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Cover illustration: Space Pole Open Door Days 2018. (Credit: Timothy Jans/Royal Observatory of Belgium)

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Preface

This report describes the highlights of scientific activities and public services at the Royal Observatory of Belgium in 2018.
A list of publications and the list of personnel are included at the end.
Due to lack of means and personnel the report is only in English.
If you need more or other information on the Royal Observatory of the Belgium and/or its activities please contact rob_info@oma.be *or visit our website* http://www.astro.oma.be.

Ronald Van der Linden
Director General

Reference Systems and Planetology

This Operational Directorate "Reference Systems and Planetology" contributes to the elaboration of reference systems and timescales, integrates Belgium in the international reference frames, and studies the interior, rotation, dynamics, and crustal deformation of the Earth and other terrestrial planets and moons of our solar system

The principal activities are grouped into two general themes:

1. *Space geodesy and timescales with GNSS (Global Navigation Satellite System), and*
2. *Rotation and interior structure of the Earth and other terrestrial planets and satellites.*

Contribution to the European Plate Observing System – EPOS

EPOS is one of the European Research Infrastructures in the Environmental research area. It focuses on the solid Earth domain and combines research infrastructures and their capital of human expertise, data, and services into one integrated system. It gathers input from geodesy, geology, seismology, volcanology, or geomagnetism. Together, they offer the key to understand the dynamic of the Earth system.

Supported by the European Commission H2020 EPOS Implementation Phase Project, 47 partners, amongst which the ROB, from 25 countries from all over Europe and several international organizations (ORFEUS[1], EUREF[2], EMSC[3]) are building up EPOS today.

On 30 October 2018, the European Commission granted the legal status of European Research Infrastructure Consortium (ERIC) to EPOS, with Belgium as one of its founding members. This was an important step in the implementation of EPOS.

The GNSS team of the Royal Observatory of Belgium contributes to the construction of the GNSS component of EPOS (GNSS: Global Navigation Satellite System). This component will consist of a European network of more than 3000 GNSS stations and will provide access to GNSS data, metadata and products, such as ground deformations.

We committed to provide from 2020 on operational services to EPOS: ground deformations from the EPN stations, a pan-European service that centralizes and validates the GNSS station metadata, a service that monitors the quality of GNSS data, and a European GNSS data node providing access to the data from the European and ROB GNSS stations. These services are a natural follow up of our 20 years of commitment as Central Bureau, Data Centre and Analysis Centre of the EUREF Permanent GNSS Network (EPN). Supported by BELSPO, we are presently upgrading our GNSS and EUREF infrastructure to respond to the EPOS needs.

Within EUREF, the Observatory computes operationally the multi-year coordinates/velocities of the EPN stations. They are updated each 15 weeks and their primary goal is to maintain the ETRS89, which is the European Terrestrial Reference System. Because the velocity field and its associated station position time series gives information on ground deformations valuable for geophysical research, the Observatory also provides these products to EPOS. Since 2018, these EUREF products are regularly delivered to EPOS.

A second EPOS service we provided became operational in 2018: our "Metadata Management and Dissemination System for Multiple GNSS Networks" (M^{3}G) reached the level of maturity required for operational use in EUREF and EPOS and was introduced to the GNSS community. This system allows validating and distributing GNSS station metadata in a fully harmonized way within EUREF and EPOS. 113 European agencies already use M^{3}G to submit, validate and distribute the metadata of their GNSS stations (1975 stations in total) which makes our GNSS metadata collection unique in Europe.

The Observatory European GNSS data node is presently under construction and is expected to become operational in 2019.

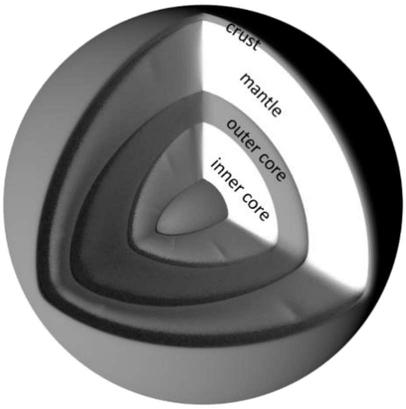
[1] The non-profit foundation to coordinate and promote digital, broadband seismology in the European-Mediterranean area.
[2] Sub-commission of the International Association of Geodesy responsible for defining, maintaining, and providing access to the European Terrestrial Reference System (ETRS89)
[3] European Mediterranean Seismological Centre

Legal Time

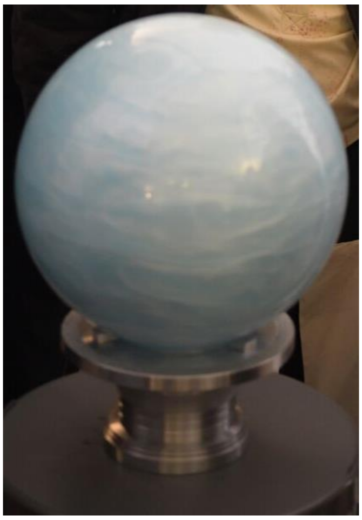
The Legal Time in Belgium was since 1892 based on the Greenwich Mean Time, i.e. a time scale determined by the rotation of the Earth and the associated path of the Sun in the sky. Since 1971, the official time in the world is now the Universal Time Coordinated, i.e. a time scale realized by a network of atomic clocks distributed in the world, among which 4 are at the Royal Observatory of Belgium. The increasing needs for precise timing and legal traceability in our electronic and digital world has pushed our scientists to propose, several years ago, a modification of the Belgian law on Time. The new law on Legal Time was finally voted at the Parliament on May 3, 2018. The law was published in the "Belgian Bulletin of Acts" on September 10. Legal Time in Belgium is now UTC + 1h (winter time) and UTC + 2h (summer time). A Royal Decree will complement this law to specify that both the Observatory and the Belgian Metrology Service (SMD) are responsible for the realization of the legal time and its dissemination.

Rotation and Nutation on a Wobbly Earth

The Earth is composed of different layers: an inner core, an outer core, a mantle and a crust (see figure below on the left). The outer core is liquid and behave like shown in the figure below on the right. The Earth is also a rapidly rotating body, generating centrifugal force and Coriolis forces. The centrifugal pull makes its shape resemble a flattened ellipsoid. The Coriolis forces influence the fluid dynamics of the oceans and atmosphere but also of the fluid outer core. They can also support waves, giving rise to oscillatory motions known as inertial waves. Periodic variations of the Earth's rotation axis (nutations) can exchange angular momentum with the fluid core and excite these inertial modes. The small flattening of the core-mantle boundary (CMB) allows the inertial modes to exert torques on the mantle in addition to viscous torques. This interaction couples the rigid-body dynamics of the Earth with the fluid dynamics of the molten core.



Modelling of the Earth interior



Rotating sphere representing the fluid motions in the Earth liquid core

The team of the ERC RotaNut (Rotation and Nutation of a wobbly Earth) developed the first high-resolution numerical model that solves simultaneously the dynamics of the mantle and the fluid motions in the fluid core. This method takes naturally into account dissipative processes in the fluid that are ignored in current nutation models.

One of the main results of the RotaNut team is that the Free Core Nutation (FCN) and the Chandler Wobble (CW), the two eigenmodes of the two-layer planet system, are the least damped. Viscous dissipation processes and the power associated with the global rotation in the fluid contribute mainly to the overall damping. There is also a fairly complex network of interactions between the FCN and modes with similar near-diurnal frequencies.

Furthermore, the team has worked on the effects of the magnetic field in these motions by adding the Lorentz forces on the fluid (in the Navier-Stokes motion equation) and by considering the induction equation (relating the changes in the magnetic field to the velocity induced field and the Ohmic dissipation). This is a fully magneto-hydrodynamic (MHD) problem that has allowed the team to consider the geodynamo effects on nutations.

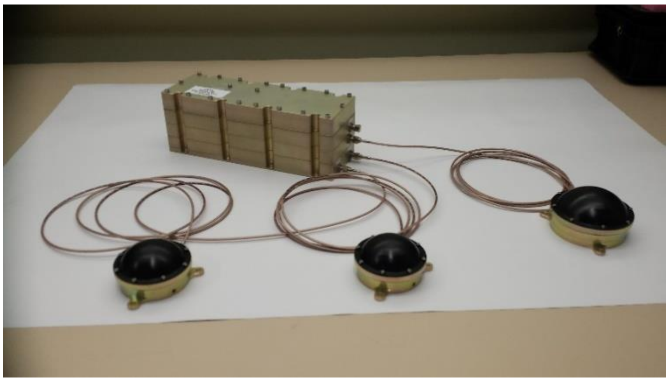
In parallel, the group has worked on the effects of a topography at the core-mantle boundary on the fluid motions and has confirmed the strong impact on angular momentum transfer. The main results obtained by team show the existence of a mean azimuthal circulation (also called geostrophic flow) resulting from non-linear interactions in the fluid and the topographic torques at the CMB.

Radio Science on Mars

LaRa (Lander Radioscience)

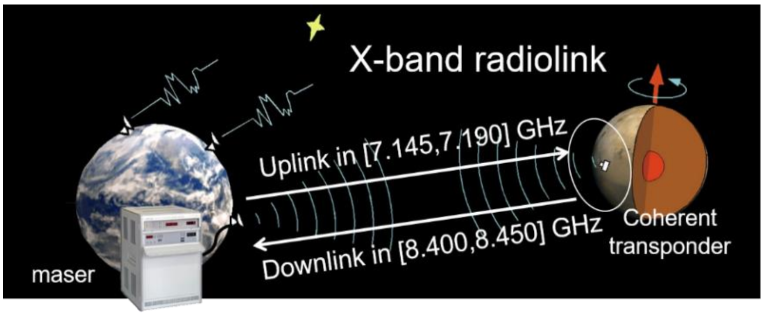
Over the last decade, new data on the planet Mars, coming from several missions and observations on the Red planet, allow scientists to better understand Mars' interior, evolution and habitability. Data obtained through new space missions are the basis of the future progress in this field.

In 2020, ESA and the Russian space agency Roscosmos will launch the ExoMars2020 mission. It consists of a rover and a surface platform that will land on Mars on 2021. Belgium develops LaRa (Lander Radioscience), one of the platform instruments. The LaRa instrument (see the figure below) is built in collaboration with other Belgian actors under the lead of ESA PRODEX and ROB which provide the instrument specifications. It is composed of three antennas designed by UCLouvain and a transponder designed by Antwerp Space. LaRa will allow radio communications between Earth and the ExoMars 2020 surface platform Kazachok.



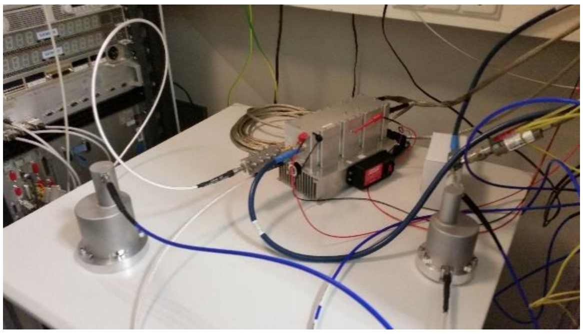
LaRa transponder and antennas Engineering Models

The transponder will catch the radio signals transmitted from Earth by the large antennas of the DSN (Deep Space Network) and will send them back without phases shift with respect to the uplink signals (see the figure below). The Earth ground stations will record the downlink signals and the LaRa scientific team will use them to accurately determine the rotation and orientation of Mars, and will deduce from that characteristics of the planet interior.

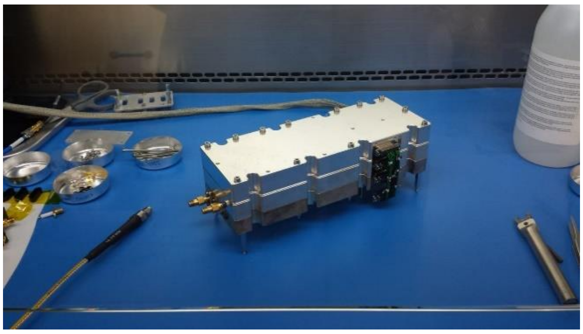


LaRa principle

Different models of the instrument parts were developed in 2018: the Thermal Model, the Structural Model, the Engineering Model and partly the Flight Model. The Engineering model that is built to test the functionalities of LaRa has been tested (see figure below on the left) at ESOC (European Space Operations Centre, in Darmstadt) and has the coherence of the instrument to be better than the requirements of the Royal Observatory of Belgium. The transponder is being built (see figure below on the right) for a delivery during the summer 2019.



The LaRa transponder and antennas (covered with a cap) at ESOC for performance testing

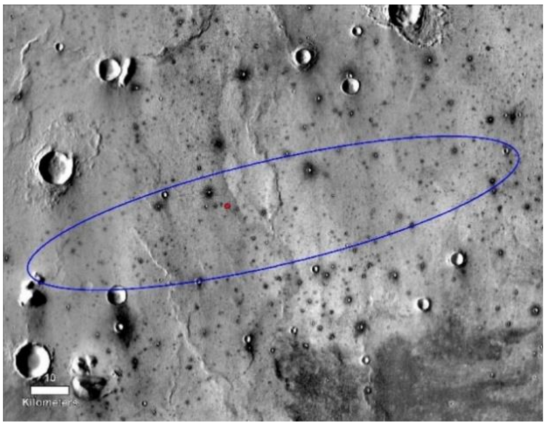


Flight Model of the transponder while mounting the PCBs. Three PCBs are already mounted

The final tests will begin in 2019, after assembly of the different transponder parts. The antennas were tested against shocks and vibrations and the flight models are ready to be sent in July 2019 with the transponder to the Russian colleagues for integration on the surface platform Kazachok.

Participation in the RISE experiment

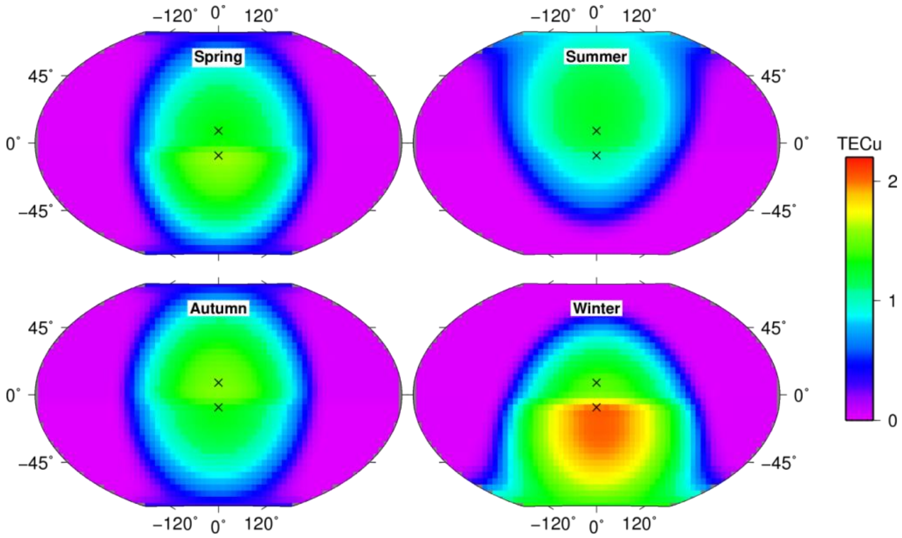
The Royal Observatory of Belgium also participates in the radio science experiment RISE (Rotation and Interior Structure Experiment) on the NASA mission InSight, which landed on Mars on 26 November 2018. Immediately after landing, our team determined its position, making possible for the HiRISE (High Resolution Imaging Science Experiment) camera of the NASA MRO (Mars Reconnaissance Orbiter) to take pictures of the lander, the heat shield and the parachute (see the figures below).



THEMIS camera image on NASA's 2001 Mars Odyssey orbiter. The red dot marks the landing location of NASA's InSight lander within the landing ellipse (blue)

Images of the parachute, the lander, and the heat shield of InSight that landed on November 26, 2018, in the region of Elysium Planitia. Copyright NASA

The Observatory participates in several studies to assess information about the deep interior of Mars that can be obtained from observations of its nutations with the RISE instrument and the LaRa instrument. Nutations are periodic variations of the planet rotation axis in space. In a first study, sources of inconsistencies between different published nutation series were identified and clarified so that confidence in the nutation series is now achieved at a level sufficiently accurate for scientific purposes. In a second study, the effect of the interior on the nutation amplitudes and on the period of rotational normal modes involved in a resonance with some of the nutations was considered.



Global maps of Mars vTEC expressed in TEC units (TECu = 1016 e-.m-2, where e- means electrons). The different maps correspond to the different outputs of the model for different seasons (in the Northern hemisphere) at local noon at the meridian origin

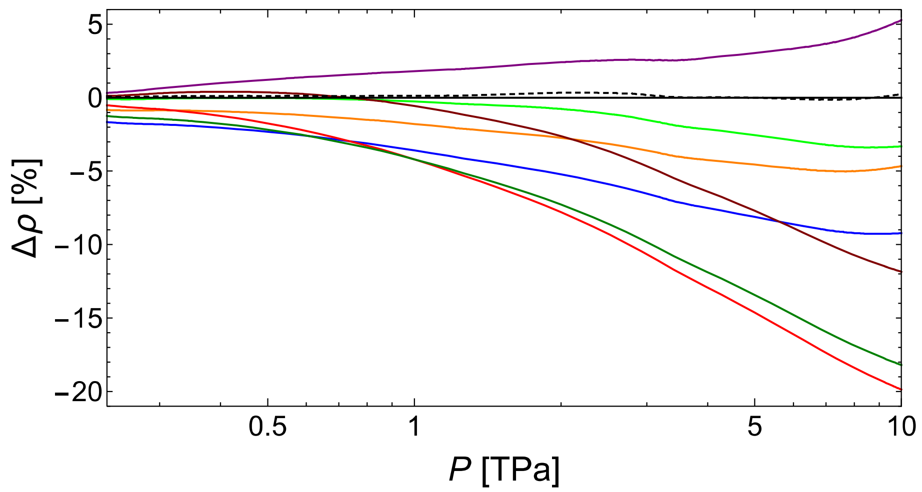
We also developed a new empirical model of the Total Electron Content (TEC) of the Martian ionosphere to be able to assess its influence on propagating radio signals. The model provides values for the vertical TEC (vTEC) for a given solar zenith angle, solar activity, and solar longitude in the two Mars hemispheres. The model can be used to support the data analysis of radio science experiments.

We showed that the Mars ionospheric contribution, even if it is generally smaller than the expected noise of the radio-science instruments, must be taken into account since its seasonal variations are of the same periods as those of the geophysical parameters that would be determined by the experiments (see the figure above). The ionospheric corrections should be applied even during moderate solar activity level, in particular for more accurate studies based on long term data (i.e. more than 1 Mars year), such as those aiming at studying the deep interior of the planet.

Material properties and planetary interiors

Planetary interiors can be studied using space missions and Earth-based observations. Since those data generally provide information on global physical quantities instead of local ones, they have to be combined with physical data about the material components of the planet in order to optimize the science return. Geodesy data are ideally suited to infer properties of planetary cores. We therefore investigate thermodynamic and transport properties of core alloys and their effect on geodesy data.

In large rocky exoplanets, pressures in the core can exceed those in the Earth core by one order of magnitude. Such pressures are currently out of reach for laboratory experiments. To compensate the lack of data, most studies have relied on extrapolations of iron equations of state which are valid under Earth core conditions. However, several of these equations are not valid at extreme high pressures.

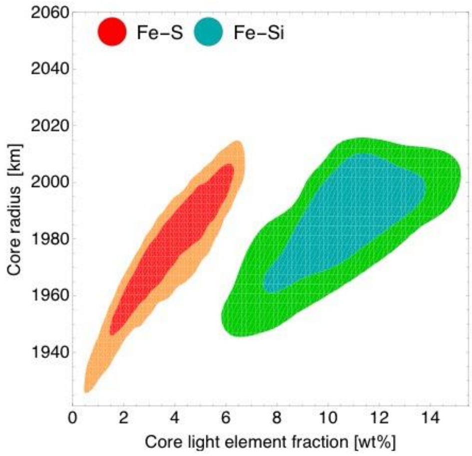


Comparison of the relative density difference in per cent between the new equation of state and different iron equations of state published in the literature

In collaboration with UGhent, we developed a new equation of state of hexagonal close packed (hcp) iron for super-Earth conditions based on density functional theory results. A comparison of this new equation of state with extrapolated iron equations of state from the literature reveals differences in density of up to 4% at 1 TPa (terapascal) and up to 20% at 10 TPa (see the figure above). Such density differences significantly affect mass-radius relations of exoplanets. Mass estimates can differ by as much as 10% for Earth-like super-Earths (core-radius fraction of 0.5) and 20% for Mercury-like super-Earths (core-radius fraction of 0.8). We integrated this equation of state in detailed models of super-Earth interior structure and also included the most recent data about mineral phases in the rocky mantle of massive exoplanets. Differences with older iron equations of state have been shown to be larger than the effect of uncertainties in temperature. Uncertainties in core and mantle compositions can create a spread in mass-radius curves that is much larger than the effect of using a not-well suited iron equation of state and dominate over observational uncertainties for many observed super-Earths.

For terrestrial planets of the solar system, one can perform laboratory experiments at planetary core pressure and temperature conditions. In particular, for Mercury, pressures at the top of the core can easily be reproduced in experimental setups because of its small size and exceptionally large core. Recent spacecraft data from the NASA MESSENGER mission indicate that silicon is the most likely light element in Mercury partially liquid core, but key thermodynamic properties of Fe-Si alloys, which are required to understand Mercury core dynamics, evolution and magnetic field, are currently missing.

European Synchrotron Radiation Facility in Grenoble, France



Core radius probability for different light elements and light element concentrations

Scientists from the Observatory, together with colleagues from VU Amsterdam, ULiège and KU Leuven, performed measurements to determine liquid Fe-Si density at pressures and temperatures relevant for Mercury core at the European Synchrotron Radiation Facility in Grenoble, France (see figure above on the left). The measurements will complement and extend the available density data of liquid Fe-Si and will enable the determination of an accurate equation of state for liquid Fe-Si. This equation of state is an essential ingredient to infer Mercury interior structure and its thermal evolution from spacecraft data, such as those from the ESA/JAXA BepiColombo mission launched in 2018.

In order to model the core of a terrestrial planet and to calculate the core alloy thermodynamic properties, we developed thermodynamic models of Fe-Ni-S and Fe-Ni-Si, based on the latest experimental data (see figure above on the right). Those modµels are used to infer the best information on the core of Mercury and Mars. For Mercury, the models are based on the newest polar moment of inertia value, estimated from MESSENGER radio science data, and the latest estimate of the tides. The estimated core radius confirms previous results that did not use the tidal data and that were based on a larger polar moment of inertia. The data cannot decide upon the existence of an inner core in contrast to results from American colleagues, who did not use the melting temperature to determine the inner core as we did. Mars models are based on the new thermodynamic model. Geodesy data indicate that the Martian core contains significantly more sulfur than previously thought, if sulfur is the only light alloy in the core. Those sulfur amounts are at odds with models that infer the composition of the core from geochemical data and formation histories. This indicates that other light elements must be present in the core, in accordance with models of the Martian core formation. The addition of a smaller amount of oxygen to an iron-sulfur core alloy with sulfur content consistent with geochemistry can explain the density of the core deduced from geodesy data.

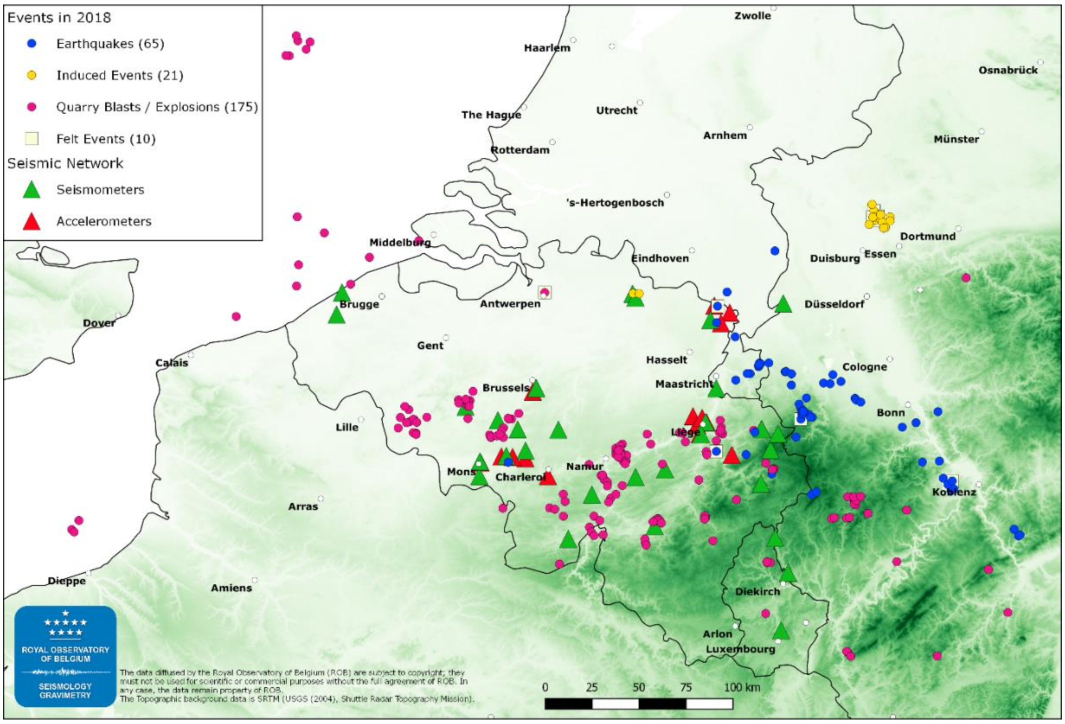
Seismology and Gravimetry

The main mission of the Operational Directorate "Seismology and Gravimetry" is studying variations of gravity and seismic activity, their causes and consequences. To support this scientific research and to provide the authorities, the media and the public with information about the seismic activity in real time in our region, this operational directorate develops and maintains a seismic network in Belgium.

Service to society

65 natural earthquakes were located in or near Belgium in 2018. The largest, felt event was recorded on 25 May 2018 in Kinrooi (ML=3.1).

During the same period, the Royal Observatory of Belgium measured 21 induced events, 175 quarry blasts and controlled explosions. The catalogue is complete for natural earthquakes and contains a selection of quarry blasts and earthquakes induced by human activities, e.g. linked to (rock) mass removal in mines or geothermal exploitation. In 2018, there were at least 19 measurable explosions at sea. Most explosions are performed by the Belgian, Dutch or French Army to destroy WW1 and WW2 bombs. Explosions in the southern North Sea might be linked to oil and gas prospection in that area. 5 earthquakes, 4 induced events and 1 explosion were felt in the region in 2018. A controlled explosion of the old docks of the Schelde River in Antwerpen was felt on 1 July 2018.



Events recorded in 2018 by the Belgian Seismic Network of the Royal Observatory of Belgium

As usual, the Royal Observatory of Belgium provided expertise on seismic hazard to several partners: Engie-Electrabel (Brussels) for Belgian nuclear power plants, NIRAS-ONDRAF, FABI (Federation of the Belgian architect and engineers,) FANC-AFCN, the Crisis Centrum, IDEA (Intercommunale de développement économique et d'aménagement du coeur du Hainaut) and VITO (Vlaamse Instelling voor Technologisch Onderzoek). In particular, the ROB provided expertise concerning the earthquakes induced by the geothermal exploitation done by VITO at the Balmatt site in Mol.

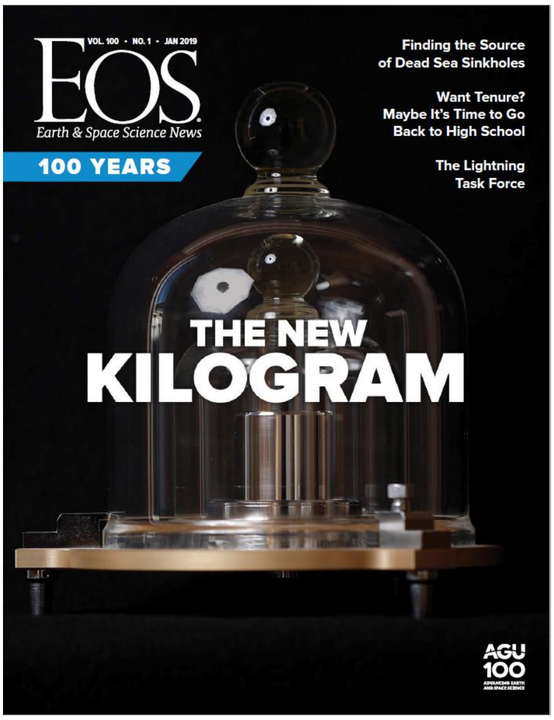
T. Camelbeeck is member of the scientific council of EDF, which develops with industries the collaborative project SIGMA-2. It aims at improving data, methodologies and methods necessary to assess the seismic risk. This is done for different tectonic contexts and for different industries such as nuclear and Seveso ones.

In 2018, the ROB delivered this report to Engie-Electrabel: Kris Vanneste & Thierry Camelbeeck, Evaluation of Earthquake Level 2 (EL-2) hazard at outcropping rock for Belgian Nuclear Units: Capable-faults approach, Report: ROB-ENGIE 2018-01 version 2.

The expertise of the Observatory in metrology: the redefinition of the kilogram

On November 16, 2018, in Versailles, the General Conference on Weights and Measures officially endorsed the new basic units of the International System of Units (SI; Système Internatiopnal d'Unités). Those units are based on seven constants, of which the speed of light *c*, the Avogadro constant N_A, and the Planck's constant *h*. This became effective on May 20, 2019. Hence, the kilogram will be officially redefined as a function of the Planck's constant, used in Einstein's energy formula: E = mc² = *hv*.

This change in definitions is necessary, since the use of the International Prototype Kilogram K, made of platinum and iridium, poses various problems. For example, there is no way to ensure its long-term stability. It might be destroyed or damaged, and it poses logistical problems when it has to be compared with its copies.



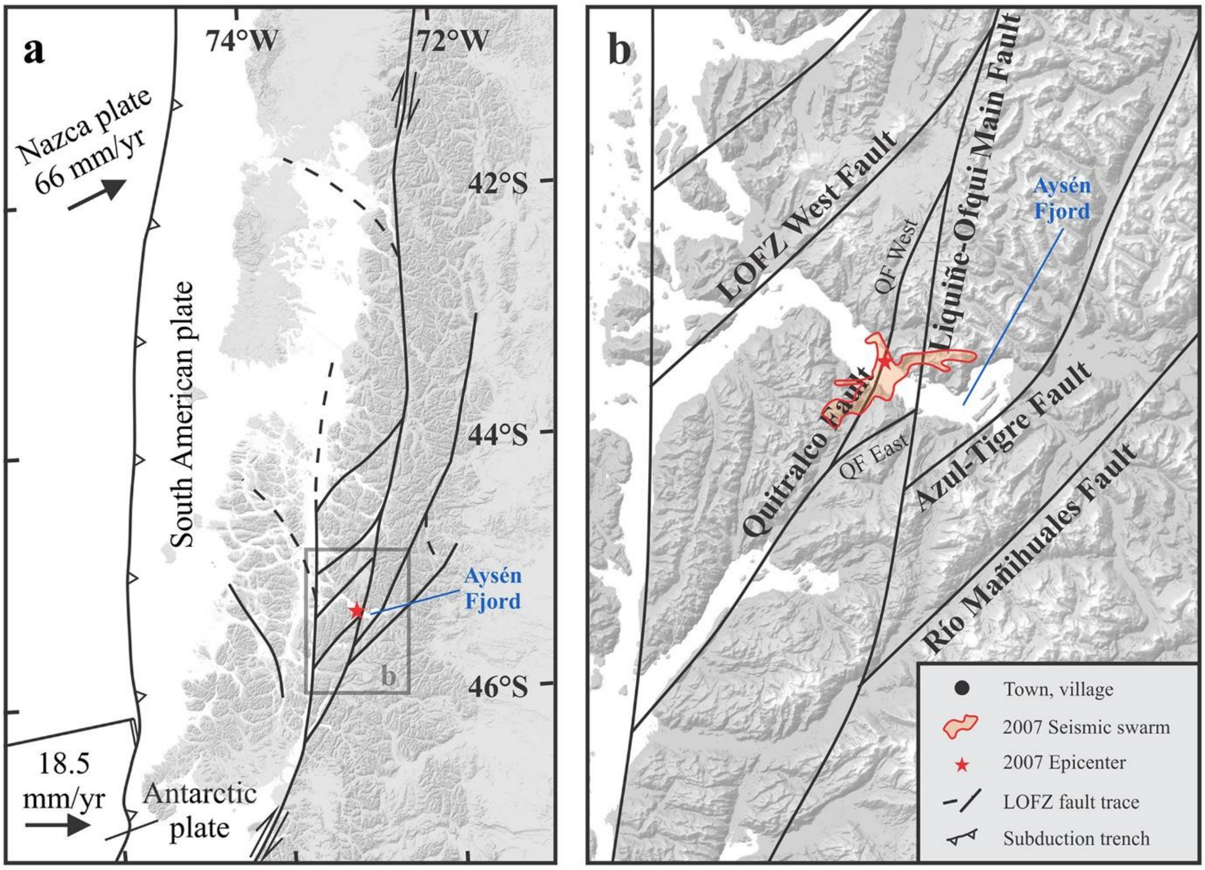
Hence, the meter, the kilogram and the second are now defined by the motions and energy of electrons, atoms and photons. However, the new constants will not be completely divorced from their historical ties. The numerical values of the constants will be such that at the time the definition is adopted, the continuity is ensured with the former system. Hence, the SI remains rooted to our home planet: originally, the meter was defined as 1/10,000,000 of the length of a quadrant of Earth's meridian, the second as 1/86,400 of the duration of the mean solar day, and the kilogram as the mass of one cubic decimeter of water.

Michel Van Camp and his colleagues at the Federal Institute of Metrology in Bern and the University of La Rochelle highlighted the importance of Earth sciences in the origin and realization of the SI. Their article was published on EOS, a magazine of the *American Geophysical Union*, and hit the headlines of the first issue of 2019 of the magazine.

Identifying sources of earthquakes in a fault zone in Chile

The Royal Observatory of Belgium aims at identifying sources of earthquakes by searching for evidence of past earthquakes in the geologic record. Investigation is focused on Belgium and neighbouring areas, but expertise is also acquired in other regions of the world. This allows extending our knowledge of the seismic cycle of slowly slipping faults in the intracontinental context of our region, and thus contribute to a better assessment of seismic hazard.

Strong earthquakes often cause landslides that may be preserved as typical deposits in lakes and fjords. Previous studies have linked the triggering of different types of landslides to minimum shaking intensities and used empirical relations with earthquake magnitude and distance in a simple way to derive the most likely location and magnitude of the earthquake. We performed a study in cooperation with Ghent University, inspired by probabilistic seismic hazard assessment, to evaluate which fault section, and corresponding magnitude, in a zone of faults is the most likely earthquake source responsible for landslide deposits.



Tectonic setting of Aysén Fjord (blue label) with indication of the nearby faults of the LOFZ. South of the fjord, the QF bifurcates in two branches, which we denote as QF West and QF East. Adapted from Wils et al. (2018). LOFZ = Liquiñe-Ofqui Fault Zone; QF = Quitralco Fault

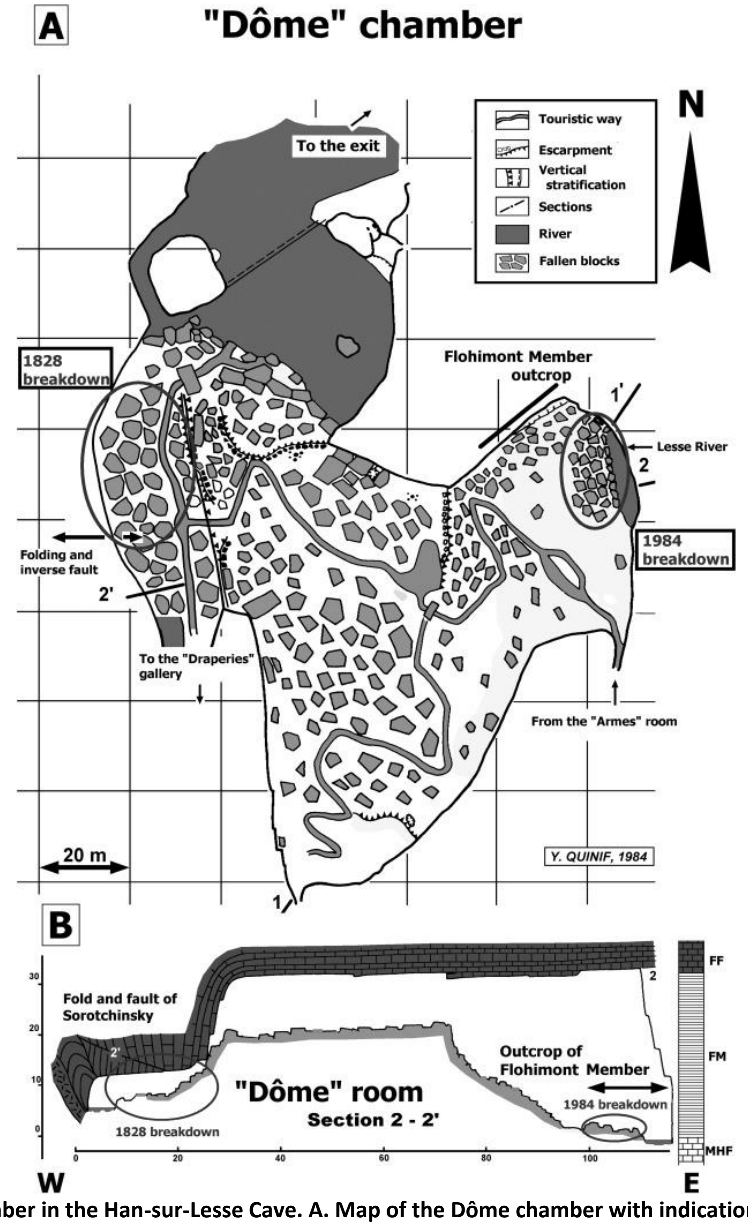
We apply our method to Aysén Fjord, located in southern Chile. An earthquake on one of these faults in 2007 caused various landslides, which are preserved in the fjord's sedimentary record, along with nine older landslide events. Our study could evidence the faults that most likely are responsible for those deposits. Our results, published in the Journal of Geophysical Research, confirm that most landslides are the result of earthquakes on faults in or around the fjord and that only a few could be the result of larger earthquakes on the subduction zone off the coast.

Study on vault collapses in the Han-sur-Lesse cave

The Royal Observatory of Belgium led a study on the relationship between vault collapses in caves and earthquake activity.

Collapse activation is an ongoing process in the evolution of karstic networks related to the weakening of cave vaults. Because collapses are infrequent, few have been directly observed, making it challenging to evaluate the role of external processes in their initiation and triggering.

A team of scientists led by the Observatory studied the two most recent collapses in the Dôme chamber of the Han-sur-Lesse Cave (Belgian Ardenne) that occurred on or shortly after 3rd December 1828 and between the 13th and 14th of March 1984.

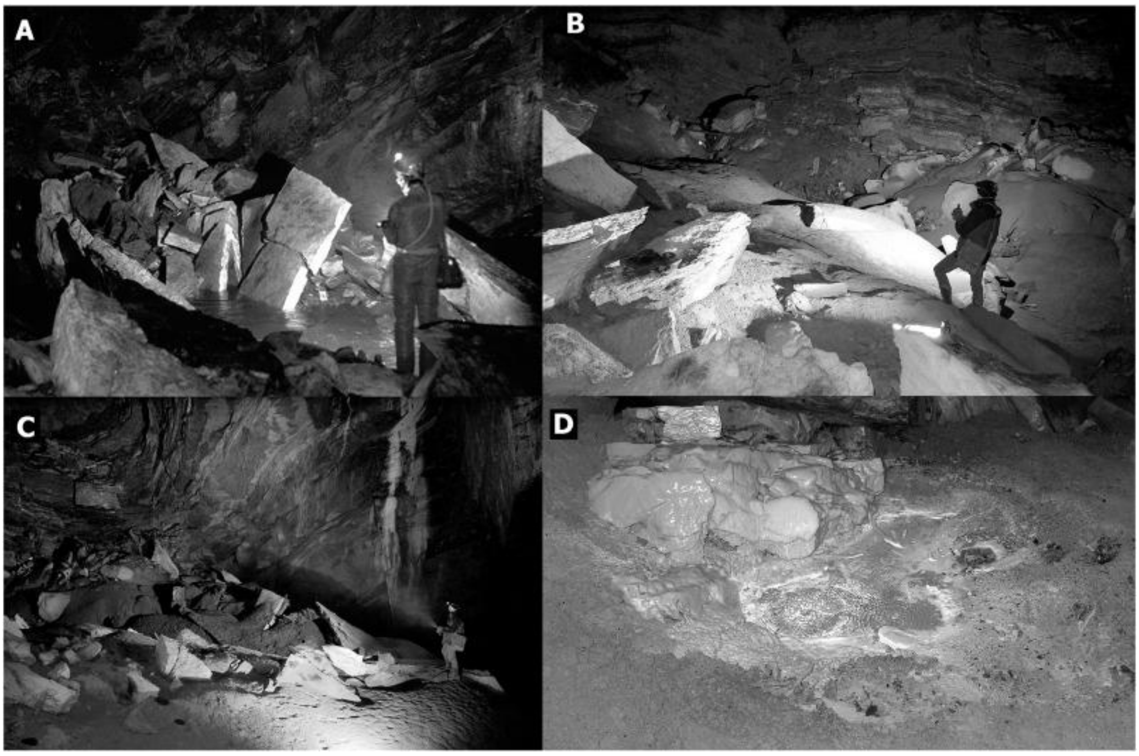


The "Dôme" Chamber in the Han-sur-Lesse Cave. A. Map of the Dôme chamber with indication of the location of historical collapses. B. W-E section of the chamber. Stratigraphic column: MHF = Mont d'Haurs Formation — FM = Flohimont member (base of the Fromelennes Formation) — FF = continuation of the Fromelennes Formation

The team found evidences suggesting that the two historical collapses in the Dôme chamber of the Han-sur-Lesse cave was induced by the 23 February 1828 Central Belgium and the 8 November 1983 Liège earthquakes.

In the study, published in the journal Geomorphology, the scientists argue that the earthquakes accelerated the cave vault instability, leading to the collapses by the action of other factors weakening the host rock. In particular, the 1828 collapse was likely triggered by a smaller Mw = 4.2 nearby earthquake. The 1984 collapse followed two months of heavy rainfall that would have increased water infiltration and pressure in the rock mass favoring destabilization of the cave ceiling.

The study suggests that earthquakes could play a stronger role than previously thought in initiating cave collapses and opens new perspectives for studying collapses and their chronology both in the Han-sur-Lesse Cave and in other karstic networks.

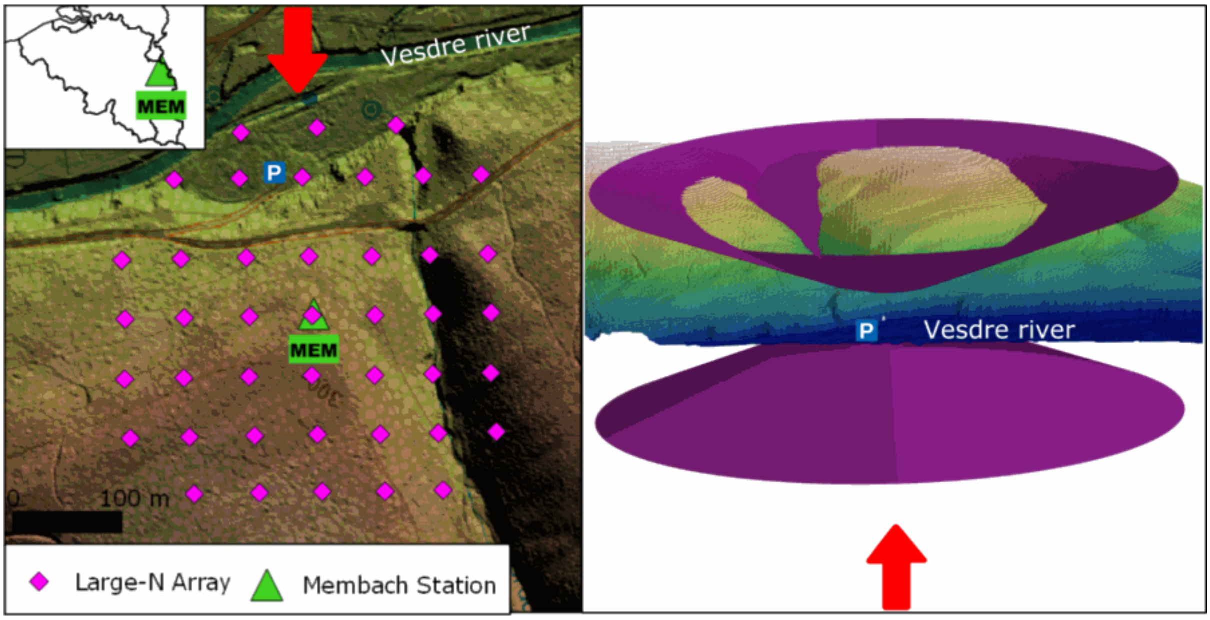


The 1984 collapse in the Dôme chamber of the Han-sur-Lesse Cave. A. Photograph taken one week after the wall collapse; B. Current state of the same area of the screen. Flood muds have invaded much of the scree's surface; C. Overview of the scree cone at the present time. The right wall is sculpted in the Flohimont member, which has a low mechanical strength; D. Development of a speleothem since the 1984 collapse essentially consisting of a pool and blocks covered with calcite. The photo covers an area around 1 m wide

The LARGE-MEM project

The LARGE-MEM project is a small-scale but dense noise-based study aiming at better understanding rainfall and groundwater storage effects on seismic velocities measured by a dense seismic network. The goal of LARGE-MEM is to demonstrate that the actual quantity and location of water in the subsurface can be estimated from measurements using a LargeN array, i.e. a dense seismic network.

To achieve this, one LargeN array consisted in a mixture of roughly 40 one- and three-component seismic sensors, on a regular grid (400x400m) was installed above the forested hill above the Membach underground laboratory. The data from superconducting and absolute gravimeters located in a gallery under the study site will be used to measure precisely the mass of water sampled by the seismic waves.



Map view of the Membach Hill (left) and 3D view (right) of the hill with the zone if larger influence on the gravimeters in the laboratory (purple). The village of Membach is located 1.2 km to the NW. The location of the underground laboratory (green triangle) and the Large-N array proposed for the project (magenta diamonds) are shown on the hill-shaded, coloured and contoured topography

In 2018, the field surveys of the LargeMEM project were a success and the data is now ready for processing. The initial processing with the "summer deployment" data show a link between seismic velocities and radar-deduced rainfalls on the forested hill.

LARGE-MEM is a 149 950€ project funded by the Brain.BE action "Pioneering Projects" of Belspo, the Belgian Science Policy Office. The project runs from January 2017 to April 2019.

Astronomy and Astrophysics

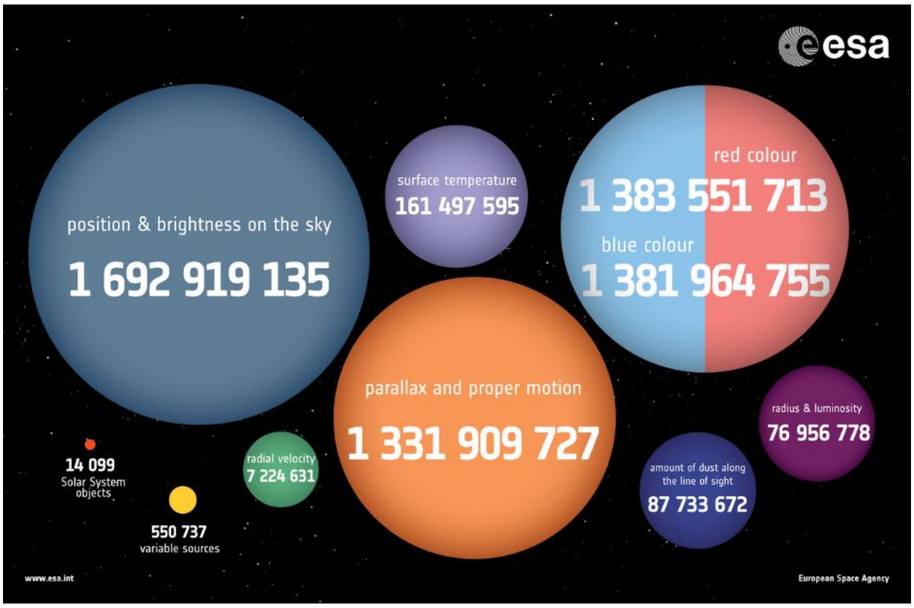
The astronomers of the Operational Directorate "Astronomy and Astrophysics" do research in astronomy and they also observe solar system objects. Stellar evolution, mass loss of stars, variable and multiple stars as well as rapidly rotating stars are studied. Astrometry of minor planets is carried out and planetary satellites are observed. The researchers are active in the preparation and/or reduction and interpretation of data coming from dedicated observational campaigns, large scale surveys and space telescopes.
The service maintains databases and provides software for scientists. General information on astronomical and related phenomena are given to the public and to the press. Digitisation and archiving of photographic plates is also a task of this group.

Gaia's second data release

On April 25, 2018, the second data release of the Gaia satellite (Gaia DR2) was made public. Gaia determines highly accurate positions, distances and velocities of a large number of stars, substantially increasing our knowledge of our Milky Way. Scientists of the Royal Observatory of Belgium, funded by Belspo through the ESA-PRODEX programme, contribute to the huge effort of turning the raw Gaia data into astrophysically meaningful quantities.

The Gaia satellite was launched at the end of 2013. Since then, it continuously scans the sky with its two telescopes, repeatedly and accurately measuring the positions of an enormous number of stars (going down to magnitude 21). By seeing how these positions change over time, Gaia can also measure the proper motion of each star. Furthermore, the Gaia satellite contains a photometric instrument made of a Blue and Red Photometer (BP and RP, respectively) that covers the 320 – 1000 nm wavelength range, and a Radial Velocity Spectrometer, which uses the Doppler Effect to measure the velocity in our line of sight. From the BP/RP photometry, stellar parameters can be determined.

Based on only 22 months of data, Gaia DR2 already contains an impressive number of results, as shown in the figure below. Compared to what was known previously, Gaia DR2 goes a hundred times deeper, is a thousand times more accurate, and contains ten thousand times more stars. For many of these stars, there is also colour information, and a substantial number have their stellar parameters determined. While Gaia is mainly intended for stellar work, it also observes objects in our Solar system, and information about a number of minor planets is included in Gaia DR2.



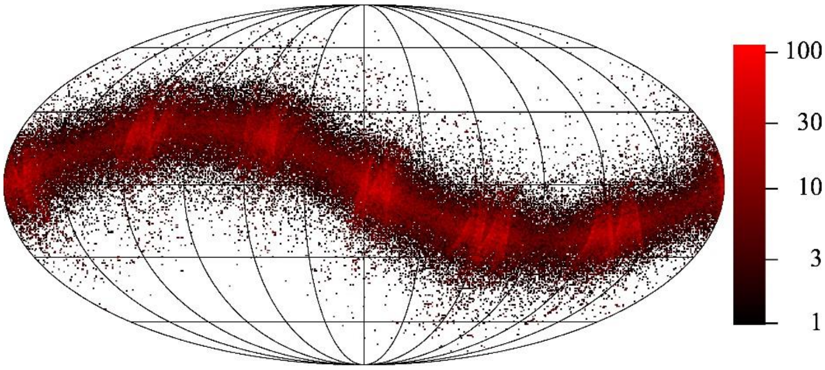
An overview of the number of data present in Gaia-DR2. Credit: ESA

DPAC

The analysis of all Gaia data is done by the Data Processing and Analysis Consortium (DPAC). This is a collaboration between some 450 scientists and software developers from over 20 countries. The Royal Observatory of Belgium, as well as other Belgian groups, are part of that consortium. The work in DPAC is spread over a number of Coordination Units (CUs), each being responsible for a specific part of the data processing. Scientists of the Royal Observatory of Belgium contribute to CU4 (Object Processing – which includes Solar System Objects), CU6 (Spectroscopic Processing), CU7 (Variability Processing), CU8 (Astrophysical Processing) and CU9 (Catalogue Access).

Solar system objects

Since Gaia is scanning the sky, thereby observing everything that comes in its field of view, the data that Gaia transmits to the ground station also contain solar system objects. The Solar System Objects (SSO) team within CU4 of DPAC takes care of the data concerning solar system objects, and asteroids in particular. The Royal Observatory of Belgium is active within this team, and is specifically involved in the transformation of the observed positions in the focal plane of Gaia to coordinates in the sky.



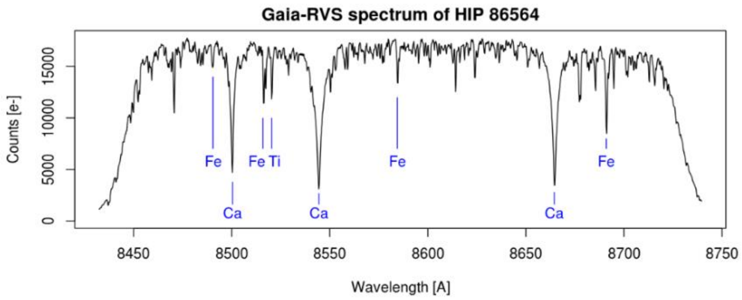
This sky map in equatorial coordinates (right ascension horizontally and declination vertically) shows the asteroid detections in the DR2 catalogue. The wavy band is the concentration of the asteroids near the ecliptic. Irregularities come from Gaia's scanning law: with only 22 months of observations, some regions in the sky have been observed more often than others

Gaia is expected to observe about 300 000 asteroids, plus some comets and satellites. Major planets are too bright and extended to be observed by Gaia. However, DR2 was the first data release containing asteroids, and was therefore treated as a test case. We selected a subset of 14 000 well-known asteroids, based on some quality criteria. One of the conditions for an asteroid to be selected for DR2 was that it would be observed at least 9 times by Gaia, so that an accurate orbit could be computed from the Gaia positions alone. The orbits themselves were not published, but were used to assess the quality of the positions: the residuals, i.e. the differences between the observed positions and those computed from an orbit, tell us whether the errors on the positions are in agreement with the computed uncertainties. The validation shown an excellent agreement for objects fainter than magnitude 10. However, brighter asteroids showed errors systematically larger than the computed uncertainties and were therefore removed from the output catalogue.

Radial velocities

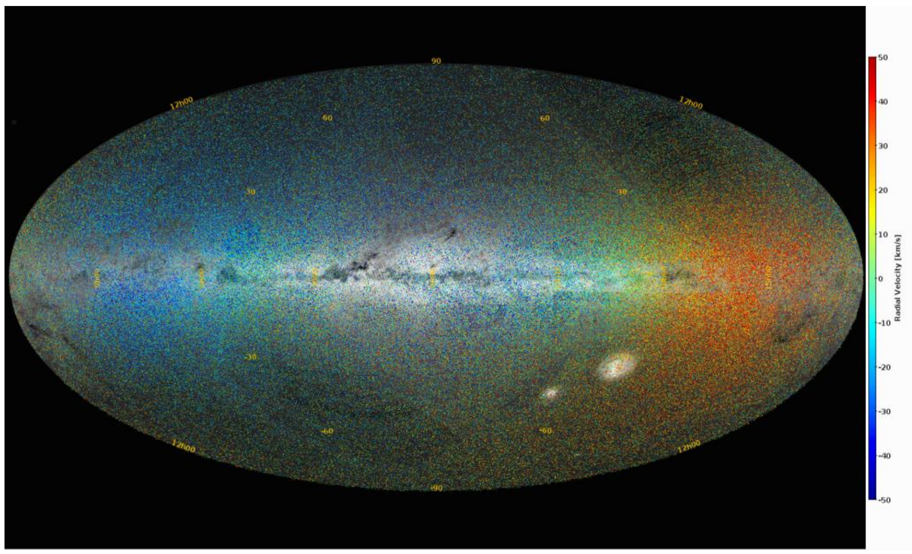
To determine the radial velocities of the stars, scientists of the Royal Observatory of Belgium make use of the spectra from the Radial Velocity Spectrometer (RVS). An example spectrum is shown in the figure below. The wavelength range covered is rather small, but for most stars it contains a sufficient number of spectral lines for the radial velocity to be determined. Because of its small wavelength range, the RVS instrument cannot reach the faintest stars that are detected by the other Gaia instruments. Its ultimate performance is expected to reach approximately magnitude 16 (in the RVS band), but for Gaia DR2 the analysis was limited to magnitude 12.

The Royal Observatory of Belgium is specifically involved in the Single and Multi Transit Analysis: each time a sufficiently bright star crosses the focal plane, the RVS instrument takes a spectrum. In the Single Transit Analysis, this spectrum is then compared with a theoretical spectrum, where the spectral lines are at their rest wavelength. Four different techniques are applied to measure the Doppler shift of the observed spectrum. In the Multi Transit Analysis, the time series of radial velocities is analysed to provide information on the constancy or variability of the stars. Average radial velocity values of constant stars have been published in DR2.



An example of an RVS spectrum. Credit: ESA

The figure below shows Gaia DR2 heliocentric radial velocities of over 677 thousand stars in the Galaxy. These stars have been selected because they have reliable position coordinates in other large sky survey catalogues. Blue colours show negative radial velocities of stars approaching the Sun, while red colours mark receding stars. The cyan and yellow colours show intermediate radial velocities. The radial velocities in different directions result from the rotation of the Galaxy and the Sun´s motion between the stars. Gaia observes more stars towards the galactic equatorial plane shown in white in the background image. Galactic regions with dense dusty clouds obscuring the stars are shown in grey and black.



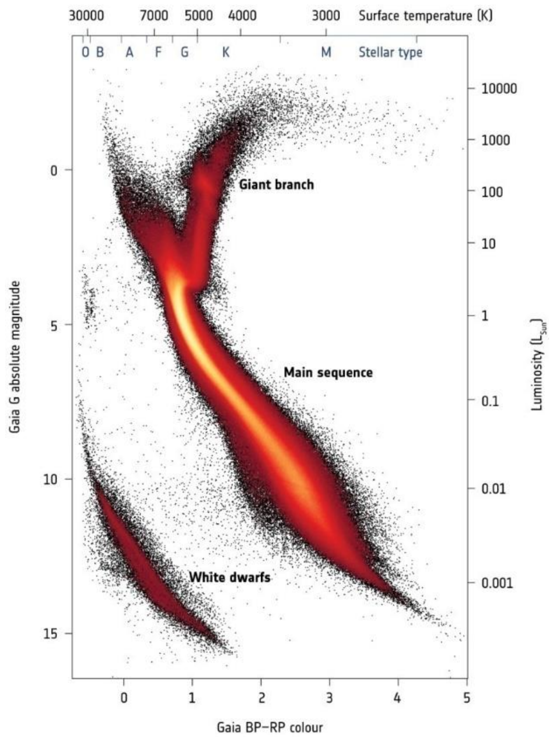
Gaia all-sky radial velocity map combined with ESA´s Gaia First Sky Map of stars in the Galaxy. It shows the colour-coded average radial velocities of over half a million stars in DR2. Blue colours mark approaching stars, while red colours show receding stars. Credit: ESA/Gaia/DPAC/A. Lobel

Variability

The ROB also contributed to the results of the variable stars, specifically the characterization of variable sources and the period determination. Gaia data on a selected number of Cepheid and RR Lyrae stars were studied in more detail.

Stellar parameter determination

The BP/RP, RVS, and astrometric data are further used to make at first a classification of the sources that have been observed by identifying their nature (e.g., stars, binary stars, emission line stars, white dwarf, galaxy, quasars), then perform their parametrization in terms of astrophysical (i.e. effective temperature, surface gravity, chemical abundances) and fundamental (i.e. mass, radius, absolute magnitude) parameters. While the BP and RP photometers will also provide dispersed photometry for the future releases, in DR2 the calibrated integrated magnitude values in all three photometric bands (G, G_{BP}, G_{RP}) were already available and used (see figure below) to provide an estimate of the effective temperature of about 161 million stars, as well as the magnitude of the interstellar reddening towards 88 million among these. This represents a real breakthrough in astronomy, as up to April 2018 only a small fraction (~7 percent) of these stars had spectral type information available in Simbad, the main astrophysical database available at the Centre de Données de Strasbourg (France).



The HR diagram of Gaia: GBP/GRP/G magnitudes and parallaxes were used to estimate the temperature, interstellar extinction, and luminosity of millions of stars. Credit: ESA/Gaia/DPAC, CC BY-SA 3.0 IGO

The archive

The ROB also contributed to making the data ready for publication in the archive. Besides the validation work done in each of the separate Coordination Units, it also took part in writing the documentation and testing the archive before it came online. The archive can be accessed at https://gea.esac.esa.int/archive/.

On the day of the public release, the ROB and other Belgian groups participated in the European-wide public outreach for this event. TV and radio interviews with ROB scientists allowed them to explain to a wide audience the importance of this data release for our knowledge of the Milky Way.

Belgo-Indian Network for Astronomy and Astrophysics

The Devasthal observatory is a new astronomical site in India, located at a 2450 meters of altitude in the Kumaun region of the Himalaya. It is operated by the Aryabhatta Research Institute of Observational Sciences (ARIES; Nainital, India) and currently hosts three telescopes: a 1.3-m optical telescope and two “Indo-Belgian” telescopes. The 3.6-m Devasthal Optical Telescope (DOT; figure below, middle and right) received this status because it has been constructed by AMOS (Advanced Mechanical and Optical Systems; Liège, Belgium) with the financial support of 2,000,000 € from the Belgian Federal Science Policy Office (Belspo). In return for the financial aid, 7% of the telescope time with the DOT is allocated for projects lead by Belgian astronomers during the first 5 years of scientific observations. The 4-m International Liquid Mirror Telescope (ILMT; figure below, left) is a Belgian initiative lead by members of the University of Liège in collaboration with institutes in India (ARIES; Nainital) and Canada (Québec, Montréal, Toronto, Vancouver, and Victoria).

The building of the 4-m ILMT (left) and the dome (middle) of the 3.6-m DOT (right)

The "Belgo-Indian Network for Astronomy and astrophysics" (BINA) was created to increase the interaction between Indian and Belgian astronomers and to stimulate the common use of the Indo-Belgian telescopes and other telescopes of interest to maximize their scientific output for solar system, celestial objects. The proposal for this bilateral project was submitted jointly in 2014 by P. De Cat of the Royal Observatory of Belgium (Belgian PI) and S. Joshi of ARIES (Indian PI). It was approved on 15/12/2014 and 05/05/2016 by Belspo and the International Division, Department of Science and Technology (DST; Govt. of India), respectively. The network that emerged from this collaboration is still expanding and currently involves colleagues from six Belgian and thirteen Indian institutes.

The 1st BINA workshop was successfully hosted by ARIES in Nainital (India) on 15-18/11/2016 with the aim to establish close collaborations between Indian and Belgian astrophysicists and to discuss the first- and second-generation instruments of these new Indo-Belgian telescopes. The 2nd BINA workshop was held at the Royal Observatory of Belgium on 09-12/10/2018. The Local Organizing Committee was chaired by P. De Cat. The Scientific Organizing Committee consisted of 4 scientists from India and 5 scientists from Belgium and was chaired by Dr P. Lampens from the Royal Observatory of Belgium.

This second workshop was organized to promote BINA as an expanding international collaboration. This goal was met as almost half of the 48 participants on site were foreigners, including 18 colleagues from India. Most Indian participants received financial help from the BINA project to attend this event. During the workshop, it was highlighted that an Indo-Belgian collaboration gives access to a large arsenal of telescopes and instruments to both sides, opening the door to many scientific fields/applications. Both countries have confirmed their wish to provide the DOT with an efficient high-resolution spectrograph and are willing to pursue this goal together, even if large efforts will be needed to achieve it. Recording of the workshop, and the PDF files of the corresponding presentations, were gathered on a dedicated website (http://aa.oma.be/18bina).

The scientific programme consisted of three major sections: (1) instrumentation, (2) data & science with the Indo-Belgian telescopes, and (3) data & science with other telescopes of interest. The science covered a large diversity of topics ranging from the Solar System (comets, asteroids & NEA's, space debris) via exo-planets (exo-planetary science) to galactic and extra-galactic astronomy. Such a diversity of topics is unusual in most scientific conferences, where the focus generally lies on a specific domain in astronomy.

Poster (left) and workshop picture (right) of the 2nd BINA workshop

Various invited reviews highlighted the connection between efficient instrumentation and quality of the scientific output, whether the instruments are equipping larger telescopes or smaller telescopes. The instrumentation currently available and offered at Indian and Belgian telescopes, as well as the recent improvements, future developments, and potential upgrades (adaptive optics) were presented against the background of actually very relevant scientific questions. The multi-wavelength (large) coverage of various instruments, both on the ground and in space, was highlighted in many talks. The presentation by AMOS was another example of expertise in high-technological instrumentation for astronomical research. It is clear that several highly performant instruments are/will be available to the astronomical communities in the (near) future.

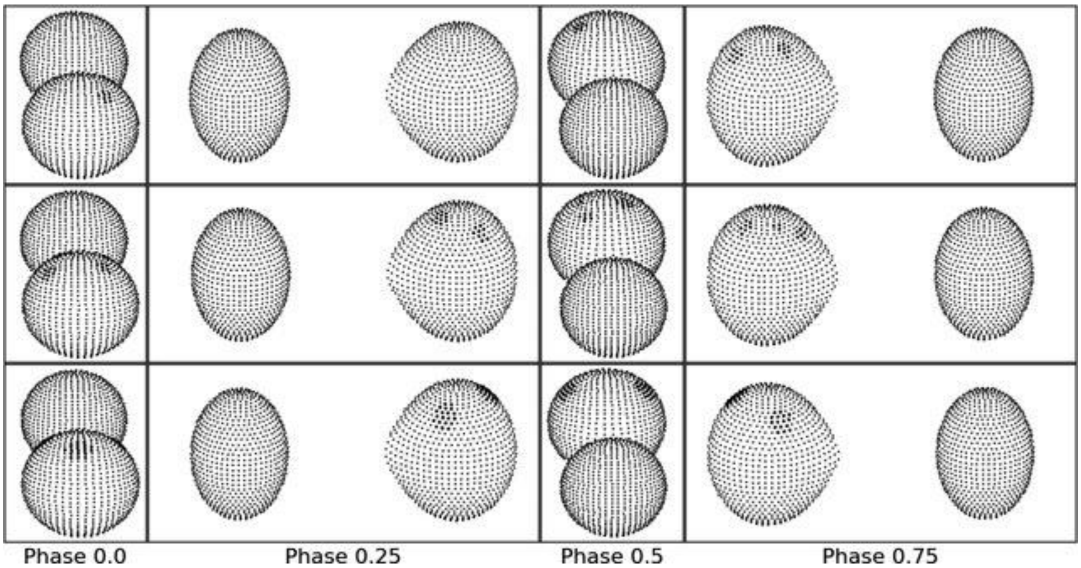
Concerning studies of small bodies of/in the Solar System, a variety of observational techniques were discussed. The need for extended observations (when the objects are distant and fainter) and high-resolution spectroscopy (chemical characterization) was highlighted. In stellar physics, the need for (spectroscopic) follow-up of space missions, for chemical tagging (detailed abundance analyses), the influence of binary star evolution and of massive stars, early stellar formation, stellar associations (clusters), stellar rotation (young clusters), as well as (various types of) stellar populations and pulsations were topics of discussion and high interest. The talks about galaxies, their stellar and dust content, their evolution (galactic archaeology), their environments and interactions were both stimulating and inquisitive. In the extra-galactic domain, the results of (multi-wavelength) studies of exotic objects such as AGN's and blazars, radio galaxies, the search for (strong) gravitational lensing were also nicely presented and summarized.

Notwithstanding the broad range of topics, the interest of all the participants for the different science cases was genuine, and this was possible thanks to a friendly atmosphere and personal contacts, and the goal of developing scientific collaboration in which the whole workshop was embedded. The final impressions, provided by Prof. Prugniel (Observatoire de Lyon, France) as an external reviewer, confirmed that this workshop has been a success, and should not be the last of its kind. The proceedings of the workshop will be published in the Bulletin de la Société Royale des Sciences de Liège, which is an open-access, peer-reviewed journal.

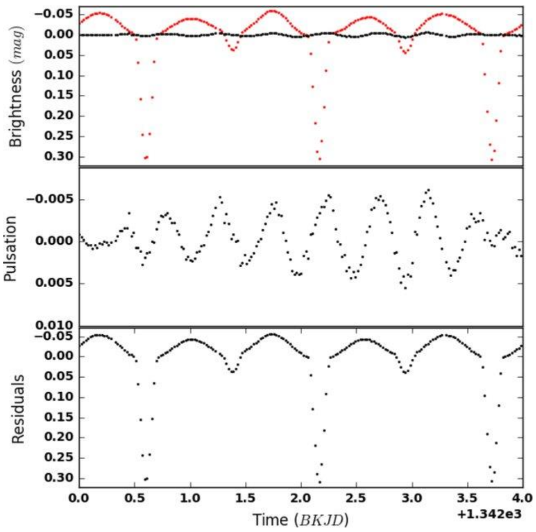
Eclipsing binary system with pulsations: KIC 6048106, a case study from the *Kepler* space mission

Pulsating stars are stars whose internal layers undergo oscillations due to an intrinsic (pulsation) mechanism. The A/F-type (δ Scuti and/or γ Dor) pulsating stars are in a state of transition of their envelopes where the outgoing energy experiences the change from radiative (for hotter envelopes) to convective transport (for cooler envelopes). Such stars may pulsate in two distinct regimes of frequencies caused by two different mechanisms: that of the acoustic modes and that of the gravity modes. Some A/F-type stars pulsate in both regimes simultaneously. Knowledge of their fundamental stellar parameters along with that of their pulsation characteristics - which allow to probe the stellar interiors - helps refining the physics of the models. When such stars are members of a binary system, they provide even more accurate and model-free fundamental parameters than in the case of their single counterparts.

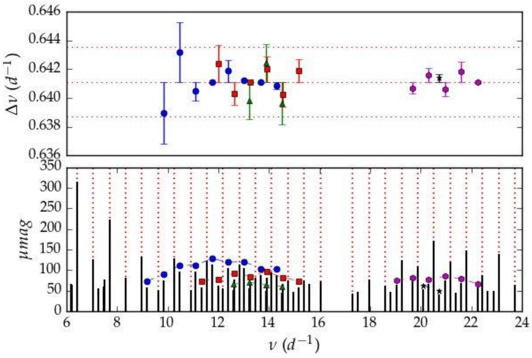
We present a model for KIC 6048106, an eclipsing binary with a period of about 1.6 d, based on *Kepler* space photometry and the modelling code PHOEBE. An **eclipsing binary** is a system of two stars whose components move in an orbit located in a plane which is parallel to the line of sight of the observer, and which produces eclipse phenomena at regular times. We performed a separate modelling of three segments of the *Kepler* light curve which show a long-term modulation possibly caused by spots. In short, KIC 6048106 is an Algol-type binary with F5-K5 components moving in a near-circular orbit with an orbital period of 1.559361 ± 0.000036 d, which also shows a change of the order $\Delta P/P \sim 3.6\ 10^{-7}$ in 287 ± 7 days. The primary component is a main-sequence star with the following properties: T_{eff1} = 7033 ± 187 K, M_1= 1.55 ± 0.11 $M_\odot$, R_1= 1.57 ± 0.12 $R_\odot$. The secondary component is a cool subgiant with the following properties: T_{eff2} = 4522 ± 103 K, M_2= 0.33 ± 0.07 $M_\odot$, R_2= 1.77 ± 0.16 $R_\odot$. The second quadrature phase in the light curve shows a brightness modulation on a time scale of 290 ± 7 days, from which we have concluded that many small near-polar spots are present on the secondary's surface. Our study thus reveals a stable binary configuration along with evidence of long-term activity (possibly of magnetic origin) linked to the secondary star (see figure below).



In this plot we show the spatial configuration of the binary model for KIC 6348106 for three stages of spot evolution and different orbital phases: phase 0.0 (primary minimum), phase 0.25 (first quadrature), phase 0.5 (secondary minimum) and phase 0.75 (second quadrature)



Top: Part of the original light curve (in red) compared with the contribution of pulsation (in black). Middle: Contribution of pulsations reproduced as the sum of sinusoidal fits to all detected frequencies, excluding the orbital frequency and its harmonics. Bottom: the preliminary binary light curve which was used to calculate the best-fitting model



Detected p modes in the range 7-24 d-1 with a regular mean spacing very close to the value of the orbital frequency (Δν = 0.64113 ± 0.00027 d-1). The dotted lines in the top panel indicate the boundaries Δν ± 3σ. The dotted lines of the bottom panel (in red) show the orbital harmonics

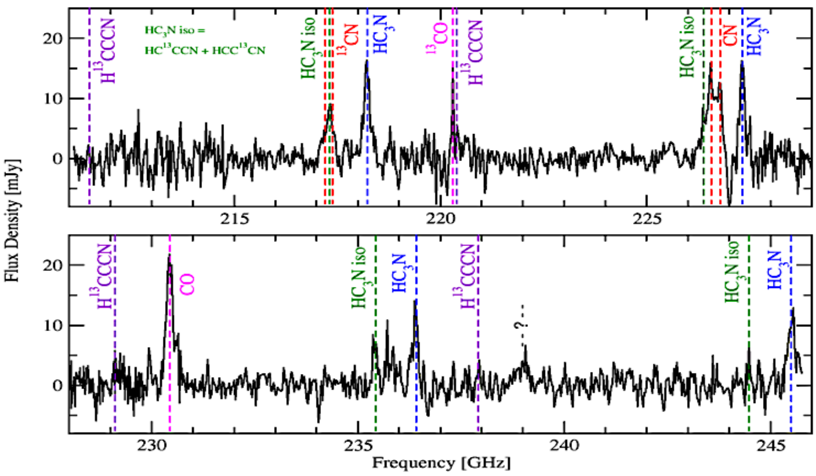
This binary system holds an intermediate-mass hybrid pulsator (figure above on the left, middle panel) for which we performed a new asteroseismic analysis (study of the seismology of the stellar interiors). Based on our model for the system and the corresponding set of fundamental stellar parameters for its components, we obtained the residual light curve after removal of the binary model, including the long-term brightness modulation. We then used Fourier analysis in combination with least squares optimization to study the residual light curve. We identified seven dominant gravity modes and 34 acoustic modes of much lower amplitude. The dominant gravity modes, located in the frequency range 1.96-2.85 d-1, show a mean spacing of ∆P = 1518 ±132 s. The acoustic frequencies are located in the ranges 7.49-15.2 d-1 and 19-22.5 d-1. From its position in the Hertzsprung-Russell diagram, we conclude that the primary component is the source of the detected hybrid pulsations. Consequently, the pulsation constants of the acoustic frequencies indicate the possible presence of the fundamental radial mode (Q = 0.033 ± 0.007 d). The remaining acoustic frequencies in that range are then radial or non-radial overtone modes. Moreover, most acoustic modes show an obvious equidistant splitting with orbital frequency (see figure above, on the right), which we interpret as tidal splitting. This is one of the first studies where such splitting can be attributed to tidal effects in perfect agreement with theoretical computations made by Smeyers & Reyniers (2003).

The real time evolution of Sakurai's object

When low- to middleweight stars like our Sun are near the end of their lives, they become red giant stars casting off their outer layers of gas and dust into space in a series of thermal pulses. Subsequently, the central star will start to heat up and ionize the ejected material, creating planetary nebulae. When all of its nuclear reactions cease, the star starts to cool and fade, becoming a white dwarf while the planetary nebula expands and dissolves into the interstellar medium.

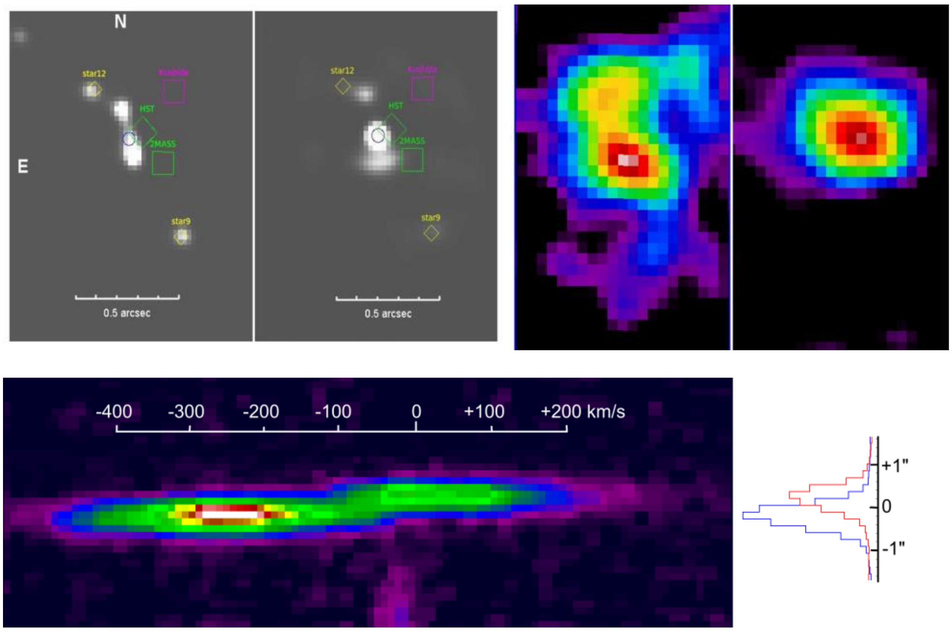
This describes the usual evolutionary path, but in some cases the central star will experience one final thermal pulse after it has gone through the planetary nebula phase and has already started to cool. This is called a very late thermal pulse, which dramatically changes the evolution of the star. The star very quickly swells up to become a red giant again and expels the remaining atmosphere in the process. This forms a new planetary nebula inside the old one. Theory predicts that 10 – 20% of central stars should undergo a very late thermal pulse, but only a handful of objects have been observed. Of those, only two have been discovered shortly after the very late thermal pulse: V605 Aql in 1919 and V4334 Sgr in 1996 (a.k.a. Sakurai's object, after the Japanese amateur astronomer who made the discovery). Since it was not possible in 1919 to continue observing V605 Aql with contemporary instrumentation, Sakurai's object is the only well-studied example of a very late thermal pulse.

The evolution after its very late thermal pulse is extremely fast (much faster than theoretically predicted) and can be followed in real time. This implies that Sakurai's Objects gives us a truly unique opportunity to study the evolution of the central star and the formation of a new planetary nebula by monitoring the changes in this object. This is what an international team led by scientists from the Royal Observatory of Belgium has been doing on a yearly basis since 2005 using state-of-the-art instrumentation from the European Southern Observatory: the Very Large Telescope (VLT) and the Atacama Large Millimeter Array (ALMA) located in Chile. With ALMA we obtained spectra in the range 1.22 - 1.43 mm in which we detected various molecules: CO, CN, and HC3N (see figure below).



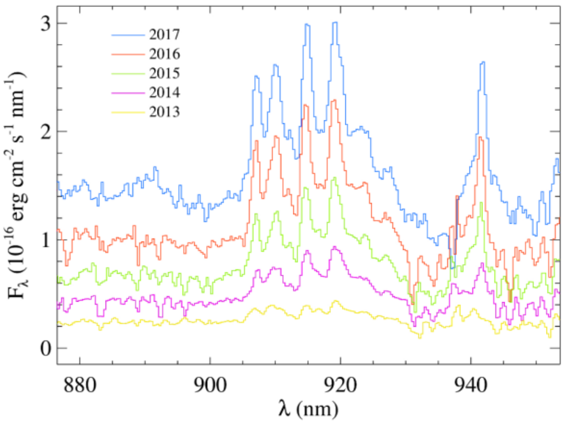
ALMA spectra. We detect CO, CN, HC3N, and 13C isotopologues

The CO and HC3N emission was spatially unresolved, but surprisingly the CN emission showed a bipolar structure (see figure below, above) that coincided with the lobes seen by HJ14. We detected the dust continuum, which was also spatially unresolved. In the optical spectra we see two sets of lines. The first is a set of nebular lines (recombination lines of hydrogen and helium, as well as forbidden lines of heavier elements) that was first detected in 1998 (helium) and 2001 (forbidden lines). These originate in the lobes detected by HJ14 (see the third figure below).



Above, from left to right: Ks images obtained in 2010 and 2013 (HJ14), our CN and CO emission images from ALMA. Below: position-velocity image of the [N II] 658.3 nm line showing the velocity along the x-axis and spatial scale along the y-axis. The graph at the right shows the spatial displacement, which corresponds well with the bipolar lobes (HJ14)

Since 2013 we see a second set of emission lines emerging. Not all lines are identified yet, but the strongest are electronically excited lines of CN (see figure on the right). They originate much closer to the central star than the nebular lines.



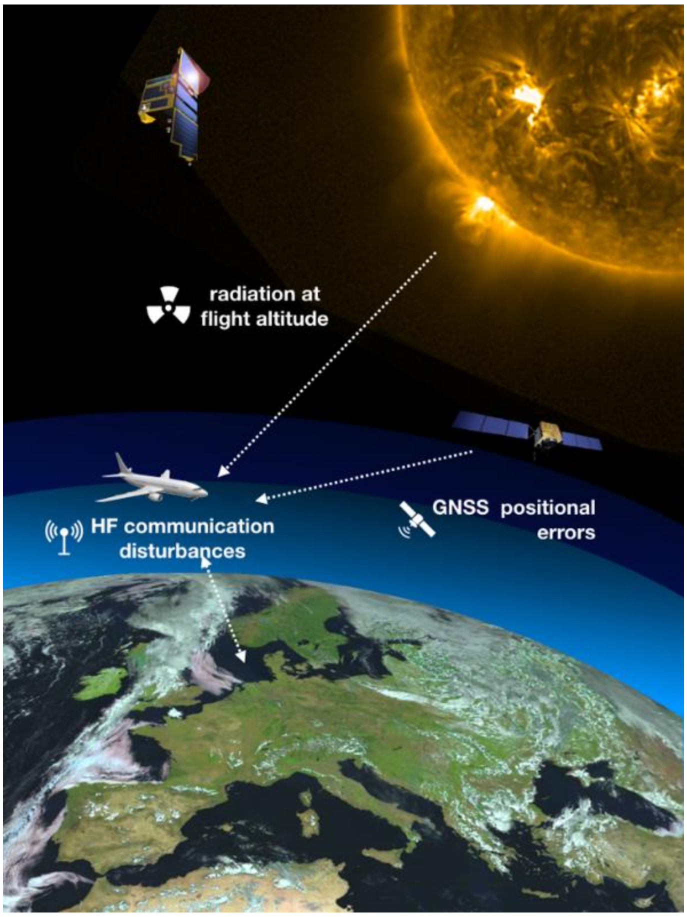
The complex of CN lines which have been increasing in strength since 2013

The combination of these results allowed us to reach the following interpretation. Sakurai's object ejected its remaining envelope in the 1990's. Soon afterwards, there was a brief strong shock, forming the nebular lines detected from 1998 onwards. This shock likely was caused by faster ejecta hitting slower ejecta. This shocked material then started cooling. A disk containing all the dust and likely also the bulk of the molecules also formed very quickly. Since 2008, we see the nebular lines steadily brightening. Using the data obtained with the X-Shooter instrument on the VLT, we could prove that these lines are excited in the bipolar lobes. There must be an increased mass loss, which could be funneled by the disk into a jet and is now hydrodynamically shaping the bipolar lobes. The nebular lines are formed in a strong bow-shock at the end of the bipolar lobes. The optical CN emission is possibly formed where the molecular wind is funneled by the disk in a bow shock, or alternatively is excited by ultraviolet radiation from the central star. The CN could be formed by dissociation of HCN in the shock and then carried into the lobes. This would agree with the ALMA observations that show that the CN emission coincides with the bipolar lobes seen by HJ14. This implies that we now have a unique and detailed data set following the very early stages of the formation of a bipolar nebula in time.

Solar Physics and Space Weather

The Operational Directorate "Solar Physics and Space Weather" studies the outer layers and the atmosphere of the Sun, with a particular focus on solar activity and the influence it exerts on the Earth and its space environment (space weather).

PECASUS, a space weather service for the aviation sector



In its 215th Session (29 Oct – 16 Nov, 2018) the Council of ICAO, the International Civil Aviation Organisation, has selected "PECASUS" as one of its 3 World Centres for Space Weather services. PECASUS is the Pan-European Consortium for Aviation Space Weather User Services (http://pecasus/eu) under the lead of FMI (Finland).

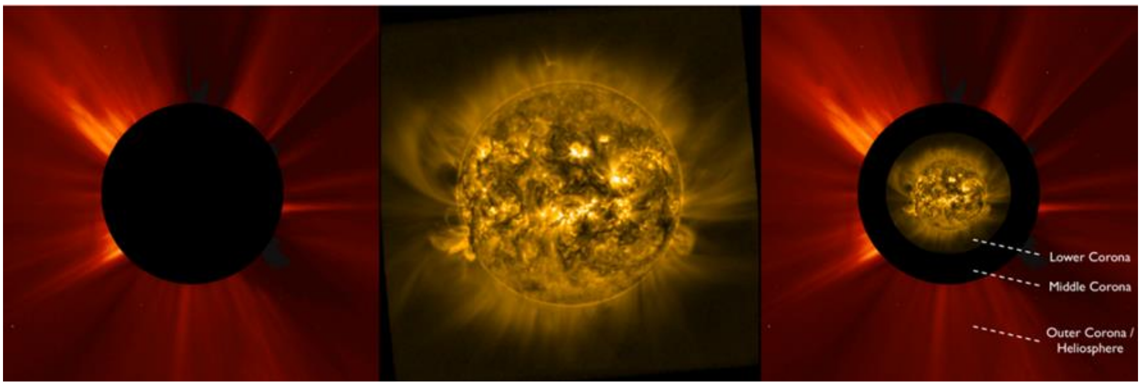
Several of the core tasks of the PECASUS Consortium will be hosted at the ROB. This includes the Solar Expert Group and the Advisory Production hub. Also, the GNSS section at ROB will provide Solar Radio Burst observations. Partners at BIRA will contribute the Radiation Expert Group and the RMI will assist for 24h/7d aspects.

Sporadic and massive eruptions of very high-energy matter and radiation from the Sun can have a pronounced impact on the aeronautical ability to aviate, navigate and communicate. In extreme cases, these eruptions pose a safety risk to passenger health. Periods of extreme solar activity are generally referred to as space weather. The exposure of the aviation community to space weather has increased since the opening of the northern polar routes at the end of the 20th century and ICAO has acted to incorporate safety from space weather effects into its aviation regulations.

The PECASUS consortium was established in response to the ICAO State Letter (AN 10/1-IND/17/11) released in June 2017. The countries forming the PECASUS consortium are Finland (Lead), Belgium, UK, Poland, Germany, Netherlands, Italy, Austria, and Cyprus. The PECASUS consortium was audited in February 2018 by space weather and operational management experts, nominated by the World Meteorological Organisation (WMO). The audit addressed a broad spectrum of criteria including institutional, operational, technical and communicational categories. PECASUS was declared fully compliant in all criteria with no areas for improvement identified.

Exploring the Middle Corona

Two primary instruments used for observing the morphology of the solar atmosphere are EUV imagers (EUV: extreme ultraviolet) and coronagraphs. The middle panel of the figure below is an image of the Sun made by the SWAP EUV imager on the ESA PROBA2 satellite operated from the Royal Observatory of Belgium. It shows the solar atmosphere in EUV, observing the Sun at a temperature around 600,000 degrees Celsius. The instrument is able to do this by filtering out all the other wavelengths, allowing us to observe just a small section of the electromagnetic spectrum. The temperatures SWAP sees make it ideal for observing the solar atmosphere, in particular the *solar corona*. The solar atmosphere is seen as a central *solar disk*, which is very bright in the center of the image, and the *off-limb* solar atmosphere surrounding it. The emission diminishes with distance from the disk, due to the density dropping with height.



Two common methods used for imaging the solar atmosphere. The left panel shows a LASCO coronagraph image, where the bright solar disk has been blocked out. The middle image shows an image from the PROBA2 SWAP instrument in the EUV section of the electromagnetic spectrum. The right panel shows the two previous images superimposed on each other allowing us to see the true extent of the atmosphere

The solar atmosphere is not uniform. It is composed of bright structures (the *Active Regions*), dark regions (the *Coronal Holes*, regions of lower or cooler emission) and the remainder, which is known as the *Quiet Sun*. All of these structures are created by magnetic fields generated deep within the Sun in the Convection Zone, extending out through the surface and permeating the atmosphere. They are made visible by the hot plasmas trapped upon them.

The Active Regions are formed of tight bundles of magnetic field and can cause violent eruptions when the fields become unstable. The coronal holes are created by magnetic fields extending far out into the heliosphere, allowing plasma to flow away from the lower solar atmosphere, creating regions that are cooler and appear darker.

The Sun undergoes an 11-year activity cycle, in which the number of Active Regions wax and wane. The images in the figure above were taken on 2014-Apr-18 when the Sun was near the maximum of its activity cycle, hence why we see more bright structures. Looking at the structures surrounding the solar disk, which extend to the edge of the field of view, we see the solar atmosphere in profile.

The left panel in the figure above shows an observation made by the LASCO coronagraph on the NASA/ESA SOHO satellite (operating since 1995). Coronagraphs create artificial eclipses by blocking the bright solar disk using an *occulter,* allowing us to see the extended solar atmosphere. Due to complications with the optics and the brightness of the Sun it’s very difficult to make observations close to the body of the Sun. Therefore, a gap has to be left between the inner edge of the coronagraph and the observed solar disk.

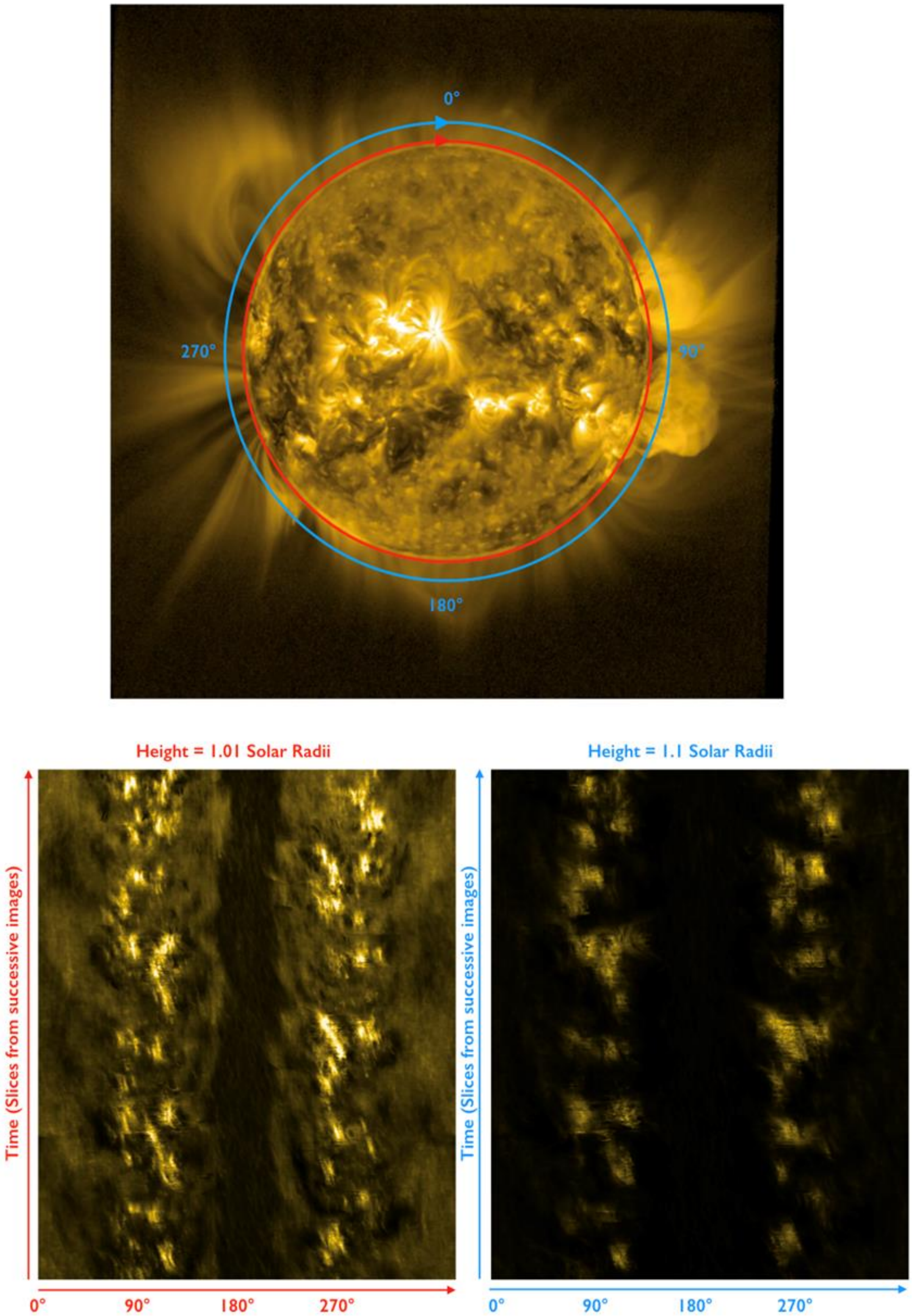


Image of the Sun made by the PROBA2 SWAP EUV imager. Two circles have been drawn around the Sun at different heights in the solar atmosphere; 1.01 Solar Radii (red) and 1.1 Solar Radii (blue). These circles are straightened out, and successive circles stacked to form the images seen in the bottom two panels. Each of these images are composed of slices taken over three rotations of the Sun

Coronagraph images reveal bright structures known as *Streamers* stretching radially outwards from the lower solar atmosphere. These structures are also formed by the Sun's magnetic field and vary over a solar activity cycle. Sometimes, the magnetic fields near the solar surface can become unstable and erupt as huge magnetic bubbles, known as *Coronal Mass Ejections*, these can be tracked through coronagraph images. These volatile structures form an important aspect of *space weather* that can affect the Earth and other structures in the solar system.

The right panel on the figure above shows the EUV image superimposed on the coronagraph image, adjusted for size, where we see the lower coronal structures extending out from the solar disk, into the outer corona. With closer inspection one can see small inconsistencies between the structures in the EUV image and those in the coronagraph. These are due to the images being created with different filters, showing different wavelengths, hence showing the Sun at different temperatures.

Most EUV observations of the Sun do not extend far above the solar disk, as the drop in emission with distance is extremely high. We had to wait until 2009 for the launch of the SWAP instrument before we could make continuous high cadence observations of this region, which is often referred to as the *Middle Corona.* This region is currently under considerable study as it is relatively unexplored, and only newly created image processing techniques have been able to tease out structures here. The region is of fundamental importance for space weather studies and how the Suns atmosphere can affect the Earth. It is in this region that Coronal Mass Ejections are accelerated and the solar atmosphere transitions from a predominantly magnetically dominated environment into a thermal pressure dominated region.

The PROBA2 team at the Royal Observatory of Belgium have been investigating and developing new techniques to explore the observations of the extended solar atmosphere, processed data is freely available here: http://proba2.oma.be/swap/data/mpg/movies/carrington_rotations/

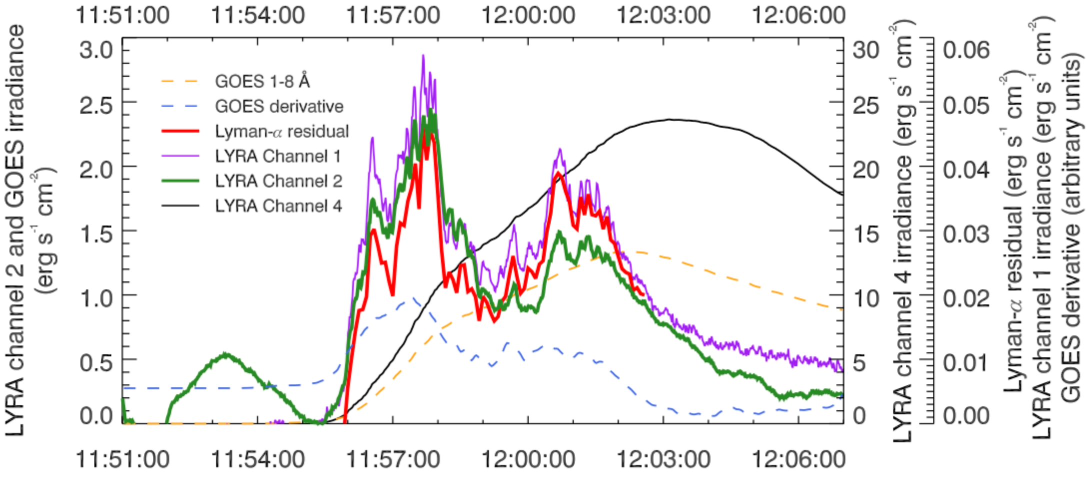
One recently developed method to explore this region is through Synoptic Maps of the Solar Atmosphere. These involve taking a slice at different heights through the atmosphere on successive images, and them stacking the slices up. An example can be seen in the figure above, which shows the changing atmosphere at different heights over a period of three solar rotations (nearly 3 months). It can be seen from these images how different structures vary over time. The PROBA2 team has automated the techniques used to make these images, and the latest synoptic map can be found here: http://proba2.oma.be/swap/data/SWAPsynopticMap/LatestSWAPsynopticMap.png

First Detection of Solar Flare Emission in Mid-ultraviolet Balmer Continuum

Solar flares and associated coronal mass ejections are the most powerful energy release events in the solar system. Surprisingly little is known about the distribution of the flare energy over the full solar spectrum. Routine measurements of the X-ray and extreme ultraviolet (EUV) emissions probe only a small part of the total energy radiated during a flare. Most of the flare radiation is emitted at longer wavelengths, but observations in this spectral range. The parts of the solar spectrum between 1000 and 3000 Å, i.e. far-ultraviolet (FUV), mid-ultraviolet (MUV), and near-ultraviolet (NUV), make a probably important but still poorly known contribution to the total energy emitted during flares.

In September 2017, after several months of relative quiet, a sudden increase of solar activity was observed on the Sun, when an active region started to grow quickly. This active region produced multiple strong flares before disappearing behind the west solar limb on September 10. Among them were the two strongest flares observed during the current solar cycle: the X9.3 flare on September 6 and the limb X8.2 flare on September 10.

LYRA is a radiometer from the Royal Observatory of Belgium, which flies aboard the satellite PROBA2 and observes the Sun in four broadband channels covering the soft X-rays (SXR) to MUV spectral range. At the time of these events, the instrument was performing a special flare observation campaign, involving one of its spare units. So, it delivered clear observations of the X9.3 flare (see the figure below), unaffected by the aging effects that otherwise affect the observations (LYRA was launched in 2009).

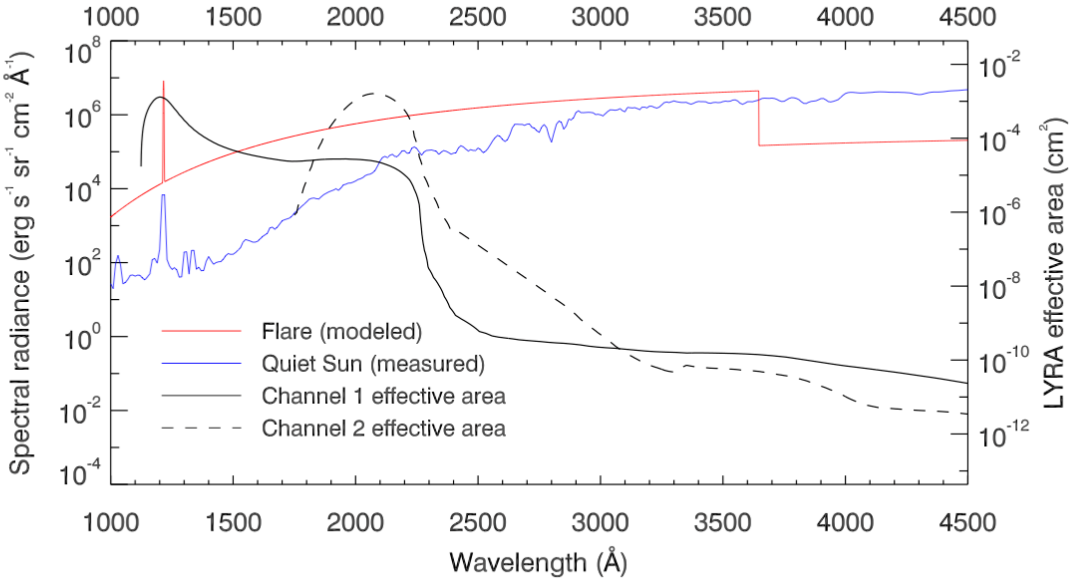


Observations of the strongest flare of the solar cycle by the LYRA and GOES instruments. The four channels of LYRA captured a signature of the flare. LYRA channel 3 was cleaned to remove the contribution from unwanted wavelengths and is therefore called "Lyman-alpha residual"

The LYRA data set for the X9.3 flare is rather unique. The two SXR/EUV channels of LYRA (named channels 3 and 4) are specifically used for monitoring solar flares and have captured hundreds of them, but flare observations are relatively rare in the channel 1 (observing the Lyman-alpha range around 1216 Å), and no flare had ever been observed with the channel 2 (which observes the MUV wavelengths around 2000 Å) until then. This time, the instrument observed signatures of the flare in all its channels

The origin of the emission in the channel 2 has been modeled (see the figure below). Comparing the model to the observations, we demonstrated that the emission detected at these wavelengths by

LYRA is consistent with hydrogen emission by a chromospheric slab heated up to 10,000 K. We determined the densities in the slab, and found it to be around 6.7 x 10^{13} cm^{-3}, which is consistent with previous works.



Model of the flare emission (red line) compared to observations in quiet-Sun conditions (blue line). The two black lines represent the spectral zones in which LYRA channels 1 and 2 are sensitive

Interestingly, the X8.2 flare on September 10, despite being the second strongest flare of the solar cycle, only produced a signature in the usual SXR channels. This may be due to the fact that the flare was located at the limb of the Sun and that at least one of the footpoints was hidden behind the limb.

Size distributions of solar proton events and their associated soft X-ray flares based on the maximum likelihood estimator

It has been known for some time that the size distributions of solar radio bursts and soft X-ray (SXR) flares have steeper power-law slopes (~1.8) than those of solar energetic proton (SEP) events (~1.2). Some scientists suggested three possibilities for this difference: (1) proton flares are fundamentally different from ordinary flares; (2) proton flares represent the large end of the total energy distribution of ordinary flares; and (3) proton flare characteristics have a threshold behavior. In some sense, each of these conjectures applies, although (1) and (3) are paramount.

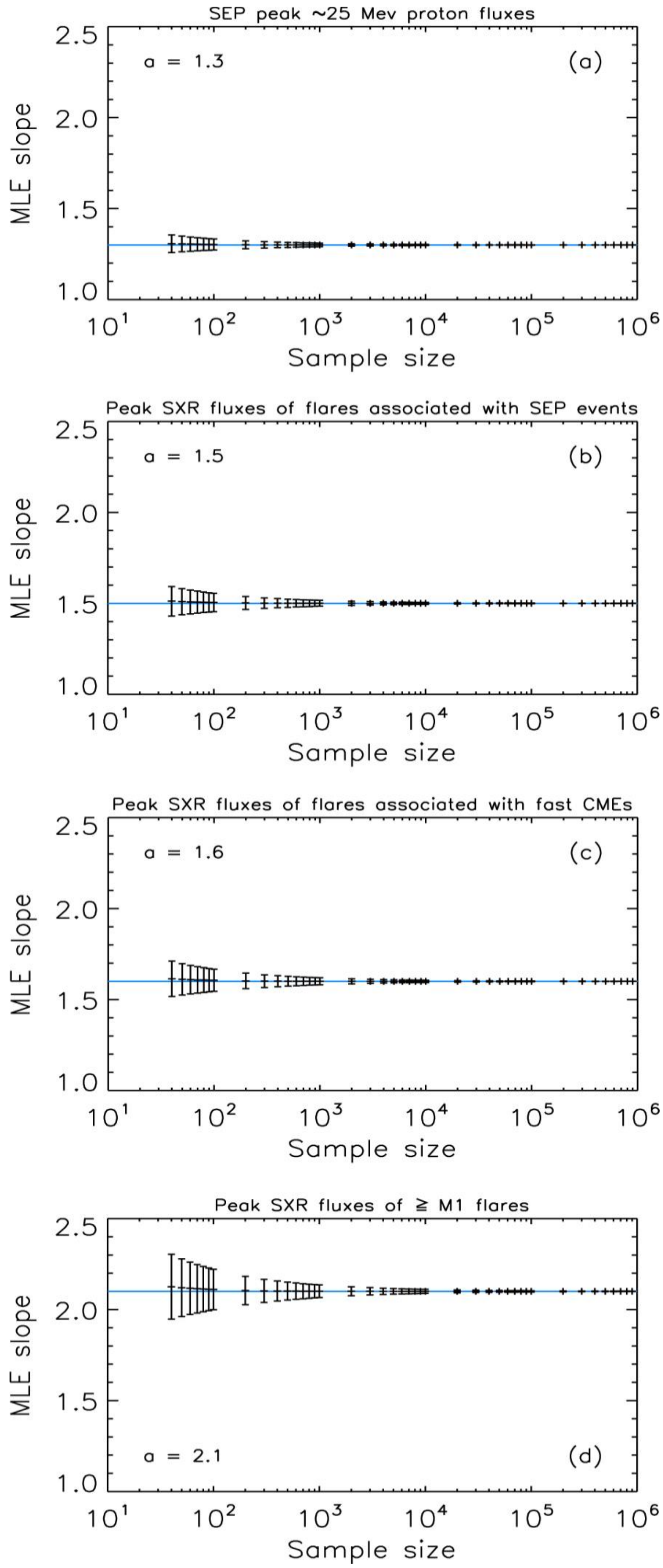
In one study (Cliver et al. (2012), ApJ 756, article id. L29), scientists argued that proton flares are fundamentally different from ordinary flares (hypothesis (1)) because they are eruptive. Because of their associated coronal mass ejections (CMEs), proton flares are intrinsically more energetic, satisfying hypothesis (2). Cliver et al. (2012) presented evidence for these points by constructing power-law size distributions for samples of large ("gradual") >10 MeV proton events (58 events), their associated ≥M1 SXR flares (52 events), ≥M1 SXR flares associated with fast (≥1000 km s-1) CMEs (59 events), and ≥M1 soft X-ray flares (540 events). They found that the power-law slopes of distributions of SEP intensity (~1.2) and the peak SXR fluxes of SEP-associated flares (~1.3) were closer to that of the peak SXR fluxes of flares associated with fast CMEs (~1.4) than they were to that of all ≥M1 SXR flares (~2.1).

In one previous study (D'Huys et al. (2016), Sol. Phys., 291, 1561), we noted that size distribution studies of solar phenomena which use graphical methods (where the power-law exponent is estimated by a linear fit on a log-transformed histogram of the data) – as was the case for Cliver et al. (2012) – require very large data samples (~103 - 104 events) to provide statistically reliable results. In lieu of such methods, we advocated use of the more robust maximum likelihood estimator (MLE). Following our suggestion, we revisited the Cliver et al. analysis using the MLE approach.

Analysis and Results

The MLE method determines a value for the power-law slope (α) of a distribution by maximizing the likelihood of the data, which is the probability that the data were drawn from that model. The results of the MLE application to samples of 136 ~25 MeV SEP events, 113 ≥M1 SEP-associated flares, 159 >1000 km s-1 CMEs, and 716 ≥M1 SXR flares, show that the pattern for α is similar to that found by Cliver et al. (2012), with the α-values for the SXR flares associated with SEP events (~1.5) and fast CMEs (~1.6) being closer to that for SEP events (~1.3) than to the α-value for all ≥M1 SXR flares (~2.1). As shown by D'Huys et al. (2016), and illustrated in the first figure of this highlight by generating random samples of different size with a given scaling parameter, a sample size of at least ~100 events is required to obtain a reliable result with the MLE method, and this minimum value increases as the slope of the distribution increases.

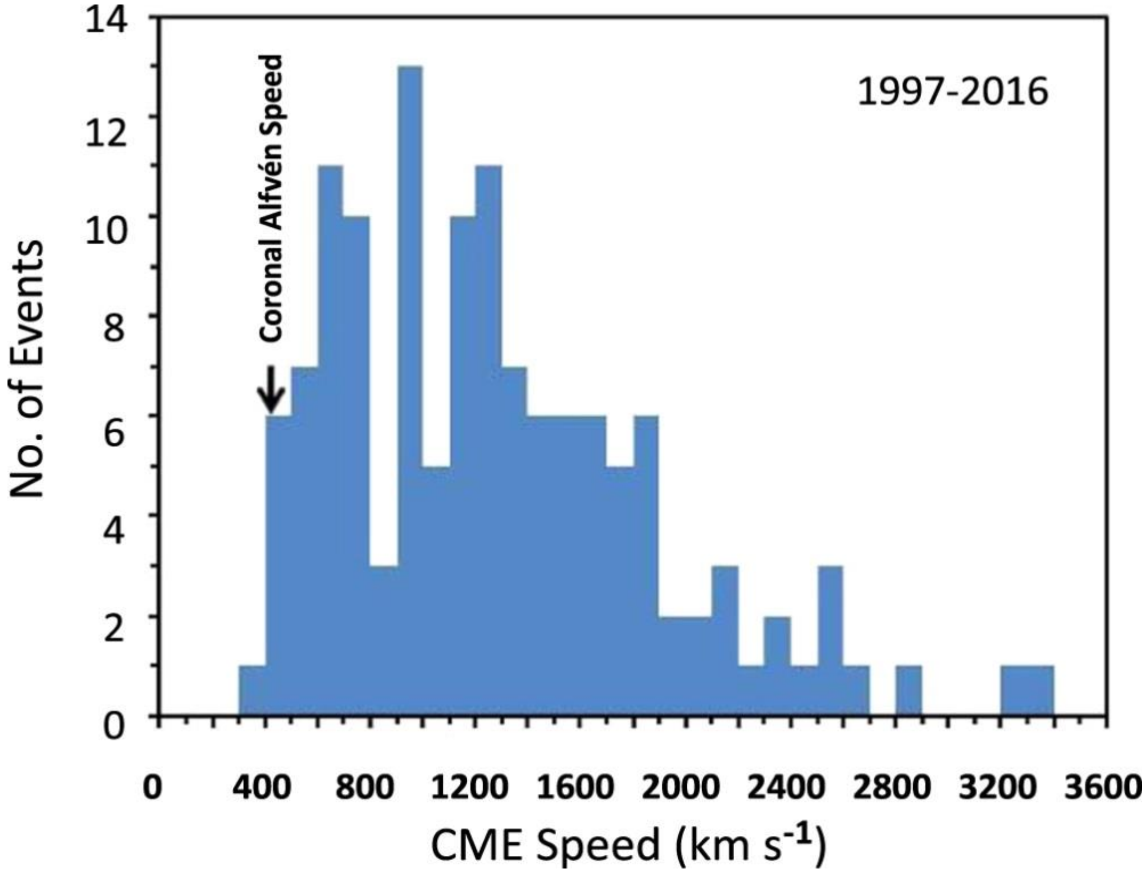
The second figure of this highlight shows that the large SEP events considered here are associated with CMEs with speeds ≳ 400 km s^{-1}, corresponding to the nominal Alfvén speed in the low corona. Thus large SEP events are characteristically accompanied by shockwaves manifested by type II radio bursts in the metric and/or decametric-hectometric (nominally 14 – 1 MHz for the Waves experiment on the *Wind* spacecraft) wavelength range.



MLE-scaling parameter estimates as a function of sample size for (a) ~25 MeV SEP events, (b) and (c) SXR flares associated with SEP events and ≥1000 km s-1 CMEs, respectively, and (d) ≥M1 SXR flares

Discussion

The figure below shows that the third possible explanation – a threshold effect – for the difference between the α-values of size distributions of flare electromagnetic emissions and SEP events is also at play. CMEs with speeds > ~400 km s^{-1} are required to drive the shocks that accelerate protons in large gradual SEP events. Smaller ("impulsive") SEP events are also commonly associated with CMEs, many with speeds in excess of ~400 km s^{-1}, but for such events the ejected mass is moving along field lines in an X-ray jet magnetic topology, whereas movement of magnetoplasma perpendicular to the ambient magnetic field (as in standard loop-like CMEs) is required for shock.



Histogram of speeds of CME associated with large ~25 MeV SEP events

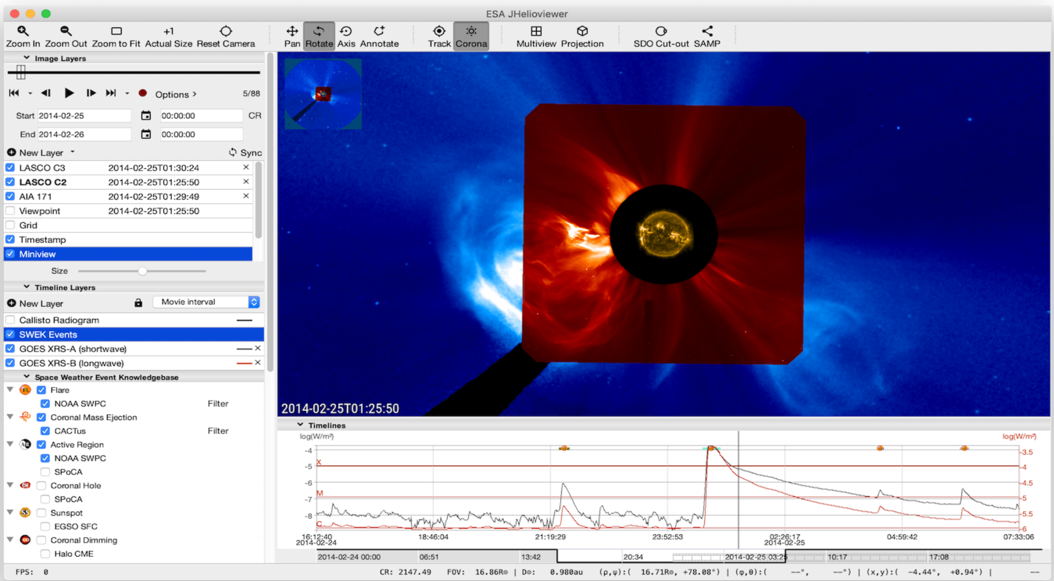
The key inference or application of the power-law size distributions of flare electromagnetic emissions is the avalanche model of Lu and Hamilton (1991, ApJ, 380, L89). In that model, based on the self-organized criticality concept, solar flares are viewed as avalanches of small-scale reconnection events. The smaller value of α for SEP size distributions argues for a different physical mechanism for acceleration of the protons that escape into space, one based on fast CMEs and coronal/interplanetary shock waves.

Next generation of JHelioviewer

Solar observatories are providing the world-wide community with a wealth of data, covering wide time ranges (e.g., Solar and Heliospheric Observatory, SOHO), multiple viewpoints (Solar TErrestrial RElations Observatory, STEREO), and returning large amounts of data (Solar Dynamics Observatory, SDO). In particular, the large volume of SDO data presents challenges. Firstly, the data are available only from a few repositories. Moreover, full-disk, full-cadence data for reasonable durations of scientific interest are difficult to download, due to their size and the download rates available to most users. From a scientist's perspective this poses three challenges: accessing, browsing, and finding interesting data as efficiently as possible.

JHelioviewer is a visualisation software developed to address these challenges using a novel approach: image data are compressed using the JPEG 2000 standard and served on demand in a quality-progressive, region-of-interest-based stream. JHelioviewer is, together with the web application https://helioviewer.org, part of the joint ESA/NASA Helioviewer Project. Since the first release of JHelioviewer in 2009, the scientific functionality of the software has been significantly extended. The JHelioviewer software is open source, platform independent, and extendable via a plug-in architecture.

With JHelioviewer, everyone from everywhere can visualize the Sun for any time period between September 1991 and today; they can perform basic image processing in real time, track features on the Sun, and interactively overlay magnetic field extrapolations. The software integrates solar event data and a timeline display. Once an interesting event has been identified, science quality data can be accessed for in-depth analysis. As a first step towards supporting science planning of the upcoming Solar Orbiter mission, JHelioviewer offers a virtual camera model that enables users to set the vantage point to the location of a spacecraft or celestial body at any given time.



Screenshot of the JHelioviewer application. The left part of the application window hosts expandable sections to manage and display time-dependent image layers, timelines, and event data. The main panel displays image data in a 3D scene that the user can interact with. The timeline panel in the bottom right displays 1D and 2D plots of time series, e.g., disk-integrated X-ray fluxes. Markers for solar events can be overlayed on both panels

In light of its popularity in the solar physics community and beyond, our team at Royal Observatory of Belgium in joint effort with colleagues from the FHNW institute from Switserland has significantly enhanced JHelioviewer in this project. We highlight the following new features:

- Displaying multi-viewpoint data in a single 3D scene, e.g., from the twin Solar TErrestrial RElations Observatory (STEREO) spacecraft;
- Real-time generation and display of difference movies;
- PFSS magnetic field extrapolation models using synoptic magnetograms from the Global Oscillation Network Group (GONG);
- Timelines of 1D and 2D data, e.g., disk-integrated X-ray fluxes and radio spectrograms;
- integrating solar event data from the Heliophysics Event Knowledgebase (HEK) and curating it into a Space Weather Event Knowledgebase (SWEK);
- Various 2D projections (orthographic, latitudinal, polar, log-polar);
- A split-screen view to display multiple images side by side;
- Save and restore scenes
- Interaction with other programs via the SAMP protocol
- A virtual camera model that enables the user to set the vantage point to the location of a spacecraft or celestial body at a given time, using an ephemeris server.

The last feature is a first step towards supporting the science planning process for the future Solar Orbiter mission, which is a key objective for the future development of JHelioviewer. In parallel, a large number of additional data sets have been added. These include data from the Hinode (XRT), PROBA-2 (SWAP and LYRA), Yohkoh (SXT), and TRACE space missions, as well as data from the ground-based facilities NSO/SOLIS, NSO/GONG, Kanzelhöhe Solar Observatory, USET telescope of the Royal Observatory of Belgium, the Nançay Radioheliograph, and the e-CALLISTO network.

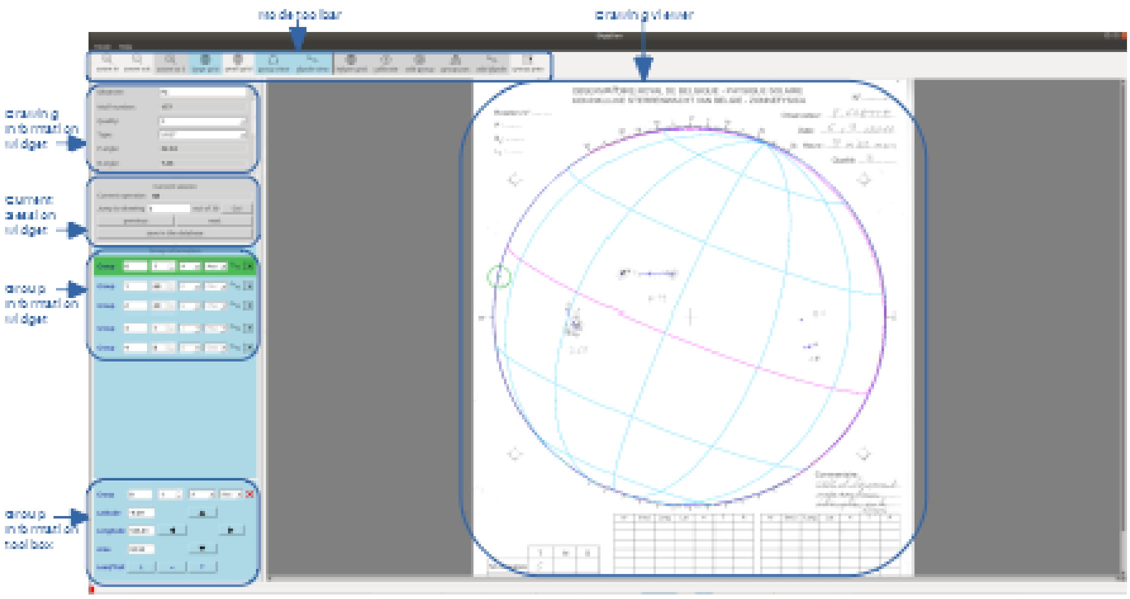
DigiSun: a tool to extract scientific data from sunspot drawings

Sunspot drawings are the base material available for deriving detailed information about the long-term evolution of the solar cycle. In this context, it is important to have the appropriate tools to convert drawings into exploitable scientific data and to extract as much information as possible from these drawings. While such a tool is obviously important for every observatory with historical sunspot drawings and/or still does daily drawing, there was no generic tool available in the solar physics community. As a side effect, there is a lack of homogeneity among the data and some sunspot drawings collections stay buried in archives due to a lack of manpower to write the appropriate software.

At the Royal Observatory of Belgium, there is a collection of 70 years of sunspot drawings that is still growing with the addition of daily input. The scanning and the first analysis of sunspot drawings are done with an in-house software called DigiSun. In 2018, a new version was designed and the code was rewritten on the basis of a first version which showed its limitation due to its lack of modularity and flexibility. DigiSun is a graphical user interface (GUI) with the following functionalities:

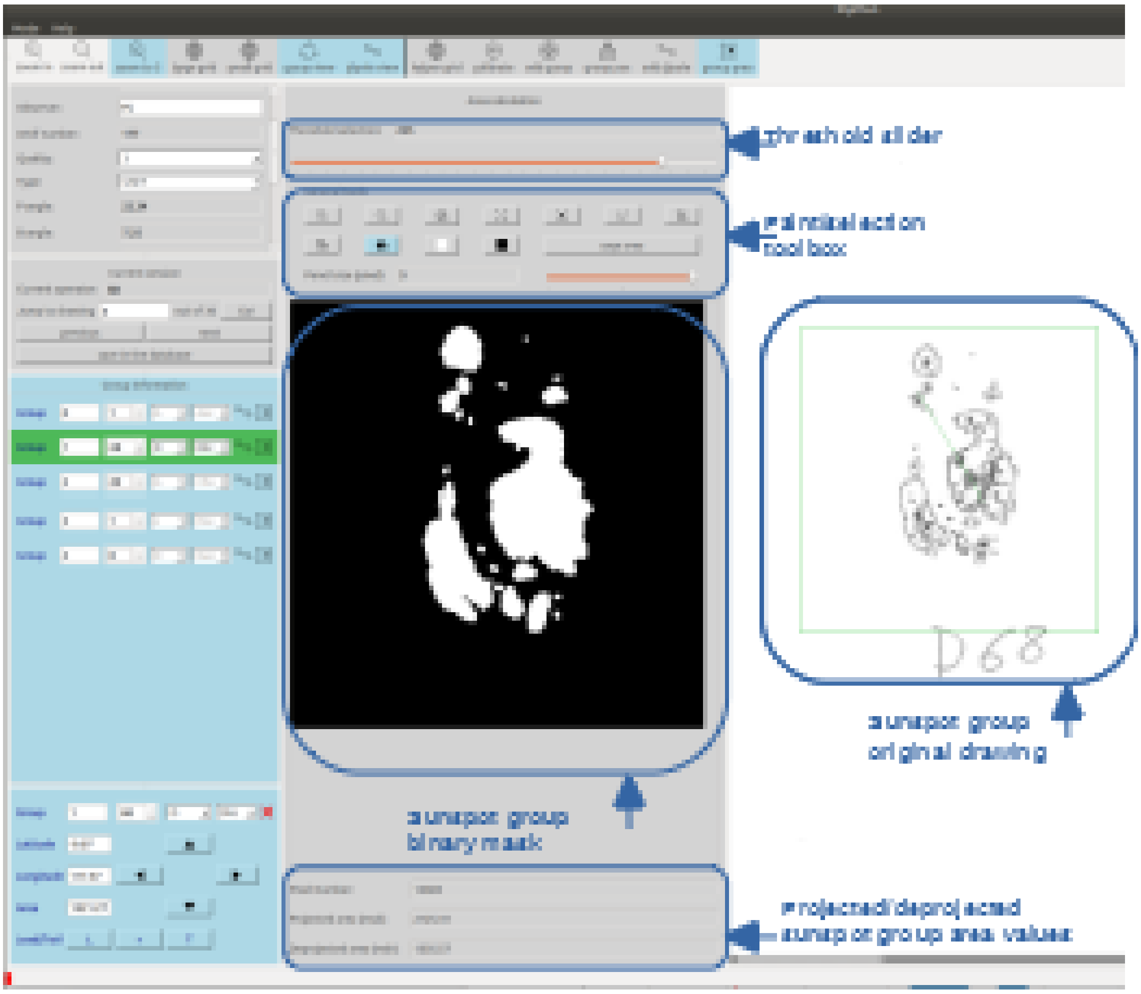
- Sunspot drawings display, variable image scale and image overlay (large grid on the figure below)
- Calculation of the solar axis angles (P, B, L) via an in-house ephemeris module
- Correspondence between pixels position and heliographic coordinates on the solar disk
- Recording of sunspot group parameters (number of spots, splitting, Zurich and McIntosh morphological classification).
- Measurement of the dipole positions and recording of the asymmetry leading/trailing
- Total area sunspot group measurement

All the parameters of the groups are then saved in an external database for relevant scientific analysis. In addition, it contains a functionality to perform the scanning of drawings making it a unique end-to-end tool to transform drawings into scientific data.



Global view of DigiSun and some of its functionalities

The latest module, added in the context of the VAL-U-SUN project, is the sunspot group total area measurement. The total area consists of the umbra and the penumbra area of the sunspot groups. It is an important measure because of its strong correlation with the magnetic field associated to the sunspot. To measure the area, a reduced frame around each sunspot group is considered (see the figure below). A selection and paint toolbox allows a fine-grained selection of the group under consideration. The bottom part of the module (see the figure below) indicates the projected and the deprojected areas, the latter taking into account the foreshortening of the group based the correspondence between pixel positions and heliographic coordinates.



Sunspot area measurement module in DigiSun

Another important feature of the new version of DigiSun is its adaptability to different drawing formats. This allows the analysis of collections from different observatories. Moreover it was written in a multi-platform programming language making it portable to any computer. A first international collaboration with the Specola Observatory in Locarno was initiated. After a few days of installation and training, the software was perfectly working on-site and is now used for the daily analysis of their sunspot drawings.

We have developed a robust and flexible tool at the Royal Observatory of Belgium for the analysis of sunspot drawings. It is now used for our daily drawings. Moreover it is used to analyze older drawings from our collection in the context of the VAL-U-SUN project, sunspot area measurements being now fast and intuitive. Another achievement is the portability of the software and the fact that it was distributed successfully to another observatory. Hence a software developed for our own needs proved to be useful to the wider, international community. As other institutes already mentioned their interest, we plan to distribute DigiSun further in the near future. This will allow access to new long-term solar data with a much better homogenization.

Communication and Information

The Communication and Information Service aims to communicate and promote the Observatory's research activities and heritage, and also to provide and relay scientific information to the public and the personal.
The activities of the service consist of several tasks: answering questions and inquiries from public, administrations, authorities and press, assisting in all kind of outreach activities such as the Open Doors, exhibition and other events, collaborating with the Planetarium, publishing the Yearbook and the annual report, managing the archives and museum and sending press releases and preparing of texts for printing or for the web site (http://www.astro.oma.be/en/news/).

The Open Doors Days 2018

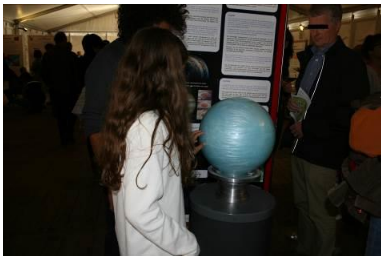
During the weekend of September 29-30, the three institutes in Uccle (the Royal Observatory of Belgium, the Royal Meteorological Institute, and the Royal Belgian Institute of Space Aeronomy) welcomed about 9000 visitors for their Open Doors Days. For the first time, the three institutes and the Planetarium, organized a social media campaign for this event.

The program is similar to the last Open Door Days of 2014 with new events and activities implemented:

- An Open Door Day for school classes on Friday September 28 afternoon (co-organized with the Royal Belgian Institute of Space Aeronomy and the Planetarium). Five primary school classes and two secondary school classes participated to the event.
- A VIP event on Saturday September 29 in the morning. A special tour of the Space Pole was given to the invitees.
- An experiment tent, in which experiments from the three institutes were gathered. From the Public Observatory enquete, this activity is among the most popular ones of this event.








As usual, this event got a high success. The services of the Observatory also took this opportunity to update or create their outreach material. Some new outreach item were the maquette of the instrument LaRa and the planetary sphere of the planetary scientists of the Observatory, made with the help of the technical service.

Information to the public and authorities

In 2018, the service replied to 1195 questions from authorities, public and media sent by email (714), telephone (443), letter or fax (24), and via the social networks (Facebook and Twitter, 14). The authorities are notably courts, police, army, Belgocontrol and the Royal Meteorological Institute. As usual, most questions were about sunset and sunrise, astronomical phenomena, calendar and time, the history of the Observatory and the Open Doors.

The service was regularly in contact with the media (TV, radio, written press, and agencie). The service gave information to them on numerous occasions. Other members of the ROB appeared in news items on other topics (Gaia Second Data Release, InSight, daylight saving time, BepiColombo, water on Mars, earthquake in Indonesia…).

Tours of the Observatory are no more organized for the general public. Group visits are still organised on special occasions. The individual visitors were mainly journalists, other media related persons, amateur astronomers and/or students. The service updated and presented the 'History and activities of the Observatory' as an introductory talk to some of the visiting groups and guided them in the institute.

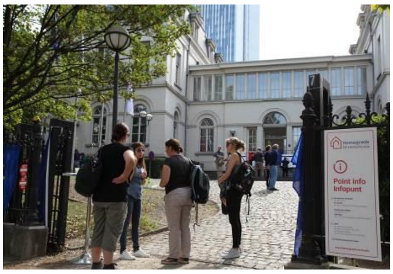
Website, news, press releases and social media

In 2018, the main website of the Observatory (https://www.astro.oma.be) got 292,143 visits. Peaks of visits appear at some periods, noticeable near the dates of the winter solstice and the dates of the daylight saving time, during the Open Door Days (between 29 September and 1 October 2018) and on 17-18 October 2018, just after de publication of the news article "Summer time or winter time? The Royal Observatory of Belgium informs". The content of the information web pages and the pages on the celestial phenomena of the month was regularly updated. In 2018, 14 topics were published in the "News" section of the ROB website (always in 3 languages: NL/FR/EN), including 5 press releases.

On 31 December 2018, the Facebook page of the Observatory had 586 likes (with 316 new likes since end 2017), and its Twitter account 441 followers (224 new followers). Since end 2017, the Observatory also has a YouTube channel, which hosts on 31 December 2018 20 videos. One of these is a promotional video for the instrument LaRa made by job students. The most successful Facebook post of this year is the one sharing the news article "Summer time or winter time? The Royal Observatory of Belgium informs".

The Heritage Days at the Ancient Observatory and other exhibitions

For the first time, the Ancient Observatory, located at the municipality of Saint-Josse, opened its doors during the Heritage Days 2018 in the Brussels Capital Region, on 15 and 16 September. About 1700 visitors came during the weekend. The Ancient Observatory, named at this epoch "(Royal) Observatory of Brussels", was the ancient site of the Royal Observatory of Belgium (and of the Royal Meteorological Institute) before it moved to Uccle in 1890. The Observatory, the institute Homegrade and the Académie intercommunale de Saint-Josse-ten-Noode/Schaerbeek organised this event.



The Observatory also participates to the annual summer exhibition of the Royal Palace. For the exhibition of this year, with the theme "Wonder", it provides two objects: the Houzeau's heliometer and a video of the Sun filmed by the camera SWAP onboard the ESA satellite PROBA2. It contributes also to the exhibition “Now is light” which took place in Lisbon, Portugal from January 26 to March 10, 2018 by lending Houzeau’s books about “uranometry” and an astronomical map.

Houzeau’s heliometer at the Royal Palace of Brussels

Archives and museum

In 2018, about 50 requests from individual visitors were related to the archives. Four requests concerned historical artifacts for scientific research purpose, seven requests concerned photographies and copyright inquiries for book publication.

The project about the transcription of Quetelet’s letters, which started in February 2017, is still ongoing. In January 2018, an article about this project have been published in Science Connection. On December 31, 2018, the volunteers transcribed 1051 letters, which brings the total number of letters to 1621. The transcribed letters are published on the website http://quetelet.oma.be/.

The Planetarium

PLANETARIUM.be

Daily activities

In 2018, the Planetarium welcomed **41,138 visitors**. This number is composed of school groups (kindergarten, primary schools, secondary schools, graduate school and universities) who come to attend a course given by one of our animators, as well as individuals (families, tourists) interested in one of the films proposed for the programme. The Planetarium is open every day of the year, including weekends and public holidays (except Christmas and New Year).

Special activities

In addition to its daily activities, the Planetarium fully participates in its role as an educational, cultural and science valorisation actor, by organizing or promoting a whole series of special activities.

The special activities of 2018 are:

- Acoustic music concert on February 2 and December 2 (partnership with Indies Keeping Secret);
- Hosting of the beSpace networking event on March 9;
- Selection of the winners of the CANSat competition (creation by secondary school students of a scientific experiment to be launched by rocket) in partnership with the Brussels Region on March 21;
- Electronic music concerts on April 21 and May 19;
- Hosting of the groups participating in the ASGARD project on April 26;
- Hosting the proclamation of the results of the Astronomy Olympiads on May 5 (VVS);
- FNRS / ROB Astronomy Day Contact Group Day on June 4;
- Launch of the new full-dome film Ghost of the Universe on June 20;
- Indian music concert on August 25 (partnership with Hide & Seek);
- Poetry under the Stars on September 7;
- Performance by Het Puntje van de tong on September 11, October 11 and December 11;
- Launch of a commemorative coin (space satellite) on September 20 (With the Hôtel des Monnaies);
- Submission of a 3D model of the ISS station made by Brussels schools to the Secretary of State for Scientific Research of the Brussels-Capital Region on October 10 (Alsvin project);
- Participation in the Noctunes des Musées bruxellois on October 18;
- Night of Darkness on October 20 organized at Rouge-Cloître;
- Announcement of the Big Bang Spacetube festival awards on November 4;
- Jean-Pascal Van Ypersele's conference on November 6;
- Participation in the Dag van de Wetenschap on November 25;
- Launch of IAU100 (celebration of the 100th anniversary of the International Astronomical Union) in Belgium on December 20.


ARTURIA


Asgard-VIII


PLANETARIUM


HARVARD

Annex 1: Publications

Refereed publications

[1] Aboudan, A. ; Colombatti, G. ; Bettanini, C. ; Ferri, F. ; Lewis, S.R. ; Van Hove, B. ; Karatekin, O. ; Debei, S.
ExoMars 2016 Schiaparelli Module Trajectory and Atmospheric Profiles Reconstruction. Analysis of the On-board Inertial and Radar Measurements
Space Science Review, 214 issue 5, pp. Id. 97, 31 pages (2018). DOI: 10.1007/s11214-018-0532-3

[2] Aerts, C. ; Bowman, D. M. ; Símon-Díaz, S. ; Buysschaert, B. ; Johnston, C. ; Moravveji, E. ; Beck, P. G. ; De Cat, P. ; Triana, S. ; Aigrain, S. ; Castro, N. ; Huber, D. ; White, T.
K2 photometry and HERMES spectroscopy of the blue supergiant ρ Leo: rotational wind modulation and low-frequency waves
Monthly Notices of the Royal Astronomical Society, 476 issue 1, pp. 1234-1241 (2018). DOI: 10.1093/mnras/sty308 https://academic.oup.com/mnras/article/476/1/1234/4848277

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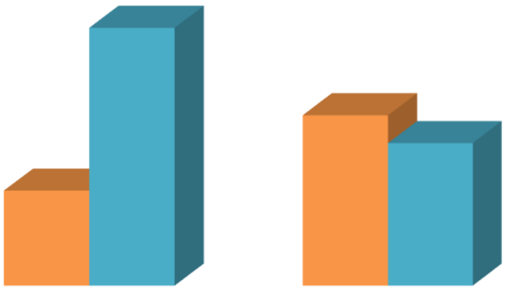
Annex 2: Workforce

On 31 December 2018, 166 employees are working in the Royal Observatory of Belgium (comprising people working at the Planetarium), of which 56 are women and 110 are men. This number is lower than in previous years (172 in 2017 and 179 in 2016).

As expected from a research institute, scientists constitute the main part of the personnel (89 agents at SW level). With the other university-level employees (employees of level A), they constitutes the main part of the staff (63 %). This reflects the fact that the expertise of the Royal Observatory of Belgium is based on scientific knowledge.

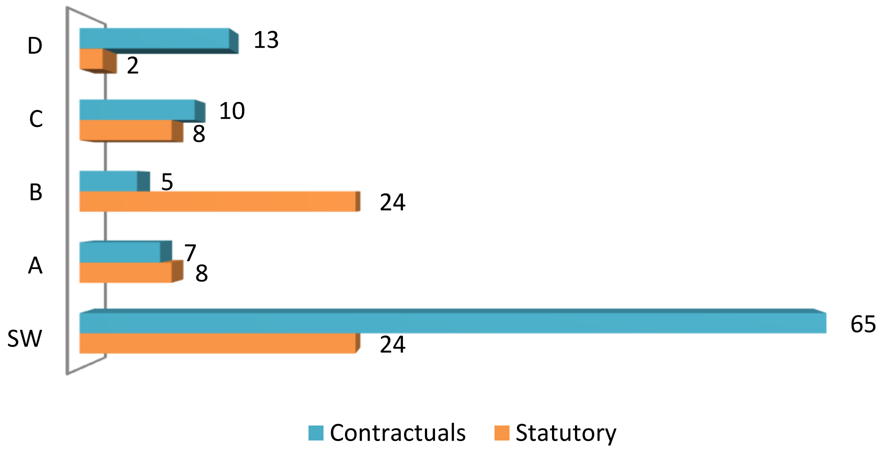
ROB staff on 31 December 2018



	Scientists	Non scientists
Statutory	24	43
Contractual	65	36

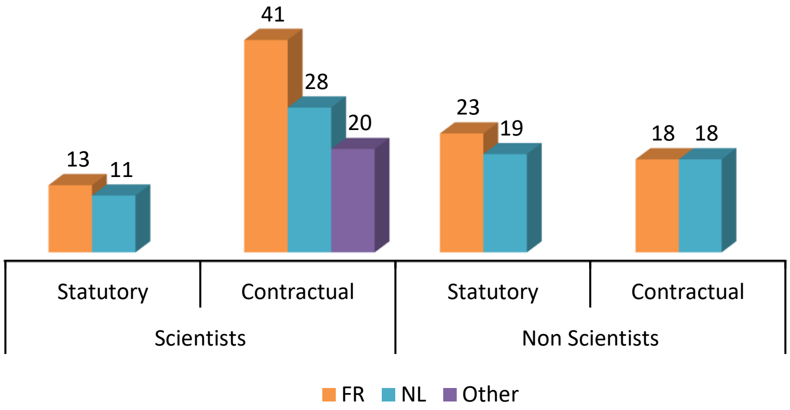
60 % of the personnal are contractual. This is particularly true at the scientific level, where contractuals constitutes 73 % of the scientific staff. This is related to the fact that scientific research is mainly funded by external projects while the dotation is shrinking.

Share by level 2018



Regarding language repartition, 39 % are Dutch-speaking people and 49 % are French-speaking people. 20 members of the scientific personnel (about 12 % of the staff), all of which being contractual, have a master in a different language than French and Dutch. This reflects the international character of the scientific environment.

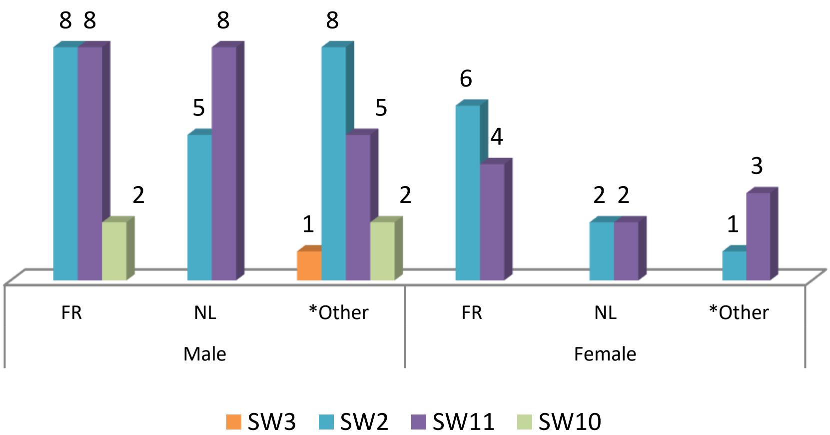
Comparison in statute and language 2018



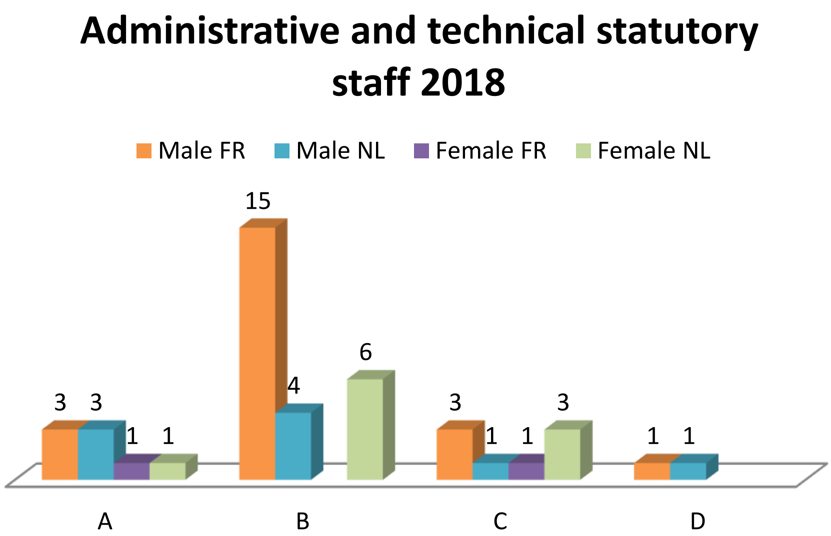
More details about the ROB staff can be viewed in the following charts.

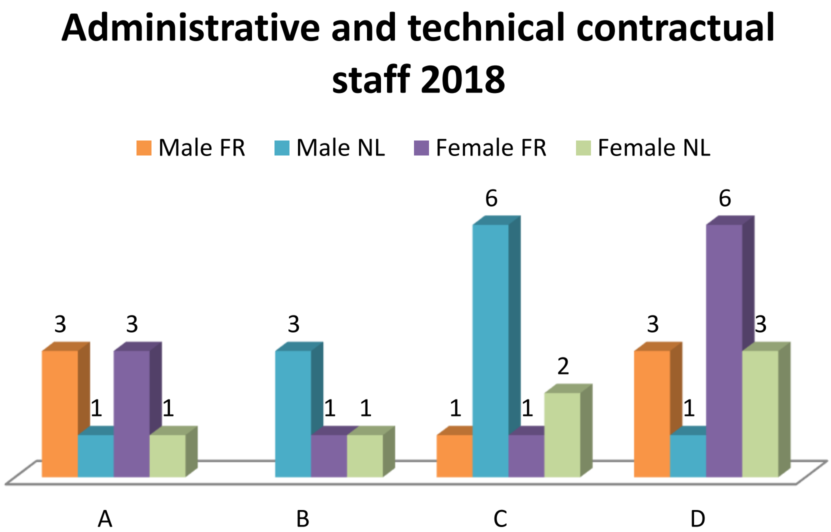
Statutory scientists 2018

Contractual scientists 2018



** Other: Master's degree in a language other than French or Dutch*


Administrative and technical statutory staff 2018
Male FR
Male NL
Female FR
Female NL
15
6
4
3
3
1
1
3
1
1
3
1
1
A
B
C
D


Administrative and technical contractual staff 2018
Male FR
Male NL
Female FR
Female NL
6
6
3
3
3
3
3
2
1
1
1
1
1
1
1
A
B
C
D