility as possible, the report is written in English.

Ronald Van der Linden

Director General

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Brief news of the Royal Observatory of Belgium

Space missions and scientific projects and collaborations

Launch of the ESA Spacecraft JUICE

On 14 April 2023, the ESA spacecraft JUICE (JUpiter ICy moons Explorer) was launched from Kourou (French Guiana) on an 8-year journey to Jupiter.

JUICE will investigate Jupiter and its icy moons and aims to answer fundamental questions about them. One such question is whether icy moons could have the right conditions for the emergence of life. Europa, Ganymede, and Callisto, the three large icy moons of Jupiter, could harbour a liquid water ocean beneath their ice shell. Liquid water is one of the necessary conditions for developing and sustaining life, in addition to biologically essential elements and energy. By investigating the interior of the icy moons, JUICE will determine whether these conditions are fulfilled in those moons.

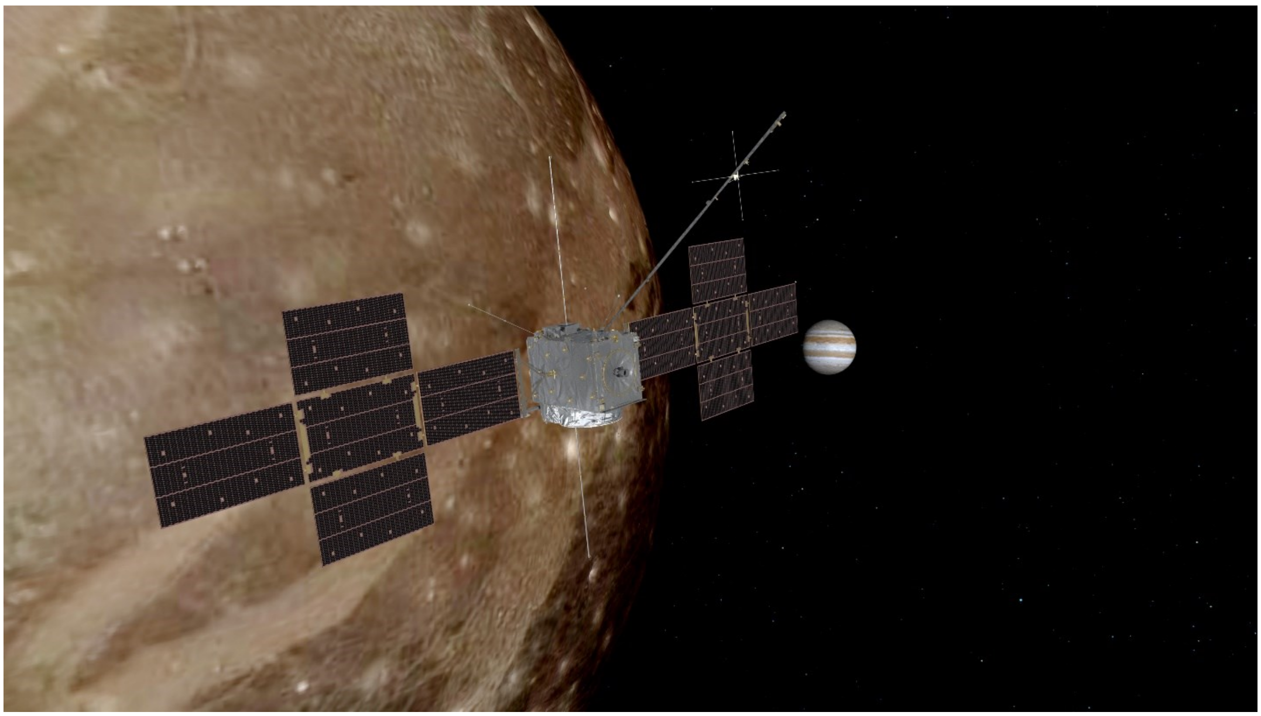


Figure 1: Artist's impression of the spacecraft JUICE orbiting Ganymede, with Jupiter in the background. Credits: ESA (acknowledgement: ATG Medialab).

The Royal Observatory of Belgium (ORB-KSB) is involved in four of the ten JUICE instruments: the radio science package 3GM (Gravity and Geophysics of Jupiter and the Galilean Moons), the Jovian MAGnetometer J-MAG, the GAnymede Laser Altimeter (GALA) and the MAJIS instrument (Moons And Jupiter Imaging Spectrometer).

3GM and J-MAG will be used to probe the interior of the moons. The magnetometer will observe the induced magnetic field generated in the subsurface ocean, and radio science will measure the gravity field, rotation and tides of the moons. GALA will determine the topography map of Ganymede and measure its tidal deformations, which lead to weekly upward and downward motions of the ice surface by a few metres. Lastly, the MAJIS instrument will provide data on the ices and minerals on the surfaces of icy moons and their connection with the subsurface.

Scientists of the ORB-KSB are looking forward to the data of the JUICE mission and to the new insights that it will make possible!

Delivery of the Spacecraft Platform for the PROBA-3 Mission

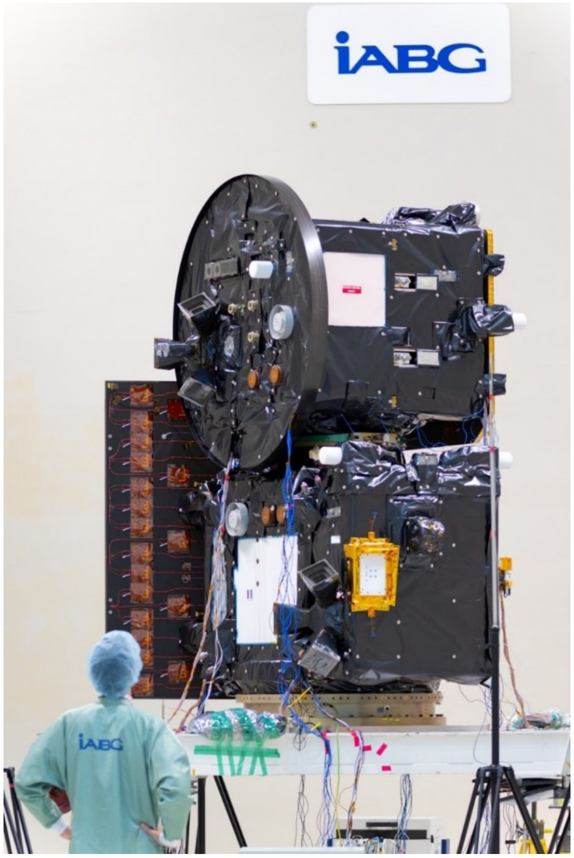


Figure 2: The two PROBA-3 spacecrafts in stack before thermal vacuum testing at IABG (Germany) in July 2023. The occulter spacecraft is on the top, featuring a circular occulting disc. The coronagraph spacecraft is at the bottom, with solar panels extending to the left. The spacecraft will be launched in this stack configuration in November 2024. Photo: ESA — S. Corvaja.

PROBA-3 is a technology demonstration mission of ESA. It will be launched in December 2024 and will demonstrate techniques and technologies of precise formation flying. The PROBA-3 platform will consist of two spacecrafts that will fly in a precise formation. The bigger spacecraft (coronagraph spacecraft) hosts the optical telescope, and the smaller spacecraft (occulter spacecraft) carries the circular occulting disc. During extended periods of time (up to 6 hours), the occulter spacecraft will cover the bright solar disc, thus allowing the dimmer corona to be seen, similarly to observations of a total solar eclipse. Together the two spacecrafts form a giant coronagraph (i.e. an instrument to observe the corona by occulting the solar disc) called ASPIICS, which stands for the Association of Spacecraft for Polarimetric and Imaging Investigation of the Corona of the Sun.

The two spacecrafts must keep the precise position and orientation ('fly in formation') with respect to each other and to the Sun. The distance between the two spacecraft during coronal observations will be around 144 meters, and the precision of their alignment will be around a few millimeters. This will allow to block the bright light of the solar disc to observe the corona in eclipse-like conditions, i.e. close to the solar limb and with very low straylight. The ASPIICS observations will provide data that are crucial to solving several outstanding problems in solar physics, namely the origin of solar wind and physics of coronal mass ejections. The ORB-KSB hosts the Principal Investigator of ASPIICS who leads the international science team, makes sure that the coronagraph is manufactured in agreement with the scientific requirements, and prepares the data exploitation.

Significant progress was reached by the engineering teams assembling the PROBA-3 spacecraft platform in 2023. The spacecraft delivery event was held on March 9 at the premises of Redwire Space in Kruibeke, Belgium. This event marked the successful completion of the integration of the two spacecrafts, which was led by Redwire Space. The assembled spacecrafts were presented to the representatives of funding agencies of Belgium and Spain (two countries contributing the most to the PROBA-3 spacecraft platform), industries (Redwire Space, Sener Aerospace), as well as ESA and scientists. The ASPIICS PI gave a presentation about the upcoming ASPIICS science to the funding agencies, science and engineering teams.

In July – August, the two spacecrafts underwent thermal vacuum testing at IABG (Germany). This type of testing is always made to simulate the space environment in which the spacecrafts will operate. Thermal vacuum testing demonstrated that the two spacecrafts can withstand harsh conditions of the space flight. After that, the final testing of the two spacecrafts continued at Redwire Space in Kruibeke.

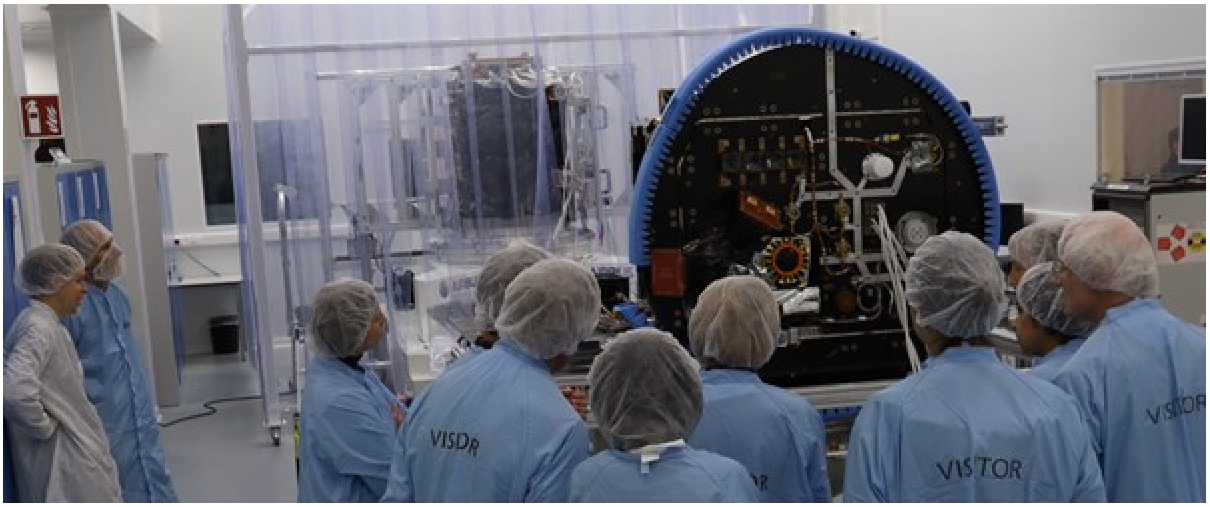


Figure 3: Members of the Science Working Team of PROBA-3 inspecting the occulter spacecraft. The coronagraph spacecraft can be seen in the background behind the curtain. (Photo: ESA — J. Versluys.)

On November 27, the members of the international Science Working Team of PROBA-3 paid a visit to the spacecraft in the clean room in Kruibeke. The ASPIICS PI gave a presentation about the PROBA-3 mission to the science and engineering teams.

Successful Test Campaign for the GRASS Instrument

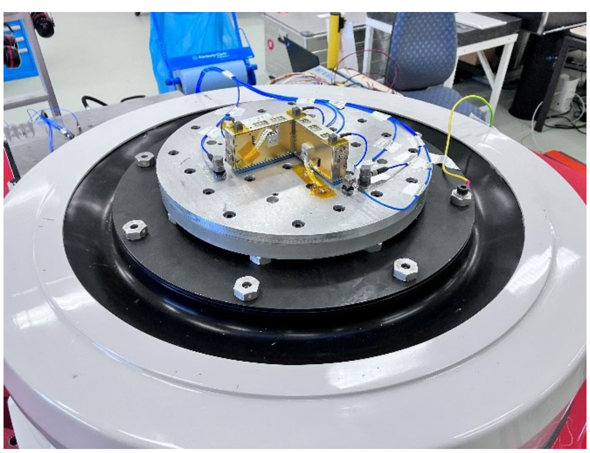


Figure 4: GRASS gravimeter on shaker. Credits: ESA/EMXYS.

The GRASS (GRAvimeter for Small Solar system bodies) instrument developed within the ESA Hera mission has undergone in 2023 a successful environmental test campaign. The tests, which were performed in ESA’s Mechanical Systems Laboratory, showed that GRASS is capable of withstanding the harsh thermal and air-free environment of space as well as the intense vibrations of the launch.

GRASS is a piece of technology, L-shaped and about the size of two hard drives, developed by the ORB-KSB with Spain’s EMXYS company. It will be the first instrument to directly measure gravity on the surface of an asteroid. The gravimeter will be landed on the surface of the Dimorphos asteroid (about the same size as the Colosseum of Rome) aboard the Juventas CubeSat –

which will itself be deployed from the Hera mission for planetary defence about the binary asteroid Didymos – and will measure gravity levels of less than a millionth of Earth's own.

Ten Years of Stellar Discoveries: The Gaia Mission

On December 19, we celebrated the 10th anniversary of the ESA Gaia satellite launch. Gaia's goal is to measure with unprecedented accuracy the position and motion of stars and objects of the solar system, the Milky Way and beyond as well as to classify these. Various versions of the Gaia catalogue, increasingly improving, were published. The latest small release took place in 2023 (see Highlight 'Building the Most Detailed 3D Map of the Milky Way: Gaia Focused Product Releases' on page 45). The 4th data release is foreseen in 2026, and the 5th and final catalogue is expected for 2030 at the earliest. In ten years, Gaia initiated a revolution in astronomy and in our knowledge of the structure, dynamics and evolution of the Milky Way and our solar system.

Inauguration of the ILMT Telescope and BINA Third Workshop

On 21 March 2023, the Belgo-Indian Network for Astronomy and astrophysics (BINA) celebrated a new milestone with the inauguration of the ILMT (International Liquid Mirror Telescope), located at the Devasthal Observatory in the north of India. This event was followed by the third BINA workshop on 22–24 March 2023, in Bhimtal, India. This international workshop was an opportunity for BINA members to emphasise the scientific potential of Indo-Belgian cooperation.

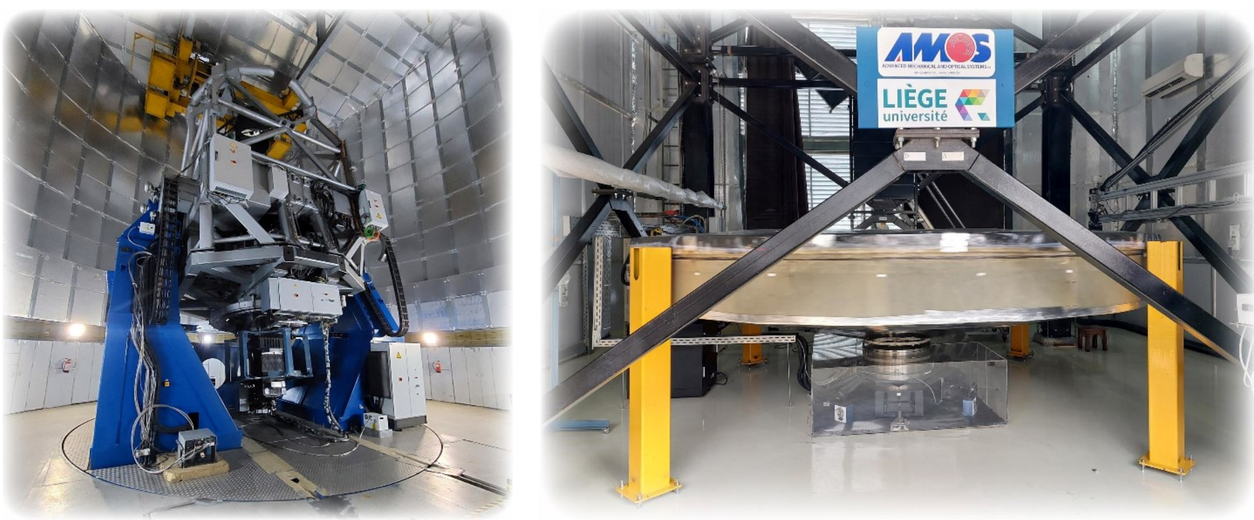


Figure 5: The 3.6-m Devasthal Optical Telescope (left) has a conventional glass mirror while the 4-m International Liquid Mirror Telescope (right) is a zenithal telescope having a mirror consisting of a thin layer of liquid mercury.

BINA is a network that fosters collaborative space research between Belgian and Indian institutes. The initiative for this bilateral collaboration was taken in 2014 by Dr Peter De Cat of the ORB-KSB (Belgian PI of BINA) and Dr Santosh Joshi of the Aryabhatta Research Institute of Observational Sciences (ARIES; Indian PI of BINA). The stimulus for this project can be found in the Devasthal Observatory of ARIES, Nainital, Uttarakhand, which hosts two Indo-Belgian telescopes: the 3.6-m Devasthal Optical Telescope (DOT) and the recently inaugurated 4-m International Liquid Mirror Telescope (ILMT) (see Figure 5). They are called

‘Indo-Belgian’ because they are located in India but were built by the Advanced Mechanical and Optical Systems (AMOS) and the Centre Spatial de Liège (CSL) in Belgium.

Figure 6: The logo for the 3rd BINA workshop. The large dots on the maps of Belgium and India represent the location of the PI institutes. They are connected with each other, symbolising bilateral collaboration, and with smaller dots, representing the other partner institutes.

BINA unites 14 Indian and 7 Belgian partner institutes (see Figure 6) and becomes a well-established concept within the astronomical communities of both countries. The initial aim of BINA was to make optimal use of these Indo-Belgian telescopes, from sharing expertise in the development of the back-end instruments to the joint scientific exploitation of their observations. The BINA collaboration has become an efficient means to stimulate all types of scientific collaborations in space sciences between Belgian and Indian colleagues.

Since 2014, the Belgian Science Policy Office (BELSPO; federal authority of Belgium) and the International Division, Department of Science & Technology (DST; federal authority India) are continuously supporting BINA by providing funding for work visits (in both directions) and the organisation of workshops. By the end of 2023, three BINA workshops have taken place.

Having received the first light in April 2022, the ILMT was inaugurated on 21 March 2023, an event attended by several scientists of the ORB-KSB. Dr Ronald Van der Linden, General Director of the ORB-KSB, assisted in the inauguration as representative of our institute. The scientific exploitation of ILMT will start soon, resuming the Indo-Belgian collaboration at full capacity.

The third BINA workshop, ‘Scientific Potential of the Indo-Belgian cooperation’, took place at the Bhimtal Campus of the Graphic Era Hill University on 22–24 March 2023 and was hosted by ARIES. The scientific programme of the workshop did not only focus on observational astronomy, but also extended to other fields of space science such as the physics of the Sun, solar system objects, exoplanets, binaries, clusters, star-forming regions, massive stars, compact objects, transient, and extragalactic objects. As an additional part of the workshop, 14 popular talks by BINA participants were organised for young students in nearby schools, colleges and universities.

Prizes, Awards and ORB-KSB Scientists in the Limelight

Véronique Dehant two times honoured in 2023

On 2 May 2023, Pr Véronique Dehant, researcher in geodesy and planetary sciences at the Royal Observatory of Belgium, was elected as an international member of the National Academy of Sciences (NAS) of the United States. Later on this year, on 16 November 2023, the European Geosciences Union (EGU) awarded Véronique Dehant as the recipient of the 2024 Jean Dominique Cassini Medal.

Until the end of 2023, Véronique Dehant is responsible for the Operational Direction ‘Reference Systems and Planetology’ at the ORB-KSB. She is also Extraordinary Professor at the Université catholique de Louvain and was involved as Principal Investigator (PI), Co-Principal Investigator (Co-PI) or Co-Investigator (Co-I) of several radioscience space experiments aiming at planetary geodesy and at physics of the interior of terrestrial planets.

She is Academician (Royal Academy of Belgium; Science class) since 2010. She has taken several international responsibilities such as President of the Geodesy Section of the American Geophysical Union. She was awarded with several prizes, including the Descartes Prize of the European Union in 2003, the AGU Whitten Medal in 2016 and the FNRS Quinquennial Prize in 2020. In 2021, she was among the top 2% most cited researchers in the world in the field of ‘Astronomy and Astrophysics’.

Her election as an international member of the NAS and the Jean Dominique Cassini Medal are therefore two additional recognitions of her outstanding contributions to Earth, planetary, and space sciences during her career.

Two ORB-KSB scientists honoured by the Royal Academy of Belgium

On Saturday 16 December 2023, the Royal Academy of Science, Letters and Fine Arts of Belgium awarded two of its prizes to Dr Orkun Temel and Dr Thibault Merle, two scientists working at the Royal Observatory of Belgium.

Orkun Temel, under FWO contract, has won the 2023 annual Academy Competition – Group II – Astronomy-Physics by answering their request for ‘an original contribution, experimental or theoretical, on exoplanets and their habitability’. In his manuscript entitled ‘Intense atmospheric convection on the dayside of a tidally locked Earth-like rocky exoplanet’, Orkun Temel demonstrates the formation of massive convective cells in the lowermost part of the troposphere, which has implications for surface-atmosphere exchange processes. These convective cells, approximately ten times larger than those observed on Earth and Mars, can initiate dust storms similar to those seen on Mars and significantly impact the vertical transport of water. This effect can lead to the loss of water initially present on the exoplanet’s surface, with obvious consequences for its habitability.

Figure 7: Orkun Temel (centre) receiving his prize from the Royal Academy with Véronique Dehant (left) and Özgür Karatekin (right).

Figure 8: Thibault Merle receiving his Paul et Marie Stroobant 2023 Prize from the Académie royale de Belgique.

Thibault Merle, under FED-tWIN contract, has been awarded the 2023 Paul and Marie Stroobant Prize for his discovery, published in the journal Nature Astronomy in 2022, of a quadruple star system whose future evolution could give rise to a supernova. Thibault Merle has shown that the outer binary system gravitationally disturbs the orbits of the inner binary system, making them more elliptical. His advanced simulations of the future evolution of this system show that such dynamics can lead to one or more collisions and mergers producing 'dead' evolved stars (white dwarfs). Following mass transfers or mergers, these white dwarfs can produce a thermonuclear explosion known as a supernova.

The winners and 2023 prizes of the Royal Academy of Belgium: https://academieroyale.be/fr/actualites-detail/messages/classe-sciences-laureats-prix-decernes-2023/

Christine Verbeke, who worked at the ORB-KSB, participated in the Flemish 2023 PhD Cup

Christine Verbeke, who until recently worked at the space weather prediction centre of the Royal Observatory of Belgium (ORB-KSB), participated in the Flemish PhD Cup.

In this contest, new PhD holders present their research and convince a jury in less than 3 minutes. The final was livestreamed by VRTmax on October 19, 2023, at 19:00. Christine presented her work on the modelling of solar storms, which resulted in a more precise estimate of the arrival time and the intensity of such events. Thanks to her research, the accuracy of the space weather predictions that are made daily at the ORB-KSB will continue to improve.

Figure 9: Christine Verbeke during the PhD Cup finale of 2023.

In addition, the PhD Cup contest also has a public prize, in which anyone can vote for one of the eight finalists. For this public prize, the chosen finalists present their research in a very short pitch. Christine's video, titled 'Gevaar uit de ruimte' (Danger from space), talks about space weather and the dangers coming from the Sun.

Christine Verbeke made it to the final of the contest. The ORB-KSB congratulates her for her achievements.

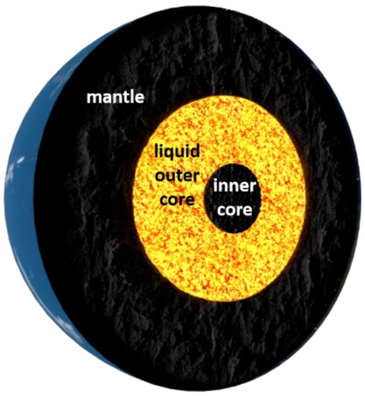
Renovation of the bust of Nicolaus Copernicus in the Brussels Planetarium

2023 marks the 550th anniversary of the birth of Nicolaus Copernicus (Mikołaj Kopernik). To mark the occasion, the Polish Institute Brussels renovated the bust of this famous Polish astronomer in July 2023.

The sculpture stands at the entrance to the Brussels Planetarium of the Royal Observatory of Belgium. It was built in 1973 to mark the 500th anniversary of Copernicus's birth.

Video of the bust renovation: https://youtu.be/Zz6tJnS4n1k

ORB-KSB scientists clarified a study on the Earth solid core rotation that confuses the media



An article in Nature Geoscience on the rotation of the Earth's core (more precisely its solid inner core) was recently published. However, the media had been misled by the press release of the science journal into thinking that the inner core stopped rotating or was even rotating in the opposite direction to that of the Earth surface, which is not the case at all. Scientists of the ORB-KSB specialised in the rotation of the Earth and planets clarified the study and provided some information on the structure and rotation of the Earth. The reader can find the clarification in the ORB-KSB news article: https://www.astro.oma.be/en/a-study-on-the-rotation-of-the-earths-solid-core-confuses-the-media/

The Royal Observatory of Belgium Commits to Gender Equality in Science

According to the UNESCO Institute for Statistics, 33.3% of the researchers are women. This percentage is of the same order of magnitude as that of ORB-KSB's researchers, which shows a general trend of between 30 and 35% of women in its scientific staff, with a slight increase since 2016. At the Royal Observatory of Belgium (ORB-KSB), initiatives to promote women in science have been carried out by several collaborators in recent years, notably within the BeWiSe (Belgian Women in Science) association and the very recent Soapbox Science Brussels initiative (see the corresponding Highlight in page 56). In addition, the ORB-KSB has very recently started working on a Gender Equality Plan (GEP), which aims to achieve a better balance and an inclusive practice of science in our institute.

The ORB-KSB Gender Equality Plan (GEP) aligns with the European Commission's 'Strategy for Gender Equality' that requires every scientific research organisation to have a Gender Equality Plan (GEP) in place in order to qualify for funding. The ORB-KSB's GEP is itself an adaptation of the Gender Equality Plan of the Belgian Science Policy Office (Belspo), the body that coordinates the Federal Scientific Establishments of which the ORB-KSB is a part.

A strategy for gender equality notably includes measures favouring work-life balance for men and women. For example, the ORB-KSB already provides the majority of its staff flexible working hours and extensive teleworking opportunities.

There is still work to be done to better promote gender equality at the ORB-KSB, and the GEP will serve as a roadmap to guide our institute towards this ideal. A first step will be to analyse in detail ORB-KSB's gender staff statistics, identify any imbalances and determine their origin and, if possible, suggest ways to correct them.

Research at the Royal Observatory of Belgium

Seismology and Gravimetry

Seismic Activity in and around Belgium in 2023

In 2023, 120 earthquakes and 3 induced earthquakes were located by the Royal Observatory of Belgium in or near Belgium. Six earthquakes were felt by the population near the Belgian territory (Germany).

In 2023, 120 natural earthquakes occurred in a zone between 1° and 8°E longitude and 49° and 52°N latitude (Figure 10). During the same period, the Royal Observatory of Belgium (ORB-KSB) also measured 3 induced events, 344 quarry blasts and at least 13 explosions offshore linked to controlled explosions of WW1 and WW2 bombs by the Belgian, Dutch or French Armies.

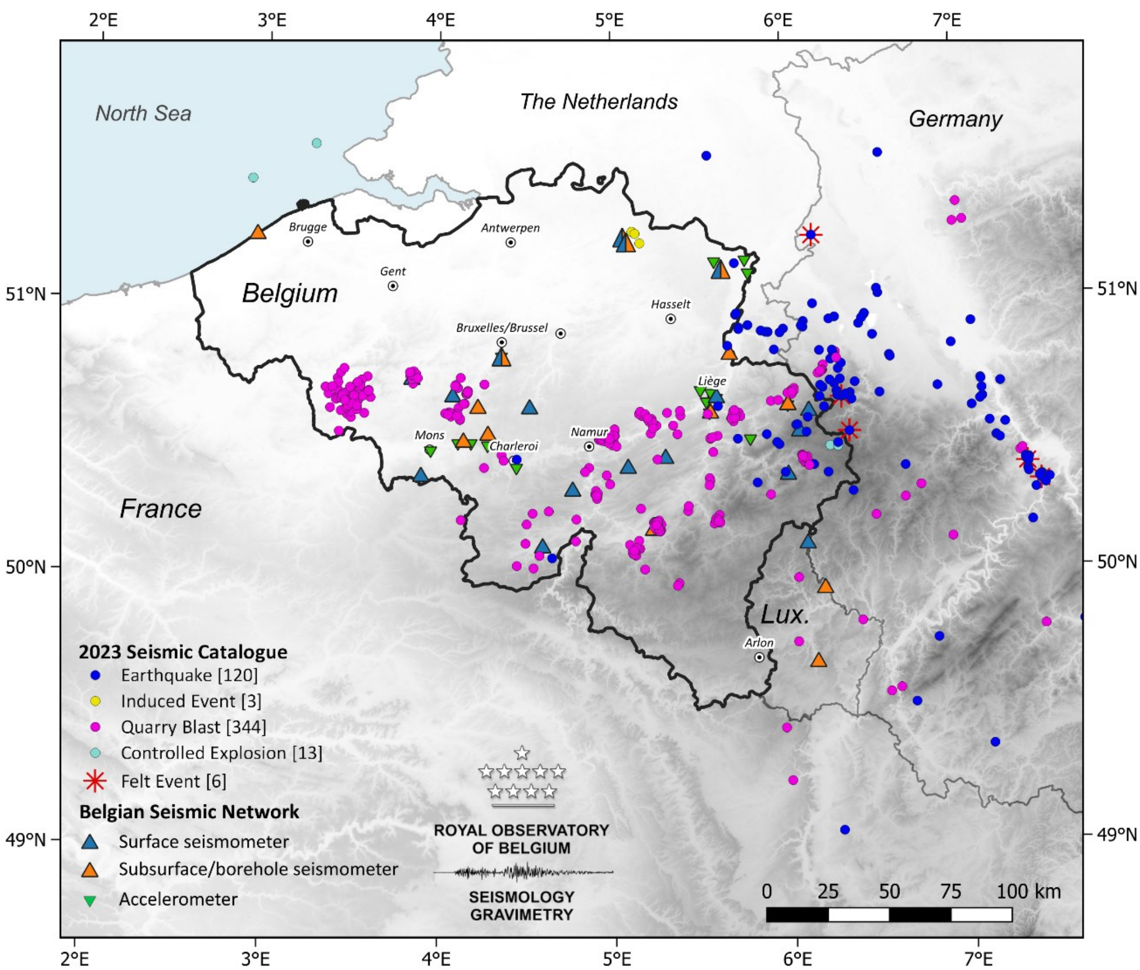


Figure 10: Events recorded in 2023 by the Belgian Seismic Network of the Royal Observatory of Belgium.

The 2023 ORB-KSB catalogue is complete for natural earthquakes with a magnitude M_L larger than 1.0. Events with magnitudes lower than 1.0 were also routinely detected where the Belgian seismic network is denser. The 2023 ORB-KSB seismic catalogue also contains a selection of quarry blasts, earthquakes induced by human activities, e.g. linked to (rock) mass removal in quarries or geothermal exploitation.

23 natural earthquakes and at least 3 induced earthquakes occurred on the Belgian territory. The largest earthquake was the event on 22 February 2023 in Maasmechelen, with a local magnitude M_L of 2.0. This earthquake was not felt by the population.

In comparison, last year, in 2022, 99 earthquakes occurred in and around Belgium.

Commemoration of the Liège 1983 earthquake

On Wednesday 8 November 1983, 40 years ago, a medium-sized earthquake shook the city of Liège. This earthquake occurred in the middle of the night at 1:49 am local time (0:49 UTC) and had its epicenter in the commune of Saint-Nicolas, a densely populated municipality west of the city of Liège. This is the last earthquake with significant damage in Belgium. The earthquake had a local magnitude of 5.0 and its hypocenter was located at a depth of 5.8 kilometers with an uncertainty of 1.2 kilometers. The earthquake was felt all over the Belgian territory, as far away as Amsterdam (Netherlands) in the north, Frankfurt (Germany) in the east and Metz (France) in the south.

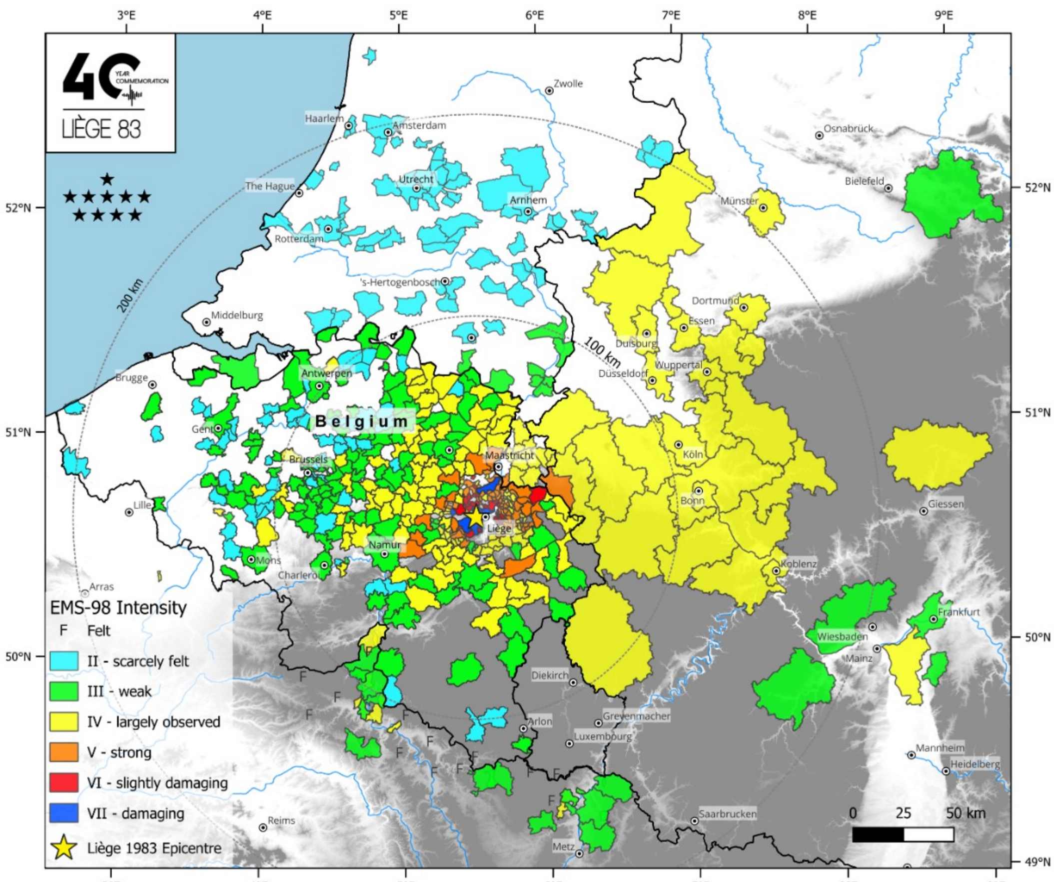


Figure 11: Macroseismic intensity map of the Liège earthquake on 8 November 1983 in Belgium. Maximum intensity was VII.

In Belgium, tectonic earthquakes usually occur at greater depths of 10 to 15 km. Due to its shallow nature, the 1983 Liège earthquake caused severe damage in the communes of Saint-Nicolas, Glain and Montegnée, as well as in the cities of Liege, Seraing, Ans and Grâce-Hollogne. Moreover, ground movements were further amplified by soft Quaternary deposits of the Meuse river and by the underlying folded geological structure. The strength and damage of an earthquake at the surface is expressed by the European EMS98 intensity scale. In the epicenter and in most of the Liège agglomeration, the intensity was the highest, i.e. intensity VII, and caused considerable damage. The impact of the ground motion at the surface is expressed by the European EMS98 intensity value. In the epicenter and in most of the Liège agglomeration, intensity VII was reached, causing damage. Older vulnerable houses experienced severe damage: large cracks across the walls, collapsing chimneys that caused additional damage after their fall and a few buildings even partially collapsed. More recent buildings experienced some cracking of the walls and chimneys were partially damaged. Many houses had already been weakened by subsidence due to mining in the Liège coal basin and due to decades of groundwater fluctuations.

Figure 12: Pictures of damage in the epicentral area around Saint-Nicolas, Flémalle and Liège.

The Liège earthquake was officially recognised as a natural disaster and, consequently, residents could have the damage to their homes compensated by the National Disaster Calamity. This info is currently kept in the Belgian State Archives and contains at least 16,000 files with detailed descriptions of damage and its reimbursement. In the end, over 100 million euros (adjusted for inflation) was reimbursed. This archive, rare in Western Europe, is a very rich database for assessing the financial impact of a shallow earthquake in urban areas. In the end, more than 100 houses were declared uninhabitable, more than 1,000 people were homeless and, sadly, there were 2 fatalities.

At the time of the 1983 earthquake, the Seismology Department of the Royal Observatory of Belgium only had 4 seismographs operational in Uccle, Dourbes, Membach and Walferdange (Luxembourg). Since seismograms were only available in analogue form and printed on paper, they had to be collected immediately after the earthquake from these seismic stations. Earthquake arrival times from European seismic stations were forwarded to the Observatory by telegram in the days after the earthquake. Calculating magnitude and depth, crucial parameters to calculate the impact of an earthquake, was a slower process at that time, which could take up to hours or even days. The 1983 Liège earthquake was therefore the trigger to install a modern dense seismic network in Belgium. Currently, the Royal Observatory of Belgium operates a network of 29 surface and borehole seismometers and 16 accelerometers, spread over the Belgian territory, which enable seismologists to determine the location, magnitude and depth of an earthquake in minutes.

On Wednesday, 8 November 2023, the 1983 Liège earthquake was commemorated at the Royal Observatory of Belgium during a scientific study afternoon that was attended by those in charge of the city of Liège, national and regional crisis centres, federal and regional authorities, geologists, seismologists, and engineers from all universities in Belgium.

Source parameters:

- Epicenter: 50.6280°, 5.5150°
- Local magnitude: 5.0
- Depth of the hypocenter: 5.9 ± 1.2 km
- https://seismologie.be/en/seismology/earthquakes-in-belgium/lv243oom5

Global Navigation Satellite Systems, Time and Reference Systems

GNSS Services for the European Plate Observing System

The European Plate Observing System (EPOS) is Europe's e-infrastructure providing multidisciplinary data and services in support of Solid Earth Science. Belgium is a founding member of the EPOS European Research Infrastructure Consortium (ERIC).

EPOS Thematic Core Service (TCS) 'GNSS data and products' (EPOS-GNSS) consists of a network of almost 2000 GNSS stations and provides access to GNSS data, metadata and products, such as ground deformations. The GNSS team of the Royal Observatory of Belgium (ORB-KSB) contributes to EPOS by providing coordination and governance services, as well as GNSS data, product and software services. The EPOS central data portal was officially released at the EGU General Assembly 2023 and the ORB-KSB's GNSS team was actively involved in the preparation of this event.

Data, Product, and Software Services

The metadata of EPOS' GNSS stations are managed through the 'Metadata Management and Dissemination System for Multiple GNSS Networks' (M3G) developed and operated by the ORB-KSB. M3G collects, validates and distributes GNSS station metadata in-line with international standards. In 2023, M3G was significantly revised to improve its performance, user experience, and progress towards using FAIR data principles.

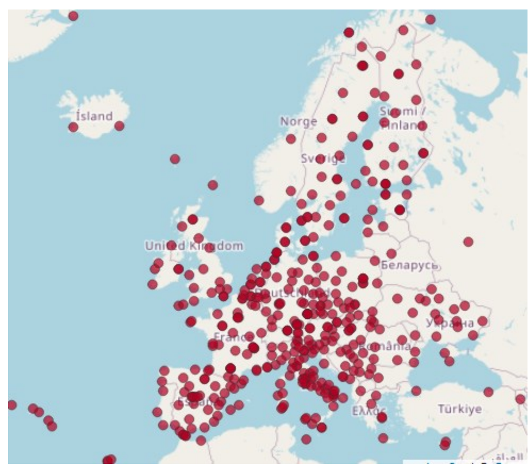


Figure 13: GNSS stations included in ROB-EUREF data node.

At the data level, the ORB-KSB ensures EPOS has access to the data from the EUREF Permanent GNSS Network (EPN) by operating the EUREF data node of the ORB-KSB (ROB-EUREF). In 2023, in the frame of the ESFRI-FED SERVE project, the design and workflow of the node have been completely revised, hence improving its operation and service. At the end of 2023, the node included 429 stations and counted 2.3 million files which are all openly available on the ORB-KSB's EUREF-EPOS website.

Moreover, since 2023, the ORB-KSB also makes the Belgian GNSS data openly discoverable to EPOS through a new Belgian data node. Next to ORB-KSB's own GNSS data, the node includes GNSS data from Digitaal Vlaanderen, Service public de Wallonie, Centre Spatial de Liège, and Institut Géographique National. The ORB-KSB curated all their GNSS data in-line with the methodology put forward in the Brain 2.0 FAIR-GNSS project. At the end of 2023, the Belgian node provided access to about half a million files for 78 GNSS stations.

Figure 14: Belgian GNSS stations discoverable through EPOS.

Supported by the BELSPO EPOS-BE and ESFRI-FED SERVE projects, the ORB-KSB has been developing a 'Data Quality Monitoring Service' (DQMS) since 2021 aimed at monitoring the data availability and quality of the EPOS-GNSS data. In 2023, this resulted in the acknowledgment of the ORB-KSB's DQMS as a new operational EPOS service and its associated portal became an EPOS community portal. The DQMS portal presents the tracking performance of 1700+ EPOS-GNSS stations and includes a unique set of GNSS data quality indicators assessing the EPOS-GNSS stations' availability and performance.

The ORB-KSB is also responsible for computing the EUREF reference frame product which consists of multi-year coordinate and velocity estimates for the EPN stations. The primary goal of this solution is to maintain the ETRS89 which is the European Terrestrial Reference System. Because the velocity field and the position time series of the EPN stations are valuable for geophysical research, the ORB-KSB provides this solution regularly to EPOS.

In 2023, the ORB-KSB took over the development of the software package dedicated to the quality monitoring of the GNSS data at the GNSS data nodes.

Coordination and governance activities

The ORB-KSB plays an active role in the governance of EPOS. In 2023, C. Bruyninx was re-elected as chair of the EPOS ERIC Service Coordination Committee. The SCC represents all the EPOS TCSs, as well as the Integrated Core Services, and provides support and advice to the EPOS Executive Director. Her membership of the EPOS ERIC Executive Committee was also prolonged with one additional year and she was re-elected for a second term as chair of the Executive Board of the EPOS Thematic Core Service 'GNSS data and products'.

In addition, in 2023, the ORB-KSB increased its contribution to EPOS by starting to coordinate the development of the software used by the GNSS data nodes.

In the background, the ORB-KSB continued to manage the EPOS-GNSS station network, attracting GNSS stations to share their data with EPOS and help them through the process of integrating their metadata and data in EPOS. In 2023, the ORB-KSB attracted more than 300 additional GNSS stations to share data with EPOS.

EPOS-BE

In 2023, in the frame of the ESFRI-FED SERVE project, the ORB-KSB completely renewed the EPOS-BE website providing now an overview of Belgian national and regional research institutes and governments providing data and services to a range of thematic domains in EPOS. The ORB-KSB also organized on Nov. 24, 2023 the webinar 'Meet EPOS-BE', in collaboration with EPOS ERIC, to make EPOS better known in Belgium.

Belgian Legal Time and the Definition of the Second

While the legal time in Belgium was defined in a law of 1892 as the mean solar time in Greenwich, and then redefined in the law of 2018 as being the Universal Time Coordinated (UTC), there was still a gap in our legislation concerning the accessibility to the legal time.

Indeed, UTC is not a physical signal available in real time. UTC is an average of about 450 atomic clocks distributed in about 80 time laboratories around the world including the one of the Royal Observatory of Belgium (ORB-KSB). UTC is computed only once per month for the previous month. Each time laboratory therefore maintains a realization of UTC which is a physical clock whose frequency is adjusted to create a physical signal closely aligned on UTC. At the ORB-KSB, we maintain such a realization and call it UTC(ORB), which deviates from UTC by no more than 5 nanoseconds.

On October 20, 2023, a Royal Decree was published in the Belgian Official Journal (Belgisch Staatsblad/ Moniteur belge), specifying that the ORB-KSB and the Metrology Service are responsible for the realization and dissemination of legal time. UTC(ORB) is therefore now the source of Legal Time for Belgium.

UTC(ORB) is currently disseminated via internet through the protocol NTP, allowing the user to get UTC(ORB) with millisecond accuracy. The ORB-KSB started this year a project named BOOSTED, for '**B**elgian **O**ptical network for **O**ptical frequency **S**tandards and **T**im**E** **D**issemination', aiming at the dissemination of time and frequency via optical fibers, allowing future research centers to receive the UTC(ORB) at the nanosecond level, and a frequency whose relative stability should be below 10^{-17} in the coming years.

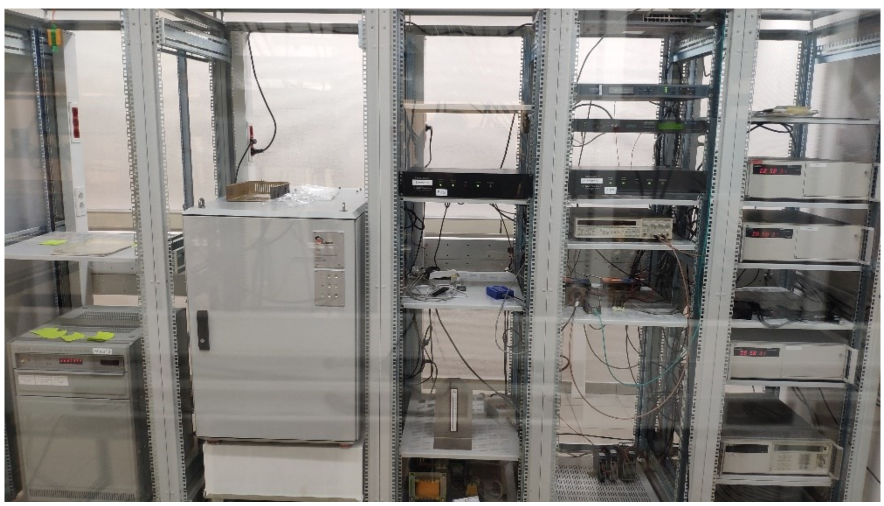


Figure 15: Atomic clocks in the Time Laboratory of the ORB-KSB.

In parallel, the scientists of the ORB-KSB take part in the work of the Consultative Committee for Time and Frequency (CCTF) Task Force on the redefinition of the SI Second. The current definition of the second relies since 1967 on the cesium atom hyperfine transition frequency. Cesium primary frequency standards are currently realizing this unit with a relative frequency uncertainty at low 10^{-16} level, but in the two last decades they have been surpassed by optical frequency standards (OFS) showing much lower uncertainties, currently 2 orders of magnitude better. The accuracy of frequency measurements is, therefore, limited by the current definition, rather than being limited by the technological level reached by the most advanced scientific teams.

The CCTF Task Force is analyzing the various options available: either choosing one single atomic transition in lieu of the Cs hyperfine transition and to fix the numerical value of the frequency of this transition, or, choosing a weighted geometrical mean of the frequency of an ensemble of chosen transitions, since so far many different atomic transitions already give optical frequency standards with uncertainties near 10^{-18}. With this latter, each optical clock based on one of these transitions would provide a primary realization of the SI second. The CCTF Task Force has defined in 2023 a ROADMAP towards a redefinition of the second (see reference at the end of the article). Some mandatory criteria and ancillary criteria have been identified, and their current fulfillment level is estimated, showing the fields that still needed improvement (see Figure 16).

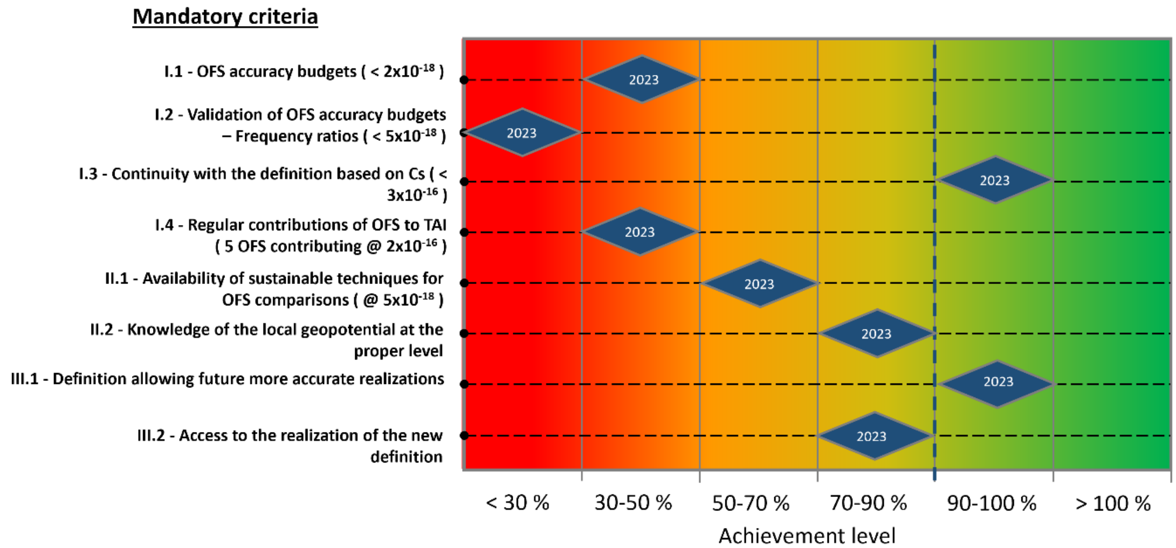


Figure 16: Fulfillment levels of mandatory criteria for the redefinition of the SI Second.

We can expect that the 28th General Conference of Weights and Measures (CGPM) in 2026 could validate a roadmap towards a redefinition in 2030 if there is a consensus on the option to be chosen, and if the work to fulfill mandatory criteria is likely to be achievable by 2030. If a redefinition is not possible in 2030, it will have to be postponed until the meeting of the CGPM to be held in 2034.

The most fundamental of the existing scientific applications that will be improved by a redefinition and an associated improvement in timing infrastructures are the tests of fundamental physics. These include the investigation of physics beyond the standard model and time variation of the fundamental constants, searches for dark matter, gravitational wave detection, and more. Better clocks will also enable higher-precision atomic and molecular spectroscopy as well as improved time synchronization for high-resolution telescope arrays and Very Long Baseline Interferometry (VLBI), geopotential monitoring with centimeter resolution through the gravitational redshift measured by atomic clocks, quantum networks for quantum encrypted communications, and others.

These emerging fields of research, that already require a better time and frequency accuracy or stability than is available today, and applications that promise to transition from research lab into commercial use in the next decades, will benefit from the improved accuracy provided by a redefinition.

Reference: Dimarcq et al., Roadmap towards the redefinition of the second, *Metrologia* 61 012001 (2024). https://doi.org/10.1088/1681-7575/ad17d2

Earth and Planetary Science

Meteorite in and Dinos out: How impact-generated dust doomed the dinosaurs

Figure 17: North Dakota in the first months following the Chicxulub impact event 66 million years ago, showing a dark, dusty, and cold world in which the last non-avian dinosaurs, illustrated with a Dakotaraptor steini, were on the edge of extinction. Artwork by Mark A. Garlick.

The Chicxulub meteorite impact triggered a global winter, which led to the demise of non-avian dinosaurs and of around 75% of species on Earth at the Cretaceous-Paleogene (K-Pg) boundary 66 million years ago. However, what effect the various types of debris ejected from the impact crater had on the climate has been debated, and which exact mechanism steered the mass extinction remains unclear to date.

A groundbreaking paper in Nature Geosciences led by scientists from the Royal Observatory of Belgium (ORB-KSB) showcases that the micrometric silicate dust released by the Chicxulub crater formation in the Yucatan is the prime factor causing the demise of non-avian dinosaurs and the Cretaceous Paleogene mass extinction 66 million years ago. Field measurements and in-situ grain size analysis were used in an in-house paleoclimate model, revealing that the fine dust blocked sunlight for years, drastically cooled the whole planet (by about 15 °C), strongly reduced photosynthesis on Earth, and disrupted the food chain on land and in the oceans. The dust caused a twenty-year-long impact winter, with no vegetation growing during the first two years.

The study introduced, for the first time, a coherent mechanism that triggered the deadly impact winter that led to Earth's last major mass extinction, based on sedimentological and grain size measurements of the impact layer on the Cretaceous-Paleogene layer in North America. The sun-blocking effect of impact-generated dust was previously thought to be minor in most models in favor of sulfur-bearing gas or soot from wildfires. This research shows that the micrometric silicate dust lingered in the atmosphere much longer and was by far the most efficient in stopping photosynthesis.

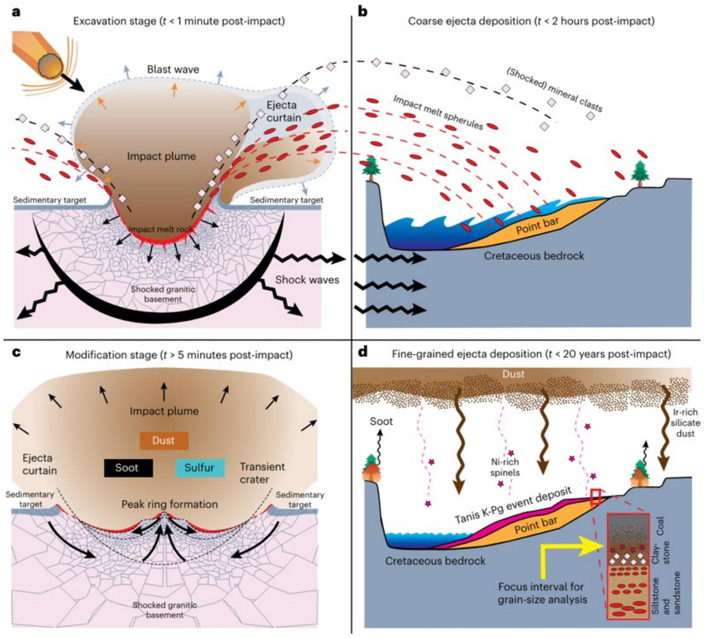


Figure 18: Conceptual model of the Chicxulub impact plume showing different stages of production, transport, and deposition of coarse and fine-grained impact-generated ejecta, not to scale (Senel et al., 2023).

Furthermore, short-term impact cooling due to the massive release of sulfur-bearing gases originating from rock vaporization is hypothesized to have been crucial. In a recent study in collaboration with the Universiteit Gent (UGent) and the VUB (Rodiouchkina et al. 2024), the amount of impact-released sulfur was estimated for the first time. Relying on the isotopic composition of sulfur within the impact structure and in a set of terrestrial K-Pg boundary ejecta sites, the value of 67 ± 39 gigatons obtained is nearly 5-fold lower than recent numerical estimates but concurs with numerical estimates from the 1990s. This unique data is incorporated into a paleoclimate model by ORB-KSB scientists to reassess post-impact climatic responses of S. The lower mass of S-released implies global average surface temperatures above freezing point with key implications for species survival during the first years following the Chicxulub asteroid impact.

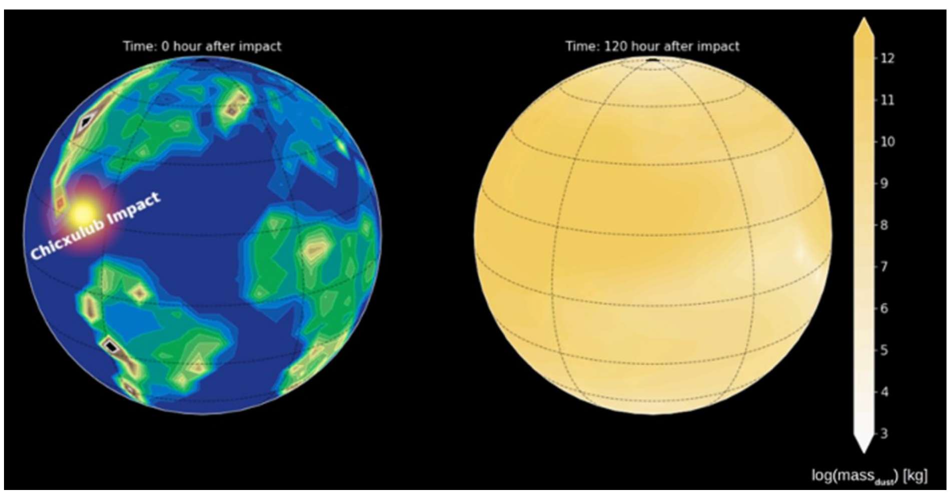


Figure 19: Paleoclimate model simulations demonstrate the rapid dust transport across the planet, indicating that the Paleogene world was encircled by the silicate dust ejecta within a few days following the Chicxulub impact event.

Understanding the dust transport, whether impact-generated or naturally occurring, is not just essential for deciphering our home planet's past ecosystems. It also provides significant implications for dusty worlds in a broader context, like Mars experiencing extreme dust storms, or even farther cosmic landscapes, such as Titan – the largest moon of Saturn.

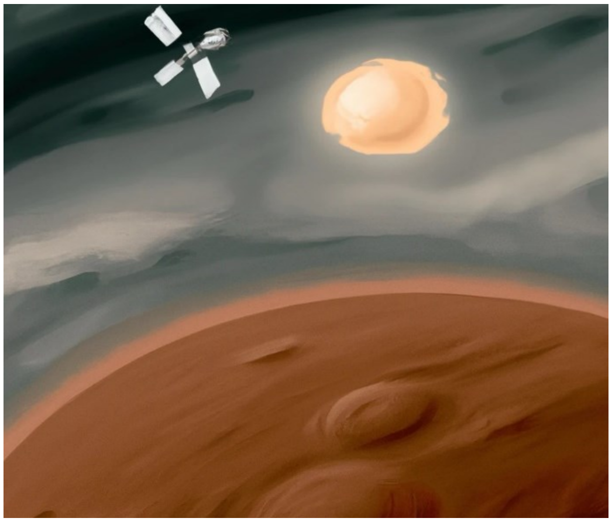


Figure 20: The illustration depicts "A voyage through dusty turbulence on Mars" (Cem Berk Senel, PhD Thesis, 2023).

References:

- Cem Berk Senel, Pim Kaskes, Orkun Temel, Johan Vellekoop, Steven Goderis, Robert DePalma, Maarten A. Prins, Philippe Claeys, Özgür Karatekin (2023). *Chicxulub impact winter sustained by fine silicate dust*. Nature Geoscience 16, 1033-1040.
- Katerina Rodiouchkina, Steven Goderis, Cem Berk Senel, Pim Kaskes, Ozgur Karatekin, Orkun Temel, Michael Boettcher, Ilia Rodushkin, Johan Vellekoop, Philippe Claeys, Frank Vanhaecke (2024). *Reduced contribution of sulfur to the mass extinction associated with the Chicxulub impact event*.EarthArXiv, doi: https://doi.org/10.31223/X5M99H
- Cem Berk Senel (2023). *Multiscale Modeling of Planetary Boundary Layers on Earth and Mars*. Doctoral dissertation, Université libre de Bruxelles, Royal Observatory of Belgium.

The way they feel inside: mapping asteroids interiors from their gravity field

In a recent Icarus article, ORB-KSB scientists proposed a new approach to constrain the distribution of the mass within an asteroid or a comet given measurements of its gravitational potential. Understanding the interior structure and composition of a small body can help to constrain its origin and history, which is closely related to the history of the Solar System itself. The gravitational potential is a direct expression of the mass distribution and can be measured by tracking its perturbations on a spacecraft trajectory. Typically, these measurements are good at determining the gravitational potential at large spatial scales but are limited in spatial resolution. Therefore, our mapping of internal heterogeneities is itself bound to be limited in resolution.

The main limitation to the knowledge we can infer about the interior comes, however, from the non-uniqueness of the problem, meaning that there are multiple mass distributions providing the same gravitational potential. It is not much different than trying to guess depth information from a photograph (quite blurred, in our case): we can never really be sure that what we see is not a distant bona fide giant holding up the tower of Pisa. Much like in that situation we would resort to our knowledge about average heights of people and monumental structures to inform our guess, here we need to introduce some prior knowledge to hope and reach a reasonable conclusion.

Our main assumption is that the inside of the body is like a tangram puzzle, divided into a few regions of uniform density which are separated by sharp boundaries. The novel aspect of our approach is that, along with the density within each region, it allows one to estimate any shape for these boundaries. This is possible thanks to the level-set method, a framework popular across various fields: notably, its use is common in the inversion of Earth local-gravity data for the imaging of subsurface structures, like mineral deposits. However, to the best of our knowledge, the level-set method had never been applied to the global gravity inversion of other bodies.

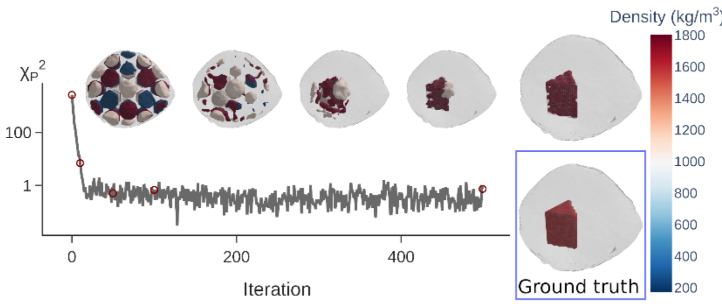


Figure 21: Convergence history for a simple simulation case.

Figure 21 shows an example of the performance of our approach in an ideal scenario of noise-free and high-resolution simulated measurements. Starting from a generic initial model, the iterative method adjusts the densities and the shapes of the physical boundaries to better fit the gravity data and converges to an interior model very similar to the ground truth (the density distribution used to generate the synthetic observable phenomenons).

In a realistic case, however, there are several complications to this ideal scenario. To cite a few: the model itself will never be composed exactly of regions of uniform density as in our assumption; the gravity data will be spoiled by noise and limited in spatial resolution; the shape of the body will not be perfectly known. As an example, Figure 22 shows the degradation in the accuracy of the retrieved distribution when the resolution of the gravity is reduced, varying from the highest to the lowest resolution that can be expected from a spacecraft encounter. We performed a sensitivity study of the performance of the method with respect to all these factors. The results proved the model to be robust with respect to noise in the data and uncertainties in the body shape, and to be able to detect shallow heterogeneities if their size is larger than the gravity spatial resolution and their density contrast higher than about 5%. These thresholds become higher for deeper heterogeneities, as also seen in Model 2 of Figure 22. Additionally, even in the case of more realistic models such as rubble-pile structures or smooth distributions, the method generally converges to reasonable approximations of the ground truth.

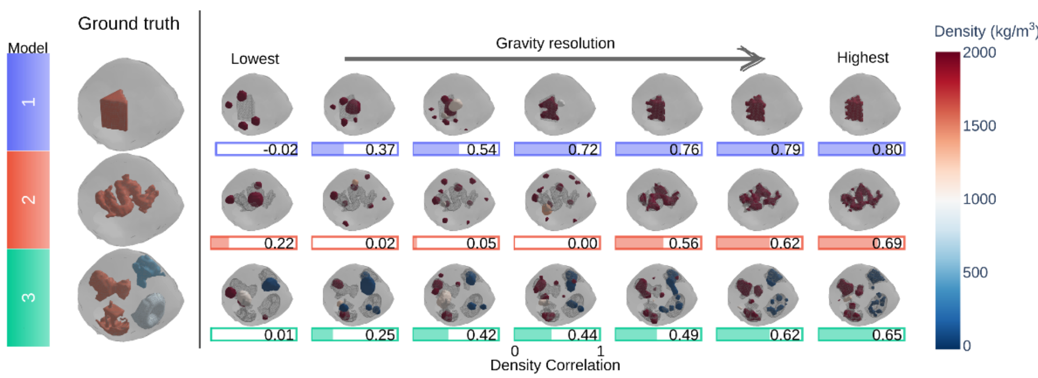


Figure 22: Retrieved density distributions as a function of resolution of the simulated gravity field.

Despite our assumptions, the retrieved solution is not guaranteed to be unique, especially with noisy measurements of low resolution. We attempt to describe the range of possible density distributions, or more poetically 'explore the solution space', by repeating the inversion multiple times with randomized initial models. Computing statistics over the resulting density distributions additionally provides uncertainty bounds associated to any detected heterogeneity.

As validation of the method, we presented its application to the inversion of the real gravity data measured by OSIRIS-REx for Bennu, demonstrating that we can retrieve a model compatible with the ring-core structure proposed by the OSIRIS-REx team, as long as light constraints demanding a less-dense equatorial region are introduced.

Constraints of this kind help mitigate the non-uniqueness of the inversion, as does considering additional (independent) measurements. For example, in the case of Phobos, we tested the inclusion of the amplitude of the forced libration in longitude, which is related to the density via the principal moments of inertia. Figure 23 shows how the addition of the libration observable can be helpful in the detection of a nearly spherical core, whose size cannot be retrieved from gravity alone.

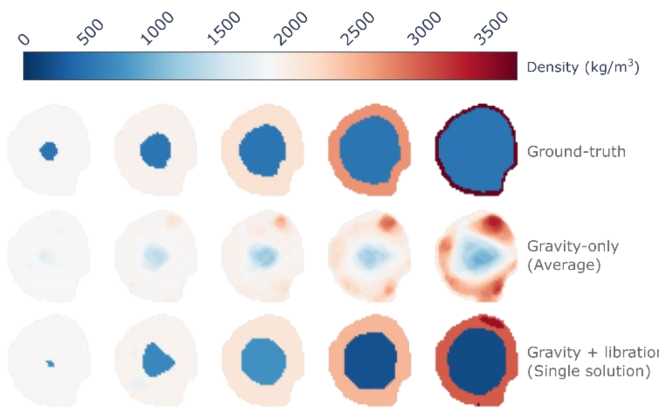


Figure 23: Impact of adding libration to the simulated dataset on the retrieval of a mantle-core model for Phobos.

Ongoing work focuses on expanding the type of constraints and measurements that can be handled by the software, to make the most out of the set of observations future missions like MMX (to Phobos) and Hera (to the Didymos system) will provide.

Reference:

Caldiero, A., & Le Maistre, S. (2024). Small bodies global gravity inversion via the level-set method. Icarus, 411, 115940. https://doi.org/10.1016/j.icarus.2023.115940.

Using Fluid Motions Excited in Mercury's Core to Investigate Its Top Stable Layer

Introduction

Mercury, the innermost planet of our Solar System, is an enigmatic planet in more ways than one. It is the smallest of the terrestrial planets but has a relatively very large inner core. It is also the only other terrestrial planet, besides Earth, that generates its own magnetic field. Interestingly, though, this dipole-dominated magnetic field is extremely weak, leading researchers to believe that the outermost region of the core is stable against convective motions, which reduces the overall strength of the magnetic field and filters out most of the non-dipole components. The existence of such a stably stratified layer is supported by thermal evolution models, some of which have been developed by the planetary science team at the Royal Observatory of Belgium (ORB-KSB; see reference 1 at the end of this highlight). However, the exact width of the layer and its stratification strength, quantified by the Brunt-Väisälä frequency N, is still unknown.

Simulating the Core Flow Response to Liberating Motions

To constrain the internal properties of the stable layer we investigated the flow motions in a numerical model of Mercury's core, both with and without a top stably stratified layer. In particular, we have calculated the response of the iron fluid in the core to variations in the rotation rate of its rocky mantle. Due to its proximity to the Sun and the resulting strong gravitational attraction, Mercury rotates in a very peculiar way. Every time it orbits twice around the Sun, it will spin on average only three times around its own axis, a so-called 3:2 spin orbit resonance. The gravitational torque exerted by the Sun on Mercury's mantle, which is shaped like a triaxial ellipsoid, will therefore increase and decrease during every orbital

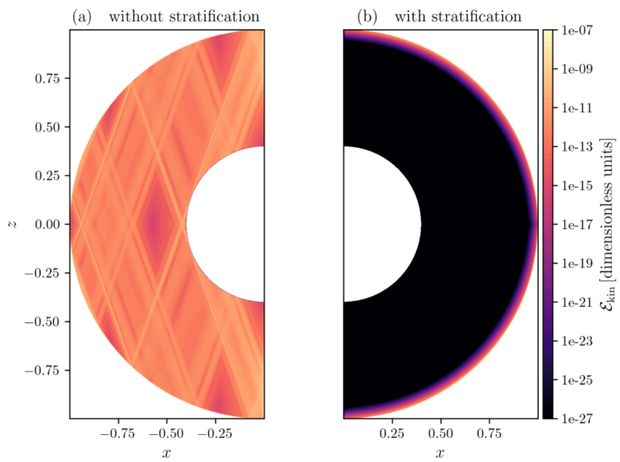


Figure 24: The kinetic energy of the simulated core flow with (right) and without (left) a stably stratified layer.

period of 88 days. This also causes the rotation of the mantle to speed up and slow down over an 88-day period. These periodic variations in the average rotation rate are called librations and form the basis of our study. This non-constant rotation of the mantle excites a flow in the core, which we have investigated using the numerical tool Kore, developed at the Royal Observatory (see reference 2 at the end of this highlight).

In a study published last year in the Planetary Science Journal (see reference 3 at the end of this highlight), we showed that there is a clear difference between the librationally excited flow in a core with or without a stably stratified layer. In the latter case of a neutrally stratified core, fluid motions are free to travel all the way down to the inner core boundary (see Figure 24(a)), whereas in the former case when a stable layer is present at the top of the core, the fluid motions are confined near the outer boundary (Figure 24(b)). It turns out that the stratified layer strongly damps radial motions in favor of horizontal motions, a mechanism that is almost exclusively determined by the strength of the stratification N. This means that we would be able to constrain the strength of the stable layer, if we can observe the signature of the horizontally confined flow.

Negligible Effect of the Flow in the Core on the Libration Amplitude

Even though direct observation of the flow in the core is impossible, there are two ways that we might still indirectly observe the librationally excited flow, by looking at measurements of either the planet's rotation or its magnetic field. First, we tested the effect of the core flow on the rotation of the mantle. Just as angular momentum of the mantle motion can be transferred to the core, so can angular momentum of the resulting fluid motion also be transferred back to the mantle. In the case of Mercury, this can, for example, be done via the viscous torque, where fluids near the outer boundary viscously drag the mantle along, or via the electromagnetic torque, where the differential motion between core and mantle causes the magnetic field lines to stretch and produce a Lorentz force on the bottom of the conducting mantle. Our calculations show, however, that both the viscous and the electromagnetic torques contribute very little to the rotation of the mantle. In fact, the combined effect of viscous and electromagnetic torques changes

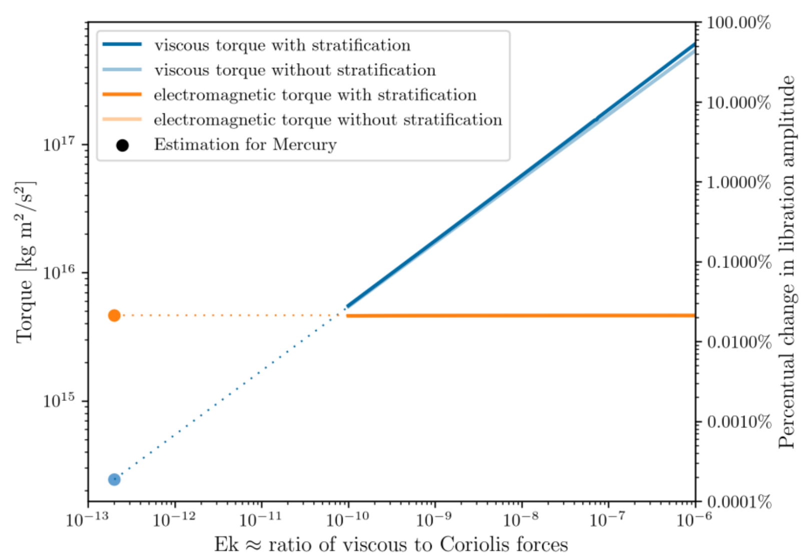


Figure 25: Viscous and electromagnetic torques acting on Mercury's mantle.

the libration amplitude by less than 50 centimeters, which is far below the current and future observational precision.

This nevertheless strengthens and confirms the prevailing assumption that the outer core flow does not need to be considered in libration studies that estimate internal properties from libration measurements.

Observable Structure in the Magnetic Field Produced by the Flow in the Core, Given a Strong Enough Stable Layer

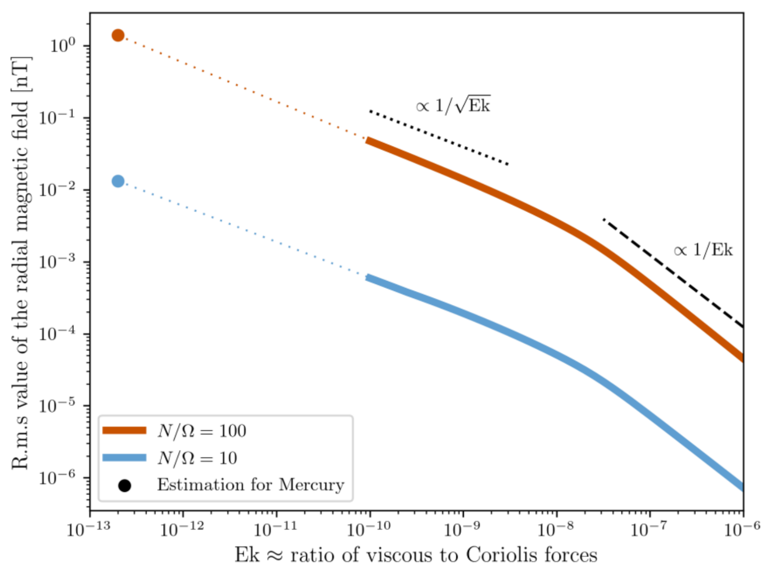


Figure 26: Induced magnetic field strength by the librationally excited flow.

A different picture emerges when examining the magnetic field that is induced by the librationally excited core flow. For the low-viscosity regime of Mercury's core, the horizontal flow near Mercury's outer boundary can become extremely strong for strongly stably stratified layers. Strong enough to induce a magnetic field of several nanoteslas if the ratio of the Brunt-Väisälä frequency to the rotation frequency is larger than 100. This magnetic field would be non-axisymmetric with an 88-day periodicity, similar, of course, to the libration period. While recent reconstructions of Mercury's magnetic field, based on magnetic field observations by the MESSENGER satellite, hint at such a non-axisymmetric field structures the observational precision so far is too low to draw any conclusions.

This could change with the anticipated 2025 arrival of the BepiColombo mission in Mercury's orbit. Magnetic field measurements are expected to significantly improve and could result in an observation of the 88-day periodic non-axisymmetric magnetic field provided, of course, that the stratified layer is strong enough. At the very least the new measurements could provide an upper limit on the stratification strength at the top of Mercury's core.

Refererences:

(1) Knibbe, J. S., & Van Hoolst, T. (2021). *Modelling of thermal stratification at the top of a planetary core: Application to the cores of Earth and Mercury and the thermal coupling with their mantles*. Physics of the Earth and Planetary Interiors, 321, 106804.

(2) Rekier, J., Trinh, A., Triana, S. A., & Dehant, V. (2019). *Inertial modes in near-spherical geometries*. Geophysical Journal International, 216(2), 777-793.

(3) Seuren, F., Triana, S. A., Rekier, J., Barik, A., & Van Hoolst, T. (2023). *Effects of the Librationally Induced Flow in Mercury's Fluid Core with an Outer Stably Stratified Layer*. The Planetary Science Journal, 4(9), 161.

Flow at the Earth's core-mantle interface

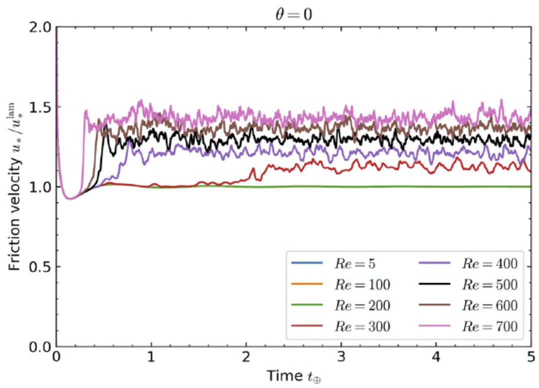


Figure 27: The flow at the core-mantle boundary becomes turbulent as the Reynolds number (a measure of the flow strength) increases.

The Earth's mantle rotation axis precesses slowly with a period of about 26,000 years. The rotation axis of the Earth's fluid core lags a bit behind that of the mantle, a motion that geodesists call the Free Core Nutation (FCN). The resulting differential motion between the mantle and the fluid core constitutes a nearly diurnal periodic flow (as seen from the mantle) with a velocity around 4 mm/s that exceeds any other flow velocity inside the fluid core. This flow at the core-mantle interface has the potential to become turbulent and therefore to dissipate energy efficiently. The observed decay rate, or damping, of the FCN might have therefore an important contribution resulting from the energy dissipated in that turbulent flow. To answer this question, scientists of the ORB-KSB simulated the FCN flow in a local region at different latitudes to determine the amount of turbulence that might be generated. The study indicated that the flow becomes unstable, and that the associated energy dissipation is about twice as much as if the flow was laminar, but still not enough to contribute significantly to the observed FCN's damping.

Reference: Sheng-An Shih, Santiago Andrés Triana, Jérémy Rekier, Véronique Dehant, *Turbulent dissipation in the boundary layer of precession-driven flow in a sphere*. AIP Advances 1 July 2023; 13 (7): 075025. https://doi.org/10.1063/5.0146932

The electrical field between two media with sliding contact

In studies of the flow inside the Earth's core, it is sometimes assumed that the fluid slides without any viscous drag over the core-mantle interface. Actually, since viscosity is always present, there is a thin fluid layer that sticks to the mantle, called the viscous boundary layer. The presence or not of viscous drag can have a profound impact on the behavior of the electromagnetic coupling between the fluid core and the mantle. We showed that the electromagnetic boundary conditions that are typically used in the literature, though correct, are based on a physically inconsistent assumption.

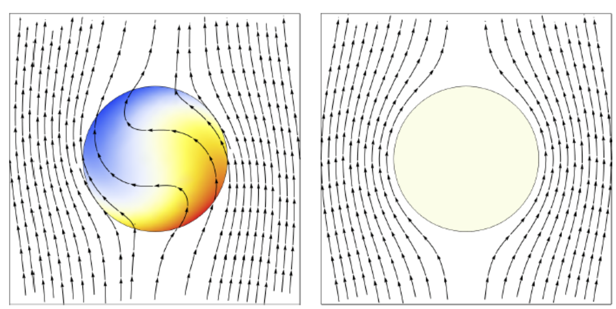


Figure 28: A rotating cylinder in a magnetized fluid drags the magnetic field lines (left) if the fluid is viscous, while no magnetic field is induced in the cylinder (right) if the fluid slides without friction.

It is often assumed that the fluid can slide with no effort with the electric and magnetic field lines behaving as if there was viscous drag. This is physically inconsistent, but we showed that it can be safely used to study the flow in the Earth's core, where models find it impractical to include any viscosity in the flow.

Reference: Rekier, Jérémy & Triana, S. & Trinh, A. & Buffett, B. (2023). *Electric interface condition for sliding and viscous contacts*. Physical Review Research. 5. 10.1103/PhysRevResearch.5.033029. https://doi.org/10.1103/PhysRevResearch.5.033029

The impact of Core-mantle topography on the Length of Day

We explored how topography at the core-mantle boundary (CMB) of the Earth affects changes in the Earth's Length of Day (LOD). Building on the seminal work by Wu & Wahr (1997), we developed innovative analytical methods to study how these deep interior features interact with the flow inside the Earth's liquid core. We demonstrated that the CMB topography can excite inertial modes, a type of fluid motion that has the potential to amplify mantle's motion at specific frequencies.

The team discovered that although amplification is theoretically possible near the frequencies of the diurnal, biweekly, and monthly tides, the resulting amplitude is small but produces a noticeable effect on the Earth's LOD, just explaining the difference between the observation and the theory without topographic torque at the CMB. This finding helps answer the long-standing question about the impact of CMB topography on LOD variations. Scientists from the ORB-KSB involved in this research are now adapting these techniques to further study nutations.

Reference: Puica, Mihaela & Dehant, Véronique & Folgueira, Marta & Van Hoolst, Tim & Rekier, Jérémy (2023) *Analytical computation of total topographic torque at the core–mantle boundary and its impact on tidally driven length-of-day variations*. Geophysical Journal International 234, 585–596. https://doi.org/10.1093/gji/ggad077

Solar Physics

EUI Onboard Solar Orbiter Discovers Jets that Could Drive the Solar Wind

The solar wind is a steady breeze blowing from the Sun into interplanetary space at speeds of hundreds of km/s. The fastest gusts of solar wind gusts can drive geomagnetic storms and come from special locations in the solar atmosphere called coronal holes. These are areas where the Sun's magnetic field stretches out in space instead of looping back onto itself. The Extreme Ultraviolet Imager (EUI), part of the Solar Orbiter mission and operated by the Royal Observatory of Belgium (ORB-KSB), has given a close-up view of these coronal holes like never before. One of its telescopes, the HRIEUV (High Resolution Imager in the EUV), snapped images on March 30, 2022, every 3s during 30 min with pixels corresponding to roughly 120 km on the Sun (see Figure 29 below). The Sun is the only star whose atmosphere we can observe in such detail, but it is likely that what we learn about the Sun is relevant for the other stars as well.

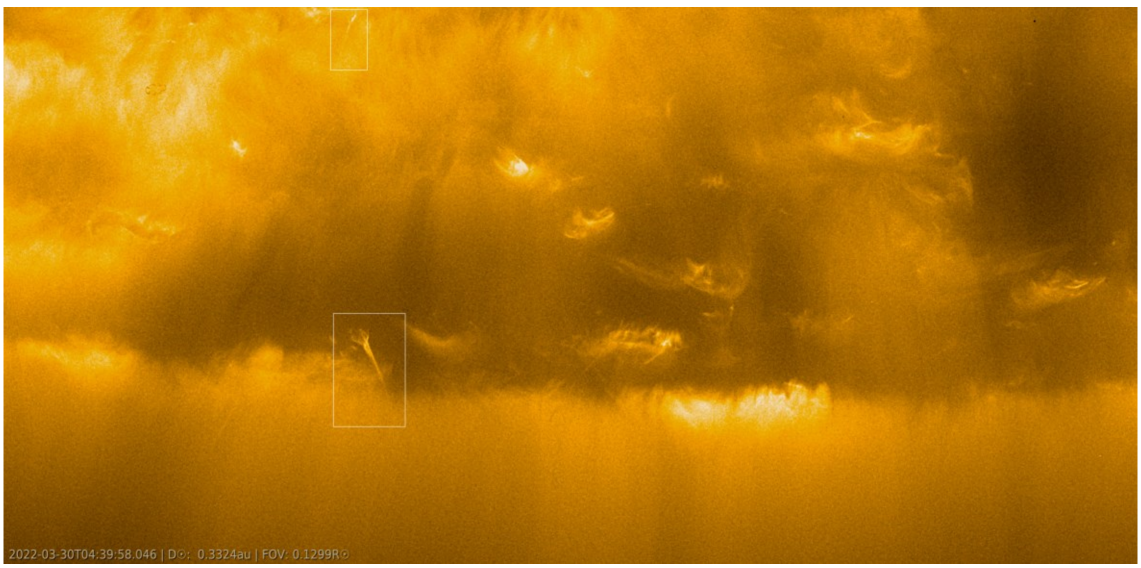


Figure 29: The south pole of the solar corona as imaged by EUI onboard Solar Orbiter. The darker area corresponds to a coronal hole where the magnetic field does not return to the Sun and from where the fast solar wind is emanating. We also see large jet-like eruptions (white boxes), caused by magnetic activity on the Sun's surface. These eruptions create streams of solar material along magnetic field lines.

Large jet-like eruptions are frequently seen in the solar corona. They are understood as events in which a small local magnetic loop reconnects with the ambient 'open' magnetic field line. In the process, an eruptive flow is created along the open magnetic field line and potentially contributes to the solar wind. But it's not just the big events that catch our attention. The Solar Orbiter mission has unveiled something new – miniature jets, lasting only 20 to 100s, and spanning just a few hundred kilometers wide. Despite their small size and brief lifespan, these jets propel solar material at astonishing speeds, up to hundreds of km per second.

Finding these tiny jets was not easy. Given the small dimensions and short timescales, the smallest events are not resolved, not even with the state-of-the-art HRIEUV performance. Also, as these events are close to the instrument noise level, it is very hard to detect them by software. The data was therefore scanned manually and careful visual checking revealed 120 jets.

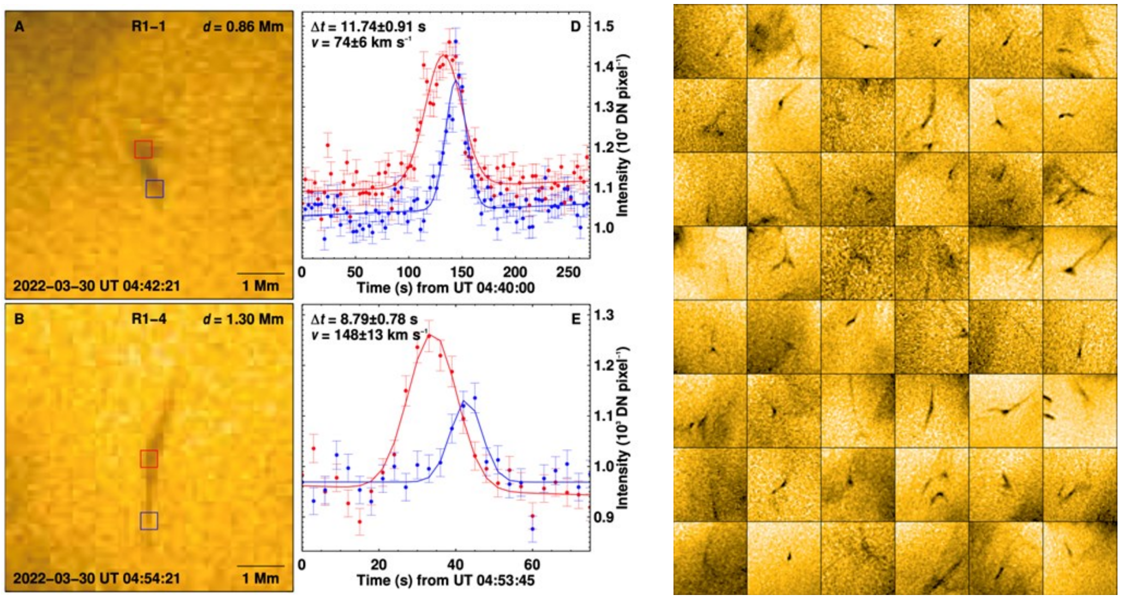


Figure 30: Some examples of the newly discovered miniature jets. The images on the left and right have an inverted color table such that the bright jets are seen as dark features. As these small jets are close to the spatial resolution of the instrument and barely stand out of the noise, it is hard to see the individual motions. A special technique was therefore employed for the graphs in the middle panel: The red and blue curve are the light curves of the respective squares on the left. One can see that the foot points (in red squares) brighten systematically earlier than the jet tops (blue squares).

Based on these 120 jets, an analysis was performed on the morphology (Y-shaped jets, linear jets), the origin (so-called plume and inter-plume regions), and the mass and energy flux. It was estimated that these jets have an energy content of 10^{17} J (10^{24} erg), which is 10^{12} times smaller than the larger flares. Therefore, these jets have been baptized ‘picoflare jets’. Further, conservative estimates revealed that the picoflare jets can account for at least 20% of the solar wind mass flux and energy flux of the solar wind from coronal holes. This estimate is considered a lower limit as there is little doubt that smaller, yet more frequent, unresolved events are hiding in the data.

During the time these observations were conducted, the solar corona exhibited what is known as a ‘solar minimum configuration’. This phase is marked by the presence of large coronal holes at each pole of the Sun, forming an overarching dipole structure in the solar magnetic field. As we edge closer to solar maximum, this orderly dipole structure breaks down into numerous smaller dipoles known as active regions, and with coronal holes appearing anywhere on the solar surface.

Looking ahead to the later years of the Solar Orbiter mission, around 2030, we anticipate the return of solar minimum conditions, characterized by coronal holes reappearing at the poles. However, by that time, plans are in place to tilt the satellite’s orbit out of the ecliptic plane by more than 30 degrees. This adjustment opens exciting possibilities. It will enable us to revisit these observations and study the picoflare jets from a different vantage point – a more top-down perspective rather than the current sideways view. By changing our angle of observation, we can gain fresh insights into the behavior of these miniature solar phenomena, enriching our understanding of the Sun dynamic processes.

This research was published in Science (Chitta, Zhukov, Berghmans et al., Sci 381, 867-872) and advertised in a press release by the ESA and by the STCE.

Space Weather Operations and Anniversaries

2023 was a year to look back at the achievements of the Space Weather Operations Team of the Royal Observatory of Belgium (ORB-KSB). For many years the ORB-KSB has invested in our aim to become an operational space weather centre. Two of the main projects through which we accomplish this and reach a large number of users are via the ESA Space Weather Network and the PECASUS consortium. In April 2023 the SSA Space Weather Coordination Centre (SSCC) of the ESA Space Weather Network celebrated 10 years since its official inauguration, while in November 2023 it marked officially 5 years since the Council of ICAO, the International Civil Aviation Organisation, selected 'PECASUS' as one of the World Centres for Space Weather services.

2013-2023: SSCC – the centre point of a growing network

The SSCC is located at the ORB-KSB and runs in coordination with our partners at Royal Belgian Institute for Space Aeronomy (BIRA-IASB). Originally set up in the context of the Space Situational Awareness (SSA) programme in 2013, to provide the first European Space Weather Helpdesk, with operators available to answer questions about the SWE Service Network or Space Weather conditions in general.

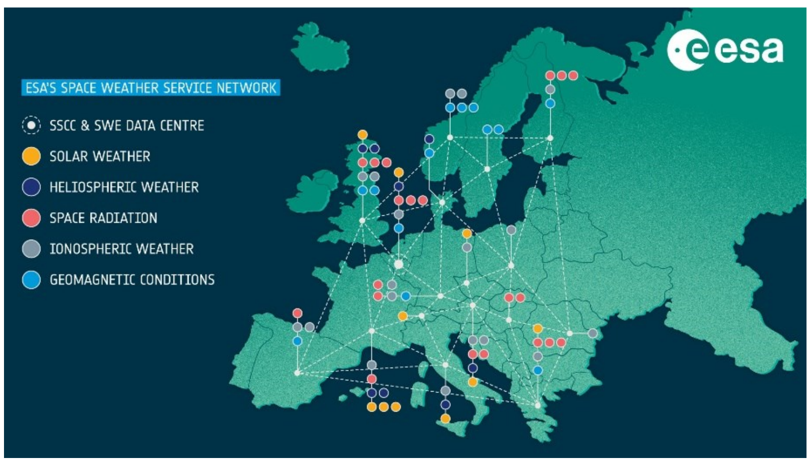


Figure 31: The ESA Space Weather Service Network with the SSCC at the Centre

Since 2020, the ESA SSA programme was replaced by ESA's Space Safety Programme, which aims at mitigating and preventing the impact of hazards from space, protecting our planet, activities and infrastructure. At this time ORB-KSB also took over the leadership of the SSCC at the Space Pole from BIRA-IASB and through these transitions the SSCC has continued to be the focal point of the ESA Space Weather Network user support, provision coordination, and the day-to-day monitoring of the continuity and quality of the service.

Figure 32: SSCC Room in 2023

The SSCC has led multiple user engagement activities in the network over the last 10 years, of which highlights include providing dedicated tailored bulletins to high priority users, facilitated by ORB-KSB's expert forecaster team. The SSCC has provided bulletins to ESA spacecraft operators including from Gaia, Venus Express, Mars Express, BepiColombo as well as bulletins for spacecraft operators outside ESA and users in other sectors such as Aviation, GNSS and Power system Operations.

Since 2013 the SSCC has coordinated more than 25 releases of the ESA Space Weather Portal: the central location for space weather data and products in Europe. The ESA Space weather portal now provides access to more than 300 products provided by more than 50 expert groups. In that time the number of users registered to the ESA Space Weather Portal has increased from 80 users in April 2013 to over 3600 users in April 2023, highlighting the important work done by the team in raising awareness of the network.

Additionally, the Solar Expert Service Centre in the ESA Space Weather Network, also led by the ORB-KSB, continues to develop the functionalities, capabilities and expertise in the domain of Solar Weather that are needed within the ESA SWE Network.

2018-2023: PECASUS – the creation of a 24/7 operational system to support civil aviation

PECASUS is the Pan-European Consortium for Aviation Space Weather User Services, which was selected to be one of the 3 world centres to provide operational Space Weather services to the International Civil Aviation Organization (ICAO) in 2018. The service has been continuously provided operationally since November 2019.

The countries that make up PECASUS consortium are Finland (Lead), Belgium (advisory generation hub), the UK (internal backup), Poland, Germany, Netherlands, Italy, Austria, and Cyprus.

Since 2019 the Solar-Terrestrial Center of Excellence (STCE) has been acting operationally as the central data repository for PECASUS, including continuous monitoring and Advisory Production hub. Our team of operators is available on call 24/7, ready to respond and issue warning messages for aviation, based on a set of thresholds predefined by ICAO. To achieve prompt and efficient response to any space weather events, the space weather operation team created detailed operator procedures and interfaces allowing for the operator to quickly and easily assess the data and create Space Weather Advisories in as short a time as possible.

As the primary data centre and monitoring hub within the PECASUS consortium, the STCE has designed specific data infrastructure to support regular data inflow from all data-providing partners, post-process and display the data on internal interactive operational monitoring dashboards.

Additionally, STCE serves as the Solar Expert Group, the Radiation Expert Group and a data provider for models of GNSS impacts.

Since 2020 an additional 4th world centre was added by ICAO, and the task of providing a space weather service for the aviation sector is divided between the four centres in a rotational system with two weeks of On Duty Center (ODC) periods, followed by Primary Backup Center (PBS), Secondary Backup Center (SBC) and a Maintenance and Observations Centre (MOC).

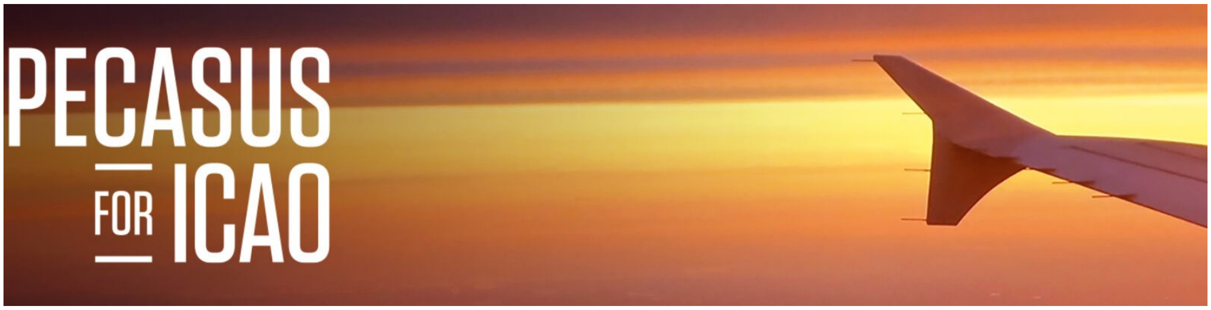


Figure 33: PECASUS for ICAO banner.

Deep Learning Helps scientists in Classifying Sunspot Groups

Solar activity has long been measured by the number of dark spots, called sunspots, appearing on the Sun's surface and visible from the Earth. Sunspots appear in groups as a manifestation of solar magnetic activity. The intense magnetic fields embedded within sunspots inhibit convection, cooling the corresponding surface regions. Corresponding areas on the solar surface where temperature has been reduced as compared to their surroundings appear as dark spots when viewed in the visible continuum spectrum, also known as White Light (WL). This enhanced magnetic field is the driving force behind the solar variability that influences the space environment of the Earth on a day-to-day basis. Its evolution may lead to magnetic reconnection and subsequent energy release, causing solar flares, or coronal mass ejections when material is ejected. The morphology of sunspots is correlated with solar flare occurrence and has therefore received a lot of attention since the end of the 19^{th} century.

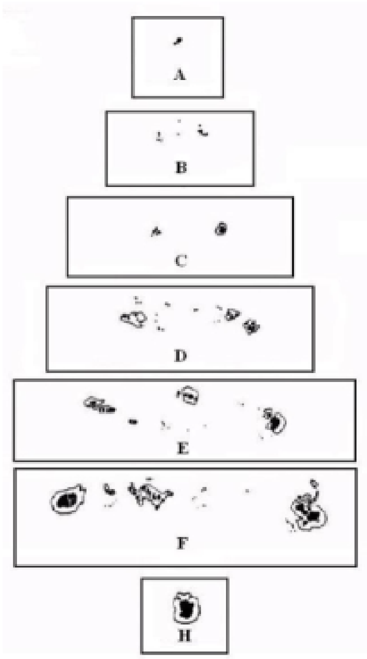


Figure 34: Representation of the Z component in the McIntosh scheme, describing the longitudinal extend of sunspot groups, and the process of development (class A to F) and decay (class H) of a sunspot group.

The *McIntosh classification scheme* describes the WL structure of sunspot groups. This scheme has three components: the first component 'Z' describes the longitudinal extent of the sunspot group, component 'p' provides information on the size and symmetry of the grey area around a sunspot called 'penumbra', and component 'c' gives information on the distribution or compactness of spots within a group. This scheme supports several flare forecasting methods based on historical records of flares occurring in each McIntosh class. Attributing a McIntosh class to a sunspot group is thus fundamental for space weather operations. Traditionally such attribution is done manually, a time-consuming task prone to errors.

The USET ground-based station located at the Royal Observatory of Belgium (ORB-KSB) provides since 2002 WL images of the Sun. In the BRAIN DeepSun project, we employed such WL observations recorded from 2002 until 2019 to build '*SunSCC*', a fully automated system addressing three essential tasks: the segmentation of sunspots from their background, their clustering into sunspot groups, and finally their classification according to the McIntosh scheme. The SunSCC pipeline is depicted in Figure 35. It takes as input 2048x2048 USET WL images and returns as output segmentation masks of individual sunspots as well as sunspot groups and their McIntosh classification, to which a reliability factor is attributed.

The first block in SunSCC deploys a convolutional neural network (CNN) with a 'U-shape'. These so-called U-net architectures have proved efficient in segmenting images in various fields such as medical imaging and natural images analysis. Their weights or parameters are estimated during a training phase, which requires a first assessment of segmentation masks. The latter are typically provided by a traditional, unsupervised, segmentation method involving a thresholding on the WL intensity image. Having a unique threshold is, however, not optimal, as the level of illumination may differ locally e.g. due to the presence of clouds or atmospheric seeing. Our solution was to train the CNN using three different segmentation masks corresponding to different thresholds. The trained CNN is then able to segment small and large sunspots more accurately than traditional methods.

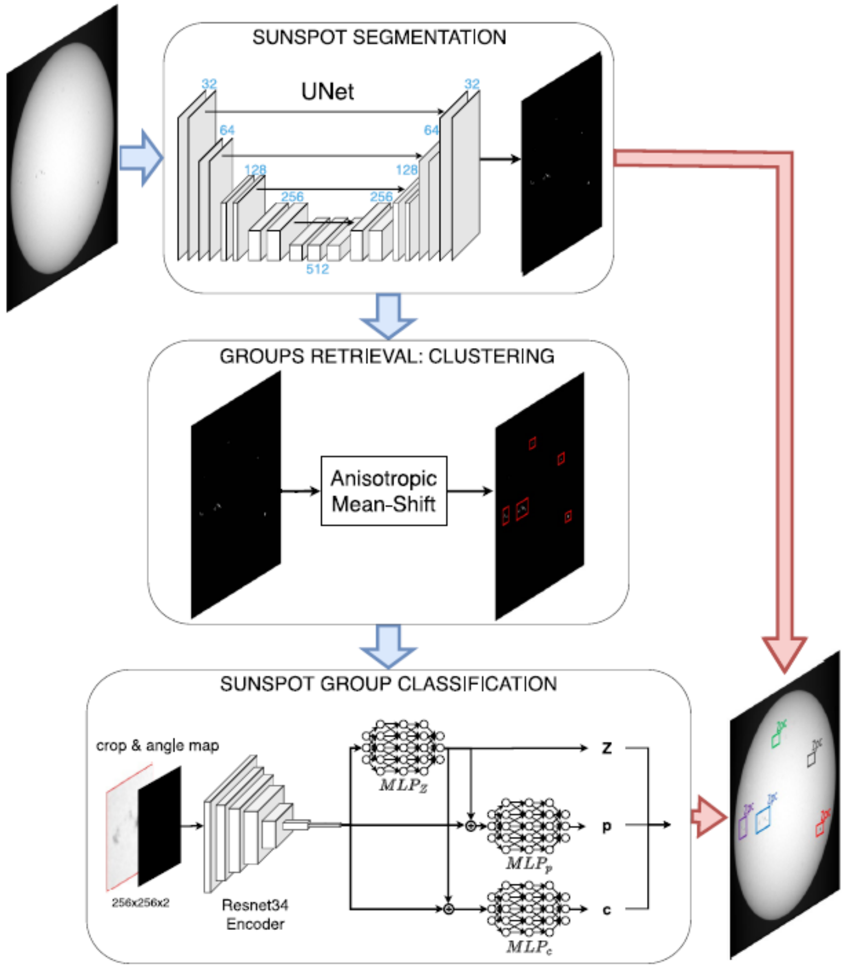


Figure 35: SunSCC pipeline for sunspot segmentation, clustering, and classification. Full-disc images with a resolution of 2048×2048 are provided as input. For segmentation, the U-net network comprises 5 levels and 4 downsampling steps in the encoding part, and reversely 5 levels and 4 upsampling steps in the decoding part. The detected sunspots are aggregated into sunspot groups by a modified mean-shift algorithm. Each identified group is provided along with an angular distance map to a classification network composed of a Resnet34 image encoder and three MLPs with 4 hidden layers and Rectified Linear Unit (ReLU) activation function. Each MLP is specialised in the classification of one component in the McIntosh system.

The second block receives as input the segmentation map from the first block and aggregates the detected individual spots into sunspot groups. We developed a tailored clustering method based on the mean-shift algorithm. It exploits local gradients of a density function to find modes, corresponding to clusters of spots. We employed anisotropic kernels to estimate this density function, to account for the fact that sunspots groups are more elongated in longitude than in latitude. We matched sunspot groups bounding boxes from the USET sunspot group catalogue with bounding boxes found by the mean-shift algorithm and obtained that 80% of USET sunspot groups were correctly recovered by our clustering method.

An identified sunspot group is provided to the third block, together with its angular distance map, for classification task. This third block is composed of an image encoder followed by three Multi-Layer Perceptrons (MLP), one for each component of the McIntosh scheme. More precisely, our classifier relies on a convolutional backbone with 34 layers called ResNet34 to encode the visual information associated to the sunspot group to be classified. Output of the ResNet34 is given as input to three MLPs. To mimic the dependency of the p- and c-components on the Z-component, the MLPs are organised hierarchically so that the output of MLP_Z is concatenated with the output of ResNet34 and given as input to MLP_p and MLP_c.

To obtain a measure of confidence in the chosen class, we adopt the precepts of ensemble learning. Multiple instances of the classification network are initialised with different seeds and trained independently, to produce multiple classifiers. For each sunspot group, we obtain a pool of predictions, which are then combined into one single output via a majority vote. Inconsistencies across the ensemble of classifiers are a valuable clue to identify misclassification by the majority vote: we observed that correct ensemble prediction has low discrepancies among the votes, while incorrect ensemble predictions have their votes more distributed among the classes. This CNN-based classifier shows comparable performance to methods using continuum as well magnetogram images recorded by instruments onboard space mission. We plan to have the SunSCC pipeline running at ROB and producing daily sunspot masks, grouping, and classification. This will constitute an aid to space weather operators and allow quality control on the USET sunspot group catalogue.

This research was published in Journal of Geophysical Research: Space Physics (Sayez, De Vleeschouwer, Delouille, Bechet, Lefèvre, JGR: Space Physics 128, doi: 10.1029/2023JA031548)

Astronomy and Astrophysics

Webb observations of the Ring Nebula

In 2023, an international team including two observers from the ORB-KSB published results from a set of infrared images and spectra of the Ring Nebula (NGC 6720) obtained with the James Webb Space Telescope (JWST) in 2022. The sensitivity and high angular resolution of the JWST instruments allowed the nebula to be observed in unparalleled detail, resulting in stunning images (Figure 36) and a scientific paper (Wesson et al. 2023).

Figure 36: NASA's JWST image of the Ring Nebula. This image combines multiple MIRI images. It highlights the dense globules (the "grainy" structure in the main ring) as well as the spikes and concentric arcs in the outer halo of the nebula (shown in blue). The color in the image results from assigning different colors to each individual filter. In this case, the assigned colors are: Purple: F560W, Blue: F770W, Cyan: F1000W + F1130W, Green: F1280W + F1500W, Yellow: F1800W, Orange: F2100W, Red: F2550W. Credit: ESA/Webb, NASA, CSA, M. Barlow (UCL), N. Cox (ACRI-ST), R. Wesson (Cardiff)

The Ring Nebula is a planetary nebula about 2600 light-years from Earth. It formed when a dying red giant star, somewhat heavier than the Sun, shed its outer layers into space, leaving a hot white dwarf at the center which then ionized the gas expelled before. The Ring Nebula is an old planetary nebula, meaning that all nuclear reactions in the white dwarf have now ceased and that it is currently cooling by radiating away the heat trapped in its interior.

It was already known that the Ring Nebula contained many dense "globules": small pockets of neutral and molecular gas that are surrounded by ionized gas. These are a common occurrence in old planetary nebulae like the Ring Nebula. Their origin is however still a matter of debate. The rival theories can roughly be divided into two groups, one saying that the molecules in these globules are a remnant of the red giant phase and somehow avoided being destroyed by the hot white dwarf until the present day, while the other states that the globules formed later, after the nuclear reactions stopped and the white dwarf started cooling down. The JWST study aims to determine the physical conditions in the globules as well as their immediate vicinity, in particular by studying the molecular hydrogen (H_2) that is ubiquitous in these globules.

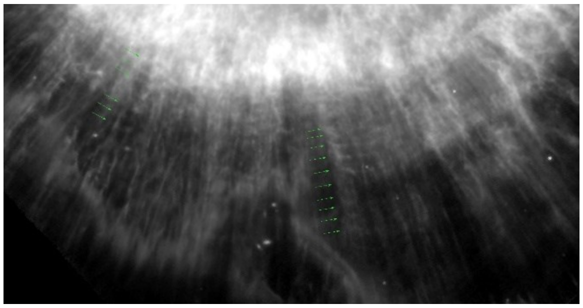


Figure 37: Regular concentric features in the outer regions of the F770W image of the Ring Nebula. Green arrows indicate the locations where these regularly spaced features are most easily seen. Credit: R. Wesson (Cardiff University)

In the Webb images, we can resolve the globules much better than was possible with the Hubble telescope. These images confirm that H_2 is indeed mostly confined to the roughly 20,000 globules that are present in this nebula. We also discovered several new structures. First, there are roughly 300 spikes radiating radially outward outside the main ring. Our proposal is that these are material (mainly H_2) illuminated directly by the central star through holes in the main ring in between the many globules. This proves that H_2 also exists outside the main ring. The second new structure we observed is the concentric arcs shown in Figure 37. This points to the fact that the outflow from the central star was modulated by a binary companion, roughly at the same distance from the white dwarf as Pluto is from our Sun. Polycyclic aromatic hydrocarbons (PAHs – an important prebiotic molecule) had already been detected in the Ring Nebula using the Spitzer Space telescope, but the location of the PAHs was not precisely known. Surprisingly, using the Webb images we could ascertain the location: these PAHs are only present in a very thin ring near the outer edge of the main structure. This proves that the H_2 could not have formed on the PAHs as was previously stated in the study of the Spitzer data. A detailed study of the physical conditions of H_2 in and near the globules is ongoing using spectra obtained with the JWST NIRSpec and MIRI/MRS instruments and the results will be published in a paper led by ORB-KSB astronomers.

The JWST images of the Ring Nebula were included on the 2024 ESA Hubble and Webb Calendar and were chosen as best JWST discovery of 2023 by Science Focus, the BBC science magazine.

References

Wesson, R., Matsuura, M., Zijlstra, A.A., Van de Steene, G.C., van Hoof, P.A.M., et al., 2023, MNRAS, 528, 3392. doi:10.1093/mnras/stad3670.

Webb is an international programme led by NASA with its partners, ESA (European Space Agency) and CSA (Canadian Space Agency).

Building the Most Detailed 3D Map of the Milky Way: Gaia Focused Product Releases

The Gaia satellite has been charting the sky since 2014, and its map includes stars that are a million times fainter than can be seen with the naked eye. Published in June 2022, the third version of the most complete and detailed catalogue of stars (Gaia DR3) is a milestone in astrophysical research. Gaia's exceptionally accurate distances, motions, and fundamental parameters of stars, as well as the accurate astrometry of asteroids, are now part of the everyday work and research of most astronomers.

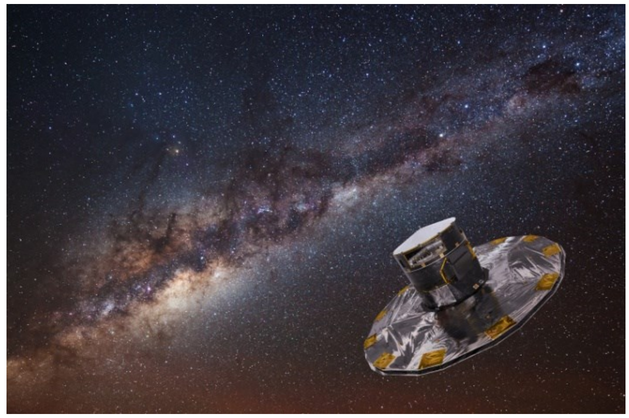


Figure 38: Image caption: Artist's view of the Gaia satellite in front of the Milky Way. Image credit: ESA/ATG medialab – ESO/S. Brunier.

While the ORB-KSB members of the Gaia DPAC (Data Processing and Analysis Consortium) are improving and validating their algorithms for the fourth release of the catalogue (Gaia DR4), ESA published a first teaser on October 23, 2023. It took the form of five 'Focused Product Releases' (FPRs), each addressing one specific aspect of the data reduction and analysis for Gaia DR4.

Three FPRs rely on data that the Astronomy and Astrophysics (A&A) department directly contributed to obtaining and analysing. The first one concerns the nearest objects that Gaia observes. The DPAC reprocessed 156,764 asteroids, using 66 months of data rather than the 34 months of Gaia DR3. Hence, in this new release, the observations of most main-belt asteroids cover a complete revolution around the Sun, closing the orbit and leading to a dramatic increase in the accuracy of the orbits.

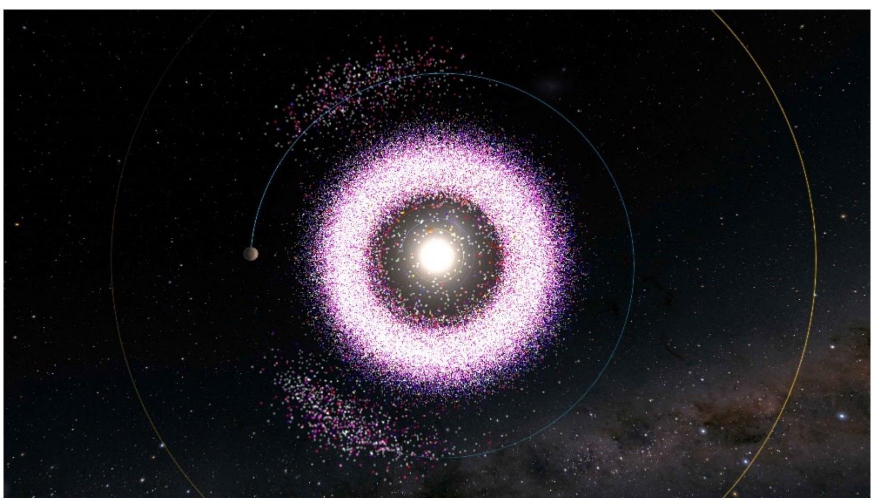


Figure 39: Overview of asteroids in Gaia's Focused Product Release. The inner (less visible) blue orbit represents the orbit of the Earth, the outer blue orbit shows Jupiter's orbit. The Trojans asteroids clustered together a bit ahead and behind Jupiter are clearly visible. The Main Belt is the region heavily populated with asteroids between Mars and Jupiter. Gaia's Trans-Neptunian Objects are not shown in this plot. Credits: ESA/Gaia/DPAC – CC BY-SA 3.0 IGO. See also the corresponding video: https://youtu.be/XYir3bQMfgQ.

The A&A department is also involved in the analysis of the spectra obtained with Gaia's Radial Velocity Spectrometer (RVS) and in the determination of accurate radial velocities. During the past 10 years, Gaia has observed all the stars several times, deriving the radial velocities at different epochs for the brighter stars. Until now, ESA only published averaged measurements. It did not prevent Gaia identifying variable stars, but characteristics such as their instant photometry and radial velocities used in the classification process will only be delivered with the next catalogue release. As we await Gaia DR4, where all observations (epoch and averaged) will be available, one of the FPRs is publishing some of the highest-quality time series of data acquired for 9164 Long Period Variables, including epoch radial velocities.

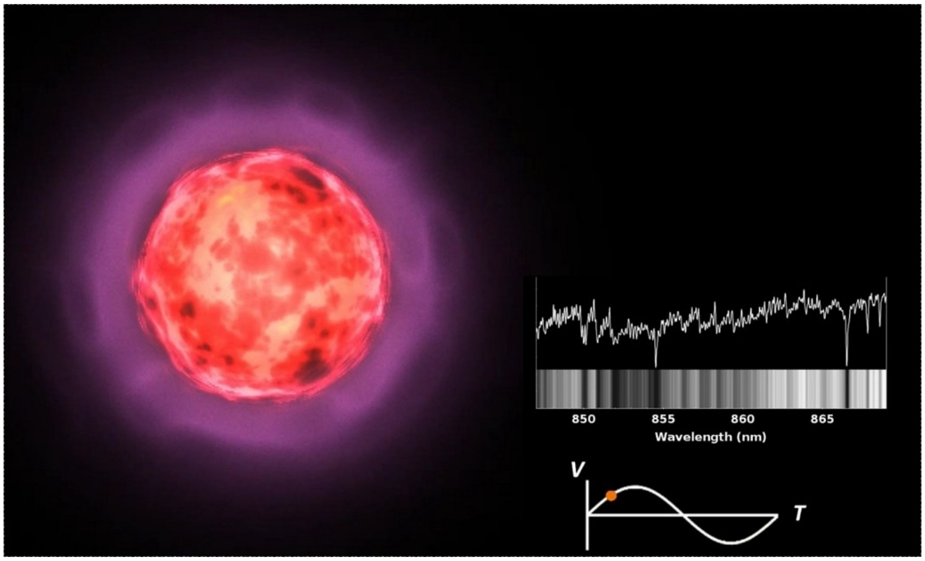


Figure 40: The ESA-Gaia spacecraft has repeatedly observed the spectrum of an unprecedented amount of cool giant stars – called Mira variables – known to continuously expand and contract their surfaces over long periods, sometimes more than one year. This artist's impression of a Mira star shows how the velocity of the surface movements and of its atmosphere are accurately measured from the (Doppler) shifts of dark lines observed in the detailed Gaia spectra. A video animation is at: http://aa.oma.be/GaiaFPR_en.

A very recent approach applied to the Gaia RVS spectra in the context of the Gaia DPAC is the detailed analysis of spectral lines of interstellar origin. Low-density gas made of atoms, ions, and molecules, as well as dust, are filling up the space between stars. This interstellar matter absorbs and scatters the light, producing a continuous reddening and weakening of the stellar flux. Additional broad features, named diffuse interstellar bands, also appear in the spectra of stars. They are due to absorption likely associated with very complex molecules found in the interstellar medium in certain directions. Such diffuse interstellar bands are present in the Gaia RVS spectra. The corresponding FPR uses these to trace the formation of the interstellar matter in the Milky Way disk and its spiral arms.

The data published through these Focused Product Releases are available on ESA's webpage. In addition to providing new data to complement the third version of the Gaia catalogue, this delivery can be seen as a proof-of-concept of various new features implemented in the data analysis pipeline, which will produce Gaia DR4 with twice as much data. They offer an overview of all the promises that the fourth version of the catalogue will fulfil in 2026.

Gaia observes cosmic clock inside heavenly jewel

The ESA Gaia mission website recently published an image of a planetary nebula, supplemented with three years of data gathered by the Gaia-satellite (Gaia IoW). Inside this object, twinkles a blue dot with a very regular pulse of light. This is the central close binary system of the planetary nebula. Truly a hefty cosmic clock in our Galaxy.

Since its launch in 2013, Gaia has repeatedly observed the central stars of planetary nebulae. The name 'planetary nebula' is not related to planets but arose in the 18th century because of the visual similarity between some round nebulae visible in the sky and the planets Uranus and Neptune as observed in small optical telescopes. The name has stuck, although modern telescopes make it obvious that they are not planets at all.

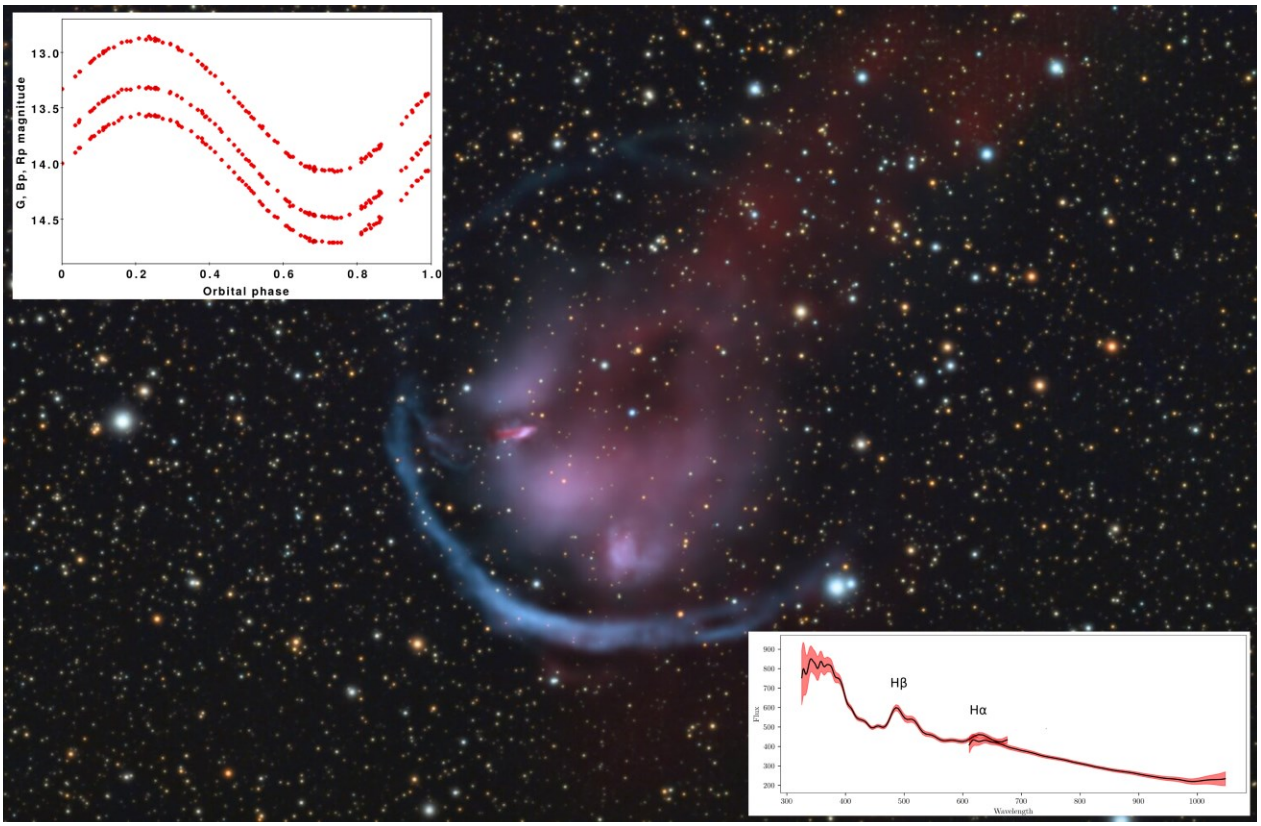


Figure 41: Planetary nebula Heckathorn-Fesen-Gull 1 observed from Earth. Gaia observed the blue star V664 Cas at its centre over a hundred times in 2014-2017. This close binary shows very regular brightness changes (top left inset panel) due to a bright surface spot. The bottom right-hand panel shows bright lines of hydrogen gas in the Gaia spectrum, classifying it as an 'emission' line star. Image credits: Peter Goodhew – Inset graphics: ESA/Gaia/DPAC.

The old planetary nebula Heckathorn-Fesen-Gull 1 (HFG1) in Figure 41 seems to be one of such cases. This planetary nebula moves through the interstellar medium at a very high speed, creating a shock wave in the surrounding hot gas, seen as a bright blue arc to the lower left, just like a boat ploughing through water. Behind it is a long cometary-like wake of material, about one third of a degree long in the sky, shining in red light.

The blue star at the centre of HFG1 is the known binary V664 Cassiopeiae (V664 Cas), observed by Gaia over one hundred times so far (and counting). The red drawn curves in the top left inset panel show very periodic brightness changes due to a close pair of stars separated by merely a few million kilometres. A small but very hot dwarf star irradiates part of a larger and cooler star (like our Sun or a red giant) heating a bright area of its surface. Gaia observes how the hot spot's projected size and apparent brightness varies while both stars orbit each other. The new observations offered in Gaia's 3rd Data Release were published online in June 2022 and provide a very accurate orbital period of 13 hours, 57 minutes and 35 seconds. Truly a hefty clockwork in our Galaxy.

Within the Gaia Data Analysis and Processing Consortium (DPAC) a wide variety of objects showing so-called bright 'emission' lines in their spectra are classified. This classification is part of the processing done by Gaia's Coordination Unit N^{o} 8, the unit responsible for the processing of Astrophysical Parameters. In the case of V664 Cas, Gaia observed the bright lines of ionised hydrogen, marked with Hα and Hβ in the bottom right-hand inset panel. Astronomers use these and other emission lines from other elements for measuring the chemical composition, temperature and density of the nebular gas, or in regions where they can also form closer to the central binary. The gas temperature of planetary nebulae can reach ten thousand degrees Celsius, whereas their central stars are among the hottest known stars in the Universe with temperatures ranging from twenty-five thousand to two hundred thousand degrees Celsius.

Gaia has not only observed the precise period and the emission lines of V664 Cas, but it also measured its parallax, allowing to place the star at 707±7 parsecs (2,300 light years) from us. A measure of the distance allows to measure the true velocity of the star, and this is crucial to develop reliable theoretical models of the formation history of HFG1's shock region and the complex dynamics of its trailing outflow. The true size of the extended outer shell of shocked gas is important to explain the rare morphology of HFG1, resembling a giant jellyfish swimming faster than the speed of sound through the thin gas that exists in the interstellar space.

The red gas trail of at least 20 arcminutes long in the sky, as we can see in Figure 41, is left behind by V664 Cas and estimated to be about ten thousand years old. HFG1 is therefore already old and will gradually dissolve in space, while its central binary star will cool and fade for billions of years. Our Sun is expected to experience the same process as HFG1, but fortunately not for another five billion years.

The combination of Gaia's astrometric, photometric and spectroscopic measurements will provide new and fundamental insights in the physics of these enigmatic objects.

The Gaia-ESO Survey: A Large Spectroscopic Survey of our Galaxy

The Gaia-ESO Survey is a public spectroscopic survey. It used the multi-object FLAMES spectrograph on the Very Large Telescope (VLT-UT2) to take spectra of just over 100,000 stars. To date, it is the only large-scale public spectroscopic survey that has been made using an 8-meter telescope. The Survey systematically covered all the major components of our Milky Way: the thick and thin disk, the bulge, the halo, and a large number of open clusters. It sampled stars covering all spectral types in all evolutionary phases, as well as open clusters ranging in ages from a few million to many billion years. It thus provides the first homogeneous overview of the distributions of kinematics and elemental abundances. Observations were collected during 340 nights between December 2011 and January 2018.

There are approximately 500 Co-Investigators in the Survey, among them are five people of the Astronomy & Astrophysics Department of the Royal Observatory of Belgium (ORB-KSB). The management structure of the project consists of 20 Working Groups with the Working Group WG13 'OBA Star Spectrum Analyses' being led by the ORB-KSB.

Figure 42: The Very Large Telescope (VLT) at Paranal, Chile. The Gaia-ESO Survey uses the Unit Telescope 2 (UT2), the second one from the right on the picture. This telescope has a multi-fibre instrument, called FLAMES, which can take about 130 spectra simultaneously. Credit: J.L. Dauvergne & G. Hüdepohl (atacamaphoto.com)/ESO.

General Impact

More than 100 refereed papers directly related to the Gaia-ESO Survey have been published. The general impact of the Survey has been important in Milky Way and open cluster science.

In the Milky Way science, the spectroscopic information allowed abundance analyses and, in this way, the study of galactic chemical evolution. Specifically, the abundance analysis allows to clearly distinguish between the thick disk (containing older, less metal-rich stars) and the thin disk (relatively younger, and more metal-rich stars). For the stars in the bulge, a bimodal distribution in the alpha elements was found.

The large number of stars allows the more detailed study of the metallicity gradient in the Galaxy, where the metallicity decreases further away from the Galactic centre. There are also a large number of lines of sight across the Milky Way, and similar sightlines to stars at different distances. This allowed the analysis of the distribution of interstellar extinction as a function of distance.

For the open clusters, the Survey made it possible to ascertain the membership of individual stars to the cluster. For these clusters the Hertzsprung-Russell diagrams were made, and the cluster age was determined. The young open clusters that were observed allowed the detailed investigation of their structure, kinematics and dynamics as well as their star formation histories, age spreads and accretion properties. On the stellar evolution side, the element abundances provide constraints on the mixing processes in the stellar interior during the different evolutionary phases. Cluster ages then help to calibrate other age indicators (abundances and their ratios), which can then be applied to field stars.

The Survey is also a precursor for future spectroscopic surveys. With this in mind, care was taken to include a sufficient number of targets that overlap with the Sloan Digital Sky Survey, as well as with targets observed by the CoRoT and Kepler satellites (for astroseismic analysis). The requirements for the analysis of the Survey data also stimulated the creation of a homogeneous list of atomic and molecular lines, as well as the development of a set of benchmark calibration stars. Both will be useful for future surveys.

Specifically for the ORB-KSB, considerable work was done on hot stars and on binary and multiple stellar systems.

Hot Stars

The ORB-KSB took a considerable part in the analysis of the hot stars (those with spectral type O, B and A) observed by the Gaia-ESO Survey. The procedure consisted of several groups (called 'Nodes') that independently analysed a part of the spectra. They did so by comparing theoretical spectra to the observed ones. They changed the parameters of these theoretical spectra until they obtained a good fit with the observed spectrum. In this way, the stellar parameters and abundances of each star were determined.

Three of these Nodes are associated with the ORB-KSB, the other Nodes are at Saint Mary's College, Notre Dame (USA), Observatório Nacional (Brazil), Instituto de Astrofísica de Canarias (Spain), Université Montpellier (France) and the Space Sciences, Technologies, and Astrophysics Research Institute (STAR Institute) of the Université de Liège (Belgium).

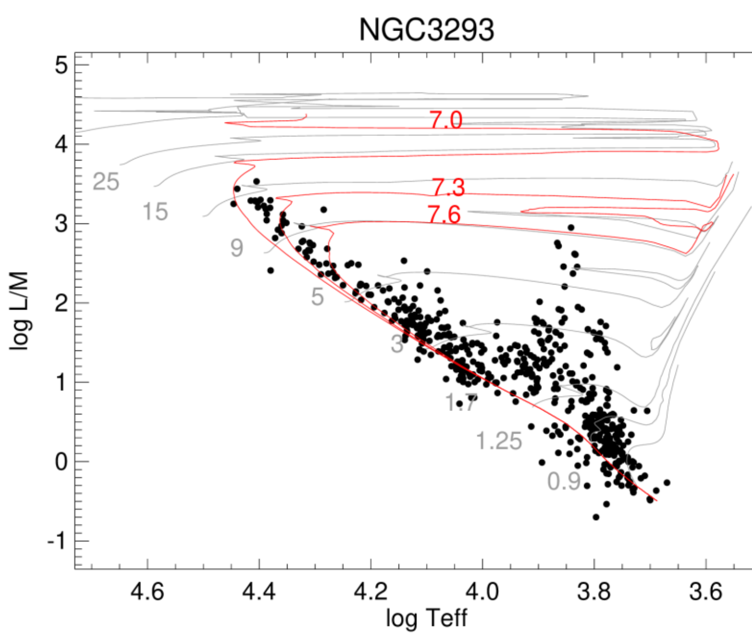


Figure 43: The spectroscopic Hertzsprung-Russell diagram of the cluster NGC 3293, based on the Gaia-ESO Survey data. The grey lines show the stellar evolution tracks and are labelled by their initial mass (in solar masses). The red lines show the isochrones, which are labelled by the logarithm of the age in years (Credit: R. Blomme).

The resulting stellar parameters (effective temperature and surface gravity) and surface abundances were then homogenised to deliver a set of recommended values. Because the hot stars cover a large range in effective temperature, any given Node could cover only part of the data. The quality of each of the Node results was determined by how well they could determine the stellar parameters of the benchmark stars, and how well a single isochrone fitted the Hertzsprung-Russell diagram of each cluster analysed. The homogenised stellar parameters were then determined by a weighted average of the Node results.

In total, 17,693 spectra of 6462 stars were analysed, and the homogenisation resulted in stellar parameters for 5584 stars. Abundances were determined for 292 stars for at least one of the following elements: He, C, N, O, Ne, Mg, Al, Si, and Sc. Following up on this work, the ORB-KSB collaborated on the scientific interpretation of the data. This was done specifically for the microturbulence in tepid stars and for stars in the cluster NGC 3293 and in the Carina region.

Microturbulence Velocity in Tepid Stars

An investigation led by M. Gebran (University of Notre Dame, Lebanon) and A. Lobel (ORB-KSB) was performed on the projected microturbulence velocity (ξ_μ) in A- and B-type stars in collaboration with the Observatoire de Paris (France). The Gaia-ESO Survey spectra of the young open cluster NGC 3293 have been used for determining stellar astrophysical parameters in the effective temperature range of Teff = 6500 K to 12,000 K. A new automated procedure for measuring these parameters was developed and applied to the Survey spectra for comparison to parameters determined with spectra from other telescopes.

For this purpose, an extensive grid of 1-D hydrostatic ATLAS atmosphere models was calculated including turbulence pressure, with depth-independent turbulence velocities ranging from 1 to 8 km/s. The spectroscopic ξμ-values were measured simultaneously with the projected rotational velocity and chemical abundances using detailed LTE radiative transfer fits to selected absorption lines.

The results using the Survey spectra confirm the conclusions of previous studies that a maximum of ξ_μ occurs around Teff of 8000 - 9000 K in samples of A-type field dwarf stars, and in A- and F-stars of the open clusters Pleiades, Coma Berenices, Hyades, and the Ursa Major moving group. The ξ_μ-values show a broad maximum from A5V to A9V (to 4±1 km/s around Teff ~ 8000 K), and a decrease to ~1 km/s for the cooler and hotter stars, consistent with earlier published semi-analytical prescriptions for ξ_μ.

NGC 3293

The Gaia-ESO Survey data resulted not only in the stellar parameter determination, but also in a fivefold increase in the number of cluster members with an abundance determination. As a result, the late B-star population of this cluster is now known in detail. Although not a primary goal of the Survey, there are some multi-epoch observations of this cluster. This allowed the detection of variability in line profiles, indicating either a binary system, or some intrinsic line-profile variability.

The Hertzsprung-Russell diagram of the B stars shows a tight main sequence, provided that the data are corrected for the rotational velocity distribution. This distribution turns out to be Gaussian with a peak around 200–250 km/s. With a few possible exceptions, all stars have a rotational velocity well below critical. The abundances show a lack of stars that have core-processed material at their surface. This is consistent with the single-star evolution scenario, assuming the stars start their evolution with very different rotational velocities. The cluster age is estimated to be about 20 Myr, which is older than previous estimates.

Carina Region

The Carina region was chosen as an interesting object for deeper study because it is one of the major massive star-forming regions in the Galaxy, and it is relatively nearby. In this study the results of 234 stars in the Gaia-ESO Survey were combined with data from Gaia Early Data Release 3. The use of Gaia data allows to distinguish cluster members from foreground and background sources. By adding brighter sources from the Galactic O-Star Spectroscopic Survey and the literature, the most complete census of massive OB stars in this region was constructed.

Figure 44: The four pointings of the telescope used for the Carina region. Because of the multi-fibre capabilities of the FLAMES instrument, a single pointing can result in about 100 spectra (Credit: Stéphane Guisard, Robert Gendler, Jesús Maíz Apellániz).

Twenty spectroscopic binary systems were identified, leading to an average observed spectroscopic binary fraction of O-type stars of 0.35. This is obviously a lower limit, as some double-lined binaries may have escaped detection, and single-lined binaries were not searched for.

Binaries and Multiple Systems

In cool stars (those with spectral type F, G, K and M), the stellar multiplicity fraction is expected to be lower compared to hot stars. Nevertheless, this is compensated by their larger number in the Galaxy. Indeed, cool stars represent more than 99% of all stars in the Galaxy, and, therefore, even a lower fraction of multiplicity induces a large number of binaries. Spectroscopic analysis of stellar spectra can reveal, thanks to the Doppler shifts of spectral lines, the presence of one or several stellar gravitationally bound companions, with orbital periods ranging from days to several years. We took a considerable part in systematically analysing the cool stellar spectra to detect such spectroscopic binaries.

It was found that the corrected spectroscopic binary fraction in cool stars is 15±3%. In addition, a clear dependence on the metallicity was shown: the fraction of metal-poor binaries is larger. This could be induced by the fact that in low-metal star forming environments, the cooling of the gas is more efficient since fewer metals are present, favouring fragmentation even on scales of 10 astronomical units and leading to the formation of more binaries in such environments.

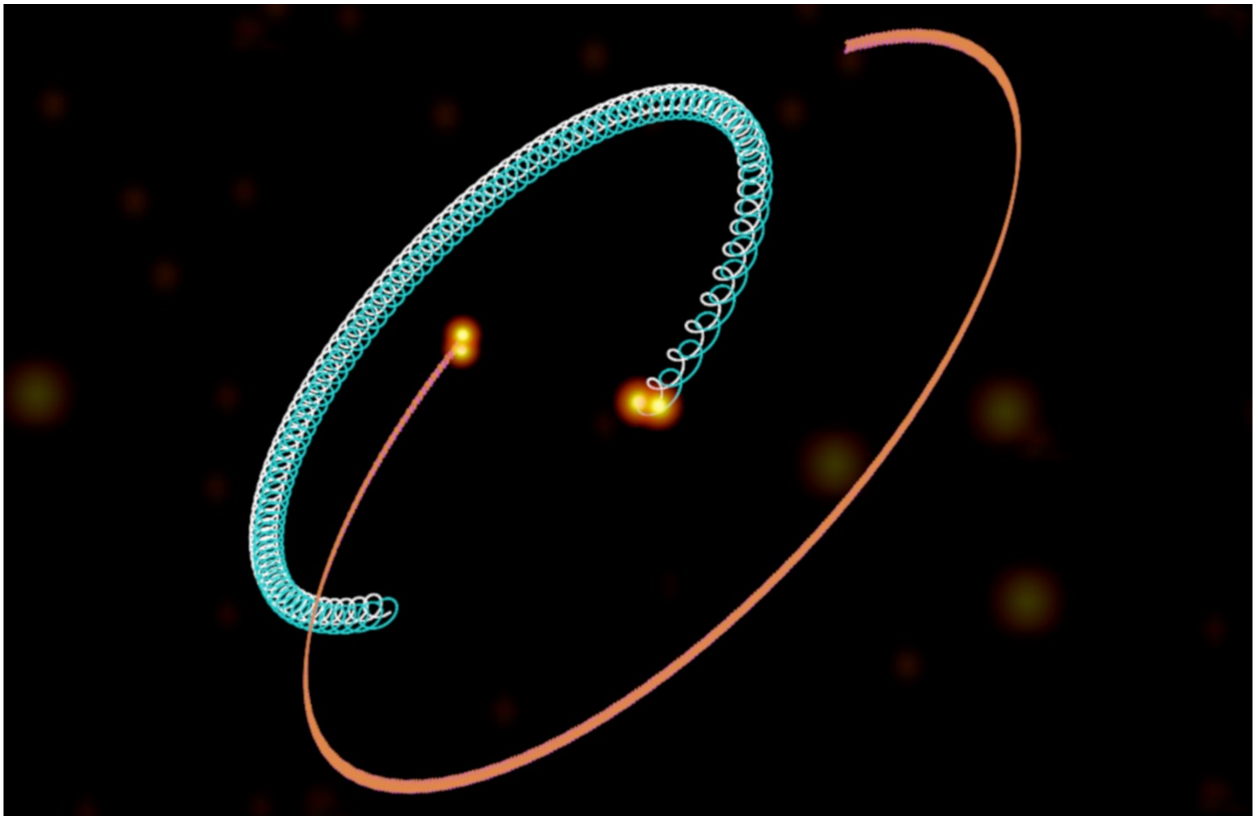


Figure 45: Artistic view of the spectroscopic stellar quadruple discovered in the Gaia-ESO Survey. This quadruple system, HD 74438, is made of two binaries with 20 and 4 days of periods orbiting each other in almost 6 years. The trajectories with respect of the centre of mass reveal a beautiful stellar ballet (Credit: T. Merle).

While many new galactic binaries were uncovered, tens of triples and one spectroscopic quadruple were also identified. With additional follow-up with the Southern African Large Telescope (South Africa) and the University of Canterbury Mt-John Observatory (New Zealand), it was shown that this spectroscopic tight quadruple was a hierarchical system made of one binary (AB, 20 days of period), orbiting another binary (4 days of period) on an outer orbit of 6 years. Interestingly, it seems that the orbits are not coplanar. This fact could result from a secular dynamic effect that can lead each binary to evolve in double white dwarfs. Simulations show that there are 25% chances to have sequential merger events ultimately leading to a thermonuclear supernova.

Final Thoughts

The impact of the Survey is best summarised by quoting Sofia Randich: The Gaia-ESO Survey 'leaves a great legacy, both for the scientific aspects, and in terms of expertise, methodology, and community building; in the era of spectroscopic surveys, Gaia-ESO remains unique in many respects'.

The Gaia-ESO Survey catalogue is available on: http://archive.eso.org/cms/eso-archive-news/Fifth-Gaia-ESO-data-release-astrophysical-parameters-of-about-115000-stars.html

Outreach and Communication

Open doors at the Humain radioastronomy station

The Humain radioastronomy station was founded in 1953 when the Royal Observatory of Belgium purchased a small piece of land, near the village of Humain, after a year-long search by R. Coutrez and E. Pourbaix for a favorable place to host the first two radio telescopes operated in Belgium. Seventy years later, and for the first time in its history, the station was open to the public in the framework of the European Heritage Days, organized in Wallonia on September 9 and 10, 2023. The event was supported by the STCE and made possible by many volunteers from the Royal Observatory of Belgium (ORB-KSB) and the Royal Belgian Institute for Space Aeronomy (BIRA-IASB), with logistic support from the Royal Meteorological Institute (IRM-KMI).

Figure 46: The public visiting the Humain station and its science exhibition (credit: L.B.S Pham).

Personnel from ORB-KSB and BIRA-IASB presented the scientific activities taking place on the site of the station: solar radio astronomy, optical astronomy, radio and optical observations of meteors, and radio observations of whistlers' waves in the plasmasphere.

Figure 47: The inflatable planetarium set up by the Planetarium team in Humain, Credit: L.B.S. Pham.

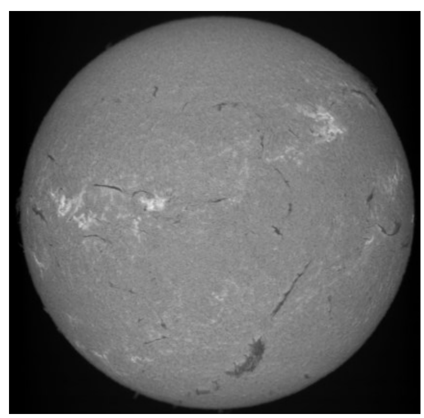


Figure 48: The first optical observation of the Sun in Humain with Solex, Credit: S. Bechet.

Special activities were set up for the public: real-time observations of the Sun with SOLEX (first optical solar observations in Humain!), a small inflatable planetarium, activities for children and an exhibition on the history of the station and its main instrument, the decommissioned solar interferometer.

Despite challenging weather conditions (the event took place during the late heat wave of September 2023), and the remoteness of the site, nearly 630 visitors came on site from nearby cities, the whole Belgium, but also France or the Netherlands.

The event received attention from local and national authorities, as well as from local and national media outlets.

Soapbox Science Brussels 2023

On June 24, 2023, the Brussels Local Organisation Committee of Soapbox Science Brussels organised their fourth edition of Soapbox Science Brussels. The event took place at the Carrefour de l’Europe between 14:00 and 17:00.

During the event, 12 speakers took turns talking about their research and interact with the public passing by for one hour each. Talks were in French, Dutch and English. There was a good reception from the visitors, from the communication from the institutes of the speakers, and from the press with which some interview were done. In particular, the Ministry of Higher Education and Research of the Belgian French Community also voiced her support for the Brussels initiative of Soapbox Science.

In 2023, Soapbox Science Brussels Sponsors are the VIB and Europlanet Benelux. The ORB-KSB, as the host institute of Soapbox Science Brussels, and the IASB-BIRA also contributed to this event for the logistics (transports, catering…).

More information:

- Soapbox Science Brussels Website: https://soapboxsciencebrussels.oma.be/
- Facebook: https://www.facebook.com/SoapboxScienceBrussels
- Twitter: https://twitter.com/SoapboxscienceB
- Instagram: https://www.instagram.com/soapboxsciencebrussels/

Asgard Balloon Launch 2023

The ASGARD 12th balloon launch took place on March 22, 2023. This event is organised by the Planetarium and in which participated the institutes of the Space Pole: the ORB-KSB, the IRM-KMI and the BIRA-IASB. The communication services of the three institutes are involved in the organisation, and Hilde Langenaken of the Communication and Information Service coordinated the organisation of the Space Pole on this day.

The ASGARD Contest is geared toward primary and high school classes who proposed an original experiment that will be loaded on a stratospheric balloon. Like every year, the finalists of the contest spent a day at the Space Pole site, during which the balloon launch of their experiments is the climax. In addition to the balloon launch, the participants also attended sessions in which scientists explain science topics in their fields and 'Meet and Greet' sessions afternoon in which scientists from different fields present themselves and their research.

Information to the Public, Website, News and Press Releases

In 2023, the Communication and Information service replied to questions from authorities, public and the media sent by email (512, with 285 in French, 169 in Dutch and 48 in English**),** by telephone (72), by social media of the Observatory (Facebook: 10 and Twitter: 8) and by paper letters or fax (2), hence 581 replies in total. 35 questions came from authorities (courts, police…) or particulars such as lawyers, with 22 in Dutch and 13 in French. To reply to some of the questions, more specific research is performed.

In 2022, 25 topics were published in the 'News' section of the ORB-KSB's website (always in three languages: NL/FR/EN), including 8 press releases. This is big increase compared to 2021 (17 topics, including 2 press releases).

New Social Media for the ORB-KSB

On 31 December 2023, the ORB-KSB Facebook webpage had 1578 likes (with 147 new likes since the end of 2022), and the ORB-KSB Twitter account had 1301 followers (106 new followers since the end of 2022) and its LinkedIn account 1008 followers (which 315 new followers since January 2023). The themes of the published posts and videos are related to all services of the institutes, comprising shared posts from the

Planetarium Facebook page, from the Seismologie.be Facebook page and Twitter account, from the EUI Twitter account and from the Royal Belgian Institute of Spatial Aeronomy and the Royal Meteorological Institute.

The most successful Facebook post of the year is a post announcing the October 25, 2022, solar eclipse, which was partially visible in Belgium. The most successful tweet is on Twitter is related to the Perseid meteor shower, which got an exceptional number of 56,457 impressions and 877 engagements while the other tweets of the top 12 tweets only got an impression below about 9000.

Since 13 December 2023, the ORB-KSB has a Blue Sky account. The purpose of creating a Blue Sky account is to create alternative social media to X (former Twitter) since some ORB-KSB scientists leave Twitter for other alternative media. On 31 December 2023, Blue Sky Account has 7 followers and 3 posts were published. Lê Binh San will try to bring the ORB-KSB to more social media like Mastodon.

The Planetarium

Daily Activities

Frequentation, Social Media and Website

2023 was a record year in terms of attendance, with **54,261** paying visitors to the Royal Observatory of Belgium's Planetarium, the highest annual attendance ever recorded. This figure is **+30%** up compared to 2022. It is due in part to the success of the new film *The Dark Side of the Moon Planetarium Experience* (see below). However, without taking this specific film into account, the number of visitors would still be 51,000, which would already be the highest attendance ever.

On 31 December 2023, the Planetarium's Facebook page had a total of **4,526** followers (an increase of 538 subscribers, or 13.5%). The more recent Instagram account is followed by **1,214** *followers*, corresponding to 353 (+41%) additional followers over the year.

The Planetarium's new website, launched in 2022, was supplemented in 2023 by an online ticketing system, which has been very popular since its launch. Individual visitors can now reserve their seats in advance of their visit, although tickets can still be purchased at the reception desk or are even compulsory in the case of a discount on presentation of an accepted card. This online purchasing system has also proved useful for managing *Dark Side* screenings, which have been sold out on several occasions, resulting in requests for bookings well in advance.

360° film The Dark Side of the Moon Planetarium Experience

To mark the fiftieth anniversary of the release of Pink Floyd's album *The Dark Side of the Moon*, a 360° film has been specially created to illustrate the ten tracks on the album.

Images of the solar system mixed with visual effects designed with the participation of the graphic artist who came up with the visual concept for the album cover accompany the musical tracks.

This show is the only planetarium event ever authorised by the band. Distributed by the *International Planetarium Society*, it was broadcast exclusively from May 2023 by several planetariums around the world, including the Planetarium of the Royal Observatory of Belgium.

Offered in the evenings on May 11 and 25, June 8 and 23, July 18, August 1 and 16, September 20, October 5 and 26, November 10 and 23 and December 8 and 21, it quickly found its audience. A total of 3,261 people viewed this *full-dome* musical production at the Brussels Planetarium in 2023.

Astronomy education research

The astronomy education research team led by Jan Sermeus took off in 2023 with the recruitment of two PhD students, Judith Vandewiere (co-tutored with the KU Leuven) and Charly Mobers (co-tutored with the Université de Mons).

Special Activities

Various events to promote science and several scientific, educational and cultural activities were organised in 2023. Participants in these events add to the number of annual visitors, increasing it by around 1,000 for activities and 2,500 for rentals.

TASTE Dissemination Event

As part of the European TASTE project (ERASMUS+ funding), in which the Royal Observatory of Belgium's Planetarium took part, the Planetarium organised a day-long event on May 26 to present the results obtained and the educational material produced. This TASTE Dissemination Event brought together speakers and participants from Germany, Italy, Greece and Belgium (universities and science centres). The results of studies in astronomy education carried out by the KU Leuven (partly conducted at the Planetarium) were presented and discussed, complemented by the discovery of educational workshops and the creation of full-ride educational modules produced by the partners in the TASTE consortium.

Friday May 26th
PLANETARIUM OF BRUSSELS
from 10 am to 4:30 pm
You are cordially invited to attend the dissemination event of
TASTE
Teaching Astronomy at Educational Level
A modest proposal for teaching introductory Astronomy in European schools with the help of Planetaria An event for Astronomy Education specialists, education policy makers and teachers all over Europe
Please register at planetarium@planetarium.be
PROGRAMME
09h30: Start of registration, with coffee
10h00: Welcoming words
10h05: Introduction
10h20: The rationale of a project called TASTE
10h40: The reasons for a school-planetarium cooperation
10h55: The astronomy education research state of the art
11h15: The astronomy education research role in TASTE
11h45: A snapshot of TASTE educational videos
12h00: Lunch
13h30: Astronomy: a teacher approach
13h45: How we got to our proposal: an itinerary history
14h15: The schoolwork
14h45: The planetarium work
15h15: Coffee break
15h30: A TASTE of fulldome videos
15h50: A TASTE of tools
16h10: A TASTE of research
16h25: Concluding remarks
16h30: End of day
PARTNERS
Liceo Scientifico A.Tassoni
Modena, Italy
CeSDA
Modena, Italy
VIA Tienen
Tienen, Belgium
KU LEUVEN
Leuven, Belgium
Haus der Astronomie
Heidelberg, Germany
NOESIS
Thessaloniki, Greece
Max-Born-Gymnasium Neckargemuend
Neckargemuend, Germany
1st Experimental Junior High School of Thessaloniki
Thessaloniki, Greece
PLANETARIUM.be
Royal Observatory Belgium
Bruxelles, Belgium
A contents and methodologies proposal to overcome misconceptions and build a solid knowledge of elementary astronomy in students
Science, Technology, Engineering and Mathematics (STEM) play an important role in contemporary society and are vital to build the sustainable society of the future. However, STEM curricula do not seem very attractive to many students and increasing the level of achievement and interest in STEM is a priority in the context of the European Erasmus+ programme. In this project, we propose to use Astronomy as a possible entry point for Science education and as such consider Astronomy as a 'gateway' science to other STEM fields.
EXIT
WEMMEL
HEYSEL
PLANETARIUM
Boechoutlaan / Av. de Bouchout 10
1020 Brussel / Bruxelles
02 - 474 70 50
WWW.PLANETARIUM.BE
Erasmus+
2020-1-IT02-KA201-079528
WWW.TASTE-PROJECT.EU

Also in 2023

• The ASGARD project was co-organised by the Space Pole and the Planetarium from 22 to 24 March.

• The Museum Nights were hosted by the Planetarium on May 4: visitors were able to watch a planetarium film and take part in a question-and-answer session with the Observatory's astronomer Patricia Lampens. These Nights were a huge success, but, unfortunately, we had to turn away several hundred visitors who queued up and were unable to get into one of the four sessions on offer between 6pm and 10pm (these people were able to return on subsequent days).

• The Planetarium team hosted a VR stand (virtual reality goggles featuring the EVEREST/Planetarium creation *From a smartphone to the Universe: a virtual reality journey* were used for the occasion) at the EUCYS (EU Contest for Young Scientists) from 13 to 15 September 2023. This activity was also part of the Planetarium's Belgian promotion of ESO.

• Several colleagues from the ORB-KSB came to run workshops during the Dag van Wetenschap on 26 November

• A new edition of the *Brussels Planetarium Poetry Festival* took place on December 15 and 16.

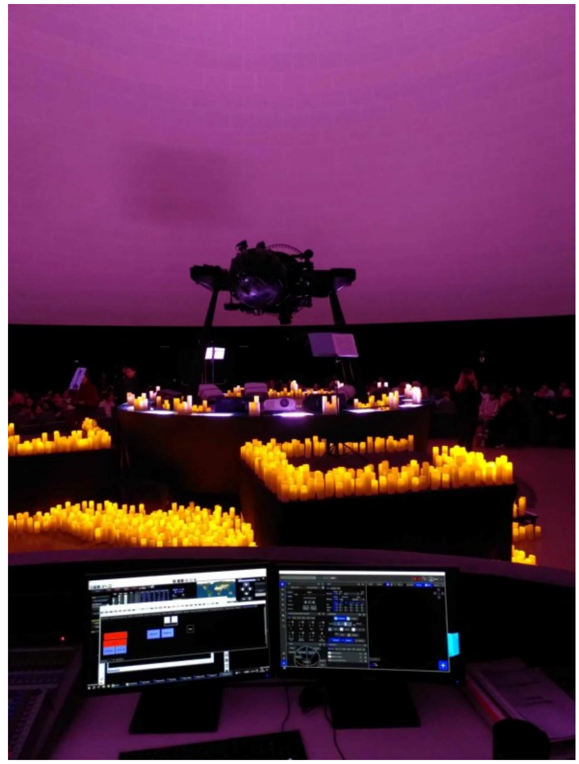
Room rental

Room rental such as the dome or the auditorium allocation were granted in 2023 for the following events:

- Alumni Ekonomika KULeuven on January 25
- VRT (interview with Frank De Boosere) on January 31
- the PITHIA conference from March 13 to 17
- a special session of the Off-Screen Festival on March 26
- the Geography Olympics on April 26
- Intermarché (advertising shoot) on April 27
- the VVS on May 6
- BRODER performance company on May 13

- the non-profit association HR Public on May 23
- EUCLID press conference on June 26

One of the most significant of these rentals is a partnership with the organisers of the successful *Candlelight* concerts for a series of dates in 2023 (and 2024). Three dates and six sold-out concerts (350 spectators per concert) were offered on November 16 and 30 and December 12.



Media interviews

In response to requests from a number of radio stations and newspapers, interviews were given by: RTBF web on January 3 (Rain of shooting stars), Radio Vivacité on May 24 (Dark Side), Radio Nostalgie (Planetarium programme) on July 10, Radio Bruzz on July 18 (Dark Side), Radio Vivacité on December 2 (Planetarium programme).

Appendix 1: Publications

Publications With Peer Review

[1] Andrae, R. ; Fouesneau, M. ; Sordo, R. ; Bailer-Jones, C. A. L. ; Dharmawardena, T. E. ; Rybizki, J. ; De Angeli, F. ; Lindstrøm, H. E. P. ; Marshall, D. J. ; Drimmel, R. ; Korn, A. J. ; Soubiran, C. ; Brouillet, N. ; Casamiquela, L. ; Rix, H. -W. ; Abreu Aramburu, A. ; Álvarez, M. A. ; Bakker, J. ; Bellas-Velidis, I. ; Bijaoui, A. ; Brugaletta, E. ; Burlacu, A. ; Carballo, R. ; Chaoul, L. ; Chiavassa, A. ; Contursi, G. ; Cooper, W. J. ; Creevey, O. L. ; Dafonte, C. ; Dapergolas, A. ; de Laverny, P. ; Delchambre, L. ; Demouchy, C. ; Edvardsson, B. ; Frémat, Y. ; Garabato, D. ; García-Lario, P. ; García-Torres, M. ; Gavel, A. ; Gomez, A. ; González-Santamaría, I. ; Hatzidimitriou, D. ; Heiter, U. ; Jean-Antoine Piccolo, A. ; Kontizas, M. ; Kordopatis, G. ; Lanzafame, A. C. ; Lebreton, Y. ; Licata, E. L. ; Livanou, E. ; Lobel, A. ; Lorca, A. ; Magdaleno Romeo, A. ; Manteiga, M. ; Marocco, F. ; Mary, N. ; Nicolas, C. ; Ordenovic, C. ; Pailler, F. ; Palicio, P. A. ; Pallas-Quintela, L. ; Panem, C. ; Pichon, B. ; Poggio, E. ; Recio-Blanco, A. ; Riclet, F. ; Robin, C. ; Santoveña, R. ; Sarro, L. M. ; Schultheis, M. S. ; Segol, M. ; Silvelo, A. ; Slezak, I. ; Smart, R. L. ; Süveges, M. ; Thévenin, F. ; Torralba Elipe, G. ; Ulla, A. ; Utrilla, E. ; Vallenari, A. ; van Dillen, E. ; Zhao, H. ; Zorec, J.
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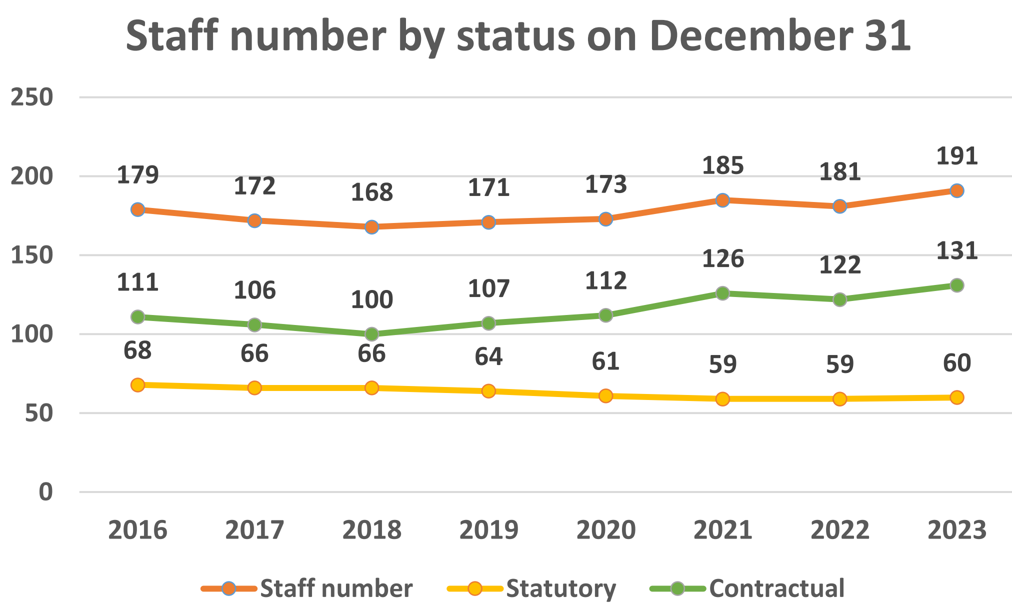
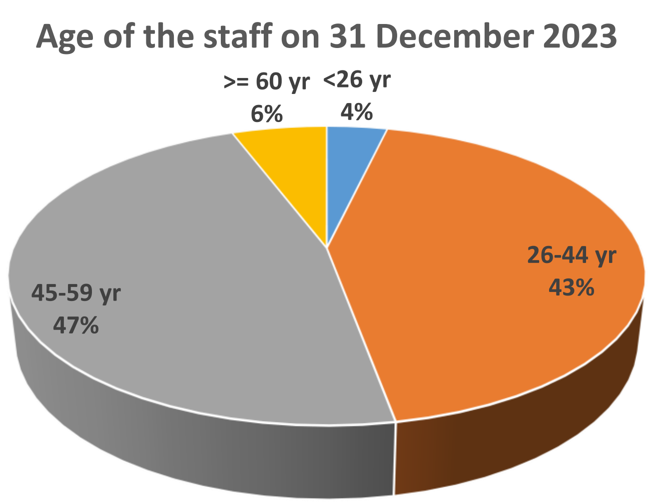
Appendix 2: Workforce

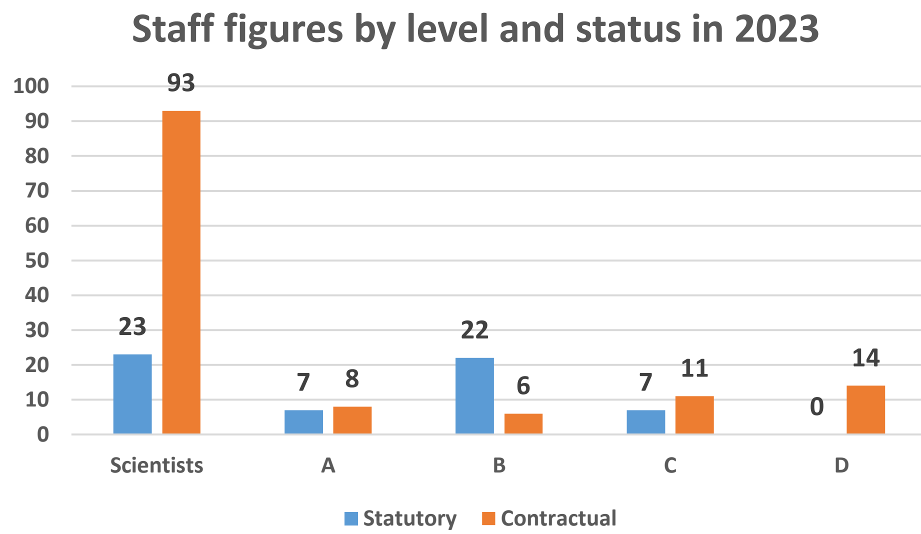
Staff Statistics

On 31 December 2023, 191 employees are working at the ORB-KSB, including people working at the Planetarium and at the Royal Academy of Overseas Sciences. Compared to last year, there was an increase of 9 contractual employees and 1 statutory employee. The mean age of the staff is 44 years, with 91% of the workers between 26 and 59 years.

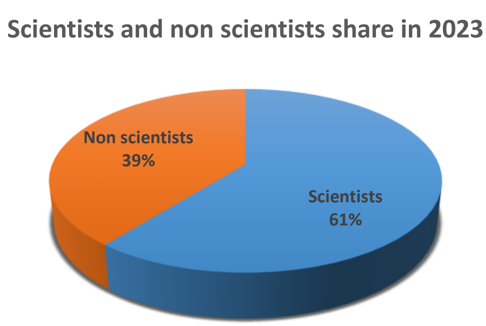


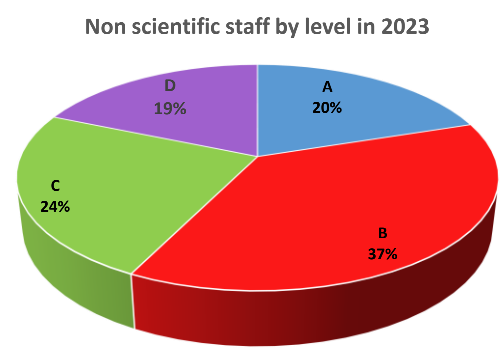


The majority of the staff (69%) are contractual collaborators. This is particularly true for scientists, in whom 80% are contractual, and particularly for employees of level D, for whom all of the staff is contractual.

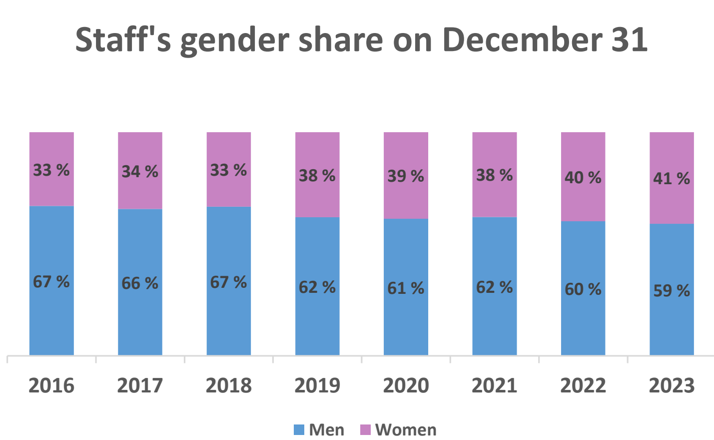


The fact that more and more scientists are contractual is because scientific research is more and more funded by external projects. Moreover, scientists constitute the majority of the staff (61% in 2023), highlighting the fact that the ORB-KSB is a research institute.





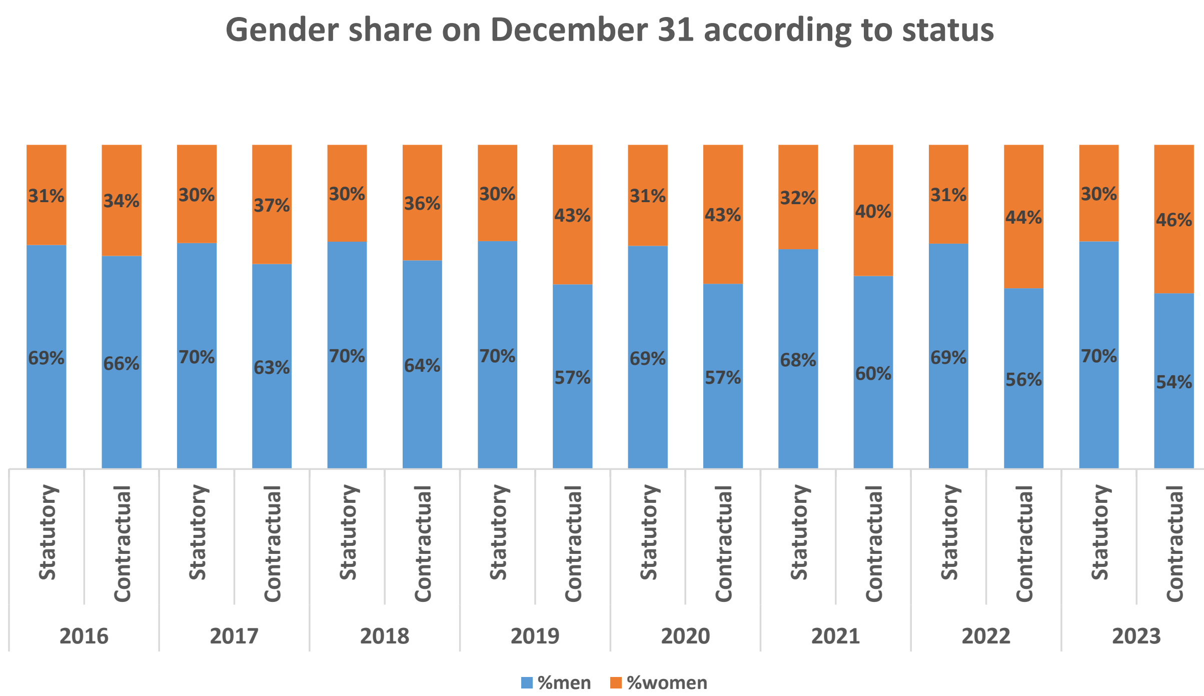
Analysis by Gender



On 31 December 2023, female staff constituted 41% of the employees at the ORB-KSB. This is a slight increase in the share of female employees compared to 2022 (40% of women), and particularly compared to 2016, where only 33% of the staff is female.

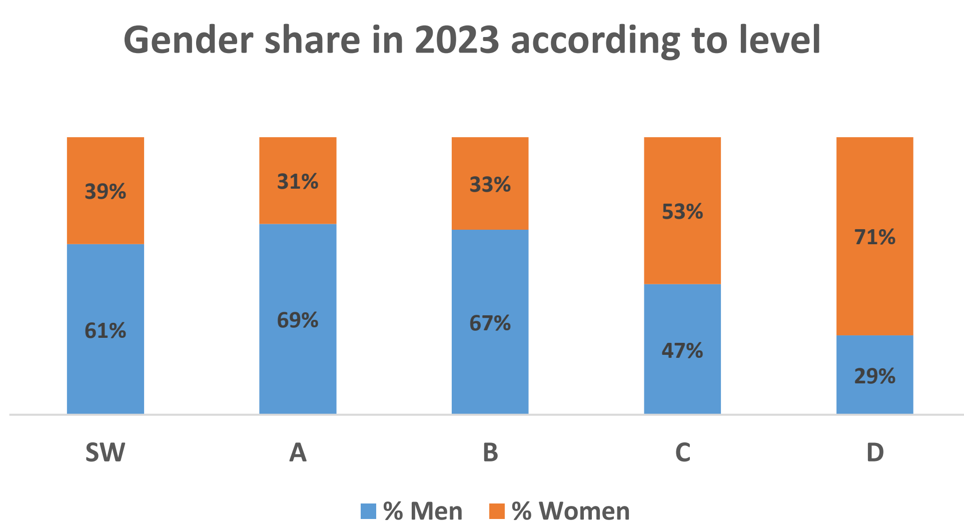
This increase of females in the workforce concerns mainly contractual where, between 2016 and 2022, female contractual staff increases by 58% (from 38 on 31 December 2016 to 60 on 31

December 2022) while male contractual staff remain stable (from 73 on 31 December 2016 to 71 on 31 December 2022). Meanwhile, the gender balance of the statutory staff does not change significantly.

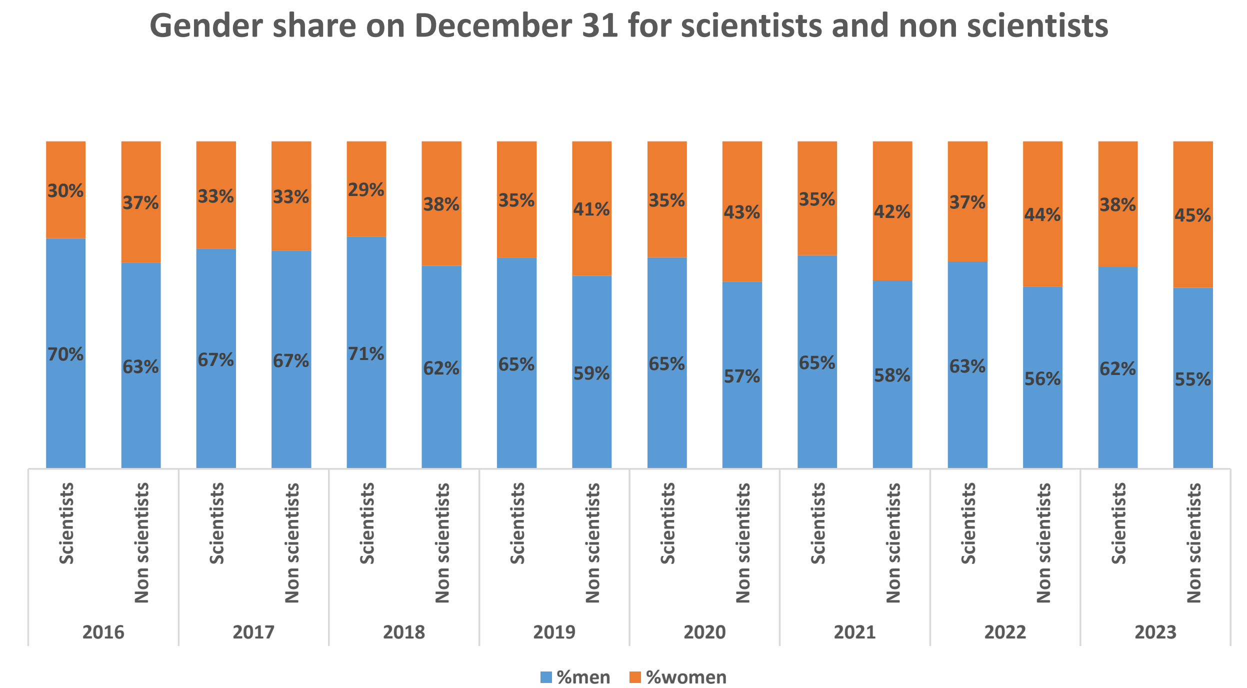


When looking through the staff hierarchy, we can see an inversion of women to men proportion between:

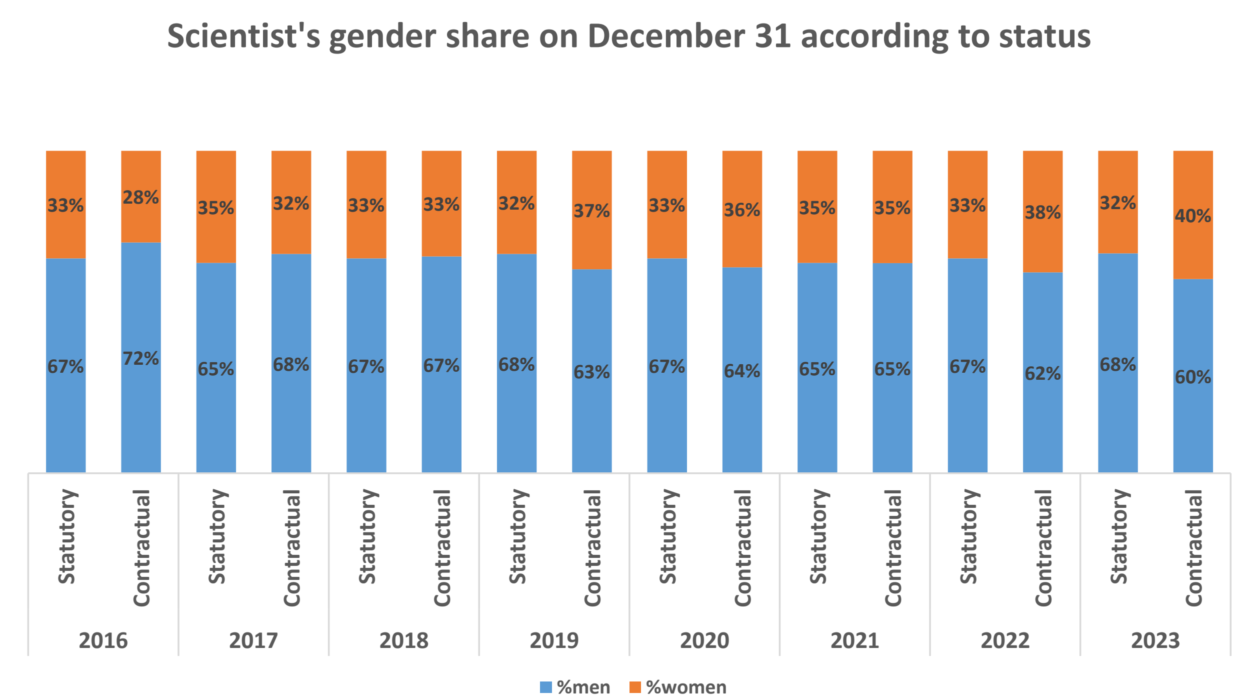
- C- and D-level workers, where women are the majority (53% for C-level workers and 71% for D-level workers) and
- Scientists (SW), A- and B-level workers, where women only make about one third of their corresponding level (31% for A-level workers and 33% for B-level workers), with a slightly higher proportion for scientists (39% of scientists being women).



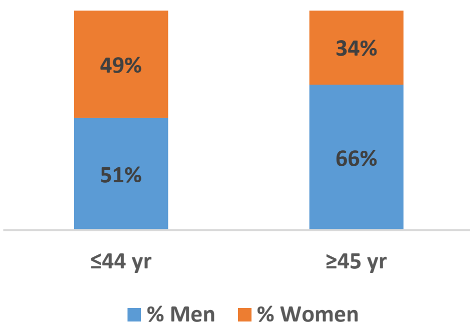
Compared to the administrative staff, women to men proportion is slightly lower among scientists, with only 38% of scientists being women on 31 December 2022, while this proportion amounts to 45% for the administrative staff.



The gender share of contractual and statutory scientists remains, however, relatively constant between 2016 and 2023, with slight increases for contractual scientists in 2019 and 2023.



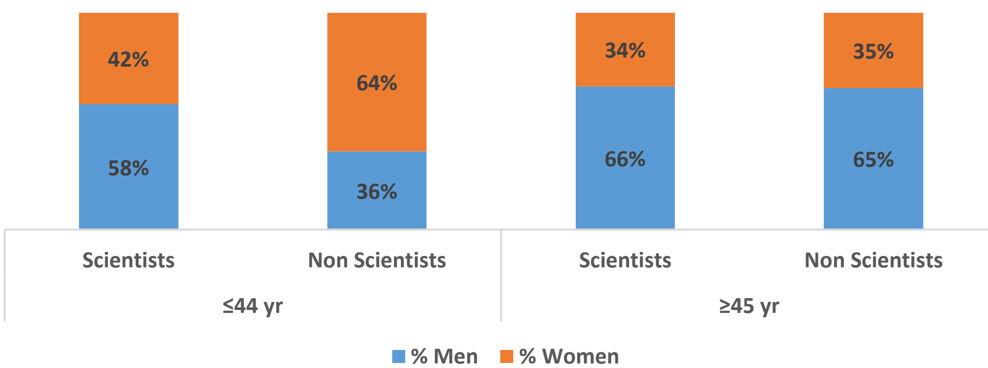
Gender share on 31 December 2023 according to age



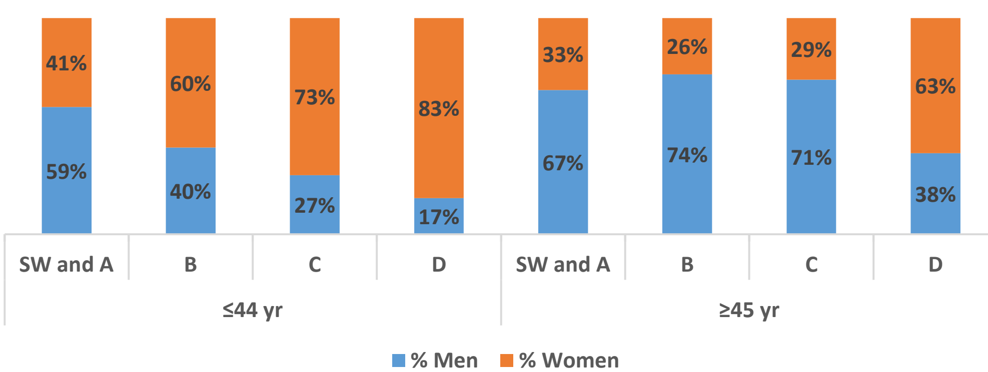
Repartition between male and female staff is more equal for younger employees, with 49% of the staff younger than 44 years old being female on 31 December 2023, while only 34% of the staff older than 45 years being male.

However, for staff younger than 44 years old, the share of female staff is higher among non-scientists (64%) and among young scientists (42%). It is particularly true for female staff at B- (60%), C- (73%) and D- (83%) levels compared to female staff in management level (A and SW, with 41% of the staff being female). For employees older than 45 years, the difference between levels and between scientists (34%) and non-scientists (35%) is much less significant except for D-level employees (64% being female).

Gender share on 31 December 2023 for scientists and non scientists according to age



Gender share on 31 December 2023 according to age and level



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