BELGIAN RESEARCH IN ASTROPHYSICS

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and

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This text is an update of the overview of Belgian research in astrophysics written by Dejonghe in 2005 (Physicalia Magazine, 27, 275-280). Large parts of the present review are (updated) excerpts from the document *Towards a strategic plan of the Belgian National Committee for Astronomy for the period 2007-2015 and a look beyond 2015* prepared by that Committee.

Many exciting developments have taken place in the last five years. In most cases, these developments were driven by new instruments, in space or on the ground. Most remarkably, several among these were purely Belgian endeavours, which mark a new step in the history of astrophysics in our country. While there is a lot of activity on instrument design, implementation and exploitation, ultimately strong theoretical modelling forms a vital ingredient to interpret (and occasionally predict) observationally-acquired knowledge. And this modelling often requires extensive computing power. For French-speaking universities, the *Consortium des Equipements de Calcul Intensif* (CECI: http://hpc.montefiore.ulg.ac.be) offers a recent and powerful alternative to the set-up of many local computing clusters. In Flanders, *the Vlaams Supercomputer Centrum* (VSC: https://vscentrum.be/nl/en) plays a similar role. However, first and foremost, an efficient exploitation requires manpower and stable working environments.

1. New ground-based telescopes

1.1. Belgian telescopes (ordered by decreasing mirror size)

The ***International Liquid Mirror Telescope*** (ILMT; http://www.aeos.ulg.ac.be/LMT/) has been proposed by an international consortium initiated by astrophysicists from the *Institut d'Astrophysique et de Géophysique* (Liège University), and comprising the following institutions : the Royal Observatory of Belgium, the Canadian Astronomical Institutes from

Québec (Laval University), Montréal (University of Montreal), Toronto (University of Toronto and York University), Vancouver (University of British Columbia) and Victoria (University of Victoria) and the Aryabatta Research Institute of Observational Science (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 on the Devasthal mountain (Uttar Pradesh, Northern India), close to the *Aryabhatta Research Institute of Observational Sciences* (ARIES), located in the town of Nainital. The ILMT, presently under construction, has mainly been funded by the Communauté Française de Belgique, the Région Wallonne, the Fonds National de la Recherche Scientifique and Liège University. The project aims at monitoring a narrow strip of the sky to study photometric and astrometric variability of celestial objects as faint as $i = 22$ 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. The ILMT will also provide a huge amount of quasar lightcurves 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. ULiège has particular expertise in time series analysis. 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*** (http://www.mercator.iac.es), located at the Roque de los Muchachos observatory (La Palma, Canary Islands) and run by IvS/KULeuven, already mentioned in the 2005 report, has continued its operations, but is now equipped with the HERMES spectrograph. 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 together with the Belgian Royal Observatory with smaller contributions from the Geneva Observatory and Landessternwarte Tautenburg, Germany. The spectrograph began regular science operation in April 2009. The fibre-fed spectrograph 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 (2 years) radial-velocity stability, measured from 35 IAU standard stars, is 97 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, barium stars…). Moreover, the KULeuven team is constructing a 3-arm fast camera MAIA, which will be ideally suited to study the pulsational characteristics of the fast sdB pulsators.

The 60 cm robotic ***TRAPPIST*** (**TRA**nsiting **P**lanets and **P**lanetes**I**mals **S**mall **T**elescope) telescope (http://www.ati.ulg.ac.be/TRAPPIST/Trappist_main/Home.html) is a project driven by the Astrophysics and Image Processing group (AIP) at the Department of Astrophysics, Geophysics and Oceanography (AGO) of the University of Liège (Belgium), in close collaboration with the Observatory of Geneva (Switzerland). Mostly funded by the Belgian Fund for Scientific Research (F.R.S.-FNRS) with the participation of the Swiss National Science Foundation (SNF), ***TRAPPIST*** is devoted to the detection and characterization of planets located outside our solar system (exoplanets) and to the study of comets and other small bodies in our solar system. It is located at the ESO La Silla Observatory in Chile.

1.2. ESO telescopes

Thanks to the financing by Belspo of the 4th Auxiliary Telescope of the ***Very Large Telescope Interferometer Sub Array*** (VISA), Belgium has been granted about 160 nights of guaranteed time in the period 2005 – 2013. Most Belgian research teams involved in stellar astrophysics have made (and will undoubtedly continue to make) a very efficient use of this observing time. This has led to a spectacular Belgian expertise in the very specific and demanding field of interferometry, which is quite remarkable considering the fact that there was formerly no such tradition in Belgium. It is beyond the scope of this general overview to provide a full list of results, but it may be mentioned that they 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 and VLTI interferometry, ULiège astronomers have directly resolved the innermost regions of the planetary system around a main sequence star for the first time, and revealed the presence of large quantities of hot circumstellar dust within a few astronomical units of the bright star Vega. Their observations suggest an inordinate replenishment rate, which may be related to a major on-going dynamical event in the planetary system.

Several ***large programmes*** from Belgian teams were approved by the ESO *Observing Programme Committee.* Given the large pressure existing on the ESO telescope time, this

remarkable achievement demonstrates the top quality of astrophysical research in our country. The UGent group has been leading an ESO Large Programme on the internal dynamics of dwarf elliptical galaxies. The IvS/KULeuven has been heavily involved in the approved ESO Large Programme on ground-based support for CoRoT running in 2007 and 2008. IvS/KULeuven, ROB, and ULB teams (plus international partners, mostly from University of Wien) are part of the ESO Large Programme ***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, Astrophysics Research Group of the University of Antwerp, ULiège) are part of the ***Gaia – ESO Survey***, a Large Programme running over several years to provide spectroscopic ground-support to the future ESA – Gaia mission. The programme aims at providing radial velocities and abundances for about 10^6 stars, to address the issue of the chemico-dynamical evolution of our Galaxy.

The ***Atacama Large Millimeter/submillimeter Array (ALMA)*** is the now largest astronomical project in existence. When completed in 2013, it will consist of an array of 50 12m antennas with baselines up to 16 km, and an additional compact array of 7m and 12m antennas. The first call for proposals for "Early Science" has been released in June 2011, and despite a very high over-subscription rate (>9), several Belgian proposals were successful: from KULeuven/IvS, one proposal related to the discovery of water vapour in the warm inner envelope of CW Leo as a follow-up of Herschel observations, another on the disk around the 'Red Rectangle', a famous post-AGB star, and yet another on R Scl, which is one of the handful of carbon-rich objects that are known to have a detached gas and dust shell. The UGent group is also involved in two successful ALMA proposals: one on massive molecular outflows in the prototypical ultra-luminous infrared galaxy Arp 220, and one on the characterization of dust emission from supernova 1987A. Both projects are follow-up studies of Herschel results.

Beyond "Early Science", the Belgian astronomical community will undoubtedly make an intensive use of the "full ALMA" in the coming years. This situation reflects the important effort made by the community to gain expertise in (stellar) radio astronomy, a field which was almost totally absent from the Belgian astronomical landscape only a decade ago. As seen above, teams at KULeuven and ROB are probing circumstellar matter around evolved stars using radio observations, whereas the UGent group has recently built up quite a strong

expertise on H I studies using the 21 cm line and submm 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 submm and mm telescopes. Prime examples are the involvement of UGent in the ***AGES project*** (http://www.naic.edu/~ages/), 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 survey*** (http://www.astron.nl/halogas/), the deepest HI survey of nearby galaxies, that is consuming almost 3000 hours of WSRT time.

Last but not least in the ESO framework, the Belgian astronomical community awaits the ***European-Extremely Large Telescope*** (E-ELT) planned for 2021, and Phase B[1] studies are already ongoing for the ***Metis*** (Mid-Infrared E-ELT Imager and Spectrograph) instrument, with strong involvements of KULeuven/IvS and ULiège.

1.3 Others

In November 2009, the Belgian Federal Science Policy Office (Belspo) signed an agreement with the Aryabhatta Research Institute of Observational Sciences (ARIES), located in the state of Uttar Pradesh (Northeast India), on the Cooperation for the Construction of a ***3.6 m optical telescope*** at Devasthal. The construction was performed by AMOS in Liège. In return of this financial investment from Belspo, Belgian astronomers will receive 7% of the time of utilisation of the telescope during its operational life, scheduled to start early 2013. The telescope will be equipped with a low-resolution spectroscopic camera, a near-infrared camera, and most probably a high-resolution spectrograph.

The Belgian Institute for Space Aeronomy (BISA) is deploying a network for the detection of meteors, called ***BRAMS*** (http://brams.aeronomie.be/), based on the principle of forward scattering of radio waves off meteor ionization trails. Two dedicated beacons located in Ieper (Western Belgium) and Dourbes (Southern Belgium) act as transmitters. Tens of receiving stations are and will be deployed throughout the country, run by Belgian radioamateurs, groups of amateur astronomers, and public observatories.

[1] For an instrument development, phase A denotes preliminary analysis, phase B definition, phase C design, and phase D construction.

2. Space missions

2.1. Belgium

The Belgian companies *Verhaert, Spacebel* and the research centre *Centre Spatial de Liège* (CSL) built the Belgian-led ***Proba-2*** satellite (standing for « PRoject for OnBoard Autonomy »). The Proba satellites are among the smallest ever to be flown by ESA, but they are making a big impact in space technology. The Proba satellites are part of ESA's In-orbit Technology Demonstration Programme, missions dedicated to the demonstration of innovative technologies. Altogether, 17 new technological developments and four scientific experiments are being flown on Proba-2. Among these are the two solar-observation experiments led by Belgian teams (from the Royal Observatory of Belgium – ROB, CSL, the Belgian Institute for Space Aeronomy – BISA, 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, that will make measurements of the solar corona in a very narrow band.

2.2 CNES

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

As apparent from the above, various Belgian teams have thus 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 in Brussels.

Belgian scientists (IvS/KULeuven, ULiège, ROB) are heavily involved in the CNES-dominated ***CoRoT*** mission, both at instrument level and for the scientific exploitation of the data, and similarly for the Nasa mission ***Kepler***. 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. Many more modes can so be detected, including

solar-like stochastically excited modes in β Cephei stars. Of particular interest are the slowly pulsating B 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 IvS/KULeuven 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 makes 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.

2.3 ESA and NASA

The ESA infrared and submillimetre ***Herschel*** satellite, launched in May 2009, is the latest most successful achievement from ESA astronomy programme. It hosts the largest mirror (3.5 m) ever flown. Belgium has been involved at the co-PI level (led by the Instituut voor Sterrenkunde – IvS / KULeuven, with industrial contributions from CSL, IMEC and OIP) in the design and construction of the Photodetector Array Camera and Spectrometer (PACS), one of Herschel's three science instruments exploring the wavelength range 60 – 210 μm over a field of view of ~1.75' × 3.5'. IvS/KULeuven has opened his right of participation in the guaranteed-time programmes of Herschel to all interested Belgian partners. The scientific issues that are being 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. They 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 also led to the involvement of IvS/KULeuven at co-PI level in the ***Mid-Infrared Instrument (MIRI)*** consortium of the future ***James Webb Space Telescope*** (with contributions from CSL and UGent), as well as in the European ***SAFARI*** instrument

planned for the Japanese/ESA infrared satellite ***SPICA*** to be launched in the window 2015 - 2025.

Belgian scientists also play a considerable role in many of the data-processing coordination units for the ESA ***Gaia satellite*** (to be launched in the spring of 2013), with ULB, ULiège, IvS/KULeuven, UAntwerp and ROB as partners (sometimes leaders) in the topics of variable stars, binaries, solar-system bodies, and quasars.

XMM-Newton (ESA)***, Chandra*** (NASA) and ***INTEGRAL*** (ESA) have opened the X-ray and gamma-ray windows for the study of massive stars: O-type stars and their evolved descendants, the Wolf-Rayet objects. ULiège has developed expertise in the multi-wavelength study of these stars which have strong chemical and dynamical impact on the interstellar medium of their host galaxy. They are important members of young open clusters and their study provides additional information on the cluster formation and evolution compared to lower-mass objects. The determination of the massive-star physical parameters such as their masses and their mass-loss rates constitutes a key point for the understanding of the evolution of these objects that is dominated by mass-loss and rotation effects. The binarity/multiplicity of O stars is also an essential tool for determining secure values for the masses. The evolution of massive stars in binary systems and the phenomenon of Roche Lobe Overflow in massive stars is an additional aspect that remains poorly understood. The study of colliding wind binaries gives access to an alternative way to get constraints on the mass-loss rates, and also to study the acceleration of particles in shocks and the subsequent non-thermal emission. The enigmatic very massive stars (luminous blue variables, Of ?p, and Oef stars) were the topic of a multi-wavelength analysis, with the aim of deriving their fundamental physical parameters.

The XMM-Newton satellite allows ULiège 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.

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/EIT, SOHO/LASCO, STEREO/SECCHI***. Together with ULg/CSL, ROB will play a

leading role in the EUI instrument (Extreme Ultraviolet Imaging) onboard the ***Solar Orbiter*** mission, recently endorsed by ESA. These activities complement those already described in relation with the Proba-2 satellite (Sect. 2.1).

2.4 Solar-system exploration

Belgium is involved in several ESA missions to terrestrial planets, such as ***Mars Express*** and ***Venus Express***, with ROB as co-I of the radioscience experiments. The ***NOMAD*** experiment with BISA as PI and ROB as co-I will fly on the ***ExoMars*** mission. It is a 3-channel spectrometer, hosting 2 infrared channels and one UV/visible channel. ROB is co-I of the ***AMELIA*** instrument hosted by the ***Entry, Descent and Landing Demonstrator Module*** on ExoMars.

Belgium also strongly participates in the ESA cornerstone mission ***BepiColombo*** to Mercury. The FUNDP and ROB are Co-I in three of its instruments: the Mercury Orbiter Radioscience 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 of Mercury, which will be confronted to models developed at ROB and FUNDP.

ULg has become PI of the JUDE candidate instrument on-board of the planned ***JUICE*** (formely known as EJSM-LAPLACE) mission to Jupiter; it will study the magnetosphere and the auroras of Jupiter. ROB is involved in the ESA Science Study Team for that mission.

BISA has a Co-I involvement in the ROSINA mass spectrometry consortium on the ***Rosetta*** mission with the aim of studying the physics and chemistry of the cometary coma.

ROB participates as co-I to the Russian ***Phobos-Soil*** mission, and exploits radio science data from many NASA missions like ***Mars Globar Surveyor***, ***Mars Odyssey***, ***Mars Reconnaissance Orbiter***, and ***Cassini*** to Saturn and its moons.

3. Instrument design and building

Although Belgian teams never succeeded so far to take the leadership of the design and construction of a large instrument, many are directly involved as partners: KULeuven and UGent for the MIRI/JWST instrument (currently in phase C/D) and the Maia fast camera for the Mercator telescope (phase C/D), ULiège for the PIONIER/VLTI instrument and the use of annular groove phase masks within the VISIR/VLT instrument, and KULeuven for METIS (awaiting phase B), the Mid-infrared E-ELT Imager and Spectrograph proposed for the

European Extremely Large Telescope (E-ELT). In 2012, phase A is awaited for the Echo satellite (possible launch in 2022), to detect and characterise extrasolar planet atmospheres, with a consortium involving KULeuven/IvS, CSL, and possibly BISA and ULiège.

This situation constitutes a substantial progress with respect to the total absence of participation in instrumental development a decade ago.

4. Synergies and pooling of resources in observational astrophysics connected to Large Infrastructures

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.

Within the discipline of asteroseismology, the institutes involved so far in this kind of research in Belgium (K.U.Leuven, ROB, ULiège) have integrated their research within the ***Belgian Asteroseismology Group*** (BAG; http://www.asteroseismology.be/) since 2000, in the framework of previous Interuniversity Attraction Poles. The BAG has served as the nucleus of the ***European Network of Excellence in Asteroseismology ENEAS*** (some 250 members from 45 institutes), which was embedded in the FP6 funded ***Helio- and Asteroseismology Coordination Action HELAS.***

On the topic of ***Mass loss from Evolved StarS (MESS)***, as studied from the Herschel guaranteed-time key program, a broad international consortium, involving KULeuven, ROB, ULiège and ULB has been established.

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.

Merging of expertises was also felt as a necessity for an efficient exploitation of the 160 guaranteed nights of observing time which Belgium has acquired on ***VLTI/VISA***, thanks to the Belspo funding of the fourth Auxiliary Telescope.

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. ULiège was also involved in the international CCCP survey of the Carina region using two weeks of observations with the Chandra facility (study of the X-ray emission of massive stars).

The ***European Leadership in Space Astrometry (ELSA)*** is 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 ***Gaia Research for European Astronomy Training (GREAT)*** network sponsored by the European Space Foundation, 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.

Finally, ULiège chairs 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.

5. Theoretical astrophysics research in Belgium

The above overview has revealed a wealth of projects connected with observational infrastructures. Such a situation contrasts with the traditionally theoretically-oriented astrophysical research which dominated the Belgian landscape till two decades ago or so. Of course, there are still many theoretical activities going on (which were exhaustively listed in the 2005 overview), the list below stressing only the most recent developments.

Nuclear astrophysics is a traditional niche of ULB theoretical research, with the computation and compilation of nuclear data of astrophysical interest (http://www.astro.ulb.ac.be/bruslib/, http://www.astro.ulb.ac.be/Netgen/form.html). The group has a strong expertise in the s-, r-

and p- processes of nucleosynthesis, studied through parametrical approaches or through uni- or multi-dimentional stellar evolution models. Theoretical research at ULB involves as well stellar evolution (http://www.astro.ulb.ac.be/~siess/Site/STAREVOL) covering all evolutionary stages from pre-main sequence to neon combustion for a vast mass range, with new developments regarding the binary evolution (BINSTAR code) and rotationally-induced mixing, using hydrodynamical tools when needed, and treating the associated nucleosynthesis. The new developments about BINSTAR are done in collaboration with VUB, which has a long-standing research history in this field. ULB is also involved in the study of superfluidity in neutron stars and in the development of nuclear energy density functionals and their application to supernovae cores and neutron stars crusts. ULB is a partner of the ESF network ***Compact Star (CompStar,*** http://compstar-esf.org/). 3D hydrodynamical models of supergiant atmospheres are also computed, and confrontations are performed with abundances derived from observations.

A strong theoretical expertise exists in Belgium (ULg, KULeuven/IvS, ROB) regarding the prediction of the oscillation spectra of various kinds of stars in the context of asteroseismology.

The Centre for Plasma Astrophysics at KULeuven (KULeuven/CPA), which will celebrate its 20 year existence in February 2012, focuses on theoretical and computational plasma physics, relevant for solar physics, astrophysics and laboratory (fusion) plasmas. Key applications include magnetoseismology in the solar corona, all aspects of space weather, relativistic plasma dynamics, and fundamental plasma physics research. KULeuven/CPA coordinates several ongoing EC-FP7 projects targeting space weather applications, namely ***Soteria*** (http://soteria-space.eu/) and ***SWIFF*** (http://www.swiff.eu), as well as SOLSPANET. It is involved in European Research and Training Networks (specifically ***Solaire***: http://www.iac.es/solaire). The group does a lot of numerical work, targeted to high performance computing, since the prime work package of the new Intel Exascience Lab (http://www.exascience.com) is on space weather modelling, with KULeuven/CPA 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 *Groupe Astrophysique et Spectroscopie* (Université de Mons) has a long-standing tradition in the determination of fundamental parameters for atoms and ions of astrophysical interest, particularly for the investigation of the chemical composition of the stars (including the Sun and the chemically-peculiar stars). 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 75 000) of transitions belonging to ions of astrophysical interest (DREAM – http://w3.umons.ac.be/~astro/dream.shtml – and DESIRE – http://w3.umons.ac.be/~astro/desire.shtml – databases) and of interest also for laser devices and for fusion (ADAS collaboration).

KULeuven (IvS, Department of Chemistry, Department of Mathematics) has been granted an Interdisciplinary Research Project (IDO) to develop a multi-dimensional theoretical code for exoplanet atmospheres, including radiative transfer, chemistry, dynamics, cloud formation etc. This code will run on the Flemish supercomputer. Expertise on the similar topic of non-LTE radiative transfer in dusty circumstellar shells around evolved stars is already existing in the KULeuven/IvS team, thanks to the code GASTRoNOoM coupled to a dust radiative transfer code (MCMAX).

NaXys (Namur Centre on Complex Systems) at FUNDP 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 expertise in theoretical cosmology as well, focusing on dark energy, numerical simulations of cosmic structure formation with N-body simulations, alternative theories of gravitation and the derivation of combined solar-system (post-newtonian parameters) and cosmological (Hubble diagram, CMB and large-scale structure physics) constraints.

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). 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. 2.3). Finally, the topic of galaxy dynamics has also developed into the investigation of dark matter halos and modified gravity: the UGent group is using mainly radio observations to determine the mass distribution in galaxies and interpreting these using either models for dark matter or alternative gravity theories.

The ROB involvement in many solar-system exploration missions goes along with the modelling of the interior structure and dynamics of terrestrial planets and moons of the solar system, building on the expertise developed from the 1960s on the rotation of the Earth. New methods are developed to investigate the deep interior structure as well as the crust and lithosphere. A particular focus is on the study of the rotation, gravity field, and tides.
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*** (EPN; http://epncb.oma.be/) with a particular emphasis on the study and mitigation of error sources degrading the positions and velocities of Global Navigation Satellite System stations. Research on stellar astrophysics at ROB focuses on visual and spectroscopic double stars (especially spectral disentangling), pulsating stars, central stars of planetary nebulae, and hot stars (winds, rotation).

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.

6. Internet directory

BISA: http://www.aeronomie.be/
FUNDP: http://www.fundp.ac.be/sciences/mathematique/sysdyn
KULeuven/IvS: http://fys.kuleuven.be/ster
KULeuven/CPA: http://wis.kuleuven.be/cpa/
RMI: http://www.meteo.be
ROB: http://www.astro.oma.be/
UAntwerp: http://astro.ua.ac.be/
UGent: http://www.astro.ugent.be/

ULB: http://www.astro.ulb.ac.be
ULiège: http://www.ago.ulg.ac.be
UMons: http://w3.umons.ac.be/~astro/indexgb.shtml
VUB: http://www.vub.ac.be/STER/