Research Activities in Astronomy and Astrophysics in Belgium

This text is a collaborative effort and an update of the overview of Belgian research in astrophysics written by Dejonghe in 2005 (Physicalia Magazine, 27, 275-280), then by A. Jorissen in 2011 (Bϕ, Belgian Physical Society Magazine, 4, 33-42).

The last years have seen the construction of important ground telescopes and instruments, while Belgian astronomers also continued to enforce their participation in the preparation, development, and the exploitation of Space missions. On the international level, these achievements allowed the Belgian astronomical community to strengthen an excellent reputation. Their implication in ambitious research projects allowed our scientists to become main actors to major breakthrough in various fields of astronomy. Most of the projects that made these contributions possible have been funded by grants from the regions, from the Belgian Science Policy Office (**BELSPO**), as well as from the European Research Council (**ERC**). Among these, ERC[1] grants are the most prestigious research grants in Europe. They fund researchers of any nationality and age who wish to pursue frontier research, and provide a high-level science stature to the person, the laboratory, and the country to which it is given. Even more encouraging is to note that a good part of these grants have been awarded to women. It makes our country quite unique and marks the beginning of a new era for astronomy in Belgium.

1. New ground-based telescopes

1.1. Belgian telescopes (ordered by decreasing mirror size)

The International Liquid Mirror Telescope (**ILMT**[2]) has been proposed by an international consortium initiated by astrophysicists from the *Institut d'Astrophysique et de Géophysique* (Liège University, Uliège), and comprising the following institutions: the Royal Observatory of Belgium (ROB), the Canadian Astronomical Institutes from Québec (Laval University), Montréal (University of Montreal), Toronto (University of Toronto and York University), Vancouver (University of British Columbia), Victoria (University of Victoria), and the Aryabatta Research Institute of Observational Science (**ARIES**) located in the state of Uttarakhand (Northeast India). The ILMT is equipped with a 4-m rotating mercury primary mirror. It has been constructed by the Belgian AMOS company and will be installed in 2018 on the Devasthal mountain (Uttararakhand, Northern India), close to the ARIES, located in the town of Nainital. The ILMT, presently under construction, has mainly been funded by the *Communauté Française de Belgique*, the *Région Wallonne*, the *Fonds National de la Recherche Scientifique* and ULiège. The project aims at monitoring a narrow strip of the sky to study photometric and astrometric variability of celestial objects as faint as magnitude $i = 22$ with a time resolution larger than one day but over long

[1] More information about the awarded projects is given in the text. To designate the type of grant we adopted the following acronyms: **StG** = Starting Grant, **CoG** = Consolidator Grant, **AdG** = Advanced Grant.

[2] http://www.aeos.ulg.ac.be/LMT/

periods of time. These observations will not only contribute to studies of micro-lensing and of time delay measurements of multiply imaged quasars but also to the detection and follow-up of supernovae, of variable stars, of proper motions and trigonometric parallaxes of faint nearby objects. In addition, the ILMT will provide a huge amount of quasar light curves that will allow astronomers to statistically investigate the nature of the intrinsic variability of quasars with the aim to get information on the central engines. These projects should provide ideal targets of opportunities for follow-up direct imaging or spectroscopic observations with the ARIES 3.6m telescope, as described below. The ILMT is open to all Belgian astronomers in the spirit of collaborative projects.

The 1.2m Flemish Mercator telescope[3], located at the Roque de los Muchachos observatory (La Palma, Canary Islands) and run by KULeuven/IvS, already mentioned in the 2005 and 2011 reports, has continued its operations. It is equipped with the highly efficient **HERMES** (high-resolution fibre-fed spectrograph) spectrograph (Raskin et al., 2011, A&A 526, A69). The design, building and integration of this luminous, high-resolution spectrograph were joint efforts of the Belgian institutes at the universities of Leuven and Brussels (ULB) together with the Belgian Royal Observatory with smaller contributions from the Geneva Observatory (Switzerland) and Landessternwarte Tautenburg (Germany). The fibre-fed spectrograph began regular science operation in April 2009, and is designed to be optimised both in wavelength stability and in efficiency. It samples the whole optical range from 380 to 900 nm in one shot, with a spectral resolution of 85 000 for the high-resolution science fibre. The dedicated tailored pipeline uses cross-correlation routines with spectral templates to derive accurate radial velocities. The long-term (5 years) radial-velocity stability, measured from 35 IAU standard stars, is 50 m/s. A better accuracy may even be achieved by using the observing mode where a wavelength-calibration spectrum is recorded simultaneously with the science spectrum. A large fraction of the HERMES/Mercator observing time (about 100 nights/year) is devoted to the radial-velocity monitoring of pooled targets of different kinds, mostly binary stars lacking orbital elements, and whose formation channel is poorly understood (sdB stars, post-AGB stars and planetary nebulae, barium stars…). A second major theme is to assemble and exploit spectroscopic information for numerous asteroseismic targets observed by the NASA Kepler mission. HERMES data have prompted a large number of peer-reviewed publications, including several *Nature* and *Science* papers on asteroseismology of stars of a whole range of masses and evolutionary stages, as well as a *Nature* paper on the use of a thermometer and of a chronometer of stellar internal nucleosynthesis of evolved low-mass stars. HERMES is also used to probe the atmosphere of evolved giant stars, through a technique known as tomography and developed at ULB. More recently, the KULeuven team constructed a 3-arm fast camera **MAIA**[4] (Mercator Advanced Imager for Asteroseismology), which is ideally suited to study the pulsational characteristics of faint subdwarf OB pulsators. This new instrument is also offered to the entire HERMES consortium.

Liège University is a junior partner of the consortium (consisting of University of Hamburg, University of Guanajuato and University of Liège) that operates the 1.2 m **TIGRE** (*Telescopio Internacional de Guanajuato, Robótico-Espectroscópico*[5]) facility in La Luz (Mexico). This fully robotic telescope is equipped with the refurbished **HEROS** (Heidelberg Extended Range Optical Spectrograph) fiber-fed

[3] http://www.mercator.iac.es
[4] https://fys.kuleuven.be/ster/instruments/the-maia-camera
[5] https://www.gaphe.ulg.ac.be/HRT/index_e.html

echelle spectrograph, which covers the almost full optical domain at a resolving power of 20 000. The instrument is dedicated to spectroscopic studies in stellar astrophysics. Liège University mainly uses its TIGRE time to monitor early-type stars of all spectral types (O, B, Wolf-Rayet, LBV,…). Furthermore, ULiège is currently designing a near-infrared spectrograph to be installed on the second, currently vacant focus of the telescope.

The 60 cm robotic **TRAPPIST**[6] (TRAnsiting Planets and PlanetesImals Small Telescope) telescope is a project driven by the Origins in Cosmology and Astrophysics group (**OrCA**) at the Department of Astrophysics, Geophysics and Oceanography (**AGO**) of the ULiège, in close collaboration with the Observatory of Geneva (Switzerland). Mostly funded by the Belgian Fund for Scientific Research[7] (F.R.S.-FNRS) and the University of Liège, TRAPPIST is devoted to the detection and characterization of planets located outside our solar system (ie. exoplanets) and to the study of comets and other small bodies in our solar system. It is composed of two telescopes, TRAPPIST-South, operated since 2010 at the **ESO**[8] (European Southern Observatory) - La Silla Observatory[9] in Chile, and TRAPPIST-North, installed in 2016 at the Oukaimeden Observatory in Morocco. TRAPPIST has been highly successful in finding exoplanets, resulting in several *Nature* papers led by the team of M. Gillon and resulting in large attention in the media in 2017. Also worth mentioning is the award of a ERC StG (**SPECULOOS** for Search for habitable Planets EClipsing ULtra-cOOl Stars, 2015-2019, PI is M.Gillon) to the ULiège team as a positive spin-off project to build new instrumentation with the aim to hunt for exoplanets around M dwarfs. Moreover, in the same year, another ERC StG (VORTEX) was offered to O. Absil at ULiège for coronagraphic studies of exoplanets.

1.2. ESO telescopes

From 2006 to March 2015, and thanks to the financing by Belspo of the 4th Auxiliary Telescope of the **VISA** (VLTI Sub Array), Belgian astrophysicists made a successful use of about 130 nights of guaranteed time (**GTO**). This has led to Belgian expertise in the very specific and demanding field of interferometry, which beyond the availability of the GTO is now fully exploited to request time on **VLTI** (Very Large Telescope Interferometer) and on other instruments. Scientific results span a wide range of astronomical objects (pre-main sequence stars, main-sequence stars with debris discs, giant stars with extended envelopes, post-mass transfer binaries with circumbinary discs, massive binaries...). Using precision near-infrared **CHARA** (Center for High Angular Resolution Astronomy) and VLTI interferometry, ULiège astronomers have directly resolved the innermost regions of the planetary system around a main sequence star for the first time, and revealed the presence of large quantities of hot circumstellar dust within a few astronomical units of the bright star Vega. Their observations suggest an inordinate replenishment rate, which may be related to a major ongoing dynamical event in the planetary system. Surface brightness asymmetries on the surface of **AGB** (Asymptotic Giant Branch) and supergiant stars were measured by the ULB group. In the same vein R Sculptoris is being scrutinized with **PIONIER** (Precision Integrated-Optics Near-infrared Imaging ExpeRiment). This instrument is also used by the

[6] http://trappist.ulg.ac.be
[7] http://www1.frs-fnrs.be
[8] http://www.eso.org
[9] http://www.eso.org/sci/facilities/lasilla

same group to compute astrometric orbits from interferometric data. The KULeuven/IvS team exploited VLTI in the topic of circumstellar and circumbinary disks of young and evolved stars leading to several ESO Press Releases on this topic. Moreover, H. Sana (KULeuven/IvS) is currently leading an ESO Large Programme to unravel the binarity and multiplicity of the most massive stars in the Universe, relying heavily on VLTI. This is one of several Large Programmes from Belgian teams that were approved by the ESO Observing Programme Committee. Given the high pressure existing on the ESO telescope time, this remarkable achievement demonstrates the top quality of astrophysical research in our country. The highly competitive national **FWO** (Fonds Wetenschappelijk Onderzoek) Starting Grant (Odysseus II, 2016-2020) offered to Hugues Sana for his re-entry as new Professor in Astrophysics at KULeuven/IvS is a direct spin-off project of his international career and ESO Large Programme. The UGent group has been leading an ESO Large Programme on the internal dynamics of dwarf elliptical galaxies. The KULeuven/IvS has been heavily involved in the ESO Large Programme on ground-based support for CoRoT running from 2007 to 2012. The ROB is actively involved in a public survey named VMC (VISTA Magellanic Cloud Survey) carried-out with the VISTA telescope in the infrared and which is aimed to study the star formation history of the Magellanic Clouds. IvS/KULeuven, ROB, and ULB teams (plus international partners, mostly from the University of Vienna) are part of the ESO Large Programme entitled *A joint venture in the red: the Herschel+MIDI+VISIR view on mass loss from evolved stars*, which started in 2011 and constitutes a follow-up of a similarly large programme carried out on ESA's *Herschel* infrared satellite. Finally, several Belgian teams (ULB, ROB, ULiège and KULeuven) are actively taking part, or even leading working groups, of the **GES** (*Gaia*-ESO Survey), a Large Programme running over several years to provide spectroscopic ground-support to the currently ongoing ESA's Gaia mission. The programme aims at providing radial velocities and abundances for about 10^5 stars, to address the issue of the chemico-dynamical evolution of our Galaxy. Astronomers from ULiège are also making the best use of *Gaia* **DR1** (first Data Release) data to identify very compact multiply imaged quasars.

The Atacama Large Millimeter/submillimeter Array (**ALMA**) is a major international astronomical project. It consists of an array of 50 12m-antennas with baselines up to 16 km, and an additional compact array of 7m and 12m antennas. Calls for proposals have been released since 2011. Notwithstanding the very high over-subscription rate, Belgian proposals have been very successful during yearly regular calls so far, with numerous peer-reviewed publications including some in *Nature.*

The Belgian astronomical community will undoubtedly continue to make intensive use of ALMA in the coming years. This situation reflects the important effort made by the community to gain expertise in sub-mm and radio astronomy, a field which was almost absent in the Belgian astronomical landscape until a decade ago. Many related observing programmes with Belgian involvement led to state-of-the-art publications and to a better knowledge of certain categories of stars. As an example, the teams at KULeuven, and ROB are probing circumstellar matter around evolved stars using radio observations. One particular case is the monitoring program of Sakurai's object[10], a famous star that was discovered in 1996.

[10] A so-called "born-again" AGB star: a central star of a planetary nebula that underwent a very late helium shell flash. The evolution of this star is extremely rapid and can be followed in real time, which makes it a good test case for stellar evolution models.

ROB researchers are monitoring its evolution on a yearly basis using the ESO-VLT telescopes, as well as ALMA to study the molecules in the circumstellar disk with the aim of deriving the isotope composition of the ejected material. This will enable a direct test of the theory of i-process nucleosynthesis. The UGent group has recently built up quite a strong expertise on H I studies using the 21cm line and sub-mm continuum observations. In particular, it has been quite successful in obtaining observing time on competitive radio observatories worldwide, including the 4 large radio interferometers (VLA, ATCA, GMRT, WSRT) and the largest single-dish sub-mm and mm telescopes. Prime examples are the involvement of UGent in the **AGES** (Arecibo Galaxy Environment Survey) project[11], a survey of galaxies in different environments with the Arecibo 305m telescope that has been granted 2000 hours of observing time, and in the **HALOGAS** (Hydrogen Accretion in LOcal GAlaxieS) survey[12] , the deepest HI survey of nearby galaxies, that is consuming almost 3000 hours of WSRT time.

The participation in radio investigations of stellar objects also developed at ULiège using VLA and **GMRT** (Giant Metrewave Radio Telescope), especially in the context of the study of particle-accelerating colliding-wind binaries and other galactic non-thermal radio sources. In particular, several fields in the Cygnus region were observed at several frequencies with the GMRT. On the other hand, collaborations with radio astrophysicists from La Plata (Argentina) and ASTRON/JIVE (The Netherlands) focus on the preparation of high angular resolution imaging campaigns using notably the **EVN**[13] (European VLBI Network).

Last but not least in the ESO framework, the Belgian astronomical community awaits the European-Extremely Large Telescope (**E-ELT**) planned for 2024. Phase[14] B (i.e. preliminary design) studies are ongoing for the **METIS** (Mid-Infrared E-ELT Imager and Spectrograph) instrument, with strong involvements of KULeuven/IvS and ULiège (Sect. 3).

1.3 Others

In November 2009, **BELSPO** signed an agreement with ARIES, on the cooperation for the construction of a 3.6m optical telescope at Devasthal (**DOT**, Devasthal Optical Telescope). The construction was performed by AMOS in Liège. In return of this financial investment from Belspo, Belgian astronomers will receive 7% of the telescope's observing time during the five first years of its operational life. The first call for early science with the DOT was launched in March 2017. There are three first generation instruments: an optical CCD imager, a near-infrared imager **TIRCAM**-2 (10-micron infrared camera, which is already available), and a spectrograph-cum-imager **FOSC** (Faint Object Spectrograph Camera, will be offered soon). These instruments allow multi-color photometry (narrowband and broadband filters) and low-resolution spectroscopy ($R < 4000$). A high-resolution spectrograph and CCD fast photometer will only be offered as second-generation instruments. The Belgo-Indian Network for Astronomy & Astrophysics (**BINA**) is a network that unites Belgian and Indian partner institutes with the

[11] http://www.naic.edu/~ages/
[12] http://www.astron.nl/halogas/
[13] http://www.evlbi.org
[14] For an instrument development: Phase A denotes the preliminary analysis; phase B, its definition; phase C, its design; and phase D, its construction.

optimization of the scientific exploitation of the Indo-Belgian telescopes (4-m ILMT and 3.6-m DOT) as ultimate goal. At the Belgian side, the network is funded by BELSPO and led by ROB. The first BINA workshop was hosted by the Aryabhatta Research Institute of Observational Sciences (ARIES) in Nainital (India) on 2016, November 15-18. It attracted 107 participants including 11 Belgian colleagues.
The Royal Belgian Institute for Space Aeronomy (**BIRA-IASB**) deployed a network of radio receiving stations for the detection of meteors, called **BRAMS**[15] (Belgian RAdio Meteor Stations), based on the principle of forward scattering of radio waves from meteor ionization trails. A dedicated beacon located in Dourbes (Southern Belgium) acts as transmitter. Almost 30 receiving stations are currently deployed throughout the country, run by Belgian radio amateurs, groups of amateur astronomers, and public observatories. In 2016, they started the citizen science project Radio Meteor Zoo in collaboration with Zooniverse, involving interested people in the analysis of the data.

Large Sky Area Multi-Object Fiber Spectroscopic Telescope (**LAMOST)** is a unique telescope located in the Xinglong Observatory (China) that combines a large aperture (3.6–4.9 m) with a wide field of view (circular with a diameter of 5 degrees). The focal surface is covered with 4000 optical fibers connected to 16 multi-object optical spectrometers with 250 optical fibers each. Hence, this instrument is ideal to obtain low-resolution (R=1800) spectra for a large number of objects simultaneously. In 2010, the LAMOST-Kepler project (PI, Peter De Cat, from ROB) was initiated with the aim to observe as many objects in the field of view of the Kepler space mission as possible for a homogeneous determination of stellar parameters (effective temperature, surface gravity, metallicity, radial velocity and an estimation of the projected rotational velocity for fast rotating objects). The observations started in May 2011 and in the first 4 years, about 200 000 objects were observed.

The Low Frequency Array (**LOFAR**) is a large radio telescope in the Netherlands operating in the 10-250 MHz frequency range. It consists of thousands of omni-directional antennas and allows for multiple observation strategies. The VUB uses LOFAR to measure short radio bursts emitted by atmospheric air showers from high-energy cosmic rays. The group is funded through a highly competitive ERC StG (LOFAR, Searching for the Origin of Cosmic Rays and Neutrinos with LOFAR, 2015-2020, PI is Stijn Buitink). In 2016, the first LOFAR results on the mass composition of cosmic rays around the galactic-extragalactic transition were published in *Nature.* Further research is aimed at improvement of the precision and energy range of these measurements as well as the implementation of a new observational mode for LOFAR that allows the search for neutrino impacts on the lunar surface.

2. Space missions

2.1. Belgian missions

The Belgian companies *Verhaert, Spacebel* and the research centre *Centre Spatial de Liège* (**CSL**) built the Belgian-led ***Proba*** (PRoject for OnBoard Autonomy satellites. The *Proba* satellites are among the smallest flown by ESA, yet they have a big impact in space technology. They are also part of ESA's In-orbit Technology Demonstration Programme, missions dedicated to the demonstration of innovative

[15] http://brams.aeronomie.be/

technologies. Several new technological developments and scientific experiments are being flown on Proba satellites. Among these are two solar-observation experiments led by Belgian teams (from the ROB, CSL, BIRA-IASB, and the Centre for Plasma Astrophysics from KULeuven): the Ly-alpha radiometer (**LYRA**), and the Sun Watcher using APS detectors and image Processing (**SWAP**) using new pixel sensor technology, taking measurements of the solar corona in a very narrow band.

Also **ALTIUS** (Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere) is part of the *Proba* family. ALTIUS is a satellite mission proposed by BIRA-IASB, aiming at the remote sensing of key atmospheric constituents at high vertical resolution. The ALTIUS mission concept has been studied since 2006 by BIRA-IASB, together with the *OIP Sensor Systems* and *Qinetiq Space Belgium* companies. After several ESA-organized reviews in 2015, BELSPO officially announced in early 2016 its support for the mission, end-to-end. Furthermore, the ESA Earth Observation Programme Board has officially accepted ALTIUS as an element of the EarthWatch programme. The road is wide open for the development of the instrument, space platform, ground segment, algorithms and launch in the nearby future.

2.2 CNES – NASA – ESA astrophysics missions with Belgian involvement

ROB and the Royal Meteorological Institute (**RMI**) are involved at co-PI level in the CNES-led PICARD mission, for the **SOVAP** (SOlar VAriability PICARD) instrument, a bolometer whose sensing element is based on micro-temperature differential thermometers placed on a thermal shunt. BIRA-IASB also hosts its Science Operation Centre at the Belgian User Support and Operation Centre (**BUSOC**) premises.

As apparent from the above, various Belgian teams have acquired internationally recognised expertise in the fields of solar and solar-terrestrial physics and work often in close collaboration on joint projects. On its own, each group is relatively small and faces various scale problems including lack of stability of technical personnel and instrument scientists over time-scales exceeding that of single projects (> 3 years). To remedy this situation, the Solar and Terrestrial Centre of Excellence (**STCE**) has been created at the Space Pole[16] in Brussels.

Belgian scientists (KULeuven/IvS, ULiège, ROB) were heavily involved in the CNES-dominated **CoRoT** mission (COnvection ROtation and planetary Transits, 2006 – 2012), both at instrument level and for the scientific exploitation of the data. This expertise led to major involvement in the NASA missions *Kepler* and its refurbished version, K2, as well as in the **TESS** mission (Transiting Exoplanet Survey Satellite) to be launched in 2018. The advent of the CoRoT and *Kepler* space missions has considerably increased the potential of asteroseismology, especially for upper-main-sequence stars and red giant stars. Of particular interest are the slowly pulsating B-type stars, which oscillate in gravity modes penetrating deeply into the star. In those, it is possible to assess the extent of the convective core from the average spacing of gravity modes and to show from the small deviations from equidistant spacing that the composition gradient above the core is different from what instantaneous mixing would require. Asteroseismology of red giants emerged when scientists from KULeuven/IvS detected solar-like oscillations in a red giant, which resulted in a *Nature* paper. Here again the long and precise data strings of satellites such as CoRoT

[16] http://www.oma.be/index.php/en/

enabled the detection of many non-radial modes with fairly long lifetimes. Confronting such modes with stellar-structure models for several hundred red giants made it possible to clearly distinguish between hydrogen-burning (first) red giant stars and helium-burning (clump) stars, and to measure the mass of their helium core. Moreover, KULeuven/IvS led a *Nature* paper on the first derivation of the core rotation from mixed dipole modes from 2 years of uninterrupted *Kepler* data. This discovery boosted extensive observational and theoretical studies on the interior rotation of evolved stars, because it was found that current evolutionary models are two orders of magnitude wrong in their prediction of the core rotation. Much stronger coupling between core and envelope must occur than currently predicted.

The heritage of the Belgian CoRoT and *Kepler* involvement led to a leading role of Belgian scientists in the ESA M3[17] mission **PLATO** (PLAnetary Transits and Oscillations of stars), selected in 2014 within ESA's Cosmic Vision Programme and currently in its implementation phase. KULeuven/IvS and CSL lead the calibration and testing of the cameras of this mission, consisting of 26 identical telescopes operating from one platform to be launched to L2. KULeuven/IvS and ULiège are heavily involved in the scientific exploitation of the mission, both for the core programme and for the PLATO Complementary Programme, the latter led by KULeuven. PLATO will be launched in 2026.

The ESA infrared and submillimetre *Herschel* satellite, launched in May 2009, was one of the most successful achievement from ESA astronomy programme. It hosted the largest mirror (3.5m) ever flown. Belgium has been involved at the co-PI level (led by the KULeuven/IvS, with industrial contributions from CSL, IMEC and OIP) in the design and construction of the Photodetector Array Camera and Spectrometer (**PACS**), one of *Herschel*'s three science instruments exploring the wavelength range 60 – 210 μm over a field of view of ~1.75' × 3.5'. KULeuven/IvS has opened its right of participation in the guaranteed-time programmes of *Herschel* to all interested Belgian partners. The scientific issues that were addressed are in the fields of star formation, mass loss of evolved stars, extreme massive stars with winds, nearby galaxies, high-redshift galaxies and cosmology. In this framework, a BRAIN.be project (STARLAB) was obtained in 2016 by ULB, KULeuven and ROB, providing a strong incentive to collaboration on evolved stars and their environments studied with *Herschel*, ALMA and HERMES. Three PhD theses in co-direction between pairs of the participating Belgian institutes are taking place in that context. These efforts have led to an impressive number of papers (co-)authored by Belgian astronomers from various institutes. Among them, e.g., a *Nature* paper on the discovery of water around carbon stars and a *Science* paper on the discovery of high-redshift gravitational lenses at submm wavelengths. This instrument activity led to the involvement of KULeuven/IvS at co-PI level in the Mid-Infrared Instrument (**MIRI**) consortium of the future *James Webb Space Telescope* (with contributions from CSL and UGent) to be launched in 2018. The *Herschel* heritage also implied involvement of KULeuven/IvS in the mission candidate **ARIEL** (Atmospheric Remote-sensing Infrared Exoplanet Large-survey), currently undergoing a design study and in competition with two other mission candidates for the M4 slot in ESA's Cosmic Vision programme (2015-2025). In addition, both KULeuven/IvS and UGent are involved in the European SAFARI instrument planned for the ESA/Japanese infrared satellite SPICA (Space Infrared Telescope for Cosmology and Astrophysics), currently proposed as a candidate M5 mission.

[17] Third medium class mission of ESA's *Cosmic Vision* programme (2015 - 2025)

Belgian scientists play a considerable role in many of the data-processing coordination units for the ESA *Gaia* satellite (launched in December 2013), with ULB, ULiège, KULeuven/IvS, UAntwerpen and ROB as partners (sometimes leaders) in the topics of variable stars, binaries, radial velocity determination and characterisation of stars, solar-system bodies, quasars, and gravitational lenses. The first *Gaia* data release (DR1) took place in September 2016, focused on the astrometry of single star-like objects. ULB, ROB, ULiège and UAntwerp are currently active in the preparation of the second data release scheduled for April 2018 as it should contain the radial velocities of 5 to 8 millions of single stars, as well as astrometric binaries and solar system objects, domains in which those Belgian teams hold some leading positions. KULeuven/IvS made the first comparison of asteroseismic versus astrometric distances of nearby dwarfs and distant red giants within CU7, pointing out excellent agreement and large future potential to rely on seismic distances for red giants too far away for *Gaia* distances to become available. Another scientific issue currently addressed with the DR1 *Gaia* data is, e.g., the Hertzsprung-Russell diagrams of several categories of misunderstood late-type stars (ULB and KULeuven).

Ever since its launch in 1999, ULiège astrophysicists have been using ESA's X-ray observatory **XMM-Newton** (X-ray Multi-Mirror Mission) to study the X-ray emission of massive stars of all spectral types. These studies provided unprecedented insight into the physics and hydrodynamics of stellar winds and have deeply changed our understanding of the wind interactions in massive binaries. For the first time, XMM-Newton data unveiled the variability of the X-ray emission of single massive stars resulting from magnetically-confined stellar winds, large-scale co-rotating wind structures, or photospheric pulsations propagating into the stellar wind. Owing to its high sensitivity and wide field of view, XMM-Newton allowed to study the X-ray emission of large populations of massive stars and low-mass pre-main sequence stars in various open stellar clusters. ULiège researchers also utilize the XMM-Newton satellite to study the cosmological Large Scale Structures through various international consortia (XMM-Medium Deep Survey, XMM Large Scale Structure Survey, and the XXL project). ULiège is in charge of the exploitation of the quasar aspect of the project. Detection of large numbers of quasars in contiguous fields, and in a homogeneous manner, will enable the investigation of their 2D and 3D spatial distribution.

The *Advanced Telescope for High ENergy Astrophysics* (**ATHENA**) is ESA's future X-ray telescope, under development for launch around 2028. It is the second large class mission in *Cosmic Vision*. ATHENA will be two orders of magnitude more sensitive than *Chandra* and XMM-Newton. The primary goals of the mission are to map hot gas structures, determining their physical properties, and searching for supermassive black holes. In addition, the mission will perform observations of all kinds of cosmic X-ray sources. The ULiège team is deeply involved in the scientific preparation of this mission, notably leading the Science Working Group 3.2 on Star Formation and Evolution. Moreover, ULiège and CSL contribute to the preparation of the X-IFU (X-ray Integral Field Unit) instrument that will provide unprecedented high-resolution X-ray spectroscopy of many kinds of cosmic X-ray sources. The UGent group is also involved in the scientific preparation of the mission.

Since 2015, the Institute for Theoretical Physics at KULeuven has developed gravitational wave science as a novel research direction. It has launched a Centre for Gravitational Waves that acts as a platform to

strengthen and to coordinate nationwide collaboration on gravitational wave science. It has also taken up a role in the gravitational wave ESA mission **LISA** (Laser Interferometer Space Antenna) which was selected for L3, the third and final large class mission in *Cosmic Vision*, earlier in 2017. LISA builds on the highly successful technology mission LISA Pathfinder (in which Belgium was not involved). An initial phase-0 study was recently completed and phase-A is scheduled to start in April, 2018. LISA's launch is planned for 2034. The Belgian co-PI for LISA is T. Hertog who is heavily involved in the fundamental physics science goals of the mission. The Belgian contribution to LISA involves also an instrumental component which is being pursued in a Belgian (KULeuven/IvS) - Dutch collaboration.

In order to study the dynamics of the external layers of the solar atmosphere, the ROB participates as co-investigator or associated investigator in space missions such as **SOHO**[18]**/EIT**[19]**,** SOHO/**LASCO**[20]**,** **STEREO**[21]/**SECCHI**[22]. Together with ULiège/CSL, ROB will play a leading role in the **EUI** instrument (Extreme Ultraviolet Imaging) onboard the M1 *Solar Orbiter* mission, to be launched in 2019. These activities complement those already described in relation with the *Proba-2* satellite (Sect. 2.1).

Euclid is the M2 optical/infrared space telescope to be launched in 2020 towards L_2 (Lagrange point) from where it will map the 3D distribution of about two billion galaxies. The subsequent analysis of the data will reveal the details of the matter distribution throughout the Universe, including the contribution of the dark matter. Moreover, it will be possible to trace the accelerating expansion of the Universe and to study the behaviour of the enigmatic dark energy that causes the acceleration. UGent astronomers are deeply involved in *Euclid*, both in its development and its scientific exploitation. The group is especially interested in studying the ~10^5 dwarf galaxies that will be detected.

2.3 Solar-system exploration missions

Belgium is involved in several ESA missions to terrestrial planets, such as *Mars Express* and *the ExoMars* missions**.** BIRA-IASB is PI and ROB co-I of **NOMAD** (Nadir and Occultation for MArs Discovery)*,* a 3-channel spectrometer, hosting 2 infrared channels and one UV/visible channel, on the *ExoMars Trace Gas Orbiter* launched in 2016. The infrared channels build upon the expertise of BIRA-IASB with its successful **SOI** (Solar Occultation in the Infra-Red) instrument which was onboard ESA's *Venus Express* mission. ROB was co-I of the radio science experiment of *Mars Express* and of the **AMELIA** (Atmospheric Mars Entry and Landing Investigation and Analysis) instrument hosted by the *Entry, Descent and Landing Demonstrator Module* on *ExoMars*. ROB is also PI of **LaRa** (Lander Radio science), the radio science experiment of the *ExoMars* 2020 mission which has the objective to observe the rotation and orientation of Mars and therewith to determine properties of Mars deep interior. Sill on the same mission, ULiège (UR GEOLOGY) is co-PI of the instrument named **CLUPI** (Close-UP Imager) and collaborator for **RLS** (Raman Laser Spectrometer) which will help to image, identify, and characterize minerals.

[18] Solar and Heliospheric Observatory
[19] Extreme ultraviolet Imaging Telescope
[20] Large Angle and Spectrometric Coronagraph
[21] Solar Terrestrial Relations Observatory
[22] Sun Earth Connection Coronal and Heliospheric Investigation

Belgium strongly participates in the ESA cornerstone mission *BepiColombo* to Mercury. ROB together with UNamur are Co-I of three of its instruments: the Mercury Orbiter Radio science Experiment (**MORE**), the BepiColombo Laser Altimeter (**BELA**), and the high resolution camera (SIMBIO-SYS). Issues addressed by these instruments are the rotation and interior structure and evolution of Mercury, which will be confronted to models developed at ROB and UNamur.

ROB leads the ESA Working Group on the interior of satellites of the **JUICE** (JUpiter ICy moons Explorer) mission to Jupiter and its satellites and is co-I of five instruments: the radioscience experiment 3GM (in which also UNamur is co-I), the *laser altimeter* (**GALA**, GAnymede Laser Altimeter), the *JUICE magnetometer* (**J-MAG**), the *VIS-NIR imaging spectrometer* (**MAJIS**), and the *Radio Interferometry and Doppler Experiment* (**PRIDE**).

BIRA-IASB was Co-I in the **ROSINA** (*Rosetta* Orbiter Spectrometer for Ion and Neutral Analysis) mass spectrometry consortium on the *Rosetta* mission, which studied the physics and chemistry of the coma of comet 67P/Churyumov-Gerasimenko. By now, ROSINA has discovered a zoo of molecules, of which a lot have never been detected in comets before. This has led to a large number of high-visibility publications.

ROB is co-I of the **InSight** (Interior exploration using Seismic Investigations, Geodesy, and Heat Transport) mission to Mars and participating scientist in the *Cassini* mission to Saturn and its moons and the **MAVEN** (MArs Atmosphere and Volatile EvolutioN) mission to Mars. ROB exploits radio science data from many NASA missions like *Mars Global Surveyor*, *Mars Odyssey*, *Mars Reconnaissance Orbiter*, and *Cassini* to Saturn and its moons.

3. Instrument design and building

KULeuven/IvS so far took the lead in the construction of the HERMES and MAIA instruments for the Mercator telescope. A direct spin-off of the MAIA camera design is KULeuven's involvement in the *BlackGEM* instrument, a 3-telescope instrument to find optical counterparts of gravitational waves. *BlackGEM* is led by the *Radboud University Nijmegen*. KULeuven designs and builds the cooling system for the cameras of the instrument, which will be installed at the La Silla Observatory site of ESO end 2018. Although Belgian teams never were able to take the leadership of the design and construction of a large international astronomical instrument due to too limited national funds, many are directly involved as partners as already discussed above. Current involvements in instrument development concern: KULeuven and UGent for the MIRI/JWST instrument (currently in development Phase D); KULeuven and ULiège for METIS (currently in Phase B), the Mid-infrared ELT Imager and Spectrograph for the ESO Extremely Large Telescope; KULeuven and CSL for the instrument calibration of PLATO (Phase C) and for the instrument design of ARIEL (Phase A).

Thanks to its expertise in high-energy astrophysics, the *High-Energy Astrophysics Group* from ULiège together with CSL have become partners of the international instrument consortium (led by CNES) that will build the *X-ray Integral Field Unit* (**X-IFU**) microcalorimeter spectrograph for ESA's next

generation X-ray observatory ATHENA as already indicated above. X-IFU is an ambitious cryogenic instrument that will provide unprecedented views of the hot and energetic Universe.

The expertise gained in space-instrumentation by the different groups also lays the foundation for a possible Belgian contribution to the next generation of ground-based gravitational wave observatories. Initial studies are underway to assess the feasibility and potential to construct a third generation gravitational wave observatory in the Dutch - German - Belgian border area: the *Einstein Telescope*. This would constitute an exceptional opportunity for Belgium not only from a scientific viewpoint but also from a broader socio-economic and educational perspective. A strong Belgian involvement in this project would benefit from a collaboration between the different space-instrumentation groups and the experimental high-energy physics community.

BIRA-IASB remains, with its *Engineering Division*, a strong actor in the design and construction of space science instruments. In-house prototyping is combined with outsourcing of the final production to industry. The division is especially skilled in the design of logic systems carrying on-board intelligence based on microcontrollers, microprocessors or Field Programmable Gate Arrays (FPGA). Associated firmware (VHDL) and software is developed for these platforms. The mechanical workshop is specialized in the design and manufacturing of structural mechanics for space. The division has a number of facilities at its disposal for functional testing and thermal-vacuum testing. In recent years, the division has successfully contributed to the operation of ROSINA-DFMS (ROSINA's Double Focusing Mass Spectrometer) on *Rosetta*, SPICAM (Spectroscopy for Investigation of Characteristics of the Atmosphere of Mars) on *Mars Express* and SPICAV/SOIR (Solar Occultation at Infrared) on *Venus Express*, to the construction and operation of NOMAD on the *ExoMars Trace Gas Orbiter* and of the *Energetic Particle Telescope* on *Proba-V* (where V stands for vegetation), and to the design of the **THOR** (Turbulence Heating ObserveR) Cold Solar Wind instrument.

4. Synergies and resource pooling

The large effort needed in the preparation and exploitation of large missions or of complex ground-based instruments often call for the creation of large consortia. Belgian teams are indeed involved in many such consortia. We list those of the past decade here.

Within the discipline of asteroseismology, the institutes involved in this kind of research in Belgium (KULeuven, ROB, ULiège) have integrated their research within the *Belgian Asteroseismology Group* (**BAG**) since 2000, in the framework of previous Interuniversity Attraction Poles. Since 2006, Belgian asteroseismologists have opened up their ambition and have been integrated into European-funded networks rather than the BAG. The first European funded network within FP6 (6th Framework Programme) concentrated on Helio- and Asteroseismology was HELAS (European HELio- and ASteroseismology network) and ran from 2006-2010. Subsequently after positive evaluations, KULeuven/IvS and ULiège were involved in the FP7 SpaceInn project (Exploitation of Space Data for Innovative Helio- and Asteroseismology, 2012-2016) and currently KULeuven/IvS is one of the partners in the H2020 Integration Action HELAS-IA, currently in Stage 2 of the competition after selection in Stage 1 by the European Commission (success rate in Stage 2 is 1/3).

KULeuven, ROB and ULB have jointly constructed the HERMES spectrograph (for the Mercator telescope, and have agreed on a Memorandum of Understanding for its exploitation, which involves more than 100 nights per year of pooled observations. The largest programme on HERMES concerns the atmospheric study and radial-velocity monitoring of a large and diverse sample of binaries with late-type components. This programme and most of the other projects that ran or are requesting data from the instrument are collaborations between the member institutes of the HERMES consortium.

Various international consortia (XMM-Medium Deep Survey, XMM Large Scale Structure Survey, and the XXL project) were mentioned in relation with the ULiège activities in XMM-Newton. Liège University was also involved in the international *Chandra* Cygnus OB2 Legacy Survey (study of the X-ray emission of massive stars in Cyg OB2) and a large multi-wavelength campaign to study the nearest massive eclipsing binary δ Ori, notably with four deep *Chandra* exposures.

The ***European Leadership in Space Astrometry (ELSA)*** was a Marie Curie Research Training Network supported by the European Community's Sixth Framework Programme (FP6), which started in October 2006, lasted for 4 years, and involved ULB. The overall objectives of ELSA were to develop the theoretical understanding and practical analysis tools of importance for the European Space Agency's astrometric mission Gaia and to foster the development of a new generation of researchers in the area of space astrometry. ELSA has been followed by the FP7 *Gaia Research for European Astronomy Training* (GREAT) network sponsored by the European Science Foundation (ESF), and involving KULeuven/IvS, ULB, ROB and ULiège.

Within the Belgian *Solar-Terrestrial Centre of Excellence* (STCE), the SIDC (Solar Influences Data analysis Center) is a Regional Warning Centre of the *International Space Environment Service* (ISES), providing space weather alerts in real time or on a daily, weekly or monthly schedule. It is a partner in the space weather segment of the ESA Space Situational Awareness Program.

ULiège chaired the European Interferometry Initiative consortium under FP6 and FP7 (http://www.european-interferometry.eu) aiming at the organization of optical and infrared interferometry projects in Europe.

Finally, the study of high energy events in the universe as supernova, active galactic nuclei and gamma ray bursts make use of a multi-messenger approach combining astronomical measurements and the detection of high energy cosmic rays, photons and neutrinos. These multidisciplinary activities are described in the "Research activities in fundamental interactions, from particles to cosmology, in Belgium".

5. Theoretical astrophysics research in Belgium

Nuclear astrophysics is a traditional niche of ULB theoretical research, with the computation and compilation of nuclear data of astrophysical interest[23,24], including the equation of state of dense matter in

[23] http://www.astro.ulb.ac.be/bruslib/

extreme astrophysical environments such as neutron stars. The group has a strong expertise in the s-, r- and p- processes of nucleosynthesis, studied through parametric approaches or through uni- or multi-dimensional stellar evolution models. Theoretical research at ULB involves as well stellar evolution covering all evolutionary stages[25] from pre-main sequence to neon combustion for a vast mass range, with new developments regarding the binary evolution (BINSTAR code) and rotationally-induced mixing, using hydrodynamical tools when needed, and treating the associated nucleosynthesis. The developments about BINSTAR are done in collaboration with VUB, which has a long-standing research history in this field. 3D hydrodynamical models of supergiant atmospheres are also computed, and confrontations are performed with abundances derived from observations. Moreover, ULB is involved in the modelling of neutron stars, their internal constitution and their hydrodynamics especially superfluidity. ULB is a partner of the COST action MP1304[26] ***NewCompStar****: Exploring fundamental physics with compact stars*.

A strong theoretical expertise exists in Belgium (ULiège, KULeuven/IvS) regarding theoretical computations of the nonradial oscillation spectra of various kinds of stars in the context of asteroseismology. In particular, thanks to the highly competitive ERC Advanced Grant team led by KULeuven/IvS (**MAMSIE**, Mixing and Angular Momentum tranSport of massIvE stars, 2016-2020, PI is C.Aerts), asteroseismology is now getting bridged with 3-dimensional hydrodynamical simulations to build new theoretical stellar evolution models of massive stars calibrated by gravity-mode oscillations.

The Centre for mathematical Plasma-Astrophysics at KULeuven (KULeuven/CmPA) focuses on theoretical and computational plasma physics, relevant for solar physics, astrophysics and laboratory (fusion) plasmas. Key applications include magneto-seismology in the solar corona, all aspects of space weather, relativistic plasma dynamics, and fundamental plasma physics research. KULeuven/CmPA coordinates several ongoing EC-FP7 and H2020 projects targeting space weather applications, namely ***Soteria***[27] (SOlar TERrestrial Investigations and Archives) and SWIFF[28](Space Weather Integrated Forecasting Framework) as well as **SOLSPANET** (Solar and Space Weather Network of Excellence). It is involved in *European Research and Training Networks* (specifically SOLAIRE[29]). The group does a lot of numerical work, targeted to high performance computing, since the prime work package of the new *Intel Exascience Lab*[30] is on space weather modelling, with KULeuven/CmPA acting as coordinator, where 5 Flemish universities, IMEC and Intel collaborate in work packages. Relativistic gas and plasma modelling for Active Galactic Nuclei jets and in the extreme conditions of Gamma Ray Bursts is done in close collaboration with Utrecht and Amsterdam colleagues, as part of the COST action MP0905. The CmPA was recently awarded an ERC Consolidator grant (BOSS-WAVES, 2018-2022, PI is T. Van Doorsselaere) for the study of backreaction of the solar plasma to waves.

[24] http://www.astro.ulb.ac.be/Netgen/form.html
[25] http://www.astro.ulb.ac.be/~siess/Site/STAREVOL
[26] http://www.cost.eu/COST_Actions/mpns/MP1304
[27] http://soteria-space.eu/
[28] http://www.swiff.eu
[29] http://www.iac.es/solaire
[30] http://www.exascience.com

The *Atomic Physics and Astrophysics Group of Mons University* has a long-standing tradition in the determination of fundamental parameters, such as radiative and collisional rates, for atoms and ions of astrophysical interest, particularly for the investigation of the chemical composition of stars (including the Sun and the chemically-peculiar stars) and the analysis of stellar nucleosynthesis. For that purpose, elaborated theoretical approaches and up-to-date experimental techniques (time-resolved laser-induced fluorescence spectroscopy, Fourier transform spectroscopy...) are currently used. In addition, several unique databases, storing atomic data for heavy elements (5th, 6th rows of the periodic table, lanthanides, actinides), have been developed containing position and intensity parameters for a large number (over 100 000) of transitions belonging to ions of astrophysical interest (**DREAM**[31] and **DESIRE**[32]) and of interest for laser devices and for fusion research (**ADAS**, Atomic Data and Analysis Structure, collaboration). A new project is currently also dedicated to the study of plasma environment on the atomic structure and processes involving K-vacancy states for different ionic systems in the context of high-density astrophysical media such as accretion disks around black holes.

KULeuven (IvS, Department of Chemistry, Department of Mathematics) has been granted an Interdisciplinary Research Project (IDO) to develop a multidimensional theoretical code for exoplanet atmospheres, including radiative transfer, chemistry, dynamics, cloud formation etc. Expertise on the similar topic of non-LTE radiative transfer in dusty circumstellar shells around evolved stars is already existing in the KULeuven/IvS team, thanks to the code GASTRoNOoM coupled to a dust radiative transfer code (MCMAX). This KULeuven/IvS team recently got a large boost thanks to the award of an ERC Consolidator grant (AEROSOL, 2016-2020, PI is L.Decin).

The ROB has been granted a BRAIN.be Networking Project for the development of the Belgian Repository of Atomic data and Stellar Spectra by the Belgian Federal Science Policy Office (BRASS, 2014-2018, PI is A.Lobel). The Project is a scientific collaboration on astrophysics research of the ROB, KULeuven, European Southern Observatory at Paranal (Chile) and ULB. The follow-up committee also involves the University of Antwerp and the Vereniging voor Sterrenkunde in the project. **BRASS** (Belgian Repository of fundamental Atomic Data and Stellar Spectra) also involves a PhD program to be completed at the KULeuven. BRASS takes a first, but crucial, step towards removing all systematic errors in atomic input data required for quantitative stellar spectroscopy. It will thoroughly assess the quality of fundamental atomic data available in the largest repositories by comparing very high-quality observed stellar spectra with state-of-the-art theoretical spectra. Whereas this type of study has currently been carried out for very few stars at the time, and mostly limited to comparable spectral types assembled from various sources, BRASS will combine, analyze, and offer the community the first uniform large collection of benchmark and reference stars[33,34]. This study will be more complete than any other to date in terms of coverage of the stellar parameter space, as well as the spectral wavelength coverage.

NaXys (Namur Centre on Complex Systems) at UNamur has recently applied its long-standing expertise in celestial mechanics and Hamiltonian theory to exoplanets (high mutual inclinations, Kozai resonance

[31] Database on Rare-Earths at Mons: http://hosting.umons.ac.be/html/agif/databases/dream.html
[32] DatabasE on SIxth Row Elements: http://hosting.umons.ac.be/html/agif/databases/desire.html
[33] http://brass.sdf.org
[34] https://www.belspo.be/belspo/fedra/proj.asp?l=en&COD=BR%2F143%2FA2%2FBRASS

and migration) or to artificial satellites and space-debris dynamics (in particular the search for stability zones – candidates for parking orbits or zones of accumulation of debris – and the analysis of the solar-radiation pressure for specific debris. NaXys has developed a full expertise in theoretical cosmology as well, focusing on dark energy, simulations of cosmic structure formation with numerical relativity techniques, alternative theories of gravitation and the derivation of multi-scale combined constraints (solar-system, Hubble diagram, compact objects, CMB[35] and large-scale structure physics). The NaXys group is member of the *Euclid* Consortium. The group is involved into tests of general relativity and inflationary scenarios with *Euclid*, which requires careful modeling of observables. The cosmology group in NaXys has recently opened a new line of research in electromagnetic detectors of gravitational waves, which are complementary to current laser interferometers since they will allow probing higher frequency ranges (kHz to THz and higher).

The UGent astronomy group focuses on the kinematics and dynamics of galaxies, including their formation, evolution, and structure,especially for dwarf galaxies, through state-of-the-art N-body/SPH simulations. This research is backed by observational collaborations and will have strong ties with the data coming from the future ESA *Euclid* mission. A second major theoretical topic is the study of the interaction of matter and radiation through radiative transfer 3D, non-LTE simulations. These radiative transfer techniques have led to the development of a radiative transfer code that is mainly used to model the dusty interstellar medium in galaxies, in particular to analyze far-infrared observations of nearby galaxies, such as those obtained by *Herschel* (Sect. 2.2). Finally, the topic of galaxy dynamics has also developed into the investigation of dark matter halos and modified gravity: the UGent group is using mainly radio observations to determine the mass distribution in galaxies and interpreting these using either models for dark matter or alternative gravity theories.

The ROB involvement in many solar-system exploration missions goes along with the modelling of the interior structure and dynamics of terrestrial planets and moons of the solar system, building on the expertise developed from the 1960s on the rotation of the Earth. New methods are developed to investigate the deep interior structure as well as the crust and lithosphere. A particular focus is on the study of the rotation, gravity field, and tides. Earth rotation theoretical studies are presently on-going thanks to a ERC AdG grant financing the project **ROTANUT** (Rotation and nutation of a wobbly Earth, PI is V. Dehant) whose objective is to better understand the fluid core contributions to the variations of the Earth orientation in space (so-called nutations). Historically, one of the first tasks of ROB was to build star catalogues and to contribute to the determination of the Universal Time from meridian observations. In the 1970s, the ROB followed the transition to atomic time, with the installation of atomic clocks and their integration in the world network used for the realization of the UTC. The ROB also provides a local representation of UTC available in real time. Current research is performed on time transfer (i.e. remote atomic clock comparisons) methods and strategies. The ROB is coordinating the *EUREF Permanent Network*[36] (**EPN**) with a particular emphasis on the study and mitigation of error sources degrading the positions and velocities of *Global Navigation Satellite System* stations. The *Astronomy and Astrophysics* department provides public access to atomic data to assist spectroscopists in the identification of atomic

[35] Cosmic Microwave Background
[36] http://epncb.oma.be/

lines in astrophysical or laboratory spectra. It is widely used in the astronomical and physical community. It is involved in the development of the open source photoionization/PDR spectral synthesis code Cloudy, which is the only interstellar medium modelling tool that can produce a self-consistent model of a photoionized region including the PDR and molecular regions surrounding it. Research in the department further focuses on visual and spectroscopic multiple stars (especially spectral disentangling), pulsating stars, central stars of planetary nebulae, and hot stars (stellar winds, rotation, etc.).

Not yet mentioned previously for ULiège are various theoretical studies on astroparticles, e.g., showing that the constraints on circular polarisation rule out axion-photon mixing as the explanation of the systematic alignment of the polarisation of light from quasars, and intensive gravitational lens modelling.

BIRA-IASB's Space Physics division has developed expertise on comets in the frame of *Rosetta*. The goal is to understand the volatile composition and the isotopic composition and to explain how these can be traced back to the properties of dense molecular clouds or processes that occurred during solar system formation and subsequent evolution. The emphasis is on gas-grain interactions and the associated chemistry. This work is carried out in close collaboration with the ULB's research group on Quantum Chemistry and Photophysics.

Within ULiege (UR GEOLOGY), the StG ERC **ELiTE** (PI is E. Javaux) focus on the study of *Early Life Traces and Evolution, and Implications for Astrobiology*. Astrobiology studies the origin, evolution and distribution of life in the Universe, starting with life on Earth, the only biological planet known so far. The project ELiTE consists on identifying the early traces of life and their preservation conditions, characterizing their biological affinities, determining the timing, pattern and causes (biological, environmental) of major steps in evolution, in particular the rise of biological complexity (the evolution of cyanobacteria and the domain Eucarya). Astrobiological implications include refining criteria for the detection of unambiguous extraterrestrial biosignatures. The project aims therefore to investigate the early traces and diversification of life and the changing habitability conditions of Earth that sustained life, from its earliest traces in the Archean through the Proterozoic. These studies are improving the characterization of (1) biosignatures and analytical protocols useful for paleobiology and exobiology missions (e.g. as co-PI of instrument CLUPI and collaborator for RLS on *ExoMars* 2020); and of (2) interactions between the biosphere, the geosphere, and the atmosphere through time. These last two points are also the focus of the *IAP PLANET TOPERS*[37] (*Planets: Tracing the Origin, Preservation, Evolution of their Reservoirs*, PI: V. Dehant at ROB; co-PI: E. Javaux at ULiege, V. Debaille at ULB, A.C. Vandaele at BIRA-IASB, P. Claeys at VUB, F. Vanhaecke at UGent, T. Spohn at DLR Germany).

[37] http://iuap-planet-topers.oma.be/

6. Cosmology

6.1 Cosmochemistry

Cosmochemistry uses the chemical composition (elemental and isotopic) of meteorites to date and investigate the condensation of the solar nebula, including the possible late injection of stellar material, the accretion of dust newly condensed with presolar grains, the formation and differentiation of asteroids, and planetary evolution. The *Laboratoire G-Time* at ULB (V. Debaille) and the AMGC at VUB (Analytical, Environmental and Geo- Chemistry, S. Goderis and P. Claeys) collaborate on this topic through several BELSPO projects and the *IAP PLANET TOPERS*. An ERC StG (**ISoSyC**) on the topic has also been granted to V. Debaille (2014-2019). To obtain meteorite and micrometeorites samples, several field campaigns have been organized in Antarctica, and more than 1000 meteorites are now present in the Belgian Antarctic collection at the Royal Belgian Institute for Natural Sciences. State-of-the-art analytical facilities, including several multi-collection-inductively coupled plasma-mass spectrometers, at ULB, VUB and UGent are used for performing high-precision isotope analyses.

6.2 Early Universe

Since 2011 the Institute for Theoretical Physics (ITF) at KULeuven has pursued an active research program in early universe cosmology. This includes the study of inflation in the early universe, its embedding in quantum gravity based models of the big bang and its possible observational signatures most notably in the form of (very long wavelength) gravitational waves. As such this program serves as a bridge between fundamental high-energy physics and gravitational wave observations. It is supported in part by an ERC CoG (**HoloQosmos**, PI T. Hertog).

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