Belgian Physical Society Magazine

1- 2018

2018 General Scientific Meeting of the BPS: April 11th in UAntwerpen.
Research Activitities in Physics in Belgium

BΦ - Belgian Physical Society Magazine

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Hawking besides Newton in Westminster Abbey

Professor Stephen Hawking died peacefully on 14 March, aged 76, at his home in Cambridge, precisely 139 years after the birthday of Einstein. He was a brilliant and extraordinary mind with courage, humour and an exemplary determination.

Professor Hawking arrived at the University of Cambridge in 1962 as a Ph.D. student. In 1974, he became one of the youngest fellows of Britain's most prestigious scientific body, the Royal Society, at the age of 32. Five years later, he was appointed Lucasian Professor of Mathematics at Cambridge University. Previous holders of this prestigious chair were the 17th-century British scientist Isaac Newton, and the 20th century prodigy Paul Dirac.

He was a scientist with a creative and nonconformist mind, who explained the Big Bang and black holes in his best-selling book "A Brief History Of Time". His most renowned discovery is that black holes, not gaining mass in another way, can evaporate to essentially nothing. This phenomenon better known as "Hawking radiation", turned him nearly instantly into one of the most famous physicists of our time.

Prof Hawking was diagnosed in 1964 with which was then identified as the fatal degenerative motor neurone disease ALS, short for "amyotrophic lateral sclerosis". He was then 22 and was given a few more years to live. Soon afterwards, rather than succumbing to depression, he began to set his sights on some of the most fundamental questions concerning the physical nature of the universe. In due course, he would achieve extraordinary successes despite his severe physical disability. Against traditional medical wisdom, he managed to live another 55 years. The image of Stephen Hawking in his motorised wheelchair, with head contorted slightly to one side and hands crossed over to manage the controls, caught the public imagination, as a true symbol of "the triumph of mind over matter", a very pointed citation by Roger Penrose, with whom he was jointly awarded the Eddington Medal of the Royal Astronomical Society in 1975.

He received numerous other prizes and awards, the last being the "Pride of Britain Award, for his contribution to science and British culture", in 2016. After receiving the award from Prime Minister Theresa May, Hawking humorously requested that she not seek his help with Brexit...

The funeral for Professor Hawking took place on the 31st March in the church of the University of Cambridge, Great St Mary's. His ashes will be placed, besides the other giants in science, Newton, Maxwell and Dirac, in Westminster Abbey, London.

With my best regards,

Jef Ongena, BPS President

BPS General Scientific Meeting 2018

It is our pleasure to announce the General Scientific Meeting 2018 of the Belgian Physical Society, which will take place on **Wednesday 11th April, 2018 at Antwerp University**. This annual one-day conference brings together physicists from Belgian universities, Belgian high schools and higher education schools, as well as from Belgian industries and companies. Its main aim is to establish links and stimulate collaborations between research groups working at different research institutions within Belgium, and to provide a platform for Belgian high school teachers to get updated on the current state of the art in physics.

Programme

- **8:00**: Registration and Welcome coffee with croissants
- **9:00**: Invited Plenary Lectures
  - **9:00-9:15** Welcome by Jef Ongena, BPS president
  - **9:15-10:00 Paulo Giubellino** (Facility for Antiproton and Ion Research in Europe & GSI) : *FAIR - The Universe in the Laboratory*
  - **10:00-10:45 Lieven Vandersypen** (QUTech & Kavli Inst. for Nanoscience, TUDelft): *A "Spins-inside" Quantum Processor*
- **10:45-11:15**: Coffee break
- **11:15-12:40**: Young Speakers Contest
  - **11:15-11:25**: Introduction & European Physical Journal (sponsor)
  - **11:25-11:50**: Boris Brun-Barrière (UCL) - *Wigner and Kondo physics in quantum point contacts revealed by scanning gate microscopy*
  - **11:50-12:15**: Jonas Bekaert (UAntwerpen) - *Monolayer materials as an ideal platform for enhanced superconductivity*
  - **12:15-12:40**: Gwenhaël de Wasseige (VUB) - *Solar Flare Neutrinos in the Multi Messenger Era*
- **12:40-14:00**: Buffet walking lunch & poster viewing
- **14:00-16:30**: Parallel sessions
  - Astrophysics, Geophysics, and Plasma Physics (Auditorium O.01)
  - Biophysics, statistical physics and medical physics (Auditorium O.02)
  - Condensed Matter and Nanophysics (Auditorium O.03)
  - Fundamental interactions, Particle and Nuclear physics (Auditorium O.04)

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  - Quantum physics, atoms and optics : (Building Q - Aula Fernand Nedee)
  - Physics and Education (Building Q - Promotiezaal)
- **16:30-17:15**: Poster session
- **17:15-17:30**: Closing session and prize ceremony
- **17:30-18:30**: Reception and sandwich dinner
- **18:30-20:00** Evening event: Movie "De Kwantumrevolutie" (Promotiezaal, building Q)

The conference will take place on the Campus Drie Eiken of Antwerpen University. The venue is "Aula Fernand Nedee", also known as building Q. There are many parkings scattered around the campus. More details on how to reach the conference site is here: https://www.uantwerpen.be/en/conferences/belgian-physical-society-2018/.

BPS Best Master Thesis Awards 2018

We are proud to announce the three laureates of the BPS 2018 Best Master Thesis Award (in alphabetical order):

- Paul Coppin (VUB) - *InIce Veto Studies for the Future IceCube-GEN2 Neutrino Observatory*
- Pablo Correa (VUB) - *Comparison of Statistical Methods to Evaluate the IceCube Discovery Potential for Steady Point Sources*
- Sacha Schiffmann (ULB) - *Relativistic semi-empirical-core-potential calculations in alkali-like systems using Lagrange meshes*

The winners will receive their prize during the closing session of the BPS General Scientific Meeting on April 11th in Antwerp.

Research Activities in Astronomy and Astrophysics in Belgium

Y. Fremat[a], S. Van Eck[b], C. Aerts[c], M. Baes[d], D. Berghmans[a], C. Bruyninx[a], S. Buitink[e], M. David[f], P. Defraigne[a], V. Dehant[a], J. De Keyser[g], S. De Rijke[d], A. Fuzfa[h], M. Groenewegen[a], T. Hertog[i], E. Javaux[j], A. Jorissen[b], R. Keppens[k], K. Kolenberg[f], K. Lefever[g]; A. Lemaitre[h], A. Lober[a], E. Neefs[g], D. Pourbaix[b], P. Quinet[l], G. Rauw[m], C. Ringeval[n], J. Surdej[o], M. Tytgat[p], R. Van der Linden[a], P. van Hoof[a], T. Van Hoolst[a].

[a]ROB: http://www.astro.oma.be/ [b]ULB: http://www.astro.ulb.ac.be
[c]KULeuven/IvS: http://fys.kuleuven.be/ster [d]UGent: http://www.astro.ugent.be/
[e]VUB: http://we.vub.ac.be/nl/astronomy-and-astrophysics
[f]UAntwerpen: http://astro.ua.ac.be/ [g]BIRA-IASB: http://www.aeronomie.be/
[h]UNamur: www.naxys.be [i]KULeuven/ITF: https://fys.kuleuven.be/gwc/
[j]ULiège (UR GEOLOGY): http://www.facsc.uliege.be/cms/c_3172635/en/ur-geology
[k]KULeuven/CmPA:http://wis.kuleuven.be/cpa/
[l]UMons: http://web.umons.ac.be/∼astro/indexgb.shtml [m]ULiège: http://star.ulg.ac.be
[n]UCL: https://uclouvain.be/en/research-institutes/irmp/cp3 [o]ULiège (AEOS): http://www.aeos.ulg.ac.be
[p]ULB: http://www.ulb.ac.be/sciences/physth/

[1][2]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[3]). Among these, ERC2 grants are the most prestigious research grants in Europe.

[1]The Belgian National Committee for Pure and Applied Physics (BNCPAP) is responsible for the content of the present review article. For any remark please contact the secretary of the BNCPAP (roger.weynants@skynet.be).

[2]This text is an update of the overviews of Belgian research in Astrophysics written by H. Oejonghe in 2005 (Physicalia Magazine, 27, 275-280 and by A. Jorissen in 2011 (Bo, Belgian Physical Society Magazine, 4, 33-42). Based in part on a recent status report requested by BELSPO, its length was substantially increased with respect to our regular entries and it exceptionally has a multi-authorship.

[3]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.

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**[4]) has been proposed by an international consortium initiated by astrophysicists from the *Institut d'Astrophysique et de Geophysique* (Liège University, ULiège), and comprising the following institutions: the Royal Observatory of Belgium (ROB), the Canadian Astronomical Institutes from Quebec (Laval University), Montreal (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 *Communaute 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 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[5], 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

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

[5] http://www.mercator.iac.es

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[6] (Mercator Advanced Imager for Asteroseismology), which is ideally suited to study the pulsational characteristics of faint sub dwarf 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 Liege) that operates the 1.2 m **TIGRE** (Telescopio Internacional de Guanajuato, Robotico-Espectroscopicot[7]) facility in La Luz (Mexico). This fully robotic telescope is equipped with the refurbished **HEROS** (Heidelberg Extended Range Optical Spectrograph) fiber-fed 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 (0, 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 em robotic TRAPPIST[8] (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[9] (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**[10] (European Southern Observatory) - La Silla Observatory[11] 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** (VL TI 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 VL TI 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

[6] https://fys.kuleuven.be/ster/instruments/the-maia-camera
[7] https://www.gaphe.ulg.ac.be/HRT/index_e.html
[8] http://trappist.ulg.ac.be
[9] http://www1.frs-fnrs.be
[10] http://www.eso.org
[11] http://www.eso.org/sci/facilities/lasilla

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 same group to compute astrometric orbits from interferometric data. The KULeuven/IvS team exploited VL TI 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[12], a famous star that was discovered in 1996. 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

[12] 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.

Survey) project[13], 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[14], 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**[15] (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[16] 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 Liege. 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 (narrow-band 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 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**[17] (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 estima-

[13] http://www.naic.edu/∼ages/
[14] http://www.astron.nl/halogas/
[15] http://www.evlbi.org
[16] For an instrument development: Phase A denotes the preliminary analysis; phase B, its definition; phase C, its design; and phase 0, its construction.
[17] http://brams.aeronomie.be/

tion of the projected rotational velocity for fast rotating objects). The observations started in May 2011 and in the first 4 years, about 200000 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 Liege* (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 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[18] 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

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

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 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[19] 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 Ul.iege 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.

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

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 Photo detector 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 $\sim$ 1.75′ x 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.

Belgian scientists playa 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**[20]/**EIT**[21], SOHO/**LASCO**[22], **STEREO**[23]/**SECCHI**[24]. Together with ULiège/CSL, ROB will playa 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 $\sim 10^5$ 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 SOIR (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.

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.

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

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, Ul.iege) 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 Ul.iege 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[25,26], including the equation of state of dense matter in 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[27] from pre-main sequence to neon combustion for a vast mass range, with new developments regarding the

[25] http://www.astro.ulb.ac.be/bruslib/
[26] http://www.astro.ulb.ac.be/Netgen/form.html
[27] http://www.astro.ulb.ac.be/-siess/Site/STAREVOL

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[28] ***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/CmP A coordinates several ongoing EC-FP7 and H2020 projects targeting space weather applications, namely ***Soteria***[29] (SOlar TERrestrial Investigations and Archives) and SWIFF[30](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[31]. The group does a lot of numerical work, targeted to high performance computing, since the prime work package of the new *Intel Exascience Lab*[32] 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.

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** (Database on Rare-Earths at Mons)[33] and **DESIRE** (DatabasE on Sixth Row Elements)[34]) 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

[28]http://www.cost.eu/COST_Actions/mpns/MP1304
[29]http://soteria-space.eu/
[30]http://www.swiff.eu
[31]http://www.iac.es/solaire
[32]http://www.exascience.com
[33]http://hosting.umons.ac.be/html/agif/databases/dream.html
[34]http://hosting.umons.ac.be/html/agif/databases/desire.html

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 KULeuvenIIvS team, thanks to the code GASTRoNOoM coupled to a dust radiative transfer code (MCMAX). This KULeuvenIIvS 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[35,36]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 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[37] 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

[35] http://brass.sdf.org
[36]

[37] Cosmic Microwave Background

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*[38] (**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 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 photo ionized 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 ULiège (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*[39] (*Planets: Tracing the Origin, Preservation, Evolution of their Reservoirs*, PI: V. Dehant at ROB; co-PI: E. Javaux at ULiège, V. Debaille at ULB, A.C. Vandaele at BIRA-IASB, P. Claeys at VUB, F. Vanhaecke at UGent, T. Spohn at DLR Germany).

Gravitational wave astrophysics is another branch of astrophysics in development in Belgium. The *gravitational waves centre*[40] (KULeuven, ULB, UCL and VUB) is a recent initiative focussed on the theoretical study of gravitational waves. KULeuven and

[38] http://epncb.oma.be/

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

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ULB are part of the **COST** (European Co-operation in Science & Technology) action CA16104 *Gravitational waves, black holes and fundamental physics* through T. Hertog and G. Compère. Gravitational wave source modelling is currently in development for extreme mass ratio inspiral and merger events, supported by the ERC StG **HoloBHC** (PI: G. Compère) and ERC CoG **HoloQosmos** (PI: T. Hertog). Fundamental physics signatures are also under development at KULeuven (B. Vercnocke).

6 Cosmology

6.1 Cosmochemistry

Cosmochemistry uses the chemical composrtion (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 the ERC CoG HoloQosmos.

The *Service de Physique Théorique* at ULB and the CP3 at UCL have a long-term activity on the physics at the interplay between particle physics and physics of the Early universe. This includes mechanisms of baryogenesis and leptogenesis to explain the emergence of the asymmetry between matter and antimatter of the universe, models of dark matter (WIMPs, axions, primordial black holes), phase transitions in the Early universe associated to the breaking of local and global symmetry, the role of neutrinos in cosmology and in astrophysics, mechanisms of inflation, including the generation of primordial inhomogeneities and their evolution, physics of the CMB and of the dark age, etc. The activities at ULB also include the field of cosmic rays (including neutrinos, positrons, antiprotons and gamma-rays) and ultra-high energy cosmic rays, in particular the study of anisotropies (member of the Telescope Array collaboration) and the modelling of the galactic and extragalactic magnetic fields.

Research Activities in Plasma Physics in Belgium

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[1]Plasma physics research in Belgium is traditionally organised along three main lines: astrophysical plasmas, hot or fusion plasmas and cold plasmas or gas discharge technology plasmas. This text gives a concise and therefore non-exhaustive review of the activities in these three areas at the Belgian universities and research institutions.
An important part of this work is taking place in the context of national or international cooperation, thus providing a lot of leverage to the relatively small groups that are involved. As such, the astrophysical effort draws strength from collaborations within Horizon 2020 projects [1] such as SOTERIA, SPACECAST, SOLSPANET, SWIFF and eHEROES, and the Virtual Space Weather Modelling Centre Consortium (VSWMC) [2] within the framework of the European Space Agency (ESA). Hot plasmas, on the other hand, are mostly studied in the context of thermonuclear fusion research by means of magnetic confinement. Since 2014 this Europe wide activity is no longer taking place in the framework of an Association with EURATOM but within the context of the Consortium for the Development of Fusion Energy EUROfusion [3].
Please note that in the area of plasma technology a lot of activities are multi-disciplinary and no attempt is therefore made to draw a border between physics, chemistry and technology of material development. An important sub-area here is plasma surface interaction for which an Interuniversity Attraction Pole (lAP) exists since 2007.
A last preliminary remark concerns the relative newcomer in this research field that is the dusty plasma. Dust grains can be immersed in ambient plasma, become electrically charged and can thereby give rise to new, sometimes intriguing phenomena. Dusty plasmas are intensively studied by space physicists in this country, but also by the gas discharge plasma community.

1 Astrophysics

Most of the Belgian plasma effort in astrophysics concentrates on the phenomena occurring in the Sun and on the interaction of the solar wind with the heliosphere and the earth magneto- and ionosphere and its role as driver of Space Weather. Of particular importance in recent years has been the collaboration within the context of the ESA or EU projects mentioned earlier, but also within the CHARM IAP P7/08 network on contemporary astrophysical and heliospheric modelling, involving the Centre for mathematical Plasma Astrophysics [4] at KU Leuven, the Astronomical Observatory [5] at UGent, the Fluid and Plasma Dynamics Research Unit [6] at ULB, the Solar Physics Research Department of the Royal Observatory of Belgium

[1]The Belgian National Committee for Pure and Applied Physics (BNCPAP) is responsible for the content of the present review article. For any remark please contact the secretary of the BNCPAP (roger.weynants@skynet.be).

[7] and the Solar Wind Research Unit of the Belgian Institute for Space Aeronomy [8], together with groups at Leiden (NL) and Durham (UK). The work packages included:

- the coupling of existing tools (software and numerical solvers) and models (PDE models/particle treatments/radiative effects) towards more realistic multi-physics descriptions,
- the confrontation of model predictions with the vastly increased armada of space instruments monitoring the Sun and the heliosphere,
- the role of turbulence in particle acceleration on astrophysical plasmas,
- the multi-scale description by correlating MHD and kinetic models,
- the role of radiation on the dynamics in gases and plasmas.

These efforts are further assisted and reinforced by specific research topics of the individual groups. As such, ***CmPA/KULeuven*** [4] concentrates its research on the dynamical interaction between plasmas and magnetic fields covering hereby a wide range of phenomena such as many aspects of our local space weather, where magnetic activity in the solar atmosphere controls the appearance of waves, instabilities, flows, shocks, heating, and the acceleration of the solar plasma into our heliosphere. Also covered are planetary and stellar magnetospheric physics, the turbulent motions in accretion disks or the relativistic jets emerging from entire galaxies. CmPA/KULeuven has also a significant effort on the numerical modelling of plasmas, from kinetic to fluid descriptions, going from non-relativistic to relativistic flow regimes. The latter are particularly important for the study of jetted outflows (Active Galactic Nuclei jets, Gamma Ray Bursts, ...). Effects of dust grains in rotating self-gravitating plasmas are also studied.

The research of the ***UGent-Astronomical Observatory*** [5] concentrates on understanding the structure, origin and evolution of galaxies, with a particular focus on dwarf galaxies, galaxy dynamics and interstellar dust (as a core team of the EU FP7-project DustPedia). The team uses both multi-wavelength observations and state-of-the-art numerical simulations, and is involved in the development of instrumentation for several new telescopes.

ULB-Fluid and Plasma Dynamics [6] studies the dynamics of conductive flows and specialises in the numerical simulation of hydrodynamic turbulence. Direct numerical simulations are complemented by large eddy simulations, based on the application of a spatial filter to the Navier-Stokes equation.

The ***SIDC at ROB*** [7] monitors solar activity in many wavelength bands, using advanced imaging techniques, and provides high-level space weather reports and solar activity predictions to industry and to the wider community.

IASB/BIRA [8] extensively studies the solar wind properties from satellite data (CLUSTER satellites) and models them by kinetic plasma descriptions. The Energetic Particle Telescope (EPT), designed by the laboratory in collaboration with the Centre for Space Radiations at UCLouvain [9] and placed on board the Belgian satellite PROBA- V, is providing important information on the generation and loss processes associated with the Van Allen radiation belts. An extensive database on the conditions prevailing on Comet 67P/G-G and obtained by the Rosetta spacecraft was also gathered.

2 Fusion Plasmas

The ***Laboratory for Plasma Physics of ERM/KMS*** (LPP-ERM/KMS) [10] is the implementing agent of EUROfusion in Belgium. Theoretical and experimental aspects of heating and confinement of fusion plasmas are the main focal points of its activities. The preferred heating method is that which seeks to make electromagnetic waves interact with the cyclotron motion of the plasma ions. To this end, refined modelling codes are developed permitting the optimised launching, propagation and absorption of the appropriate waves. A spin-off of these studies is the design of high-power wave launching and heating systems for fusion machines. As such, the design, construction and testing of a new "ITER-like antenna" on JET (the Joint European Torus) has led to proposal of a high power density launcher (∼10 MW/m2) which was adopted by and is now implemented for ITER (the International Tokamak

Experimental Reactor). The confinement of fusion plasmas relies heavily on the thermal insulation provided by the plasma edge properties. The effect of edge turbulence, possible tailored by the use of radial electric fields or of plasma seeding by edge radiating impurities on the thermal insulation is a further research topic of this group. Note that appropriate diagnostic means are developed where needed.

The ***Belgian Nuclear Research Centre SCK•CEN*** [11], provides the Belgian technology input to EUROfusion. Although not related directly to plasma physics, these studies form a crucial element in the justification of the energy orientation of fusion plasmas. Of particular importance is the testing of first wall and structural reactor materials under neutron bombardment. A multi annual irradiation campaign of innovative new tungsten alloys under High Temperature High Flux conditions in BR2 started in 2017. Radiation hardened microelectronics for diagnostics and remote handling units, under development with an industrial partner. and a novel plasma current sensor based on birefringence in optical fibre are other recent research projects. Recently sensors to measure the local magnetic field in ITER during operation were successfully tested for neutron exposure.

At the ***Department of Applied Physics*** of ***UGent***, the research unit Nuclear Fusion [12] develops novel techniques for the real-time analysis of fusion plasma signals and images, as well as data mining techniques for massive fusion databases (disruptions, scaling laws), using a probabilistic approach. The study of the physics, the technology and the processes accompanying the application of plasma heating using the ion cyclotron range of frequency method is another core research area, pursued in close collaboration with LPP-ERM/KMS and the MPI for Plasma Physics in Munchen (D). Ghent University is the coordinator of the Erasmus Mundus 'International Doctoral College in Fusion Science and Engineering' and of the Erasmus Mundus 'European Master in Nuclear Fusion Science and Engineering Physics'

At the ***KULeuven, Department of Mechanical Engineering*** [13], the neutral particle transport in the plasma edge is modelled with a Monte Carlo simulation of the kinetic equation, taking into account all microscopic processes. Optimisation of magnetic control for power exhaust in divertor Tokamak reactors is also studied.

Experimental work is performed at ***UCLouvain*** (***NAPS*** [14]) to provide absolute cross-sections for many elemental atomic or molecular reactions occurring in the edge of fusion plasmas, or to calibrate some of the particle beams that are used as diagnostic tools for many fusion plasma parameters.

The kinetic and the fluid description of fusion plasmas, including magnetohydrodynamic effects, heating and neoclassical transport theories is actively studied at ***ULB-Fluid and Plasma Dynamics*** [6].

At ***CPA/KULeuven*** [4], several software tools have been developed and applied to diagnose tokamak equilibria (for both static and stationary, rotating axisymmetric configurations), and accurately quantify all MHD wave modes, important for active and passive MHD spectroscopy and instabilities occurring in fusion plasmas.

3 Plasma technology

The last few decades have seen an exponential development in industrial applications of cold plasmas for such diverse purposes as material processing, etching and coating, plasma light sources and displays, decontamination and detoxification, environmental and medical applications, etc .. Several Belgian groups contribute to the plasma physical understanding of this area of plasma technology and to the initiation of yet further applications.

Several activities in plasma surface interaction are currently taking place in the context of **Interuniversity Attraction Pole** (lAP) *Project P7/34* on the Physical Chemistry of Plasma-Surface Interaction (PSI) [15]. The partners in this endeavour are ULB (4MAT [16], CHANI Plasma [17], UAntwerpen (PLASMANT [18]), UCLouvain (BSMA, Polymer coating group [19]), UMons (Chemistry Department [20]), as well as groups from Toulouse and Eindhoven. This project merges the expertise of the research units in plasma diagnostics (optical, electrical probe, laser induced fluorescence and mass spectrometry techniques), in the fundamental study of the ionized gas phase and its hydrodynamics, in bulk plasma and plasma-surface interaction modelling (molecular dynamics, Monte Carlo) and in (organic and inorganic) material synthesis, functiona1ization and characterization using state-of-the-too1s. The specific contributions of the participant groups are appearing below.

At ***ULB***, ***the 4 MAT group*** [16] performs experimental and modelling investigations of plasma-catalysis for CO_2 or CO_2/H_2O dissociation. A further activity deals with select different materials or coatings capable of meeting the stringent mechanical and economical requirements of Micro CHP Applications (ECOJET). ***The CHANI Plasma Team*** [17] tailors surfaces by atmospheric plasmas: deposition of organic, inorganic, metal and hybrid nano-layers. Important projects are: Transformation and valorization of CO_2; synthesis and grafting of nanoparticles to develop catalysts (including for fuel cells) and sensors; degradation of COV by atmospheric plasma process; synthesis of fluorinated membranes for fuel cell applications; study of water reactivity at a plasma/polymer interface.

The ***BSMA Polymer coating group of UCLouvain*** [18]), focuses on the understanding of the structure and the local chemistry of polymers synthesized or treated in (almost) atmospheric pressure plasmas.

The ***Chemistry of Plasma Surface Interactions Unit of UMons*** [19] studies the conversion of polluting gases, synthesizes nano-objects and deposits thin layers by means of Physical vapour deposition (PVD) and Plasma-enhanced chemical vapour deposition (PECVD).

At ***UAntwerpen***, the ***PLASMANT research group*** [20] covers a broad spectrum of plasma applications. It aims at plasma-based optimisation of CO_2 conversion into value-added chemicals and renewable fuels and of nitrogen fixation. In plasma medicine, the potentiality of the reactive species in plasma jets for bacterial killing and cancer treatment is strongly pursued. Recent focal points in the domain of microelectronics and nanotechnology are cryogenic plasma etching, modelling of the growth of carbon nanotubes and the design and development of nanocatalysts and nanoclusters. With an eye on analytic chemistry, inductively coupled plasma sources operating at atmospheric pressure or glow discharge sources at reduced pressure are extensively studied and modelled to extend their deployment. A number of simulation techniques are also developed in the realm of accelerated molecular dynamics (MD) and enhanced sampling, in particular force bias Monte Carlo (fbMC) simulations and collective variable-driven hyperdynamics (CVHD) simulations.

At the ***Department of Applied Physics of UGent***, the research unit ***Plasma Technology*** [21] uses non-thermal plasmas for the abatement of volatile organic compounds in waste gas streams and for biomaterial treatment, such as the treatment of porous scaffolds and biodegradable polymers and cleaning of metallic surfaces used for implants. A number of plasma sources at medium or atmospheric pressure are further used for the treatment of polymer films and textiles. The ***Plasma Physics and Engineering*** group [22] has three main lines of investigation (i) absolute density measurements of active species (OH, O, O3, Arm) in cold plasmas by means of laser spectroscopy, (ii) the development of novel atmospheric pressure plasma sources for applications in surface engineering, biomedical and environmental technology, (iii) plasma generation and dynamics in bubbles, plasma-liquid interactions and radical production in connection to material and waste treatment applications.

At ***UNamur***, ***the Laboratoire interdisciplinaire de spectroscopie électronique*** (LISE) [23] applies plasma treatment techniques (cleaning, coating, functionalization) to a variety of materials such as nanotubes, fullerene, graphene, ceramics, polymers and biomaterials and investigates their surface properties.

VITO, the ***Flemish institute for technological research*** [24], currently focuses on cold plasma technology at atmospheric pressure for a broad range of surface treatment applications. Applications include the control of adhesion or release properties, biofunctiona1, anti-bacterial and low friction coatings, etc. Moreover, plasma enhanced catalysis is studied to convert greenhouse gases into useful chemical precursors. VITO has developed several atmospheric plasma systems for specific surface functiona1ization: in 2017, the spin-off Apemco was founded, which builds and maintains plasma-machines based on VITO's know-how. More information can be found on www.apemco.eu.

At ***IMO***, the ***Institute for Materials Research, UHasselt*** [25], a number of plasma techniques are used for the deposition and synthesis of materials, such as UHV plasma etching, reactive ion etching and microwave plasma-enhanced CVD. With the latter, a wide variety of diamond layers can be grown on several substrates, possessing unique properties for advanced applications, such as dye sensitized solar cells or diamond UV -detectors.

Het ***Interuniversitair Micro-Elektronica Centrum (IMEC)*** [26] studies plasma etching by means of inductively-coupled plasma (ICP) or RF capacitively coupled sources (RFCCP) or by high-density plasma chemical vapour deposition (HDPCVD). Methods are developed on how to cope with the continuous downscaling of integrated circuit and the use of new materials. Recent lines of investigation are damage prevention, such as by the use of low energy and low fluence, or cryogenic precursor condensation while etching porous substrates.

A research group at the ***Von Karman Institute (VKI)*** [27] works on the synthesis of metallic and ceramic nanoparticles by means of radio frequency (RF) thermal plasma processes. The research activities are mainly focused on the development and validation of mathematical models of the plasma reactor and of nanoparticle formation (generation and growth). VKI also develops small scale plasma sources (Minitorch and MPT) based on RF and microwave to generate subsonic and supersonic plasma flow under situations representative of high speed atmospheric entry conditions, also studied on the PLASMATRON device, the world largest inductively coupled plasma torch.

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Research Activities in Computational Physics in Belgium

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[1]Computational physics (CP) is in first instance the study and implementation of numerical and symbolic models and algorithms for the simulation of physical systems, based on an existing quantitative theory. CP is maturing as the third leg of the scientific enterprise alongside with experiment and theory. Computer performance that evolves at an exponential rate allows new ways of apprehending and solving problems. We are now able to investigate computationally fundamental questions in physics with unprecedented fidelity and level of detail. And that trend will surely continue for many years.

However, CP implies more than using simulation to provide insight and interpretation. The IUAP commission on computational physics [1] has broadened the field to include the computational control and data processing of experiments, programming and computational environments, and the physical basis of computer machinery. Thus, CP also involves the acquisition and management of seas of experimental data (as in high-energy physics) and new techniques of data acquisition and handling.

As a result, computational physics covers a very wide range of problems from quantum mechanical calculations to highly complex data processing and it is not always easy to pinpoint specific research in the field. New developments appear mostly as by-products of other researches made in different fields by groups that rely on computers to perform their works. This inventory of the Belgian contributions in CP will thus collect works made by physicists that are heavily involved m developing and improving computer codes and architecture in order to perform their research.

For convenience, the following global structure for the present inventory[2] was chosen:

1. Numerical and symbolic models and algorithms for the simulation of physical systems.
2. Computational control and data processing of experiments
3. Programming and computational environments
4. The physical basis of computer machinery.

[1]The Belgian National Committee for Pure and Applied Physics (BNCPAP) is responsible for the content of the present review article. For any remark please contact the secretary of the BNCPAP (roger.weynants@skynet.be).

[2]An update of the 2010 version by Gonze and Weynants, and the 2005 version by HP Garnir

1 Numerical and symbolic models and algorithms for the simulation of physical systems

1.1 Atomic and molecular physics and astrophysics

The Institut de Physique Nucléaire, Atomique et de Spectroscopie at ULiège [2] has several research topics in Computational Physics. The cold atom physics group develops numerical simulations in the field of cavity quantum electrodynamics with cold atoms. The atom-field interaction is modeled in the particular case when the atomic motion must be described quantum mechanically and special algorithms are used and developed to solve the Schrödinger equation. Cold atoms are very often used in the current thematic of quantum computers. The group "Theoretical calculations in atomic physics" determines new atomic data related to the radiative and collisional properties of atoms and ions, based on sophisticated computer codes such as HFR, SST and MCDF.

In the field of atomic physics, and more particularly atomic spectroscopy, substantial progress has been achieved by the UMons Astrophysics group (PAAS) [3] by improving sophisticated computer codes that allow to model, in a more and more realistic way, the atomic structures characterized by very complex electronic configurations.

Along the same line, the ULB "Quantum Chemistry and Atomic Physics" unit of the service of "Chimie quantique et photophysique" [4] focuses on the calculation of the structure and dynamics of atomic and molecular species that are relevant in various fields such as spectroscopy, atmospheric chemistry, astrophysics and astrochemistry, cold molecules, nanoelectronics or quantum computing.

The Center for Molecular Modeling of UGent [5] develops and disseminates [6] several computational tools to facilitate and automate the analysis of molecules and their dynamics (MD-Tracks, MolMod), to construct molecular models (Zeobuilder) or to analyze the electronic structure of molecules (HiPart).

Some members of the Nanoscopic Physics (NAPS) pole of the Institute of Condensed Matter and Nanosciences (IMCN) of UCLouvain [7] develop algorithms for the numerical resolution of Schrodinger equation in time, to study the interaction processes of atoms and molecules with ultrashort electromagnetic pulses.

Molecular modeling is also done at Laboratory for Physics of Surfaces and Interfaces (LPSI) of UMons [8]. Using the complementary techniques of molecular dynamics (MD), Monte-Carlo simulations, and genetic algorithms, dedicated codes and software are developed providing access to all types of interaction potentials and very large systems of > 1.000.000 particles. Specific modules allow to study viscosity, surface tension, and static and dynamic contact angles.

1.2 Condensed Matter and Nanosystems

The ab-initio calculation of the entire structure of a molecule or of an aggregate of atoms (nanostructure) requires a huge amount of calculations. The ABINIT project [9] initiated in Belgium in 1997 and coordinated in Louvain-la-Neuve is aimed at the calculation of such structures and involves a lot a computer code development. On the technical side the huge code (800000+ lines), freely available, relies on modem techniques for its development, and the program itself is continuously improved by more than 50 developers all around the word and has more than 1900 registered users. At UCLouvain, the research mainly focuses inter alea on developments in Many-Body Perturbation Theory for electronic, transport and optical properties calculations, temperature-dependent and zero-point motion effects on electronic and optical properties, improved determination of relaxed atomic geometry and structural parameters, dielectric properties and magnetic responses, and improved functionals for vibrational properties. A new axis of research, high-throughput calculations, has opened recently. Simulations based on ab-initio calculations at UCLouvain, in the Nanoscopic Physics (NAPS) pole of the Institute of Condensed Matter and Nanosciences (IMCN) also rely on other software applications and cover optical functional materials, carbon-based nanostructures, materials for nanoelectronics [10].

At the Physics Department of ULiège, the groups of Theoretical Physics of Materials [11], Nanomaterials [12] and Physics of Solids, Interfaces and Nanostructures [13] are active in extending ab initio tools such as ABINIT, Quantum Expresso, Crystal, Octopus and BoltzTrap, in different domains : TDDFT, hybrid functionals, molecular dynamics, non-linear optical susceptibilities, Raman tensors and electro-optic coefficients, electrical resistivity, electron-phonon coupling, thermoelectric properties. Most of the main ab initio software packages are also used for the study of a wide diversity of systems: ferroelectric and multiferroic nanostructures, 2DEG at oxide interfaces, metals and intermetallics, phase-change materials, liquid semiconductors, nanodiamonds, semiconducting and metallic nanostructures, carbon nanotubes, ...

Another group at the ULiège, the group of Theoretical Physical Chemistry [14] is modeling the electronic, optical and transport properties of different kinds of nanostructures and molecular systems. These models are applied to molecular logic and could lead to the design of nanosensors. The group is also active in the field of attochemistry and ultrafast molecular dynamics. It develops time-dependent quantum methodologies to follow the dynamics of coherent electronic wave packets prepared by ultrashort attopulse in molecular systems, as well as their probing by photoionization.

The Condensed Matter Theory (CMT) group of the Department of Physics of the UAntwerpen [15] conducts theoretical research in the area of mesoscopic physics and nanophysics. Many computer programs have been developed over the years. Hands-on experience is available on calculations of the strain distribution in self-assembled dots, Hartree-Fock approaches, density functional theory, finite difference techniques e.g. to solve coupled nonlinear differential equations (e.g. the Ginzburg-Landau equations), Monte Carlo simulations, molecular dynamics simulations, variational quantum Monte Carlo simulations, stochastic variational techniques. For its calculations the group relies on its own clusters of workstations and on the UA cluster (see section 3).

Computational modeling of materials is also a primary research program of the EMAT group of UAntwerpen [16]. First-principles electronic structure calculations are carried within the Density Functional Theory formalism and beyond (GW, Bethe-Salpeter), to study the structural, electronic, optical and magnetic properties of functional materials. A large part of its work is devoted to the determination of electron energy core and low loss spectra for carbon based materials and metallic nanoparticles, whereas optical spectra have been calculated for TCOs and solar cell absorbers. A high-throughput methodology is used in combination with DFT calculations to screen large classes of potential candidate materials with specific properties and improved performance. Another important part of the work is devoted to the effect of impurities and native defects on the electronic and optical properties of these materials.

The Centre for Molecular Modelling of UGent [5] performs computational material research on the nanoscale. In its quest to design optimal catalysts, the group aims at predicting, from first principles, accurate rate constants for the chemical kinetics of catalytic reactions taking place in nanoporous materials. Under particular scrutiny are zeolite materials and Metal-Organic Frameworks (MOFs).

The Laboratory for Physics of Surfaces and Interfaces of UMons [8] studies the properties of material surfaces and their interactions with surrounding media. Computer modeling is a tool to enhance the performance of a material as regards coating, wetting, adsorption, friction and wear, optics, etc.

The Centre de recherches en Physique de la Matière et du Rayonnement (PMR) of UNamur [17] has a long experience in numerical modeling for solid state physics and nanomaterials. Some of their electronic and optical properties have been explained successfully by researchers of PMR, including e.g. structural coloration of insects. Currently, there is a strong focus on carbon nanostructures and two-dimensional materials. The group also has expertise in the modeling of nucleation and growth of thin films and of electron energy loss spectroscopy.

1.3 Particle Physics

To predict or analyze the events and experimental signals expected from high-energy accelerators, computational particle physics (CPP) has developed several important tools such as numerical computations on lattice field theory, the automatic calculation of particle interaction or decay, event generators and data reduction software. Several Belgian groups are active in this area. Variational lattice theory and non-perturbative quantum chromo dynamics are developed by the Mathematical and Theoretical Physics group of UGent [18]. The collider physics simulation tools, developed by the Cosmology, Particle Physics and Phenomenology group at UCLouvain [19] provide all aspects of an event chain and are widely used by the high-energy physics community at large. Optimization of the Cherenkov detectors of the IceCube Neutrino Observatory is performed by the Elementary Particle Physics group at UGent [20] by means of detailed Monte-Carlo simulations. At the Interuniversity Institute for High Energies IIHE (ULB- VUB) [21] similar techniques were developed to optimize Positron Emission Tomography detectors.

The already mentioned high-energy groups of UGent, UCLouvain, ULB and VUB, as well as the Particle Physics team at UAntwerpen [22] extensively apply the CPP tools in their elaborate participation to the data analysis of the Compact Muon Solenoid and NA62 at CERN and the IceCube polar detectors. In addition, they deploy together an important High-Energy Physics "Tier-2" computing center for the CMS experiment that is part of the Worldwide LHC Computing Grid (W-LGG) (see section 3). The resources deployed allow the treatment of data volumes of unprecedented size and complexity in the field of particle physics.

1.4 Physics of the Globe

The GeoHydrodynamics and Environment Research group at ULiège [23] uses 3D models of marine systems to predict circulation patterns, pollution dispersion, ecosystem evolution, thermohaline structures of the ocean and many other marine parameters. To do so, a set of coupled non-linear 3D partial differential equations is solved numerically using finite volume methods. To be able to handle the size of the problem (107 state variables advanced in time over 104 time steps), parallel computing based on domain decomposition is implemented.

The G. Lemaître Centre for Earth and Climate research of UCLouvain [24] studies the climate evolution and the interaction between human activities and the natural environment. They rely on very complex calculations that are performed by applying different models that are continuously improved. All these calculations involve huge computer power and the development of new algorithms.

1.5 Dynamic systems

Included here are

1. Continuous dynamical systems: Hamiltonian systems, Liouvilles's theorem, dissipative systems, local stability analysis, non-linear oscillators, bifurcation analysis in one and two dimensions.

2. Discrete dynamical systems: Iterated maps, logistic map, cycles and stability, period doubling, bifurcations, Lyapunov exponents.

3. Stochastic processes, Brownian motion, stochastic calculus.

A large, coordinated effort is devoted to Dynamical Systems, their Control and Optimization in the context of several Interuniversity Attraction Poles (lAP), which have been running since 1987 and have been extended till 2017 [25]. The work packages concern: (i) large scale data and systems, (ii) estimation and modeling and (iii) distributed systems, decision, control and communication. This effort is multidisciplinary and finds many applications not just in physics, but throughout the sciences. The Web pages of the partners are: INMA (UCL) [26]; OPTEC (KUL) [27]; NAXYS (UNamur) [28]; SYSTEMS (UGent) [29]; ELEC (VUB) [30]; Pôle BIOSYS (UMons) [31]; Systems and Modeling (ULiège) [32]. The Federal lAP program is however finished now, and a new structure for interregional research has been set up (the EOS funding).

The Department of Applied Mathematics and Computer Sciences at UGent [33] works on the development of numerical methods and software for problems that can be formulated in terms of differential equations, many of which are inspired by physical applications. Particular attention is paid to numerical methods and software for dynamical systems of ODEs allowing bifurcations and for the Sturm-Liouville and Schrödinger equations. Among the developed software MATCONT and MA TSLISE should be highlighted.

1.6 Astrophysics and Cosmology

In its development of the Energetic Particle Telescope (EPT), the Center for Space Radiation (CSR) [34] of UCLouvain, in collaboration with the Belgian Institute for Space Aeronomy [35] is simulating (by Monte-Carlo methods) the interactions of energetic particles present in space with matter or gas by using the CERN developed GEANT software toolkit [36].

The Centre for Mathematical Plasma - Astrophysics of KULeuven [37] studies space Weather (the popular name for energy-releasing phenomena in the magnetosphere) and coordinates the EU-FP7 Space Weather Integrated Forecasting Framework. It develops, on massively parallel computers (shared with the Von Karman Institute for fluid dynamics [38] specific computational models, based on the three-dimensional magneto hydrodynamics (MHD) equations as well as kinetic (Particle-in-Cell) simulations. It also creates the software needed to implement such computational models on modem supercomputers.

1.7 Physics of Deformable Solids and Fluids

Computational physics of deformable solids and fluids is a very important subject for engineering. Because of this reason, research groups will traditionally appear in polytechnic faculties or engineering schools. For sake of completeness, we nevertheless mention several groups working in this domain in Belgium.

At UCLouvain, the Institute of Mechanics, Materials and Civil Engineering [39] develops multi-scale modeling for such diverse applications as ocean modeling, crystal growth, the deformation and fracture of advanced metallic alloys, composites and bonded joints as well as for cardiovascular and respiratory applications.

The Service "Sciences des Polymères" at ULB [40] uses statistical mechanics and numerical simulation techniques in order to model at the microscopic level the structure as well as processes which take place inside complex states of matter (polymers but also soft matter). They design and develop simulation programs for molecular dynamics techniques, Monte Carlo or Brownian dynamics.

At the von Karman Institute for fluid dynamics [38], Computational Fluid Dynamics is used to do research on multiple fields, among them: Turbulence and aero-acoustic effects (Reynolds Averaged Navier-Stokes, Large Eddy Simulation and/or Direct Numerical Simulation); Multiphase flows (Large Eddy Simulation with Volume of Fluids); Prediction of hypersonic re-entry involving complex multi-physics (Direct Simulation Monte Carlo coupled with Finite Volume or Residual Distribution Schemes); Multidisciplinary Optimization & Design method with Artificial Intelligence and Neural Network.

The Computational Fluid Dynamics group of VUB [41] focuses on algorithmic developments for schemes and solvers as well as large eddy simulation and its application in different fields such as computational aero acoustics, combustion, biological flows, sedimentation problems, etc. Research on fluid dynamics is also performed in the Fluid mechanics group of UGent [42] and the group of thermal and fluid engineering at KULeuven [43].

2 Computational control and data processing of experiments

This topic is one of the concerns of the lAP VII-DYSCO collaboration mentioned under 1.5 [25].

The Laboratory of Biophysics and BioMedical Physics (BIMEF) of UAntwerpen [44] specializes in interdisciplinary physics research in the biological and medial field. The group has three main research directions: biomechanics and optical metrology, molecular biophysics and spectroscopy, vestibular research and medical statistics. Current research topics in computational control and data processing of experiments include the development of electro-optic metrology systems for shape, deformation and vibration measurements in biomedical applications and biomechanics. and finite element modeling in biomechanics, with special focus on human middle ear and cochlear mechanics, and functional biomechanics in animals.

At ULiège, the IPNAS laboratory [3] has constructed many new apparatus that use imbedded microprocessors and rely on the virtual instrumentation paradigm [45].

The Databases and Theoretical Computer Science group of UHasselt [46] new techniques to identify incompleteness, inconsistencies, inaccuracies and errors in databases.

3 Programming and computational environments

3.1 Belgian research computer infrastructure

The Belgian computer infrastructure has seen a profound restructuring over the last decade through the formation of consortia in the Flemish and the French communities.

The five Flemish University associations have created in 2007 a partnership called Vlaams Supercomputer Centum [47] aiming to align and integrate their existing supercomputer infrastructure, to make their expertise available to the public and private funded research and to construct of a competitive grid and HPC infrastructure available to all researchers in Flanders. The VSC is financed by the Flemish Government. The VSC-infrastructure consists of two layers. The central Tier-1 infrastructure is designed to run large parallel jobs. It also contains a small accelerator testbed to experiment with upcoming technologies. The Tier-2 layer runs the smaller jobs, is spread over a number of sites, is closer to users and more strongly embedded in the campus networks. The Tier-2 clusters are also interconnected and integrated with each other.

The Tier-1 supercomputer:
At the end of October 2016, VSC inaugurated its second Tier-1 supercomputer at the data center of KU Leuven, representing an investment of 5,5 million euros. The company NEC was selected to build the machine through a public tender procedure. This supercomputer, which consists of 580 computing nodes with two 14-core Intel Xeon processors, has a processing power of more than 600 TFlops, the equivalent of 2000 fast PCs. It has a capacity that is three times that of the first Tier-1 supercomputer at VSC. The new Tier-1 supercomputer is equipped with the latest Intel processors. Also the memory, the internal network and the storage capacity have been adapted, allowing the supercomputer to efficiently perform complex computations. At time of its installation, this new supercomputer was one of the 200 fastest computers in the world. [48]

The main local Tier-2 clusters:
The **Tier-2 of UA** comprises two clusters. The first one, Hopper, consists of 168 nodes (with two 10- core Intel E5-2680v2 Ivy Bridge) developing 75 TFlops. Storage capacity is 100 TB.
The second cluster, Leibniz, was installed in the spring of 20 17. It is a NEC system consisting of 152 nodes with two 14-core intel E5-2680v4 Broadwell generation CPUs connected through a EDR InfiniBand network. 144 of these nodes have 128 GB RAM, the other 8 have 256 GB RAM. The nodes do not have a sizable local disk. [49]
The **Tier-2 of VUB** (Hydra) consists of 3 clusters of successive generations of processors with a peak capacity of 75 TFlops (estimated). The total storage capacity is 446 TB. It has a relatively large memory per computing node and is therefore best fit for computing jobs that require a lot of memory per node or per core. This configuration is complemented by a High Throughput Computing (HTC) grid infrastructure. [50]
The **Tier-2 of Ghent University** (Stevin) represents a capacity of 226 TFlops (11.328 cores over 568 nodes) and a storage capacity of 1,430 TB. It is composed of several clusters, 1 of which is intended for single-node computing jobs and 4 for multi-node jobs. One cluster has been optimized for memory-intensive computing jobs and BigData problems. [51]
The **joint KU Leuven/UHasselt Tier-2** housed by KU Leuven focuses on small capability computing and tasks requiring a fairly high disk bandwidth. The infrastructure consists of a thin node cluster with 7.616 cores and a total capacity of 230 TFlops. A shared memory system with 14 TB of RAM and 640 cores yields an additional 12 TFlops. A total storage of 280 TB provides the necessary I/O capacity. Furthermore, there are a number of nodes with accelerators (including the GPU/Xeon Phi cluster purchased as an experimental tier-1 setup) and 2 visualization nodes. [52]

The VSC system is mostly used for space weather calculations, fluid and plasma dynamics, nanotechnology, modeling of materials, biophysics, bioinformatics and computational chemistry.

In 2010, the 5 universities of the French-speaking community of Belgium created the "Consortium des Équipements de Calcul Intensif" (CECI) [53], that is supported by the F.R.S.-FNRS. The main facilities of the consortium also comprise a Tier-1 and a Tier-2 infrastructure.

The Tier-1 supercomputer:
The Tier-1 supercomputer (zenobe) consists of two parts with nearly 14,000 computing cores resulting from an investment of nearly 5.5 million euros, achieved in three stages:

- a calculator acquired in 2011 constituting a base of approximately 3300 calculation cores,
- its extension financed by the grant PRACE Supercomputer Tier-1 of the Walloon Region, adding at the end of 20 13 about 8200 computing cores to this base, and
- the renewal, at the end of 2015, of the calculation nodes acquired 4 years earlier, providing 5760 computing cores of the latest architecture.

The Tier-1 configuration was put into operation in July 2014. It has a sustained computing capacity of more than 330 TFlops. Its best position in the world ranking of the 500 most powerful calculators was recorded in November 2014 in 300th place. [54]

The main local Tier-2 clusters:
The **Tier-2 of UMons** (dragon1) is a cluster of 26 computing nodes, each with two Intel Sandy Bridge 8-cores E5-2670 processors at 2.6 GHz, 128 GB of RAM and 1.1 TB of local scratch disk space. The compute nodes are interconnected with a Gigabit Ethernet network (10 Gigabit for the 36 TB NFS file server). Two additional nodes have two high-end NVIDIA Tesla 2175 GPUs (448 CUDA Cores/6GB GDDR5/515Gflops double precision). [55]
The **Tier-2 of UNamur** (hercules) consists of approximately 900 cores spread across 65 compute nodes. It mainly comprises 32 Intel Sandy Bridge nodes, each with two 8-core E5-2660 processors at 2.2 GHz and 64 or 128 GB of RAM (8 nodes), and 32 Intel Westmere compute nodes, each with two X5650 6-core processors at 2.66 GHz and 36 GB ,72 GB (5 nodes) or 24 GB (5 nodes) of RAM. All the nodes are interconnected by a Gigabit Ethernet network and have access to three NFS file systems for a total capacity of 98 TB. [56]
The **Tier-2 of ULB** (vega) features 44 fat compute nodes with 64 cores (four 16-cores AMD Bulldozer 6272 processors at 2.1 GHz) and 256 GB of RAM, interconnected with a QDR Infiniband network, and 70 TB of high performance GPFS storage. [57]
The **Tier-2 of ULiège** (nic4) consists of 128 compute nodes with two 8-cores Intel E5-2650 processors at 2.0 GHz and 64 GB of RAM (4 GB/core), interconnected with a QDR Infiniband network, and having exclusive access to a fast 144 TB FHGFS parallel filesystem. [58]
The **Tier-2 of UCLouvain** comprises two clusters. Lemaitre2 comprises 112 compute nodes with two 6-cores Intel E5649 processors at 2.53 GHz and 48 GB of RAM (4 GB/core). The cluster has exclusive access to a fast 120 TB Lustre parallel filesystem. All compute nodes and management (NFS, Lustre, Frontend, etc.) are interconnected with a fast QDR Infiniband network. This cluster will be replaced in 2018. [59]
Hmem mainly features 17 fatnodes with 48 cores (four 12-cores AMD Opteron 6174 processors at 2.2 GHz). 2 nodes have 512 GB of RAM, 7 nodes have 256 GB and 7 nodes have 128 GB. All the nodes are interconnected with a fast Infiniband QDR network and have a 1.7 TB fast RAID setup for scratch disk space. All the local disks are furthermore gathered in a global 31 TB Fraunhofer file system (FHGFS). [60]

The Belgian WLCG CMS "Tier-2" computing project for data analysis of the CMS experiment at the CERN laboratory, which was mentioned in section 1.3, consists of two physical clusters, one being located in Brussels [61] and one in Louvain-la-Neuve [62]. These two clusters also integrate computing resources for the IceCube and NA62 experiments as well as the high energy physics simulation project MadGraph. As of January 2018, the two centers offer 7000 cores of processing power and 5000 TB of disk storage.

Belgian scientists can also respond to calls for proposals from PRACE [63], the EU partnership for Advanced Computing in Europe, that manages the following Tier-0 resources:
- The 2 PFlops CURIE facility ofCEA, Bruyeres-Le-Chatel, France [64]

- The 5.9 PFlops WQUEEN facility at Forschungzentrum Juelich (FZJ), Julich, Germany [65]
- The 6.8 PFlops SuperMUC of the Leibniz Supercomputing Centre (LRZ) Garching, Germany [66]
- The 7.4 PFlops HAZEL ZEN facility at Hoechstleistungsrechenzentrum (HLRS) Stuttgart, Germany [67]
- The 11.1 PFlops MARENO STRUM facility at the Barcelona Supercomputing Center (BSC), Barcelona, Spain [68]
- the 13 PFlops MARCONI facility of CINECA, Bologna, Italy [69]
- the 19.6 PFlops PIZ DAINT facility of Swiss National Supercomputing Centre (CSC), Lugano, Swiss [70]

3.2 BELNET and BEgrid

In Belgium, the universities, colleges, schools, research centers and government departments are connected by a national research network that provides high-bandwidth Internet connection. This infrastructure, called BELNET [71], has been initiated in 1989 by the Belgian Science Policy Office's programming department, with the aim of enabling intensive transfer of data between scientists, and remote connections to powerful computers.
In 2003, BELNET started a new project called **BEgrid** [72], the computing/data grid infrastructure of the Belgium Grid for Research. The general principle of grid computing consists in the availability of a network that connects geographically spread computing and storage resources while giving many user groups access to the network. Grid computing means in fact globalization and virtualization of computer infrastructures. Current participants to BEgrid, and providers or resources are KULeuven, UAntwerpen, UGent, ULB, Vlaams Instituut voor de Zee (VLIZ), VUB, and CETIC.

4 The physical basis of computer machinery

The Interuniversity Microelectronics Centre (IMEC [73]), is heavily involved in the research aiming at the reduction of the size and power dissipation of computer chips. Its efforts encompass material and transistor architecture studies, tool and process step exploration, integration options and advanced characterization towards process technology platforms applicable in high-volume manufacturing of future logic and memory ICs. All research carried out is inextricably linked with quantitative material and device characterization and reliability analysis.

5 Conclusions

Even if this review is not exhaustive, it proves that computational physics activity in Belgium is important and that a lot of physics groups are active in the field. Computer programs are developed and improved in almost all universities often as byproducts of main researches.

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Research Activities in Hard Condensed Matter and Semiconductor Physics in Belgium

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[1] Condensed Matter and Semiconductor Physics is remarkable for the breadth and depth of its impact on physics as well as on other scientific disciplines. It is a very active field, with a stream of discoveries in areas ranging from superconductors and semiconductors to the optical, electronic, magnetic, and mechanical properties of materials and devices. It includes the study of well-characterized solid surfaces, interfaces and nanostructures.
The following briefly describe the main research activities at Physics Departments of Belgian Universities. The text is not an exhaustive review but mentions the topics studied in various laboratories. For more details we refer to the website addresses.

1 University of Leuven

1.1 The Laboratory of Solid-State Physics and Magnetism (VSM)

Website: http://fys.kuleuven.be/vsm/

The laboratory is a leading center for research into magnetic, semiconducting, dielectric and superconducting systems. Specifically, the overall goal is to understand the above physical properties in systems with reduced dimensionality and nanoscale confinement of charge, spin and photon. The systems studied range in size from three-dimensional thin film heterostructures to individual nanoscale clusters. The laboratory has outstanding thin film and atomic cluster preparation expertise, with a range of in-situ characterization and nano lithographic patterning techniques. Sample characterization and measurement is undertaken using state-of-the-art equipment including a range of advanced scanning-probe microscopes, low-temperature systems for transport and magnetization measurements, Raman and photoluminescence spectroscopes.

1.1.1 The Research Group ”Nanoscale Superconductivity & Magnetism”

Website: https://fys.kuleuven.be/vsm/nsm

The main objective is to investigate the effect of nanoscale confinement on the electrical, magnetic, and optical properties of materials. The group wants to reveal the fundamental relation between quantized confined states and physical properties of these materials: principle of "quantum design".

[1]The Belgian National Committee for Pure and Applied Physics (BNCPAP) is responsible for the content of the present review article. For any remark please contact the secretary of the BNCPAP (roger.weynants@skynet.be).

Scientifically, quantum design is a challenging objective in condensed matter physics, since it bridges the gap between physics of single atoms and bulk solids. A variety of state-of-the-art preparation and research equipment are used. The current research topics include superconducting nanostructures, vortices in superconductors, superconducting/ferromagnetic hybrids, and plasmonic nanoantennas.

1.1.2 The Research Group "Clusters and Laser Spectroscopy"

Website: https://fys.kuleuven.be/vsm/class

The group focuses on condensed matter down to the atomic scale where finite size effects, including in particular quantum confinement and electron correlations, become dominant. The challenge is to understand and develop the tunability of physical properties as matter is assembled from individual atoms towards bulk systems. The aim is to understand and tailor the unique properties of clusters of a few up to several 100 atoms and induce new properties in cluster-assembled and low-dimensional systems. Research ranges from studies of the physics and chemistry of small clusters in the gas phase using laser spectroscopy and mass spectrometry over investigations of individual clusters on surfaces with scanning probe techniques.

1.1.3 The Research Group "Scanning Probe Microscopy"

Website: https://fys.kuleuven.be/vsm/spm

The study of physical processes occurring at the nanometer scale has been substantially upgraded by the development of scanning probe microscopy (SPM). A whole family of scanning probe varieties has been and is being developed, providing unprecedented access with nanometer resolution to the structural properties as well as to the nanometer scale variations of various other physical properties, including the local electrical, magnetic and mechanical behaviour. The group has access to state-of-the-art SPM facilities and research topics include quantum confinement in metallic nanoparticles, finite-size effects in patterned ferromagnets, and properties of carbon nanotubes and biomolecules.

1.1.4 The Research Group "Functional Nanosystems"

Website: https://fys.kuleuven.be/vsm/fun/index

The group focuses its research on advanced nanomaterials and their assembly into functional devices and systems. Advanced nanomaterials include nanoparticles, 2D nanostructures, thin film heterostructures, and bio-hybrids. They explore their functional response, important for many applications in fields like electronics, materials science, catalysis, energy production and medicine. The approach covers experimental and theoretical efforts as well as nanoscale up to macroscale synthesis and characterization. Research topics include nanomaterials (carbon nanotubes and carpets, nanowires and nanoparticles), oxide-semiconductor interfaces, materials with metal-insulator transitions, and novel functional materials for rechargeable batteries.

1.2 The Institute for Nuclear and Radiation Physics (IKS)

Website: http://fys.kuleuven.be/iks/

1.2.1 The Research Group "Nuclear Solid State Physics"

Website: http://fys.kuleuven.be/iks/nvsf/home

The research is concentrated on four different domains: magnetic nanostructures, silicides and germanide thin films, doping of semiconductors, surfaces and nanoparticles. The group has access to a variety of experimental conventional and nuclear techniques. The current research topics include:

- *magnetic nanostructures* studied for their interesting fundamental properties and applications;
- *doping semiconductors* for applications in e.g. magnetic storage media;
- *silicide and germanide thin films* as essential parts of microelectronic devices; and
- *surfaces and nanoparticles* such the structure of (passivated) semiconductor surfaces (Si, Ge, GaAs, InGaAs, ...) and the growth of nanostructures on these surfaces as well as embedded nanoparticles created by ion implantation.

1.3 The Laboratory for Semiconductor Physics

Website: http://fys.kuleuven.be/hf/

The laboratory is experimentally oriented and principally addressing semiconductor/insulator heterostructures and amorphous materials of reduced dimensions. The main focus is on interfacial electrical and structural properties. The approach is a combination of interface-specific experimental methods sensitive to local atomic structure, and methods to probe both the extended and localized spectrum of electron states. The experimental techniques used are: Electron Paramagnetic Resonance (EPR) which is virtually the sole method of identification of point defects at the atomic scale; Internal Photoemission Spectroscopy (IPS) for the determination of band diagrams of semiconductor/insulator structures; and Inelastic Electron Tunnelling Spectroscopy (lETS) for interface characterization at a length scale below 2 nm.

1.4 The Institute for Theoretical Physics

Website: http://itf.fys.kuleuven.be/

1.4.1 The Research Group" Interfaces and Wetting"

Website: http://itf.fys.kuleuven.be/∼joi/

The main areas of research interest are wetting transitions, novel fractal structures, topological-dependent interactions and biased percolation on scale-free networks. The wetting phase transition is illustrated through its occurrence in a variety of condensed matter systems, ranging from classical fluids to superconductors and Bose-Einstein condensates. Currently special attention is devoted to i) the study of physical and interdisciplinary applications of novel fractal structures including hierarchical deposition! population models and bio film structures, and ii) topology-dependent interactions and percolation in scale-free networks including degree-dependent interactions.

2 University of Antwerp

2.1 The Research Group "Electron Microscopy for Materials Research "(EMAT)

Website: www.uantwerpen.be/en/rg/emat/

EMAT is one of the leading electron microscopy centers in the world and has expertise in both fundamental and applied electron microscopy. Its goal is the study of (inorganic) materials by different electron microscopy techniques. It has built up a wide range of activities concerned with fundamental solid state physics, materials science, solid state chemistry, and materials characterization. With decreasing dimensions down to the nanometer and sub-nanometer scale, electron microscopy is a unique technique, being able to relate structural properties to physical or chemical properties. Increased understanding of the basic phenomena involved in the interaction of electron beams with materials and improved computer power allow to better determine the local structure, the local composition and even the local electronic structure. This is applied to a wide field of materials such as semiconductors, superconductors, alloys, polymers catalysts and small particles, surface layers, multilayers and composite materials. Advanced electron microscopy not only involves resolution at the subnanometer level, it also includes advanced diffraction techniques for determining the local structure and analysis of the inelastic scattered electrons to obtain compositional and electronic information. EMAT has several state-of-the-art electron microscopes including two aberration corrected, high end FEI- Titan instruments, a dual beam FIB, and an environmental SEM. The following list gives the major current research themes investigated: shape memory alloys, multiferroic materials, ceramic thin films, nanostructured materials, carbon based materials, zeolites and mesoporous materials, soft matter and polymers.

2.2 The Research Group "Experimental Condensed Matter Physics" (ECM)

Website: https://www.uantwerpen.be/en/rg/ecml

The group investigates a range of topics such as high-spin molecular compounds, point defects in wide bandgap materials, electro-optical and nonlinear optical molecules, materials for organic electronics including photovoltaic's, carbon nanotubes and crystalline nanostructures. State-of-the art instrumentation is available for continuous wave and pulsed electron paramagnetic resonance (EPR) in X- and W-bands, high-sensitivity fluorescence, Raman scattering, and pulsed laser experiments for time-resolved optical spectroscopy and nonlinear optics. The main research themes are high-frequency EPR of high-spin transition metal compounds, point defects in wide band-gap materials, photographic materials, semiconductor nanostructures and devices, organic electro-optic materials, and organic nonlinear optics.

2.3 The Research Group "Condensed Matter Theory"(CMT)

Website: https://www.uantwerpen.be/en/rg/cmt/

The group concentrates on the theoretical study of materials (semiconductors and superconductors) of micrometer and nanometer size. Their electrical, magnetic and optical properties are studied using theoretical modeling and computer simulations. New hybrid systems consisting of combinations of semiconductors and ferromagnets or superconductors are investigated. The goal is the increase of the functionality of semiconductor structures. The main research subjects are: i) graphene which is a unique single layer material with extremely unusual properties; ii) superconductivity with focus on the properties of the vortex matter in various structures; iii) colloids by employing molecular dynamics to study properties of interacting particles; and *ab initio* calculations to gain insight into the new or even hypothetical materials.

2.4 The Research Group "Theory of Quantum Systems and Complex Systems" (TQC)

Website: https://www.uantwerpen.be/en/rg/theory-of-quantum-sy/

The group studies systems for which quantum mechanical behavior becomes macroscopic, e.g. superconductors, liquid helium, atomic superfluids, and polariton superfluids. Feynman's path integral theory is the tool of choice to study their behavior. They look for quantum behaviour in several specific areas:

- *in solids*: investigation of mechanisms for superconductivity and modeling how superconducting properties can be modified by nanopatterning. For example studies of collective excitations of electrons in plasmonics, interplay of light and metallic nanoparticles, and quantum dots.
- *in atomic gases*: superfluidity and Bose-Einstein condensation in ultracold atomic gases, both bosonic and fermionic. The adjustability of the interatomic interaction strength, the possibility to build artificial gauge fields into the effective Hamiltonians, and the versatility of the confinement geometry are used.
- *in condensed light*: Photons in a cavity can be hybridized with excitons, and form polaritons, resulting in a fluid of interacting photons with a small effective mass. In the appropriate regime of temperatures and density, this also becomes a superfluid.

3 University of Ghent

3.1 Department of Solid State Sciences

Website: https://www.ugent.be/we/solidstatesciences/en/

The department has activities in the broad field of Solid State Sciences related to deposition and (surface) analysis of thin films, to magnetron deposition, conformal coating of nanomaterials, detection and microscopic characterization of paramagnetic defects in solids by means of Electron Paramagnetic Resonance (EPR) and Electron Nuclear Double Resonance (ENDOR). It includes also the study of defects in semiconductors, i. e. physical properties, identification, quantification of analytical techniques and the growth & characterization of photo- and electroluminescence of sulfide phosphors. At present the department counts 6 research groups.

3.1.1 The Research Group "Conformal Coating of Nanomaterials" (CoCoon)

Website: http://www.cocoon.ugent.be/

The research of CoCoon is situated within the continuing trend towards miniaturization in microelectronics. The group focuses on all levels of thin film devices, from deposition to their different applications after extensive characterization. The research activities are concentrated on deposition of thin films (atomic layer deposition of conformal nanocoatings and combinatorial deposition of thin film materials libraries), characterization of thin films (*in situ* during deposition - *ex situ* at synchrotrons), and applications of thin films (nanoelectronics, solar cells, non-volatile memories, and Li-ion batteries).

3.1.2 The Research Group "Defects in Semiconductors (DISC)

Website: https://www.ugent.be/we/solidstatesciences/en/research/groups/disc

The research of DISC focuses on the study of defects in semiconductor materials in order to explain their effects on electrical and optical properties of semiconductor devices. The semiconductors studied are Si, Ge, diamond, III - V, II -VI and Cu(ln!Ga)Se2, with applications in microelectronics, optoelectronics and photovoltaics. Defects are investigated trough their electronic, vibrational, and electron magnetic resonance spectra. The aim is to obtain information on the physical properties, structural identification, and quantification of defects via various electrical characterization and (quasi) spectroscopic techniques.

3.1.3 The Research Group "Dedicated Research on Advanced Films and Targets" (DRAFT)

Website: http://www.draft.ugent.be/

The research group DRAFT studies magnetron sputter deposition in general. Beside the research of industrial interesting materials such as superconductors or (photo)catalytic systems, the focus is on fundamental aspects of reactive sputter deposition. The long tradition in magnetron sputtering resulted in an international status on reactive sputtering.

3.1.4 The Research Group "Dynamics of Functional Nano Materials (DyNaMat)

Website: https://www.ugent.be/we/solidstatesciences/dynamat

DyNaMat's research activities cover various subjects in the domain of magnetism:

- *Skyrmions and chiral systems*: ferromagnet films can be chiral due to the Dzyaloshinskii-Moriya nteraction (DMI) induced by symmetry breaking at interfaces. This chiral interaction is studied in spin structures such as spin spirals, spin cycloids, and skyrmions.
- *Exchange bias*: wheen cooling a ferromagnetic/antiferromagnetic bilayer in a magnetic field below the Neel temperature, an unidirectional shift of the hysteresis loop is observed. This shift is accompanied by an enhanced coercivity. The influence of this interface interaction on FMI AFM bilayers is studied.
- *Artificial spin ice*: in some magnetic systems interactions result in the inability to minimize all its competing interactions, called frustration. An example of a frustrated system is water ice. The ordering of the magnetic moments in a square lattice of magnetic islands is studied.
- *Domain wall motion*. When the magnetization at two ends of a nano strip are aligned anti parallel, there will be a small region in between where the magnetization turns 180 degrees. These regions are called domain walls. The group studies the mobility of a domain wall under the influence of disorder, thermal fluctuations, and driving forces like magnetic fields and spin polarized currents.

3.1.5 The Research Group "Electron Magnetic Resonance" (EMR)

Website: https://www.ugent.be/we/solidstatesciences/en/research/groups/EMR

The EMR group studies the microscopic structure of paramagnetic point defects in solids by means of Electron Magnetic Resonance (EMR) Spectroscopy. They are known for detailed characterization of paramagnetic centers, but also for the use of high sensitive and non-destructive techniques. The research is focused on irradiation damage of organic crystals, transition-metal or lanthanide activated optical materials and semiconductors. The group uses ESR (Electron Spin Resonance) also known as EPR (Electron paramagnetic resonance), ENDOR (Electron Nuclear Double Resonance), and EI-EPR (ENDOR-induced EPR).

3.1.6 The Research Group" Luminescent Materials" (LumiLab)

Website: http://www.lumilab.ugent.be/

The LumiLab group brings together various domains of light research:

- LED phosphors, mainly binary and ternary sulfides for wavelength conversion in white LEDs;
- persistent luminescence, glow-in-the-dark materials and their perceived brightness;
- non-aqueous sol-gel synthesis and protection of particles by coating, solvothermal synthesis;
- X-ray absorption spectroscopy as a tool to investigate rare earth ions in host crystals; and
- photocatalysis for fast removal of volatile organic molecules and air purification.

Various facilities are available such as fluorescence spectrophotometry, absorption spectroscopy, decay measurements, ellipsometry, X-ray diffraction, and scanning electron microscopy.

3.2 The Research Division "Nuclear Materials Physics "(NUMAT)

Website: http://www.numat.ugent.be/

The division is dedicated to the study of fundamental and technological properties of materials by means of experimental methods, which use nuclear radiations or the interactions of the nuclei with electromagnetic fields. They concentrate on Mossbauer spectroscopy and positron annihilation spectroscopy. Mossbauer spectroscopy can be performed only on a limited number of isotopes of which the most important is ^{57}Fe. Therefore the research is mainly on iron-containing materials such as magnetic oxides, nanomaterials, thin films, iron-nickel meteorites, minerals, clays, high pressure synthesized minerals, Fe-bearing precursors for carbon nanotubes. In the field of positron annihilation the interest is mainly in defects in metals and alloys, and the many aspects of the behavior of positronium in insulating materials.

4 University of Hasselt: The Institute for Material Research (IMO)

Website: https://www.uhasselt.beIUH/IMO/About-IMO-IMOMEC

The Institute is a research centre with a vast knowledge in the field of materials science. It has an intensive collaboration with IMOMEC, the department of IMEC at the university campus. While most of the more fundamental research is carried out at IMO, the largest part of applied research and projects in collaboration with industry are concentrated within IMOMEC. Within IMO, Physics Materials Research is conducted in a number of subgroups. Website: https://www.uhasselt.beIUH/IMO/Visit-the-groups/

4.1 The Research Group "Energy Materials and Interfaces" (EMINT)

This group aims to gain mechanistic insight into reactions of materials and interfaces. Research focuses on electrochemical interfaces, in particular related to positive electrodes of Li-Ion Batteries, but also on electrodeposition and corrosion. Chemical and electrochemical reactions take place on the molecular or atomic scale requiring high-resolution techniques to gain deeper understanding. Next to common laboratory-based techniques and other more advanced structural methods such as Atom Probe Tomography, the group further employs in-situ X-ray diffraction using synchrotron light.

4.2 The Research Group "Engineering Materials & Applications" (EMAP)

The group is active in electronics and electromechanics. The applied research is situated within three domains. In the domain of "Biomedical Device Engineering" the research focuses on the development of dedicated measuring platforms that can process the signals of sensors and thermal or optical based biosensors into a fully functional point-of-care system. In the domain of "Energy Systems Engineering" the research is concentrated on materials for photovoltaics and batteries. The primary interest lies in the reliability of the components. In the domain of "Functional Materials Manufacturing" different printing and coating processes are used such as inkjet printing, screen printing or spray coating onto different substrates.

4.3 The Research Group "Photonics and Quantum Lab" (PQL)

This group addresses cross disciplinary scientific topics of photonics, optical device physics and biology. It uses nanofabrication tools to fabricate semiconducting and quantum physics based devices, which are used to probe and image semiconducting and biological systems at the nanoscale.

4.4 The Research Group "Functional Materials Engineering" (FME)

The FME group investigates printing and coating techniques of functional materials on different substrates. The focus is threefold: i) Investigation towards the printability of functional materials, organic materials, and scratch and wear resistant materials. ii) Deposition of these materials on different substrates (glass, foil, paper, textiles) using printing and coating techniques. The properties are determined using characterization techniques for opto-electronic, thermal and mechanical investigations. iii) Application of the functional materials and upscaling towards use in organic electronics (solar cells, light emitting devices ...).

4.5 The Research Group "Nanostructure Physics" (NSP)

The NSP group focuses its research on fundamental topics in nanometer-scale science and technology with emphasis on new materials (mainly metal particles and organic/inorganic hybrid structures). The main goal is the understanding of physical and chemical properties related to the reduced dimensions of nanostructured materials; including electronic & atomic (molecular) structure, charge transport, optical, magnetic, and thermodynamic properties, and chemical reactivity.

4.6 The Research Group "Design and Synthesis of Organic Semiconductors" (DSOS)

Research is focused on the design, synthesis and characterization of small organic molecules, oligomers and polymers for application in plastic and advanced healthcare. Besides the study of novel synthetic methods, modifications of existing polymerization pathways are developed. Attention is paid to the development of new materials, fundamentals and concepts in organic semiconductor technology. A broad pallet of advanced electronic materials is available for further studies in devices, e.g. light-emitting diodes (OLEDs), organic field-effect transistors (OFETs), organic photovoltaic devices (OPVs), organic photodetectors (OPDs) and chemo- or biosensors.

4.7 The Research Group "Wide Bandgap Materials" (WBGM)

The group is active in the field of wide bandgap materials with emphasis on the deposition and characterization of CVD diamond films. The properties of novel materials like hexagonal boron nitride (h-BN) nanowalls and thin piezoelectric aluminium nitride (AIN) layers are also investigated. Recently, the emphasis is on the use and functionalization of nanodiamond particles and film surfaces with small molecules. Besides fundamental research, like the nucleation and doping of diamond, the materials are used in structures like "solar-blind" UV detectors, or acoustic wave sensors based on heterostructures of nano- and microcrystalline diamond with piezoelectric materials like AIN.

4.8 The Research Group "Organic Opto-Electronics" (OOE)

The OOE group aims to understand fundamental opto-electronic processes in organic and molecular semiconductors and exploit them for organic electronic applications, with a main focus on photovoltaics. Charge carrier generation and recombination in these materials are dictated by the properties of excited electronic states at organic donor-acceptor interfaces, such as excitons and charge transfer states. They search for structure-property relations, guiding the synthesis of new materials with improved performance in devices such as solar cells, photo-detectors and light emitting diodes.

4.9 The Research Group "Electrical and Physical Characterization (ELPHYC)

The group is active in the characterization of materials systems and microelectronic components using high resolution in-situ measurement techniques. Activities involve analytical & electrical characterization of materials systems and/or experimental sensor devices. The focus is on the development of electronic interfaces for biosensors and the development of reliability equipment for solar cells and modules. The group also acts as a major service center towards industry with services from laser optics to biomedical devices and from raw materials to solar panels or high speed processors.

5 University of Brussels (VUB): The Research Group "Applied Physics"(APHY)

Website: http://we.vub.ac.be/aphy/

The Applied Physics group is a multidisciplinary group of researchers from the Departments of Physics and of Applied Physics & Photonics. They use experimental and theoretical methods to address fundamental challenges in biological physics, condensed matter physics, electromagnetism, laser physics and photonics. The main research themes are the study of metamaterials and nanophotonics, bio-inspired approaches to machine learning, the dynamics of semiconductor lasers, non-equilibrium pattern formation, and solitons dynamics. The following research lines can be distinguished.

- *Dynamics of semiconductor lasers*. Nonlinear dynamics, bifurcation theory and stochastic processes are used in lasers, in particular semiconductor lasers. This theoretical study allows investigating the dynamic behavior of semiconductor lasers. These theoretical predictions are tested experimentally.

- *Coherent properties of lasers*. Research of methods to modify and control the spatial coherence in order to generate spatially incoherent emission of a laser source. The objective is to understand, model, optimize and apply this unique emission regime in innovative applications.

- *Metamaterials*. Study of complex structures that are composed of small, resonant electric circuits. These building blocks are smaller than the wavelength of light. The problems studied range from the simulation of elementary metamaterial building blocks, over photonic devices, to the development of meta material-based systems.

- *Dissipative solitons*. Study of structures that arise in extended spatial systems in nature, both patterns as well as localized structures. Investigation of the dynamic behavior of solitons, study of the fundamental principles, and unraveling the underlying bifurcation structure.

- *Coupled networks with delay*. With such systems, synchronization may occur in which the oscillators vibrate with the same frequency and/or phase. The systems have universal data processing properties (reservoir computing or liquid state machines) that are investigated.

- *Nonlinear oscillators with delay*. Those delay systems have universal information processing properties. With a single non-linear node one can achieve the same computational performance as with a neural network. The investigations are related to the information processing capacity and the computational properties.

6 Université Catholique de Louvain: The "Institute of Condensed Matter and Nanoscience" (IMCN)

Website: https://uclouvain.be/en/research-institutes/imcn/research-divisions.html

Research is focused on condensed matter and nanoscience from the atomic and molecular levels to real materials. The research concerns the synthesis, design, manipulation, implementation and modeling of (bio-) molecules, (bio-) surfaces and solid materials. The compounds, materials or devices are investigated for their functions, properties or reactivity, leading up to applications. The institute consists of three research divisions (BSMA, MOST, NAPS). The divisions and research groups related to condensed matter physics and semiconductors are briefly described hereunder.

6.1 Research Division "Bio-and Soft Matter" (BSMA)

Website: https://uclouvain.be/en/research-institutes/imcn/bsma

6.1.1 Functional Nanomaterials and Nanodevices

Website: https://uclouvain.be/en/research-institutes/imcn/bsma/functional-nanomaterials-andnanodevices. html

The ability to selectively arrange nanosized domains of inorganic and/or organic materials into hybrid nanomaterials offers an attractive route to engineer new nanostructured materials that can be used in (spin) electronics, energy, memory and microwave devices, catalysis, sensor and bio-medical. The BSMA division has expertise in the development of synthesis methods (nano imprinting, electro deposition in nano porous templates, thin-film deposition, nano assembly) to control the composition and shape of such hybrid nanostructures.

6.1.2 Functional Hybrid Multi Segmented Nanotubes and Nanowires

The membrane-template method is combined with layer-by-layer (LbL) assembly and/or electrodeposition to sequentially synthesize multi segmented nanostructures composed of metals, polymers, synthetic and biological poly electrolytes, and colloids. The electrochemical approach controls the architectural parameters of the resulting structures, whereas the LbL adsorption technique permits to integrate non conducting materials.

6.1.3 Hybrid materials for Potential Thermoelectric Applications

Thermoelectric materials are interesting due to their ability to convert energy for cooling (Peltier effect) and electric power generation (Seebeck effect). The performance of thermoelectric materials depends on the dimensionless figure of merit including the temperature, athe Seebeck coefficient, the electrical resistivity and the thermal conductivity.

6.1.4 Hybrid Systems for EM Absorption and Metamaterial Properties

Wireless communication via electromagnetic transmission in the microwave range has become ubiquitous. In parallel, electronic devices are becoming more compact. These trends generate a growing issue with electromagnetic interference with consequences ranging from annoying to dangerous. Classical EM radiation is shielded by Faraday cages which reflect the signal. By contrast, EM absorbers are more attractive because they truly eliminate the bothersome EM wav

6.1.5 Ferromagnetic Nanowire Substrates for RF Electronics

Ferromagnetic nanowires embedded into porous templates are an interesting alternative route to ferrite-based materials. Over the last decade, the groups at UCL have successfully prepared a variety of ferromagnetic nanowire substrates to design various prototypes of microwave devices, such as or circulators, isolators and phase shifters useful for wireless communication and automotive systems.

6.1.6 Nanomagnetism in Nanoparticle Arrays

Arrays of magnetic nanowires and nanotubes embedded in non-magnetic dielectric templates are of considerable interest for fundamental studies and for their exploitations in applications such as patterned media for magnetic storage, microwave and spintronics devices. Control and tuning of their magnetic properties requires further understanding of the interplay between intrinsic and shape effects as well as interaction among individual nanostructures. Magneto elastic effects provide an additional parameter to control the magnetic properties because of the large surface area between nanowires and host matrix.

6.1.7 Spintronics in Magnetic Nanowires

The template-based strategy has been successfully developed to fabricate arrays of magnetic multilayered nanowires. The nanowires system has provided an important opportunity in exploring giant magnetoresistance effects in the current perpendicular to the planes geometry and in testing theoretical models in various limits. Extensive giant magnetoresistance measurements were performed on various nanometer-scale multilayer structures, such as ColCu and NiFe/Cu nanowires.

6.1.8 Template Free Electro Deposition of Nano Rod Arrays and Devices

The fabrication and characterization of ZnO nanowires is the subject of intensive research in, due to their potential applications in highly integrated nanoscale electronic and optoelectronic circuits with improved performance for solid-state display devices, sensors, solar cells, energy harvesting devices, switchable hydrophobic surfaces, ...

6.2 Research Division ”Nanoscopic Physics” (NAPS)

Website: https://uclouvain.be/en/research-institutes/imcn/naps

At the nanoscale quantum mechanics plays a prominent role, both for experimental investigations and theoretical simulations. The researchers in NAPS explore various aspects of this world, from atoms, photons and ions to nanoscale devices, through the crystalline state and molecules. The following topics are studied.

6.2.1 Spectroscopy and Optics

The expertise in applied optics comes from the development of laser techniques for fundamental research in atomic physics. Progressively, this activity has focused on questions driven by industrial applications. Today the activities are grouped in four research topics.

- Optical properties of bio-inspired nanostructures
- Optical characterization: coherence tomography, electro-optic sampling, deflectometry
- Laser generation of fast ions
- First-principles study of optical functional materials

6.2.2 Light-matter Interaction

The following activities are related to condensed matter physics and magnetism.

- Development of algorithms for numerical resolution of Schrödinger equation
- Attosecond control of magnetism with an ultra short electromagnetic pulse at the atomic scale
- Study of interaction of atoms with super intense field of low frequency
- First-principles study of optical functional materials

6.2.3 Numerical simulation at the nanoscale

The following activities are related to condensed matter physics and magnetism.

- First-principles study of optical functional materials; materials for nanoelectronics; carbon-based nanostructures
- Ab initio quantum transport in nanostructures
- STM imaging: experiments and ab initio modeling

6.2.4 Electronic transport at the nanoscale

The research activities are focused on transport properties imaging.

- Ab initio quantum transport in nanostructures
- STM imaging: experiments and ab initio modeling
- Imaging electronic transport at the nanoscale
- Quantum transport in low-dimensional systems

7 University of Liège

7.1 The Pole "Soft Matter and Complex Systems"

Website: http://www.facsc.ulg.ac.be/cms/c_950347/pole-de-recherches-matiere-molle

The pole deals with the interactions between large numbers of microscopic entities, which give rise to collective macroscopic phenomena. Experimental and numerical studies cover complex fluids, nonlinear systems, biophysics and statistical physics. Statistical physics creates a link between those microscopic features and the non-trivial macroscopic behaviors. Soft matter refers to structured liquids, colloids, biological membranes, polymers, gels, foams, grains, and active materials. The group is equipped with instruments for microfluidics, rheology, imaging, laser spectroscopy.

7.1.1 The Research Group for "Research and Applications in Statistical Physics" (GRASP)

Website: http://grasp-lab.org/

The research projects are dedicated to the study of nanoparticles, suspensions, monolayers, biosensors, self-assembling systems, powders, colloids, granular systems, droplets, antibubbles, microfluidics, soap films, emulsions, foams, complex fluids, active matter, rheology, chaos and non-linear phenomena.

7.2 The laboratory "Physics of Functional Materials, Nanostructures and Biological Systems" (FunMat)

Website: http://www.facsc.ulg.ac.be/cms/c_950345/pole-de-recherches-materiaux

The FunMat laboratory performs research in the field of functional materials, in particular semiconductors, thermoelectrics, ferroelectrics, piezoelectrics, multiferroics, superconductors, and biological systems. The objective is to understand the behavior of matter at the atomic, molecular, and mesoscopic length scales. The unit is structured in five complementary subgroups with theoretical and experimental competencies: i) physics of materials and nanostructures, ii) theoretical materials physics, iii) biomedical spectroscopy, iv) physics of solids, interfaces, and nanostructures, and v) experimental physics ofnanostructured materials.

7.2.1 The Research Group "Physics of Materials and Nanostructures (Nanomat)

Website: http://www.nanomat.ulg.ac.be/

The Nanomat group investigates the electronic and vibration properties of materials for energy applications and novel generation electronics. The research activities are concentrated on: - Thermoelectrics: materials, which couple differences in temperature and electrical voltage. Applying a heat source to one side of a sample will induce a voltage across it, or conversely by applying a voltage the sample can be used to cool one side or heat the other (solid state refrigerators/heaters with no compressors or moving parts). The challenge is to understand the processes, and to find materials which will allow these principles to be scaled up to industrially useful devices. - Phonons and electron-phonon coupling: by inducing a deformation of the atomic structure, the coupling between electrons and phonons gives rise to interesting phenomena such as superconductivity, normal resistivity, thermal resistance, or the Seebeck effect. Using ab initio tools one can calculate phonons and electron-phonon coupling to good precision. - Attosecond dynamics: of electrons and molecules poses serious challenges to both experiment and theory. The challenge is to come up with a unifying picture to understand the multiple configurations and trajectories of the density of electrons, and especially to predict trajectories.

7.2.2 The Research Group "Theoretical Material Physics" (TheMa)

Website: http://www.phythema.ulg.ac.be/

The group is specialized in the first-principles modeling of multifunctional materials. This includes regular dielectrics, ferroelectrics, piezoelectrics, magneto-electric multiferroics, thermoelectrics as well as materials for non-linear optical applications. Recent works concerned the understanding of the evolution of the properties in various types of nanostructures (ultra-thin films, superlattices, nanowires or nanoparticles) and the design of artificial nanostructures with new and optimized properties.

7.2.3 The Research Group "Solid State Physics: Interfaces and Nanostructures" (SPIN)

Website: http://www.spin.ulg.ac.be/

The research activities of SPIN are dedicated to the study of the electrical and optical properties of semiconducting materials and systems, with a particular interest in crystalline ultra-thin films and engineered nanostructures. The objective is focused on the consequences related to intentional or non-intentional atomic-scale variations of structure composition, in terms of the impact on the electrical activity, the crystalline quality of the deposited nanostructures and of their interfaces. Experimental techniques used are admittance spectroscopy, transient photoconductivity, absorption and photoluminescence.

7.2.4 The Research Group "Experimental Physics of Nanostructured Materials" (EPNM)

Website: http://www.mate.ulg.ac.be/

The research of EPNM is devoted to the investigation of confinement effects in mesoscopic systems including nanomagnets, structured superconductors, plasmonics, and hybrid heterostructures, with the aim of unveiling new phenomena that are not present in large size systems. The main idea behind structuring materials down to dimensions matching the characteristic sizes determining the physics of the elementary blocks (i.e. electrons in metals, photons in dielectric media, plasmons at metallic interfaces, or fluxons in superconductors) is that boundary conditions, surface effects, and interfaces become more relevant and lead to pronounced modifications of the general response of the system. The group is particularly interested in hybrid systems where the interplay of different physical mechanisms can lead to entirely new phenomena.

8 University of Brussels (ULB)

8.1 The "Laboratoire d'Information Quantique" (LIQ)

Website: http://liq.ulb.ac.be/index.php?option=com_content&view=article&id=2&Itemid=2

Manipulating information at the quantum level is different from manipulating it classically. This opens the door to some new and surprising applications such as quantum cryptography or quantum computers. LIQ is actively working on different aspects of quantum information.

- *Theoretical work*: dealing with many aspects of quantum information, including quantum state estimation, quantum cloning, quantum non-locality and communication complexity, quantum cryptography, and quantum coin tossing.
- *The experimental quantum computing* includes the realization of an all fiber demonstration of algorithms, an all fiber demonstration of error filtration for quantum communication. Present work is focusing on the development of novel sources of entangled photons, both in fiber and in silicon waveguides.

8.2 The Research Group "Optique Nonlinealre Theorique" (ONT)

Website: http://www.ulb.ac.be/sciences/ont/

The main field of application of the research done in the ONT group is optics. One of their specificities is the pursuit of analytical results, notably through asymptotic methods. They are also active in building mathematical models for optical systems. Current research themes are quantum dots/dashes and their application in optoelectronics; semiconductor lasers; laser mode locking: modeling and stability; transverse nonlinear effects: optical structures in space or time; localized states and dissipative solitons; negative refraction index materials; micro-structured optical fibers; nonlinear media and Bragg gratings; plasmons; nonlinear optics in micro-cavities with whispering gallery modes; and solar cells.

8.3 The Research Group "Physics of Complex Systems and Statistical Mechanics"

Website: http://complex.ulb.ac.be/

The research activities aim at understanding complex phenomena on the basis of mathematical descriptions. The following research activities are distinguished: fundamental aspects of complex systems, non-equilibrium thermodynamics and stochastic processes, non-equilibrium statistical mechanics, classical transport from micro- to macro scale, complex quantum systems, out-of-equilibrium nanosystems, in-and out-of-equilibrium surfaces, and multistep nucleation theory.

9 University of Namur

9.1 The Namur Institute of Structured Matter (NISM)

Website: https://directory.unamur.be/entities/nism?_LOCALE_=en

The research interests cover various topics in the field of organic and physical chemistry, materials chemistry, surface science, solid-state chemistry and physics from both a theoretical and experimental point of view. It enables the exchange of ideas and competences in the field of synthesis and functionalization of molecular systems and novel materials (OD, ID, 2D and 3D), the rational design of solids with specific architecture and surface properties, as well as the development of advanced techniques for the study of their physicochemical properties. An important role is played by the theoretical approaches, through numerical simulation and modeling. The following topics are studied.

9.1.1 Nonlinear Optics and Photonics

Research is carried out in nonlinear optics (NLO), quantum NLO, plasmonics, and photonics, applied to multiscale structured matter (i.e. molecules, surfaces, biomaterials, nanomaterials, metamaterials, and crystals). Optical responses and their coupling to vibration and electronic excitations are predicted, from theoretical models using numerical simulations, and measured, using dedicated experimental setups.

9.1.2 High Performance Computing (HPC) Multiscale Modeling

The HPC pole aims at 1) sharing computational techniques, skills and tools in order to develop new materials and predict their final properties and 2) improving the modelling techniques and computer codes to account for most of the chemistry and physics of structured matter.

9.1.3 Functional Structured Materials

The expertise is divided in two areas:

- The development of 3D porous architectures including hierarchical organizations, MOF or MOF-like systems, organic/inorganic hybrids both using silica and carbon- based media, nanocomposites, etc.
- The functionalization of nanostructures such as carbon nanotubes, fullerenes (C60), pillararenes, etc. The applications cover various topics including: Li-batteries, C02 conversion, biomass conversion, photosynthesis, (photo)catalysis, inhibition of viral and/or bacterial pathogens, biomaterials, sensors ...

9.1.4 Surfaces, Interfaces and Carbon Nanostructures

Synthesis, characterization and modeling of novel materials, with particular attention to interfaces and to low-dimensional structures including carbon nanostructures (graphene, nanotubes). A choice of deposition and characterization methods is available. A theoretical support is provided to understand 2D materials synthesis and growth, and to interpret experimental data.

9.2 The Research Center "Physics of Matter and Radiation (PMR)"

Website: http://pmr.unamur.be/fr

The researchers of the Department of Physics of the UNamur of are grouped under the banner "Research Centre in Physics of Matter and Radiation" (PMR). The research themes of the department deal with the interaction between matter and radiation, for instance, being linked to progress in materials, but also to developments in laser spectroscopy, theoretical calculations and life sciences. Concerning new materials PMR has developed a great expertise in the field of all types of thin film deposition (metallic, semiconductor, oxides, polymers, and biomolecules) by different physic-chemical techniques: sputtering, evaporation, epitaxy by molecular beam or low-pressure cold plasma. These new materials are very often nanomaterials, with dominant or quantic interface effects because of the nanometric scale of created objects. These effects give unique properties to materials. For example, these nanomaterials are nanoparticles (functionalized carbon nanotubes, nanocomposites combining two types of nanoparticles (carbon nanotubes and metal), and bioinspired materials.

9.3 The Research Group "Carbon Nanostructures" (Carbonnage)

Website: http://www.unamur.be/en/sci/ carbonnage

The group is active in the field of carbon nanostructures (graphene, nanotubes, graphite, diamond-like carbon, etc.), which are studied both experimentally and theoretically.

- *Experimentally*: the synthesis, functionalization and characterization of carbon nanostructures nanotubes and graphene) is studied. A part of this research is dedicated to the synthesis of vertically aligned nanotubes on planar substrates, the other part is the synthesis of graphene by various techniques. The chemical modification of nano carbon materials is achieved, either by functionalization or post-synthesis doping, using different techniques. The characterization of samples is realized by a variety of equipment.
- *Theoretically*: support is provided either to understand graphene synthesis and growth mechanisms, or for the interpretation of experimental data. Electronic structure calculations are performed with both ab initio approaches and semi-empirical techniques. The quantum chemical design of carbon nanostructures related to graphene, called nanographenes, is studied for their remarkable optical properties.

9.4 The Namur Center for Complex Systems (naXys)

Website: http://www.naxys.be/

Complex systems are composed of interacting parts/agents whose local behavior, resulting from the interactions, cannot provide a complete understanding of the global behavior. Several levels of description!modeling of the system should be present at the same time: micro-meso-macro. This forces complex systems to be studied by trans disciplinary teams, able to understand the whole construction and critically analyze the connections among the description levels. This property is the result of a large number of elementary constituents and of the non-linearity of the interactions between them.

10 University of Mons

10.1 The Research Group "Micro- and Nanophotonic Materials"

Website: www.umons.ac.be/nanophot

Through numerical simulations and (semi-)analytical methods the group examines the behavior of light in structures with (sub-)wavelength scale elements. The following research subjects are considered:

- *Plasmonics*: studying the coupling between light and free electrons in a metal. They developed a novel angle-optimized plasmonic structure demonstrating better theoretical properties than ITO. The plasmonics research aims to develop novel nanostructures for detectors, optoelectronics or photovoltaics.
- *Graphene*: The main goal of their graphene research is to understand the interactions between light and graphene taking in account its structural and doping defects and designing original optoelectronic applications.
- *Parity time symmetry*: The similarity between the equations of quantum mechanics and optics allows micro- and nano-photonics to test of new non hermitic Hamiltonians. The goal of the research is to adapt or create photonics structures.

10.2 The Research Institute for Materials Science and Engineering

Website: http://portail.umons.ac.be/EN2/infossur/intranet/materiaux/Pages/default.aspx

The institute combines the activities from three research centers: the Centre of Innovation and Research in Materials & Polymers (CIRMAP).; the Research Centre of Material Engineering (CRIM); and the Research Centre In Material Physics (CRPM, see LPSI).
CIRMAP studies the morphological, electronic, optical, and transport properties of organic (semi)conducting materials in thin films. They determine the chemical nature, the structure, and the electronic properties of organic/organic and organic/inorganic interfaces. CRIM studies metals and metal alloys, the electrochemistry of functional ceramics, glasses and cements; heterogeneous catalysis and absorbents, geo materials, structures and construction materials. For this survey we consider only the activities of LPS.

10.2.1 The "Laboratory of Physics of Surfaces and Interfaces (LPSI)"

Website: http://portail.umons.ac.be/en2/universite/facultes/fs/services/institut_physique/physique_surfaces_interfaces/pages/default.aspx

The goal of LPSI is to understand how the interfacial characteristics of materials affect their function and performance, and hence determine their technological importance. The following subjects are studied:

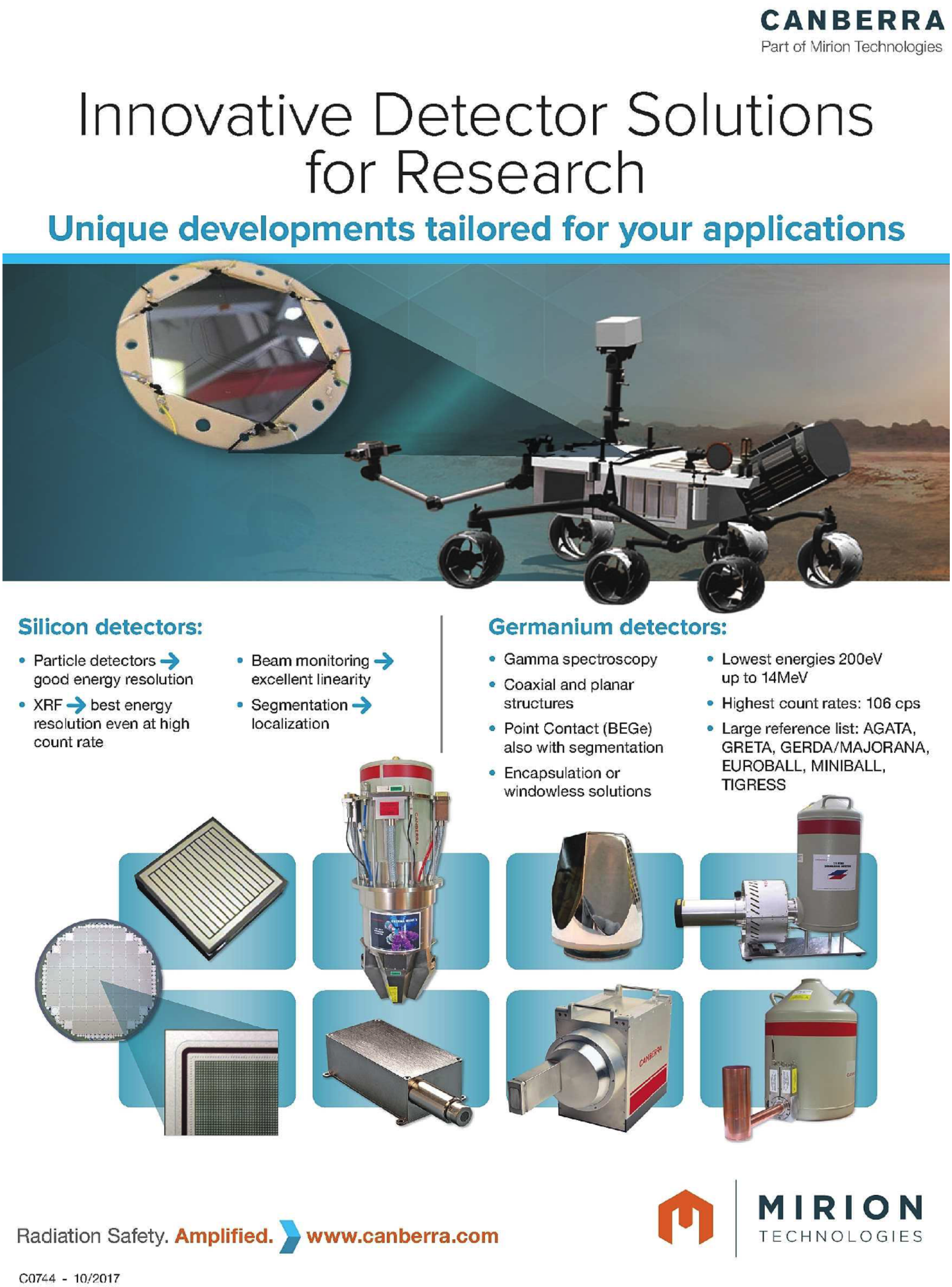
- *Surface treatments*: Minute compositional changes can drastically modify the energetics and dynamics of interfaces. Interface science can therefore be a very efficient way of optimizing materials, in particular in areas such as microfluidics, where surface effects dominate.
- *Surface and interface characterization*: Research is concentrated on wet ability, coating, drying, friction and wear, lubrication, adhesion and adhesives, optical properties. Modern techniques are combined to explore material properties at various length scales.
- *Molecular modeling*: Studies are based on the three complementary techniques of molecular dynamics, Monte-Carlo simulations, and genetic algorithms. Specific modules address collective properties such as viscosity, surface tension, and static and dynamic contact angles.

11 Conclusions

Condensed matter physics, including semiconductors, broadened its scope toward material science and chemistry. The last thirty years the research has been impressive by its permanent renewal and it regularly produces major conceptual breakthroughs e.g. mesoscopic and nanostructured materials, carbon-based materials, magnetic materials, topological materials, dielectric and ferroic oxides, multiferroics, new superconductors, structures for quantum computation, etc .. The importance is supported by the variety of experimental tools available e.g. scanning probe microscopy, enhanced synchrotron and neutron spectroscopy, new electron microscopes, free electron lasers, etc. Intelligent use of better performing computers produced a revolution in theory.
During the past years, university laboratories in Belgium have contributed substantially to state-of-the-art scientific achievements. This involved research exploiting the expertise in theory and experiment,

and via active collaborative programs sharing this expertise amongst various groups.

Leuven, February 2018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