Physicalia Mag. 27 (2005) 3 pp 275-280

BELGIAN RESEARCH IN ASTROPHYSICS

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In this overview of Belgian research in astrophysics, it is good to bring into memory the general context in which astronomy has evolved during the 20th century. More in particular, the scope of the field has widened substantially. In fact, at the beginning of the 20th century, 'positional astronomy' (with its practical applications such as time keeping and navigation), 'astrometry' (charting the heavens and the light that comes from it) and 'celestial mechanics' (the mechanics of our solar system) dominated astronomical activities. At that time, the field of 'astrophysics' was new, intended to be in the true sense of the word "the study of the physics of the stars". As is well known, the advent of spectrographs and the advances in nuclear physics were instrumental in its development, and it can truly be said that the 20th century was the period in which our understanding of "the physics of the stars" has come of age. However, many important and new disciplines have established themselves in the second half of the 20th century, thanks to ever increasing observational capabilities. To mention a few: the study of the Milky Way, the interstellar medium, galaxies, cosmological structures and the early universe. For all of them, the connection with physics is strong through a firm relation with many physical disciplines. Clearly, the distinction between astronomy and astrophysics is outdated nowadays. In the sequel, we will therefore try to paint an overview of Belgian 'astronomical' activities, and the word 'astronomy' is meant to cover all aspects that are just mentioned. It should also be noted that no attempt has been made to cover in a systematic way these activities that are traditionally called "space research", though some overlap is obviously present. This report has been prepared with the input of the members of the Belgian National Committee for Astronomy.

Belgium has a good and long standing track record in furthering the European cause, and scientific affairs are no exception. The Belgian astronomers in charge around the middle of the 20th century were very well aware that, just as in every physics discipline, the experiments, in this case the observations of the sky, constitute the driving factor. Hence Belgium can be proud to be amongst the 5 founding members of the European Southern Observatory (hereafter ESO) in 1962, and an important part of the current astronomical activities is framed within the possibilities that are offered by ESO. The organization itself has over the years increased substantially in size, scope and membership, and now operates several observatories in Chile. Programs of Belgian astronomers are present on all ESO telescopes. Similarly, Belgium was a founding member of the European Space Agency (hereafter ESA) in 1973. Though the activities of ESA incorporate an important technological component, ESA also carries a mandatory scientific program. Belgian astronomers contributed and contribute to this program as well.

There is a broad consensus within the astronomical community that support of ESO projects should remain strong, and hence contribution to them must remain a high priority. Hence the community has secured substantial funding for a Belgian hardware contribution to the Very Large Telescope Interferometry project (hereafter VLTI), which realizes interferometry

between the four 8 meter telescopes (the Very Large Telescope or VLT) and a number of smaller Auxiliary Telescopes (the ATs) in a wavelength span that for some of them ranges from the optical to the thermal infrared. The community is now preparing itself in order to make efficient use of the next large ESO project (together with North American institutes), which is called the Atacama Large Millimeter Array (ALMA). It will be a synthesis radio telescope consisting of some 50 dishes, each with a diameter of 12 meter, that will operate in the millimeter and sub millimeter wavelength range. In a more distant future, there are plans to participate in an Extremely Large Telescope project (a so-called ELT), which could realize a telescope of up to 100 meter in diameter. Similarly, the community intends to follow the developments of plans for the Square Kilometer Array (SKA), which will be a giant radio telescope. As for ESA's scientific projects, the GAIA mission (foreseen launch in 2011) has already generated a lot of interest in the Belgian astronomical community. The mission will create the largest and most precise three dimensional chart of our Galaxy by providing unprecedented positional and radial velocity measurements for about one billion stars in our Galaxy and throughout the Local Group.

Given the size of the country, there are quite a few astronomical institutes, and hence some of them are rather small. Beyond the effort of maintaining a few faculty positions and teaching assistants, there are generally insufficient institutional funds to fully support astronomical projects of substantial size. Hence, many institutes succeed in carrying out their projects on the basis of bilateral negotiations with the regional and national funding agencies, or submit their projects to these agencies on a competitive basis. In some cases, networks among a number of institutes (of course not necessarily all Belgian) have been formed. Finally, it must also be noted that Belgium has a good tradition in theoretical astronomical research.

In what follows, an overview of the activities of the various institutes is given. The institutes are listed in alphabetical order according to their geographic location. Because of the scope of this overview, it is impossible to be exhaustive, nor has it been possible to list all important achievements of the past. Therefore, hyperlinks are included where more information can be found.

Astrophysics Research Group, U.Antwerpen

The Astrophysics Research Group was created in 1985 to study, both theoretically and observationally, the structure and the dynamical state of star forming regions during the last phase of their evolution, i.e. systems of recently formed stars embedded in the remains of the interstellar cloud from which they were formed and whose total mass often exceeds the total mass of the stars. More specifically the group contributes to the study of dynamics in embedded open clusters, to the collection of observational data and to the improvement of data-reduction software. In recent years most efforts were devoted in particular to the increase of precision and accuracy in the measurement of radial velocities of early-type stars, in collaboration with several foreign research groups. Current activities include a spectroscopic survey to investigate the binary population in the Sco-Cen association, and several feasibility studies on behalf of the Spectroscopy Working Group for the preparation of the GAIA mission. More information can be found at http://www.win.ua.ac.be/hpwisinf/astrofysica.html

Institut d'Astronomie et d'Astrophysique, U.L.Bruxelles (IAA)

The IAA staff members teach courses covering a broad range of matters from introductory astronomy to specialized topics. Over the years, a coherent research strategy has been developed in the field of stellar physics. It involves observational studies (chemical composition of giant stars, binary properties, tomography of stellar atmospheres) that make use of the large ESO telescopes as well as of other major instruments. These observations are complemented and supported by theoretical studies of mass transfer in binary systems, of

standard and non-standard stellar evolution (including the modelling of stellar hydrodynamical nuclear burning for application to certain thermonuclear supernovae), and of nuclear astrophysics (a field in which physicists at the ULB have long been internationally recognized as experts), including the theory of nucleosynthesis. With a strong involvement in the preparation of the GAIA mission from ESA, astrometry is by now an active research component of the IAA. Besides topics specific to GAIA, that preparation also includes the re-processing of the Hipparcos Intermediate data and collaboration to the Sloan Digital Sky Survey. Research in the field of extra-solar planets is also pursued, as well as the preparation and continued maintenance of the 9th catalogue of spectroscopic binary orbits. The IAA activities in stellar astronomy are now supplemented with theoretical research in galactic and extra-galactic astronomy (including galactic dynamics). A variety of more or less broad national and international collaborations have been set up in all the IAA research topics. It has also become recently a member of the HERMES consortium to build a high-resolution, high-efficiency spectrograph for the Mercator telescope at the Roque de los Muchachos Observatory (La Palma). More information can be found at http://www.astro.ulb.ac.be/

Astronomy group, V.U.Brussel

The Astronomy Group incorporates two Research Units. The theoretical research team applies massive close binary evolutionary models to population number synthesis studies, and investigates the influence of massive close binary evolution on the variation of the massive star content in starburst regions. The observational research unit is involved in long-term photometric monitoring of pulsating variables (beta Cephei stars, delta Scuti stars and Luminous Blue Variables) and cataclysmic variables. The team is also involved in cometary research. More information can be found at http://www.vub.ac.be/STER/astronomy.html

Sterrenkundig observatorium, UGent

The astronomy department dates from the beginning of the 20th century, and has long focussed on its educational duties. Only during the past 2 decades has research taken a prominent role in its activities. The astronomy group in Gent has acquired expertise in extragalactic astronomy, focusing on the following topics: stellar kinematics and dynamics of the Milky Way and extragalactic systems, galaxy evolution, the interstellar medium, radiative transfer processes in dusty galaxies, dynamics of clusters of galaxies. Care has been taken to obtain a balance between observational studies, detailed modeling and theoretical research. The research group uses the major ESO telescopes and has also successfully applied for other telescopes that are available to the international community, such as the Hubble Space Telescope. It has expertise in far-infrared and sub-millimeter astronomy with telescopes such as SCUBA, and in radio astronomy, more in particular through observations of the 21 cm line of atomic Hydrogen, with telescopes such as ATCA and GMRT. Research in space plasma physics focuses on linear and nonlinear waves in plasmas in general, with astrophysical and heliospherical applications in mind. These include the pickup of cometary ions by the solar wind, and the modeling of specific differences between wave phenomena in ordinary and in dusty plasmas. More information can be found at http://wns.ugent.be/

Institute for Astronomy, K.U.Leuven

Research in observational astronomy at K.U.Leuven was initiated in the 1930s, with a focus on variable stars. Theoretical studies on stellar oscillations started in the 1960s. Current research at the institute builds on this tradition, combining observations and theory in truly asteroseismological investigations of stellar interiors. The group has played a pioneering role in the asteroseismology of massive stars and continues to put emphasis on such studies. The Mercator Telescope operated by the IfA at la Palma Observatory is a crucial instrument for obtaining the long time series of data needed for this research. The team has contributed to

the analysis of variable stars by the Hipparcos mission and is now involved at the PI level in space asteroseismology missions such as COROT. Research on stellar evolution focuses on stars with a dusty circumstellar environments: it includes on the one hand young stellar objects with circumstellar disks, and on the other hand evolved objects undergoing mass loss. Research topics include detailed photospheric modeling, chemical analyses, modeling of the spectral energy distributions and circumstellar environment, as well as global population studies. Ground-based data rely on the major ESO telescopes, including VLTI, and on several other facilities worldwide. The exploitation of space missions such as IUE, HST, ISO, and Spitzer enables a multiwavelength approach. Since the ISO (Infrared Space Observatory) mission in 1995-98 the institute directly contributes to the construction of instruments for space missions, through the development of data analysis software, calibration strategies, as well as test procedures. This way the institute is involved at the co-PI level in the PACS instrument for the ESA cornerstone Herschel and in the MIRI instrument for the NASA-ESA James Webb Space Telescope. More information can be found at http://www.ster.kuleuven.be/

Centrum voor Plasma-Astrofysica, K.U.Leuven (CPA)

The mission of the CPA comprises the study of waves, instabilities, flows, shocks, heating and acceleration of magnetic plasmas in the Sun, other stars, galactic disks, accretion disks, magnetospheres, and thermonuclear fusion machines. The favorite research subject is definitely the Sun, which is regarded as a showcase (Rosetta stone) for plasma behaviour in astrophysical objects. Current research at the CPA includes as main topics (1) the MagnetoHydroDynamics and Kinetic Theory of coronal loop dynamics and coronal heating and the acceleration and heating of the solar wind, (2) the numerical simulation of the initiation and the interplanetary evolution of Coronal Mass Ejections (CMEs) and associated shocks and their interaction with the Earth's magnetosphere, and (3) the observational aspects (automatic detection) of solar flares and CMEs. More information can be found at http://cpa.wis.kuleuven.ac.be/

Institut d'Astrophysique et de Géophysique, Liège University (IAGL)

The Cointe Observatory, later named the Institute of Astrophysics and Geophysics of Liège (IAGL), is 125 years old and has played a leading role in most of the Belgian as well as European and international astrophysical endeavours, all the way from laboratory and solar research to solar system observations, stellar evolution theory, galactic and extragalactic astrophyscis. Its main activities also include teaching (cf. organization of a master in space science studies starting in September 2007) and the frequent organization of international colloquia and seminars. In space research, IAGL has participated to the conception and the construction of experiments such as aurora spectrographs launched with rockets, the S2/68 spectrophotometer onboard the TD1 satellite, the ATMOS Fourier transform spectrometer onboard several space shuttles, the Faint Object Camera onboard HST, and more generally in research activities related to various space experiments : TD1, ANS, Atmosphere Explorers, Solar Mesosphere Explorer, Copernicus, IUE, Hipparcos, UARS, ROSAT, and more recently HST, ISO, SOHO, FUSE, IMAGE, XMM, INTEGRAL, ERS-2 and ENVISAT. Several members from IAGL are actively involved in the preparation of future space missions like HERSCHEL, GAIA, COROT, SCISAT, MARS PREMIER-07, Pegase, DARWIN, etc., very often in close collaboration with scientists from CSL (Liège Space Center). The recent space activities have been made possible thanks to the partial support from PRODEX. Members from IAGL have also been very active in organizations such as the European Southern Observatory (ESO), the European Space Agency (ESA) and the International Astronomical Union (IAU). The main themes of active research in astrophysics within IAGL presently concern asteroseismology, stellar and galactic evolution, massive luminous stars and high

energy astrophysics, extragalactic astrophysics, the international liquid mirror telescope and, finally, ESO's Very Large Telescope Interferometry (VLTI) and astrophysical studies at high angular resolution. A more detailed description of these modern aspects of theoretical and observational astrophysics are part of the Interuniversity Attraction Pole P5/36 and may be found at http://www.astro.ulg.ac.be/

Groupe Astrophysique et Spectroscopie, Université de Mons-Hainaut

The research unit has a long tradition in the determination of fundamental parameters for atoms and ions of astrophysical interest, particularly for the determination of the chemical composition of the stars. For that purpose, elaborated theoretical approaches and up-to-date experimental techniques are currently used, in the framework of national (ULB) and international collaborations. In addition, a unique database has been developed containing data for a large number of transitions of rare-earth ions. More recently, some investigations have been carried out, in collaboration with NASA and IVIC (Venezuela), related to modeling of emission and absorption structures, involving inner shells of cosmically abundant elements (like O and Fe), observed on high resolution X-ray spectra observed with current space observatories (CHANDRA, XMM-Newton). More information can be found at http://w3.umh.ac.be/~astro/indexgb.shtml

Celestial Mechanics group, University of Namur

The research unit has conducted research in theoretical Celestial Mechanics and its applications to the dynamics of the Solar System since 1970. Techniques for analytical and/or semi-numerical perturbation methods, for the investigation of chaotic dynamics, for the use of adiabatic invariants, have been developed. The applications concern the theory of the motion of the Moon and of the Galilean satellites, the asteroid belt (proper elements for highly inclined or eccentric asteroids, formation of the Kirkwood gaps), capture into resonance of pairs of natural satellites, spin-orbit resonances of the Moon, the Galilean satellites and Mercury, secular behaviour of exoplanetary systems. The group maintains close contacts with similar European groups (Observatory of Nice, Bureau des Longitudes in Paris, University of Lille, Pisa, Thessaloniki, Allicante, etc.) partly with the help of European twining projects. More information can be found at http://www.fundp.ac.be/recherche/unites/en/2712.html

Royal Observatory of Belgium (ROB)

The institute was founded at St Joost ten Node in 1826. In 1890-1891 it moved to its current site in Uccle and was renamed to Royal Observatory of Belgium. During its long existence, research at the ROB included scientific activities outside the traditional domain of astronomy/astrophysics, such as meteorology (later split off to form the Royal Meteorological Institute) and seismology (still a core activity today), but these are not included below. A large part of the activities of the ROB are oriented towards services to the public and the scientific community and towards education and public outreach. The latter is mainly concentrated in the Planetarium on the Heizel, which forms an integral part of the observatory. In the following, a brief description of these activities is given, organized into a number of themes. More information can be found at http://www.astro.oma.be/

Time and time transfer: The ROB is part of the international timescale community through the project 'Time and Time transfer'. The ROB maintains presently five high-quality clocks in a temperature-controlled environment, monitored at the nanosecond level, for participation in two international timescales: the International Atomic Time (TAI) and the International GPS Service timescale (IGST). *Earth rotation, geodesy and geophysics of other planets:* This incorporates not only modeling the Earth rotation and orientation variations, and the study of the interaction between the solid Earth and the geophysical fluid dynamics, but also research

of rotation, nutation and libration, gravity field, tides, and interior structure of terrestrial bodies in general. Since the beginning of this research in the sixties, a recent major objective has been to show the feasibility of a geodesy experiment with a mission involving landers dedicated to the geophysics of Mars. The ROB participates in the ESA missions Mars Express, Venus Express, and BepiColombo to Mercury. *Astrometry:* The ROB is still active in the astrometric detection and observation of minor planets with local instruments, which also frames in the international effort concerning the protection of the Earth against the threat by minor planets. In addition, the mutual phenomena of the Galilean Satellites of Jupiter and stellar occultations by asteroids are observed. *Binaries, stellar clusters and galaxies:* Visual binaries allow a direct calibration of the masses on the lower main sequence via the study of their orbital motions. The goal is to investigate a volume-limited sample of visual binary and multiple stars that is as complete as possible. In parallel, work is being done in the context of the scientific preparation of data on visual double stars that will be collected by the ESA astrometric mission GAIA, as a continuation of the preceding ESA mission HIPPARCOS, in which the ROB played an important role in this respect. The study of galaxies comprises the chemo-dynamic evolution of galaxies and the modeling of stellar thermonuclear combustions associated with explosive astrophysical events. *Stellar astrophysics:* This includes asteroseismology (monitoring of pulsating stars with the aim to probe their internal structure), the study of hot stars with radiatively driven stellar winds and the study of the final stages of evolution of intermediate mass stars, in particular the evolution from the post-asymptotic giant branch through the planetary nebula stage. *Solar physics:* The research focuses on the external layers of the solar atmosphere, mainly through the exploitation of images made in the extreme-ultraviolet and visible light. To that end, the ROB participates in the space missions SOHO/EIT, SOHO/LASCO, STEREO/SECCHI, PROBA2/SWAP and PROBA2/LYRA. Using the Uccle Solar Equatorial Table (USET), daily solar observations are made in white light and H-alpha. Sunspot drawings are still made to maintain the consistency of the historical characterization of solar activity. In the radio-astronomy station in Humain, the integrated solar radio flux at 600 MHz is monitored. *Solar activity and space weather:* these activities focus on the study, the monitoring and the operational forecasting of solar activity in all its forms. It is also dedicated to the study of the solar cycle, the maintenance of the Sunspot Index database (World Data Center), and the analysis of the impact of solar activity on Earth. The SIDC (Solar Influences Data analysis Centre) enjoys an increasing credit as a center of expertise regarding all aspects of solar activity and its impact on space weather. The SIDC also runs RWC Belgium, a Regional Warning Centre of the International Space Environment Service (ISES) and is a data analysis service of the FAGS. Together with the Centre for Plasma Astrophysics of the KULeuven, theoretical and numerical studies about solar activity and space weather are performed. *Digital access to archived data:* The aim of this pilot project is to preserve the historic scientific information contained in the astrophotographic plate archive of the ROB and in the aerial photographic archives of the NGI and the RMCA. The goal is to digitise with very high positional accuracy the information contained in the photographic plates, as well as the associated metadata, in order to make them directly usable for scientific research. This yields valuable information of long-term variability of some stellar objects. Another interesting application of this work is the computation, from these digitalized data, of planetary moon ephemerides. These computations are of high interest for the flybys of spacecrafts near these natural satellites. The ROB also performs the data treatment of some of these flybys.