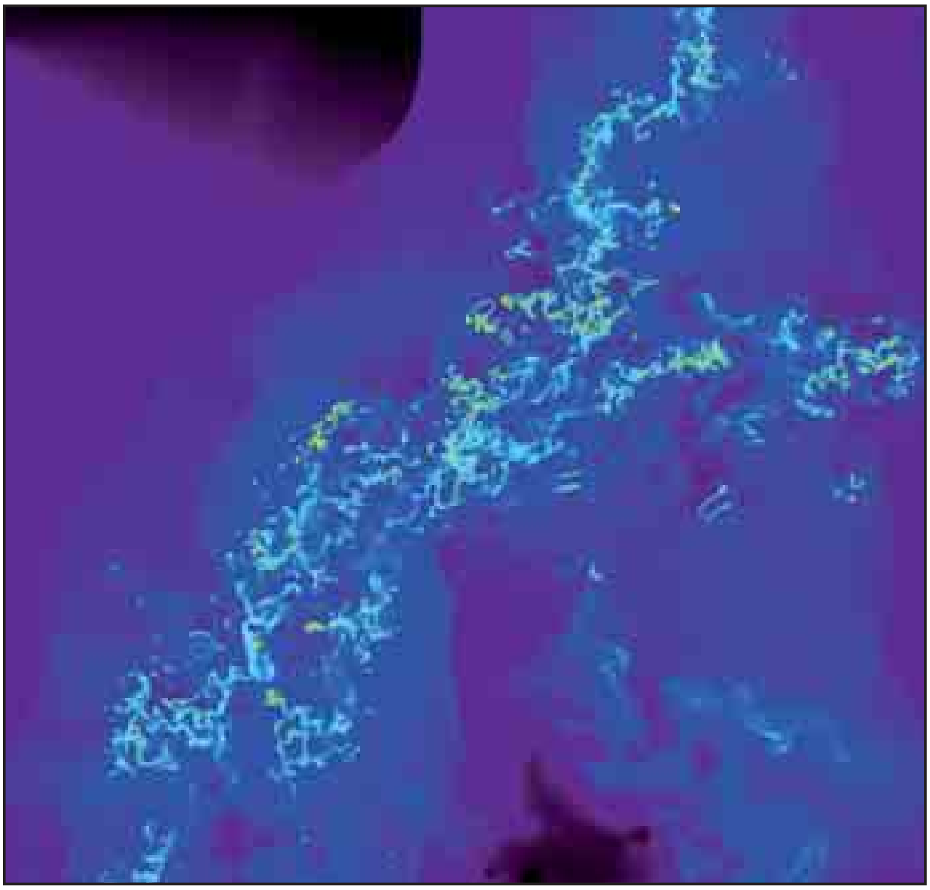
SAp

Service
d'Astrophysique

SAp



2004 - 2006

dapnia
cea
saclay

Cover: Numerical simulation of
the fragmentation of the interstellar
medium (see p. 38)
Credit CEA

Directeur de la publication : Pierre-Olivier Lagage
Mise en oeuvre : Michel Talvard
Principaux rédacteurs : Philippe André, Jean-Louis Auguères, Jean-Pierre Chieze, Bertrand Cordier, Anne Decourchelle, David Elbaz, Philippe Ferrando, Christian Gouiffès, Andrea Goldwurm, Pierre-Olivier Lagage, Olivier Limousin, Vincent Minier, Claude Pigot, Alexandre Refregier, Michel Talvard, Sylvaine Turck-Chieze.

Conception graphique et maquette : Christine Marteau
Réalisation et mise en page : Atefo
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Contents

Overview

The aim of astrophysics is to understand the evolution of the Universe (the formation and evolution of stars, planets, galaxies, galaxy clusters, etc.). Astrophysics is also concerned with testing the validity of current fundamental laws of physics under extreme conditions, far removed from conditions possible on Earth. The Astrophysics Division at CEA, by combining high-performance space- and ground-based instrumentation with an outstanding contribution to data interpretation, has consistently played a leading role in the astrophysics community.

Astrophysics: national and international context

Astrophysics is a fast-growing science because of the enormous potential it offers for making new discoveries. Many aspects of the Universe are unexplored and 96% of the energy content of the Universe is thought to be made of two components: dark matter and dark energy, the nature of which is still an open question.

Increasingly numerous and powerful ground- and space-based instruments are probing the Universe with greater angular resolution and sensitivity, across the entire electromagnetic spectrum. At the same time, numerical modeling has taken on an increasingly important role in astrophysics since astrophysical problems are complex and call upon various fields within physics.

Since the 1960s, astrophysics in Europe has become very well organized, with two organizations that are dealing with large infrastructures: ESA for space projects and ESO for ground-based projects. Prospects for the next 10 years are satisfactory with the ESA "2015-2025 Cosmic-Vision" plan and the ESO Extremely Large Telescope (ELT) project. It should also be stressed that astrophysics in France takes advantages of the French space agency, the 'CNES', which, in addition to its input to ESA, successfully develops scientific missions, often in partnership with other countries' national space agencies.

Astrophysics will also benefit from the growth in investment in large infrastructures that are not specifically dedicated to astrophysics, such as:

- large computing facilities, which are now coordinated in France by the GENCI agency ("Grand Equipement National pour le Calcul Intensif") set up in January 2007, and which should soon be coordinated at European level;
- high-power laser facilities such as the French LMJ ("Laser MegaJoules") project in Bordeaux, which will be able to reproduce in the laboratory plasmas similar to those encountered in various astronomical environments.

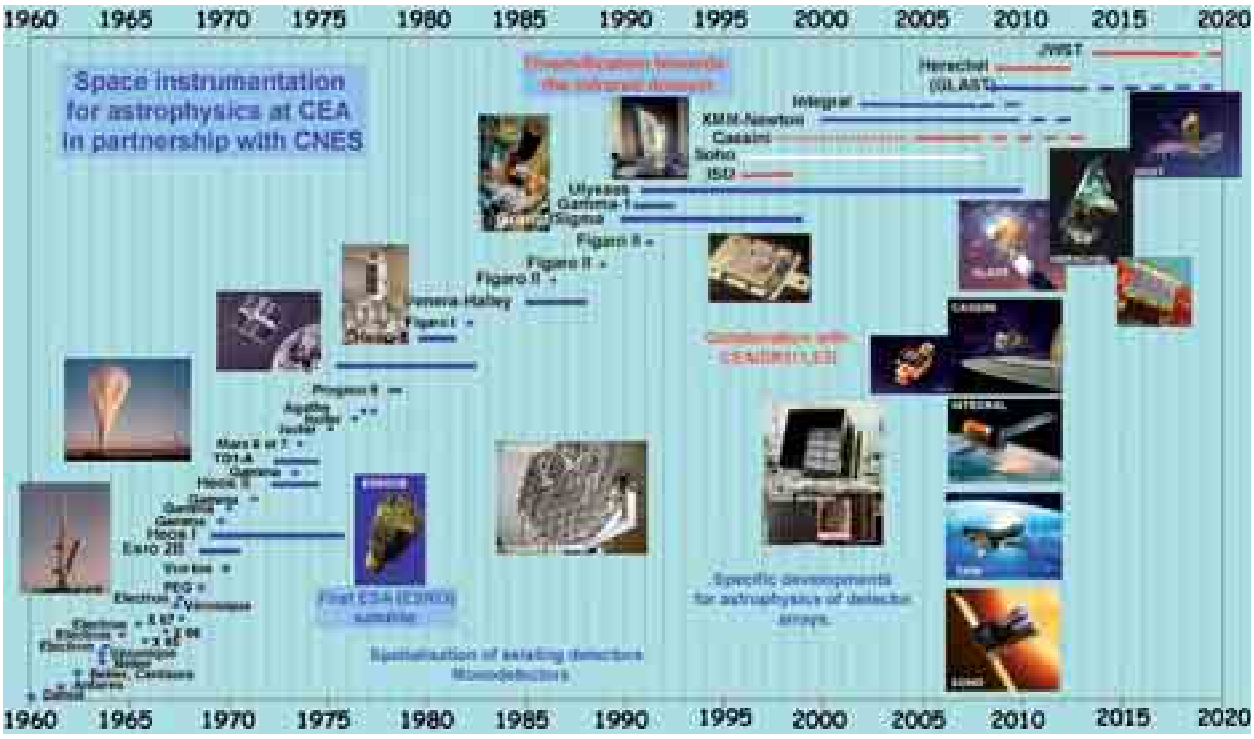

Figure 1. *Overview of space projects with the participation of the CEA Astrophysics division.*

History of astrophysics at CEA

Astrophysics activities at CEA really began to take off in the mid 1960s. Back then, the CEA role was to develop nuclear applications (both civil and military) and CEA already had wide experience in instrumentation for detecting X and γ radiation. At the same time, French space research was launched with the foundation of CNES in 1961. Since X and γ radiation from space are absorbed by the atmosphere, it was only natural that CEA and CNES should combine their expertise to develop high-energy astrophysics. SAp then became one of the first French space laboratories dedicated to astronomy and, in partnership with CNES, was involved in major astronomy projects investigating cosmic-rays (HEAO and Ulysse), γ radiation (CosB, Sigma and Integral) and X radiation (XMM) (see Fig. 1).

Since the 1980s, CEA has diversified and developed a high technology center. Astrophysics is a driver of technological development because the instruments used in astrophysics require exceptionally high performances, if they are to observe the faintest objects in the Universe. In parallel, it was realized that astrophysics had to become a multi-wavelength science. The Astrophysics Division has kept up with these trends and has been able to diversify towards a new sphere of excellence: the thermal infrared cosmic radiation, taking advantage of technological developments in detectors made for astrophysics application at CEA Grenoble's LETI laboratory. The Astrophysics Division consequently took charge of the development of the Isocam camera on board of the ISO satellite (November 1995 – May 1998), participated in the US led CIRS instrument on board of the Cassini space probe (launched in 1997 and entered into orbit around Saturn on 30 June 2004). Another diversification in the 1980s has been our involvement in the Soho/Golf helioseismology instrument launched in 1995 and in operation ever since.

In 2005, we celebrated 40 years of astrophysics space research at CEA (Fig. 3).

Astrophysics today at CEA

Since 1992, the Astrophysics Division (SAp) has been one of the administrative units of Dapnia, the "laboratory for research into the fundamental laws of the Universe".

On October 1, 2007, SAp was hosting 171 staff members, including 96 CEA permanent staff (51 physicists including 4 with administrative duties, 28 engineers, 17 technicians including 4 administrative), together with 15 permanent staff from the University of Paris Diderot (7 physicists) and CNRS/INSU (6 physicists and 2 technicians). The latter, together with all the CEA physicists but 6, work at the AIM "Astrophysics Interaction Multi-scale" laboratory, based within SAp in Saclay. In addition to these positions, 60 people with non-permanent positions (28 students, 26 post-doctoral students and 6 engineers) work full-time at SAp.

While the number of permanent staff positions has been kept constant in recent years, there has been a significant increase (+21) of non-permanent positions as compared with the situation at the time of the 2001-2003 report; we have been able to attract more students (12 new students are starting work on their thesis in 2007), to make use of the new French research agency (ANR) to secure funding for post-doctoral positions (see Table below); we have also hired engineers on non-permanent positions supported by projects, mainly JWST/MIRI.

ANR proposal title	Proposer	Field	Amount (k€)
ARTEMIS (2005)	Ph. André	Instrumentation	450
HORIZON (2005)	R. Teyssier	Numerical modeling	156
D-SIGALE (2006)	H. Aussel	Galaxy evolution	135
MAGNET (2006)	E. Audit	Numerical modeling	170
SINeRGHY (2006)	E. Audit	Numerical modeling	320
VORTEXPLO-SION (2006)	T. Foglizzo	Supernova explosion	150
ACCELRSN (2007)	A. Decourchelle	Cosmic-ray acceleration	121
DESIR (2007)	E. Daddi	Galaxy evolution	137
DUSTY DISKS (2007)	S. Charnoz	Circumstellar disks	47

Table 1. *SAp projects funded by the new French research agency (ANR)*

SAp's strategy is based on 3 activities:

- an instrumental activity in conjunction with two technical divisions of Dapnia (SEDI and SIS);
- an observational activity;
- a modeling activity, which relies heavily on computer modeling.

The fact that these three activities have been developed together at SAp is a huge advantage, which explains the Division's incredible dynamism. Indeed, these three activities are mutually enriching. The instrumental activity makes it possible to obtain substantial guaranteed-time observations and contributes to expertise in the knowledge of instrument limitations. The modeling activity

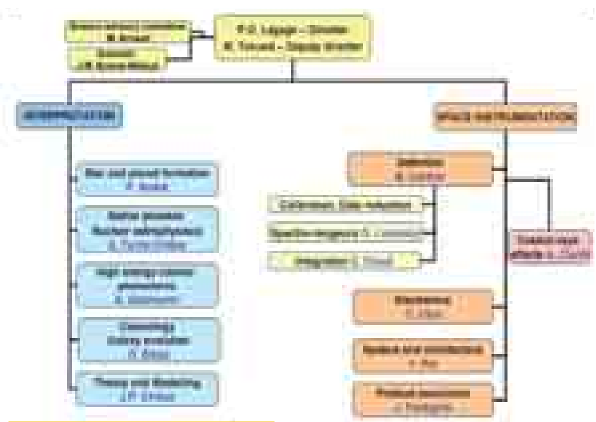

Figure 2. *SAp organization chart.*

makes it possible to choose the best observables in order to correctly analyze data, and helps preparing for future projects. Scientific excellence is a key factor in being awarded contracts for future projects.

Since 2002, SAp has been organized into nine units, five dedicated to the study of a particular branch of astrophysics, and four dedicated to space instrumentation – including one detection unit, uniting physicists, engineers and technicians (see organization chart in Fig. 2).

Main research areas

Current research at SAp is focused on the following subjects:

- energy content of the universe (dark matter and dark energy)
- structuration of the Universe (star formation rate history, galaxy collisions, galaxy clusters, etc.);
- star and planet formation (fragmentation of molecular clouds, first stages of star formation, circumstellar disks, Saturn's rings and planet migration);
- stellar and laboratory plasmas (dynamical processes in the Sun and in stars at various evolutionary stages, etc.);
- compact objects (supernova explosion, accretion and jets, microquasars, X-ray binaries, galactic center, etc.);
- cosmic rays (acceleration in supernova remnants, in synchrotron nebulae, interaction with interstellar matter, etc.).

Figure 3. *Poster celebrating 40 years of space research at CEA.*

Many different subjects are studied, which is an advantage given the "multi-scale" approach developed at the AIM laboratory. This approach consists in:

- no longer considering an object in isolation but taking its environment into account (for example, star formation in galaxies and the filament-like structure of the Universe);
- putting in perspective the physical processes at work in various systems on different scales (Saturn's rings and circumstellar disks; microquasars, active galaxy nuclei and γ-ray bursts).

Such an approach is a way to enhance dialogue between astrophysicists working in various fields within AIM.

Instrumentation

Our technical expertise is focused on space projects. Such expertise has been built up through the various space projects we have been involved. We are one of the few European astrophysics research laboratories that have the capacity to manage the development of a space instrument. In terms of hardware, we are specialized in the technological development of large imagers, which puts SAp in an especially strong position in French Astronomy research. All our space projects are conducted in partnership with CNES, which supports half the development costs of space instruments.

Instruments in operation

The table 2 shows the list of instruments with SAp involvement currently used by astrophysicists at SAp.

INSTRUMENT		Field
SOHO-GOLF (visible)	Since 1995	Solar interior by heliosismology
CASSINI-CIRS (Infrared)	2004 - 2012	Saturn rings
XMM-EPIC (X-rays)	1999 - 2012	SN remnants ; galaxy clusters
INTEGRAL-IBIS and SPI (γ-rays)	2002 - 2012	Compact objects; Galactic center
GLAST (γ-rays)	2008 - 2018	Sources catalog Interstellar medium
HESS (γ-rays)	2004 - 2014	Cosmic-ray acceleration
VLT-VISIR (Infrared)	2004 - 2009	Circumstellar disks
CFHT-MEGACAM Visible	2004 - 2008	Wide and deep fields

Table 2. *Instruments in operation.*

Instruments in progress

During the period from 2004 to 2006, we had to deal with the issue of achieving our contribution to the PACS (see Fig. 4) and SPIRE Herschel instruments. Both these projects were extremely challenging. The exceptional motivation and personal commitment of the staff working on these projects were key factors in the successful development of the projects. These projects are discussed in detail in Chapter II. We are now eagerly waiting to see first light in space, expected at the end of 2008.

Figure 4. *Flight model of the HERSCHEL-PACS photometer delivered to MPIA mid 2006. Novel bolometer arrays for the sub-millimeter camera were developed by the LETI for this instrument.*

We are currently involved in the manufacturing phases of two major projects (see Chapter VIII). The first one is our contribution to MIRI, the mid-Infrared instrument of the JWST, which will be the successor of the Hubble Space Telescope in 2013 (see Fig. 5). The second one phase is the ArTeMiS project. As outlined in the 2001-2003 report, it was essential to find a way of capitalizing on the successful developments of novel sub-mm bolometer arrays for the Herschel-PACS instrument and develop a wide-field sub-mm camera for ground-based telescopes. We have succeeded in funding this project, which has been selected by the ANR. A prototype has already been tested and successfully installed early in 2007 on APEX, a German, Swedish and ESO telescope in Chile (see Chapter "Experiments under progress"). This project is complementary to the Herschel project. Having access to the PACS, SPIRE and ArTeMiS instruments will place us in a unique position to develop our programs on star formation and galaxy evolution.

Figure 5. *Final inspection at SAp of the validation model of the JWST-MIRI imager instrument, just before delivery to Rutherford Appleton Laboratory (May 2007).*

Instruments under study

All our space programs are the result of winning competitive calls issued by space agencies. We have been very active and successful, as never before, during the last few years. In 2003, we answered the call for proposals from CNES. Three out of our 4 proposals as Principal Investigator (PI) have been selected for competitive phase 0 studies: ECLAIRS in the CNES microsatellite line, DUNE in the minisatellite line and Simbol-X in the formation flight mission line.

Since then, ECLAIRS has moved to a French/Chinese consortium minisatellite mission named SVOM and has now been selected for Phase B studies (2007-2008). Simbol-X was the only one out of 4 formation flight missions to be selected for Phase A studies. Italy joined the consortium and is contributing to Phase A studies. Phase B should start in 2008. After a Phase 0 assessment with CNES, it appears that DUNE would cost more than what was feasible for a CNES-led mission. The DUNE concept was therefore internationalized and proposed to ESA within the framework of the ESA's "Cosmic Vision 2015-2025" call relative to medium-sized projects. We also proposed another project to ESA, the DynaMiccs mission to study the Sun. One of the instruments used for this mission is the Golf-NG seismology instrument, which has been prototyped (see Chapter "Experiments under progress").

Space mission	Collaboration	Scheduled launch
SVOM/ECLAIRs (γray burst)	France - China	2012
Simbol-X	France - Italy	2014
DUNE (Dark Universe)	CNES Phase 0 done. Submitted to ESA under Cosmic Vision framework.	2017

Table 3. *Mission under study under SAp leadership.*

Concerning instrumentation for ground-based telescopes, our plans are twofold: first, to put forward the engineering innovation achieved with the ArTeMiS project to propose new instrumentation for very large sub-millimeter ground telescopes (IRAM, LMT, CCAT, etc.); and second, to be involved in developing mid-infrared instrumentation for the future European ELT.

Research and development strategy

For previous projects such as ISO/ISOcam, INTEGRAL/ISGRI and Herschel/PACS, we were developing innovative detector arrays in the course of project development. This was very challenging and gave us a very hard time. CNES, well aware of the risks associated with this approach, has organized itself to help in preparing technologically challenging experiments and thus significantly increased its budget for Research and Technology (R&T).
We have subsequently taken part in CNES R&T programs in preparation for the detection focal plane of the Simbol-X formation flight mission. Excellent results have already been obtained. We are now in a satisfactory position for ensuring that the scientific requirements of the Simbol-X focal plane detector will be met. We are also developing detectors for sub-mm applications in space (SPICA mission), together with X-ray spectral-imager developments for space (XEUS mission). In other words, the SAp R&T program can be presented as follows (see Chapter "R&D Programs in Spectro-Imagers for Astronomy"):

- a program to develop Cadmium Telluride (CdTe) pixels for X and γ spectral imagers (program in conjunction with Dapnia/SEDI);
- a program to develop a cryogenic bolometer adapted to the X-ray spectro-imager (program in conjunction with CEA/DRT/LETI and Dapnia/SEDI);
- a program to develop bolometer arrays for imagers in the sub-mm range (program in conjunction with CEA/DRT/LETI). In parallel, and in conjunction with Dapnia/SIS, we are studying the quality of the Dome C site in Antarctica with a view to installing a future sub-mm facility.

Theory and modeling

Modeling, especially numerical modeling, is an activity which has developed at a fast pace in recent years. Several high-performance source codes have been developed at SAp. This expertise has enabled our teams to make full use of the computing facilities offered at CEA, as well as at other national and international supercomputer centers where time is allocated on a very competitive basis. SAp's know-how in this field has also been acknowledged in France with the award of three ANR grants. Fast growth in this activity and the highly technical skills needed to use modern massively parallel supercomputers make it necessary to set up teams consisting of numerical-astrophysicists and software engineers. A first step toward setting up such a team was made through the CoAst (Computational Astrophysics) project involving 4/5 engineers in software development and database management from Dapnia/SEDI (see Chapter "Modelling and Numerical Simulations"). In order to keep up in this very competitive field, the efforts to have a local computer about ten times smaller than the national supercomputers should be pursued.
Note that numerical codes developed at SAp are also employed to interpret data from laboratory plasma experiments conducted using high-power lasers for astrophysical purposes (shocks, instability, etc.). We are in a very good position at SAp to ensure that astrophysics enjoys the full benefits of major CEA investment in laser and computing facilities.

Scientific production

Between 2004 and 2006, 413 papers were published in high-level journals. Of these, 22 were published in Science or Nature (8 based on Cassini observations and 6 on Hess observations); during the first six months of 2007, 4 papers were published in Nature and Science. These papers, with SAp astrophysicists as first authors, are enlightened below (Fig. 6-11).
As for prizes, the French Society of Astronomy and Astrophysics (SF2A) awarded S. Corbel (AIM-UP7) the 2006 SF2A prize for outstanding work by a young teacher/researcher. The French Physics Society (SFP) awarded the Jean Perrin prize to R. Lehoucq (AIM-CEA) in 2004 and to A. Brahic (AIM-UP7) in 2007, in acknowledgement of their outstanding contribution to making science accessible to a broad public.

Figure 6. "The nature of soft gamma-ray emission from the Galaxy", F. Lebrun et al., Nature 428, 293-296 (18 March 2004).

It should also be pointed out that two young astrophysicists from AIM-CEA (F. Brun and E. Daddi) have successfully passed (September 2007) the first stage of the selection process for a European Starting Grant, (a new feature of the 7th European Framework Program).

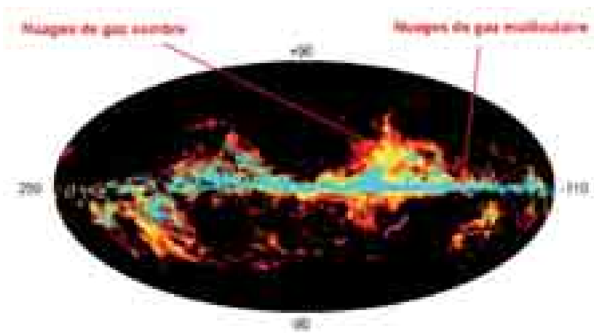

Figure 7. "Unveiling extensive clouds of dark gas in the solar neighborhood", I. Grenier et al., Science 307, 1292-1295 (25 February 2005).

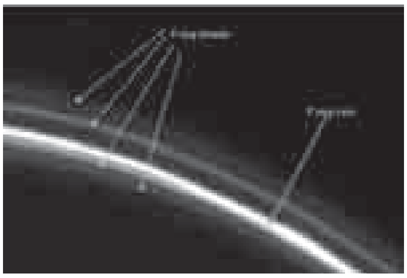

Figure 8. *"Cassini discovers a kinematic spiral ring around Saturn", S. Charnoz et al., Science 310, 1300-1304 (25 November 2005).*

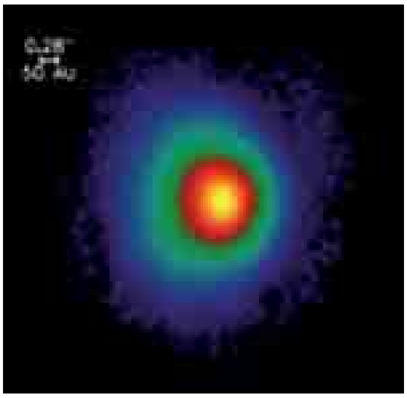

Figure 9. *"Anatomy of a flaring proto-planetary disk around a young intermediate-mass star", P.-O. Lagage et al., Science 314, 621-623 (27 October 2006; published online 27 September 2006).*

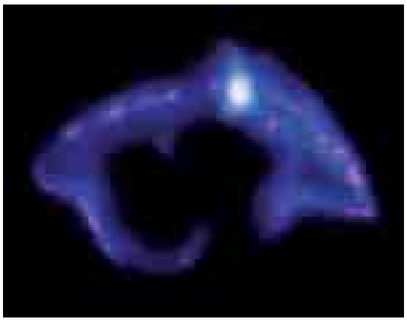

Figure 11. *"Missing mass in collisional debris from galaxies", F. Bournaud et al., Science 316, 1166-1169 (25 May 2007; published online 10 May 2007).*

Outreach

The Astrophysics Division, aware of the interest from the general public for Astronomy and of the need to popularize science in particular trough the youngest generations, is making a major effort to make its activities accessible to a broad public. Descriptions of the various projects it is involved in and outlining major scientific results using various supports are part of this effort. The internet site of Astrophysics Division (http://www-dapnia.cea.fr/Sap/) has been completely redesigned in 2006.

Figure 10. *"Tracking solar gravity modes: the dynamics of the solar core", R A. García et al., Science 316, 1591-1593 (15 June 2007; published online 2 May 2007).*

Organization of the report

The report is organized as follows. The following chapter is devoted to the major achievements obtained within the framework of the PACS and SPIRE instrumentation projects for the ESA Herschel mission. The five subsequent chapters are devoted to SAp's main scientific results. Chapter VIII deals with the projects currently under development. Projects under study and R&T are described in Chapters IX and X respectively. Information on human resources, publications, teaching and outreach activities, etc. is given in the Appendixes

HERSCHEL AND THE PACS & SPIRE PROJECTS

The Infrared Space Observatory HERSCHEL is one of the "cornerstone" projects of ESA. Its launch by the carrier Ariane V is planned for the second half of 2008. HERSCHEL will operate for more than three years from the Lagrange L2 point located 1.5 million km antisunwise away from the earth. It measures 7 m high and 4.3 m across with a launch mass of 3.25 tonnes.

The main scientific objective of HERSCHEL is to learn more about the formation and evolution of galaxies, star formation, and the physical and chemical properties of the interstellar medium. It will also be used to study planets, comets, etc.

Working in consortia with CNES and CNRS laboratories, the CEA helped develop PACS[1] and SPIRE[2], two of the three onboard instruments. PACS and SPIRE are two spectral imagers using complementary wavelengths, 57-210 µm and 200-670 µm respectively.

Figure1. *Herschel satellite (artist's rendering).*

Role of SAp

The Astrophysics Division oversees the CEA's contribution, which primarily includes the supply of control and acquisition electronic units for SPIRE and the PACS photometer (3 units and their power supplies) as well as the focal plane for the PACS photometer, based on matrix bolometer detectors developed by LETI/LIR and for which cooling to 300 mK is performed by a cryo-refrigerator developed by the SBT[3] at CEA Grenoble.

From 1998 to 2000, SAp worked on the R&D for the bolometer technology LETI has now developed. In 2000, the CEA's proposal was selected for the focal plan of the PACS photometer.

At that point, a CEA HERSCHEL team working conjointly on SPIRE and PACS was organised. This took advantage of the similarities between the two instruments and facilitated the sharing of resources and skills. In 2003 and 2004, this team had up to 70 direct partners (DAPNIA/SAp/SIS/SEDI, LETI and SBT) organised in groups according to specialty: Science, Management, Systems, Product Assurance, Electronics, Thermal, Mechanics, Cryogenics, Microelectronics, Software, Development-Integration-Tests, etc. All partners drew on industry groups for certain specialised tasks (mechanical constructions, cabling, power supply, etc.).

Development

Several models for each subsystem (focal plane, electronics) were built to validate the design and qualify "deliverable" objects considering the environments they would encounter before, during and after launch.

The three electronic flight units required development and construction of 33 novel circuit boards. For each of these units, in addition to the flight model, a structure and thermal model, and two qualification models were produced. All together, these models require 65,000 components. The power supply units were built by industry groups according to SAp specifications.

Building the focal plane for the PACS photometer was a major challenge, but the countless difficulties were all overcome.

Figure 2. *One of the two SPIRE electronic flight units coupled with its power supply.*

[1] PACS: Photoconductor Array Camera and Spectrometer
[2] SPIRE: Spectral and Photometric Imaging REceiver
[3] SBT: Service des Basses Températures

The bolometer matrices designed and produced by LETI were a world first in matrix technology and the number of detectors deployed (2560 implemented overall). The detection component has two stages: detection + amplification at 300 mK and amplification at 2 K. A novel detector housing design by SAp enabled thermal and mechanical coupling with multiple constraints: reversible assembly, thermal insulation (10 µW for all designs) and mechanical strength that would resist launch conditions.

Figure 3. *The "blue" focal plane with its 8 matrices of 256 bolometers developped at LETI.*

Cooling to 300 mK from the 2K supplied by the satellite is achieved by a He3 adsorption cryo-refrigerator designed and built at the SBT in Grenoble. It provides 48 hours of autonomy between two regenerations.

Figure 4. *2K-300 mK cryo-refrigerator developed by the SBT.*

The photometer's mechano-thermal structure was designed at the SAp. It ensures the mechanical strength of the various components (detector systems, optical filters, cryo-refrigerators, electronics and connectors) as well as the interface with the other PACS components. In addition SAp has designed and developed many significant cryogenic test benches as well as assembly tools (especially for the PACS focal plane). Tools for electronics testing have also been designed and implemented by SAp and SIS (simulators).

Figure 5. *Qualification model for the PACS photometer.*

Performance

Instrument performance is most important for electronics + detector couplings.
For SPIRE, because the detectors were provided at a late phase by JPL, only the performance of the electronic units was checked before delivery. The detectors were later coupled to these units without any major problems, confirming the excellent performance of the electronics.

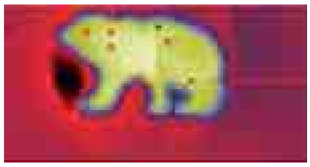

Figure 6. *Test pattern for the focal planes of the PACS photometer. The test pattern (Pacsy, the PACS mascot honouring the Big Dipper) is lighted by an infrared heat source, and the camera records the signal. The pattern's movement makes it possible to check signal homogeneity for the entire detector.*

For PACS, it was possible to check overall performance (detectors + electronics) before delivery using test capabilities implemented at SAp. The analyses showed that the expected performance levels were in fact obtained; they were even slightly superior to those estimated from tests at Saclay. The PACS photometer specifications were thus respected, and delivery was made with a high degree of confidence regarding PACS integration.

Flight model deliveries

The flight models were delivered with success to MPE[4] (PACS) and to RAL (SPIRE)[5] between June and August 2006.
After integration and testing, the instruments were delivered to ESA, in May 2007 for SPIRE and in July 2007 for PACS. ESA will now oversee the final phases of verification prior to launch

[4] MPE: Max Planck Institut für extraterrestrische Physik (GE)
[5] RAL: Rutherford Appleton Laboratory (UK)

The formation of stars and planets

For several years the astrophysicists in the Star & Planet Formation Laboratory (LFEP) have carried out pioneering observational research on the early stages of star formation in interstellar clouds. The advent of the Herschel Space Observatory and the ground-based ArTéMiS submillimetre camera in the near future, as well as the increasing use of numerical simulations, have provided additional new impetus for these studies. Star formation research is supplemented by work on the structure of protoplanetary discs in an effort to shed light on the conditions required for planet formation. Closer to home, spectacular advances have been made in our understanding of planets and the rings of Saturn using the Cassini probe.

Simulations of the formation of interstellar clouds

The atomic hydrogen (HI) component of the interstellar gas is fundamental to our understanding of the structure and evolution of the interstellar medium. While, for many years, the multiphase nature of this gas and the resulting simulation difficulties have made it impossible to investigate satisfactorily, current computers are now enabling significant advances to be made. It is now possible to make high resolution simulations of two-dimensional turbulent and multiphase flows (cf. Audit & Hennebelle 2005). These have led to a better understanding of the consequences of these two gas flow phenomena and their influence on the formation of molecular clouds. The first stage in the formation of a molecular cloud appears to be the production of cold condensations of atomic gas in the so-called cold neutral medium (CNM). This study has made it possible to establish a link between the number of formed condensations and the turbulence, to characterise the mass spectrum of formed structures [$N(m) \sim m^{-1.7}$], and to propose semi-analytical models to explain this behaviour.

The formation of stars in interstellar clouds and the orgin of the IMF

The initial mass of a star is a key parameter that determines the star's lifetime. A star with the mass of the Sun has a life of around 10 000 million years, while stars with ten times this mass have a life of only a few million years. The mechanisms that lead to star formation and determine stellar masses are highly debated within the scientific community. Are stars born independently of each other, and are their masses pre-determined by the initial physical conditions in the parent cloud ? Or, alternatively, do they form from the interaction and coalescence of embryonic protostars following the fragmentation of the parent molecular cloud? Why do some stars attain a much higher mass than their siblings? How does this happen and over what kind of timescale?

The astrophysicists in the LFEP laboratory are attempting to provide answers by addressing one of the major unsolved problems in modern astrophysics; the origin of the mass distribution of newborn stars, the Initial Mass Function (IMF). The astrophysicists of the LFEP Laboratory are

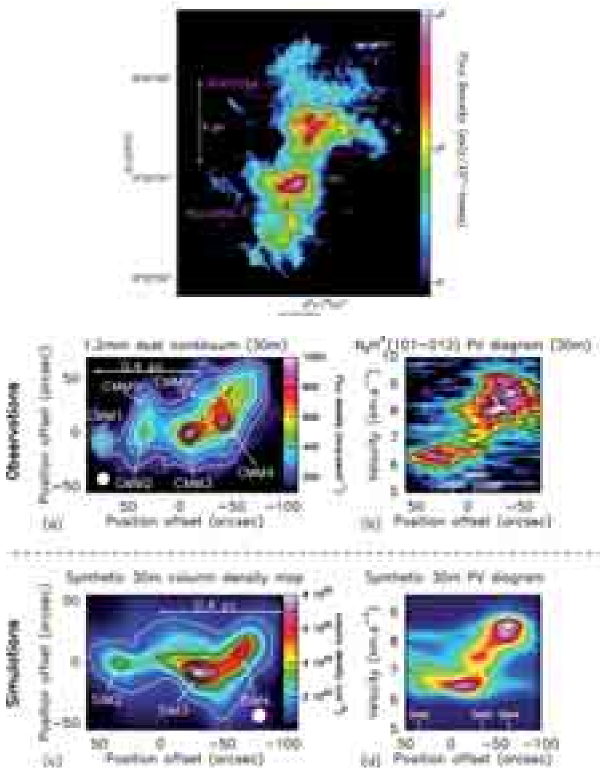

Figure 1. *Above : Map of the 1.2 mm continuum emission in the NGC 2264 C & D cluster-forming clumps taken with the MAMBO-2 bolometer array on the IRAM 30m telescope (Peretto, André, Belloche 2006). Below: (a): Blow-up 1.2 mm dust continuum image of the NGC 22264-C cluster-forming clump. The main protostellar cores are labelled CMM. (b): Position-Velocity diagram along the axis passing through CMM2, CMM3 and CMM4. (c): Synthetic image of the column density distribution obtained from hydrodynamic simulations. The fragments are labelled SIM. (d): Position-Velocity diagram obtained from the simulations along an axis passing through SIM2, SIM3 and SIM4. Note that the numerical simulations [(c) and (d)] are able to reproduce the observations [(a) and (b)] remarkably well (from Peretto, Hennebelle, André 2007).*

investigating molecular clouds in our galaxy by detecting molecular line emission from interstellar gas and observing the thermal continuum emission from solid dust particles associated with the gas. Observations of regions in which the formation of solar-type stars is taking place, either alone or in combination with more massive stars, suggest that the processes underlying the formation and growth of stars may vary depending on the local environment. In low-mass star-forming regions, the IMF appears to be almost entirely determined at the pre-stellar stage, corresponding to the fragmentation of the parent cloud into self-gravitating condensations (Motte et al. 1998, André et al. 2007). In more massive star-forming complexes, the observations indicate that massive stars (of mass between 10 and 100 solar masses) form very rapidly, possibly as a result of a highly dynamic process (Motte et al. 2007).

More precisely, the work currently being carried out by the LFEP laboratory in the field of star formation is aiming to explain how interstellar gas clouds contract and collapse to form protoclusters which then fragment to form pre-stellar cores and eventually protostars. Observations in the infrared have shown that the vast majority of stars in our Galaxy forms in clusters. However, these observations only provide data on those stars that have already acquired most of their mass. In contrast, the precursors of stars in molecular clouds (prestellar cores and young `Class 0' protostars) are very cold objects (~10 K) which emit most of their radiation at far-infrared to submillimetre wavelengths. This wavelength regime can be investigated with ground-based radio telescopes such as IRAM and APEX, with the Herschel Space Observatory in the near future, and subsequently with the ALMA large millimetre interferometer currently being built by ESO in Chile.

The earliest stages in the formation of solar-type stars have only been observed in the past twenty years or so and are still very poorly understood. The corresponding astrophysical objects include prestellar cores on the verge of gravitational collapse and protostars at the beginning of their accretion/ejection phase (cf. André et al. 2000 and Ward-Thompson et al. 2007 for reviews). These initial phases are critical as they must contribute to some degree to the origin of the stellar IMF. Firstly, the reservoir of mass available for the formation of a solar-type star is largely determined at the prestellar stage and, secondly, this mass is acquired by the protostar during the protostellar accretion/ejection phase, i.e., prior to the pre-main sequence 'T Tauri' phase. A recent detailed study of the dynamics of the nearby rho Ophiuchi cloud (André et al. 2007) has confirmed that the IMF of solar-type stars is largely determined by pre-collapse cloud fragmentation at the prestellar stage, as opposed to `competitive accretion' at the protostellar stage.

While the early stages of the formation of solar-type stars are still poorly understood, the corresponding stages for massive stars (10 to 100 solar masses) remain to be discovered. We have no understanding whatsoever of the high-mass analogues to prestellar cores and Class 0 protostars. Do they exist? What is their lifetime? What are their characteristics? New molecular cloud complexes have been identified by members of the LFEP laboratory based on a near-infrared extinction map of the entire Galaxy derived from 2MASS data. The largest of these complexes is Cygnus X. For a long time thought of as a collection of independent molecular clouds, a detailed study of the interactions between these clouds and the stellar clusters has now shown it to be a single large cloud (Schneider et al. 2006). Cygnus X is therefore the closest complex of molecular clouds capable of actively forming numerous massive stars. An extensive millimetre continuum survey of Cygnus X (Motte et al. 2007) has shown for the first time that the early phases of massive star formation (prestellar cores and protostars) are quantitatively different from the initial stages of low-mass star formation observed in nearby molecular clouds. The formation of massive stars takes place rapidly, so much so that massive prestellar cores are at best transient objects with very short lifetimes.

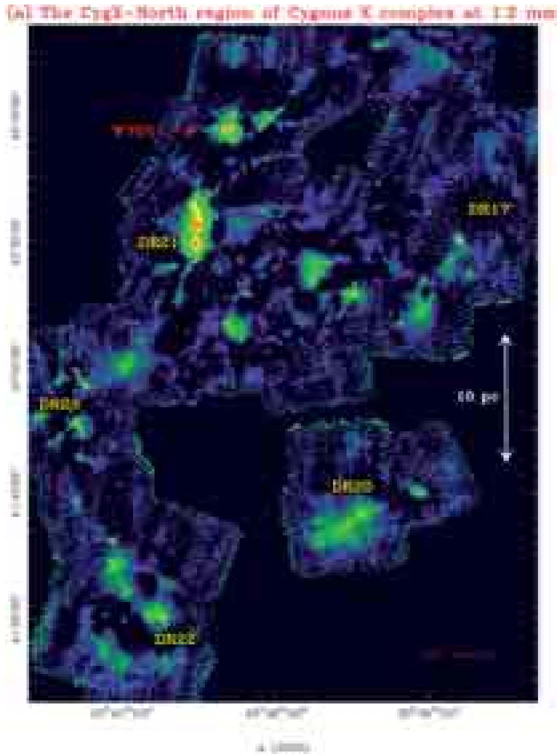

Figure 2. A 1.2 mm continuum image of the Cygnus X molecular cloud complex taken with the MAMBO-2 camera on the IRAM 30m telescope. The massive protostars (compact sources covering ~0.1 pc) can be seen embedded in molecular clouds (emission extending over 0.5 - 5 pc). These protostars were identified using a multi-resolution technique based on the MRE software package developed by Jean-Luc Starck. A statistical study of Cygnus X has shown that there are probably no massive prestellar cores and that the formation of massive stars is much more dynamic than that of the solar-type stars in nearby molecular clouds. (From Motte et al. 2007).

An alternative approach to studying the formation of massive stars is to identify high-mass star formation sites using an unambiguous indicator, such as MASER emission from methanol molecules in molecular clouds. Astrophysicists from the LFEP laboratory are actively involved in the systematic identification of sites emitting methanol masers. At the present time, 520 such sites have been found, each of which appears to be a site of massive star formation (Pestalozzi, Minier & Booth 2005). The massive cloud fragments identified in the immediate vicinity of these methanol masers appear to be the precursors of massive star clusters (Minier et al. 2005; Hill, Burton, Minier et al. 2005; Longmore, Burton, Minier et al. 2006).

Studies of the early stages of massive star formation and of their association with various tracers of protostellar activity, such as protostellar outflows and methanol masers, have made it possible to propose a preliminary evolutionary sequence for high-mass young stellar objects. Infrared-bright protostars and, on a larger scale, infrared protoclusters appear to be preceded by a class of submm-only objects that may be the high-mass analogues to solar-type Class 0 protostars.

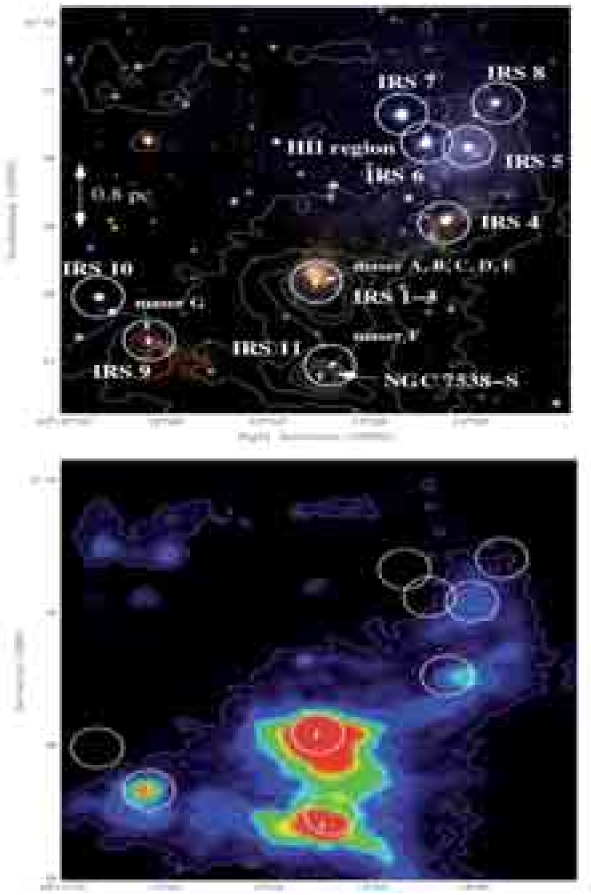

Figure 3. *Above: A 2 µm image of NGC7538, a region where the formation of massive stars is taking place. Below: A 1.2 mm image taken by the MAMBO-2 camera on the IRAM telescope. Three new protoclusters have been detected in the south of the complex where the infrared emission is weak and the (sub)millimetre emission is strong. Massive protostars (+), identified by the detection of methanol masers, are associated with each cluster. (From Pestalozzi, Minier et al. 2007).*

The star formation research of the LFEP laboratory has strong ties with two European-scale instrumental projects, the Herschel Space Observatory and the ArTéMiS bolometric camera. The Herschel telescope is a European Space Agency project dedicated to making observations of the Universe at far-infrared and submillimetric wavelengths. When Herschel is launched in 2008, its 3.5 m diameter mirror will make it the largest telescope ever to have been sent into space. Herschel will carry three instruments, PACS, SPIRE and HIFI. DAPNIA/SAp is responsible for the construction of the PACS photometric camera and its associated electronics, together with some of the electronics for the SPIRE camera. Herschel will dedicate a large fraction of its time to studies of the star formation process. One of the main goals in this area is to gain insight into the problem of the origin of the IMF. Two major guaranteed-time key programmes are coordinated by researchers in the LFEP laboratory (cf. http://starformation-herschel.iap.fr/): a) a full mapping survey of nearby molecular clouds in the Gould Belt with the SPIRE & PACS cameras, and b) a survey of more distant complexes in the Galactic Plane where massive stars are forming. The high sensitivity of the imaging instruments, coupled with the spatial resolution provided by the 3.5 m mirror, will enable a complete survey of prestellar cores and protostars to be made in nearby clouds. The Herschel observations will provide direct estimates of physical quantities such as temperature and mass for the detected objects, which in combination with other observations will advance our understanding of the origin of the IMF.

The astrophysicists in the LFEP laboratory are also responsible for the scientific aspects of the ArTéMiS project. The aim of this project is to build a large-format submillimetre camera using monolithic matrices of bolometers to be operated on a ground-based telescope such as APEX on the ALMA site in Chile. The main scientific driver of ArTéMiS is the study of embedded star formation throughout the Universe. The camera will make use of the novel technology developed by CEA for the PACS instrument on Herschel. A prototype 450-micron camera was successfully tested in March 2006 at the focus of the Kosma 3m telescope (Gornergrat observatory, Switzerland) and in March 2007 on the APEX 12m telescope. In particular, a first 450-micron image of the massive star-forming region NGC6334 could be taken at APEX (see Chapter VIII-2).

Protoplanetary discs and the formation of planets

The astrophysicists of the LFEP laboratory are also studying the protoplanetary discs that lead to the formation of exoplanets. These are planets orbiting stars other than the Sun. Around 200 candidate exoplanets have been discovered in the past decade. These planets are formed in the discs of gas and dust surrounding young stars, but the exact circumstances of their formation are still unknown. In an attempt to understand this process, the astrophysicists are studying protoplanetary discs in the mid-infrared (8.6 microns). At this wavelength, the radiation is dominated by emission from complex molecules known as polycyclic aromatic hydrocarbons (PAH) distributed within the dust. These molecules absorb light from the central star and re-emit infrared radiation that can be used to establish an accurate map of the surface of the disc.

The work of the LFEP laboratory in relation to these discs is carried out using the VISIR instrument (VLT Imager and Spectrometer for the mid-Infrared), installed on the ESO VLT telescope in Chile. This instrument was designed by

DAPNIA and Astron (Netherlands). Located at the focus of a giant 8 metre diameter telescope, it can distinguish details with a resolution unmatched by any other current imaging instrument. Recent images taken with VISIR have revealed a large disc around the star HD97048 which is a good example of a protoplanetary disc at an early stage in its life (Lagage, Doucet, Pantin et al. 2006).

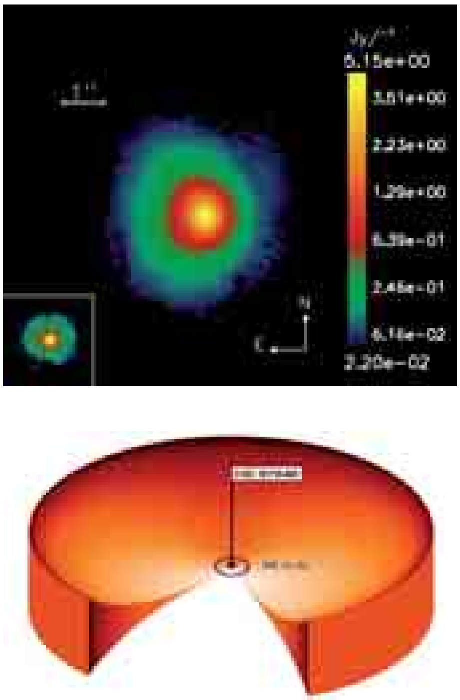

Figure 4. Above: VISIR false colour image of the infrared emission at 8.6 µm from the circumstellar matter around the star HD 97048. A comparison with the image of a star without such a disc (insert at the lower left) shows that the star HD97048 is surrounded by a disc extending outwards up to at least 370 astronomical units. Below: Schematic representation of the inferred geometry of the thick, flaring disc around the star HD97048. The disc lies at an angle of 42° when viewed from the Earth and contains a mass of dust equivalent to 40 times the mass of the Earth and a total mass of gas and dust around ten times greater than the mass of Jupiter. The central region (40 AU, i.e. the size of the Solar System as far out as Pluto), which may already contain planets, is still not observable (in blue). (From Lagage, Doucet, Pantin et al. 2006.).

Planets and the rings of Saturn

Finally, the researchers in the LFEP laboratory are also working on planets within the Solar System, especially the rings of Saturn. The Cassini-Huygens space probe has been in orbit around Saturn since the 30th of June 2004. The Composite Infrared Spectrometer instrument (CIRS), built by an international consortium including DAPNIA, has measured the temperature of the rings to an unprecedented accuracy on both the sunlit and dark sides. These initial measurements have revealed an astonishing fact. The rings seem to have identical temperatures on both the sunlit and the dark sides. This surprising result has led to a better understanding of the nature of the particles which make up the rings.

The Pioneer and Voyager missions had already revealed the infinite variety of features within the rings, typical of a 'fractal' structure. The arresting images from the Cassini mission have shown them to consist of an enormous number of light and dark tracks like the grooves in a vinyl record. In theory, if the rings where isolated form all external influences, they should be totally homogenous, spreading out gradually with no internal structure. However, in reality they are constantly disrupted by the many small satellites of Saturn, and it is the gravitational forces exerted by these moons that have created the lace-like structure of the rings. When entering orbit, the Cassini probe overflew the rings at a distance of less than 60 000 km, sometimes coming as close as 16 000 km. By comparison the diameter of Saturn is 120 000 km and that of the rings 300 000 km. These overflights revealed new structural details with a resolution never before observed

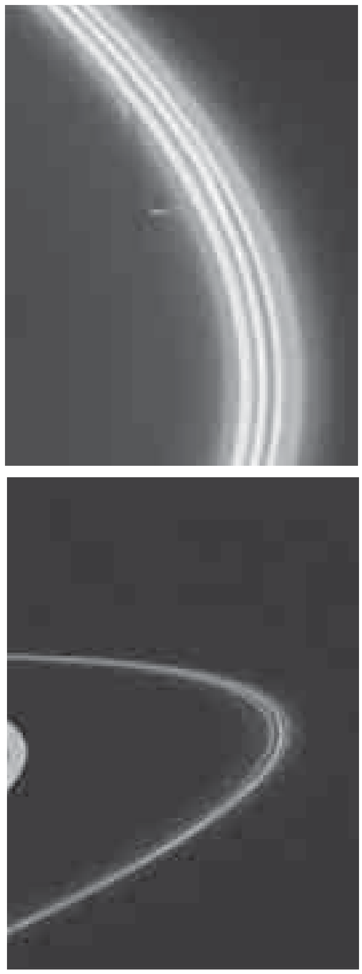

Figure 5. Above: Panoramic view of the F ring taken on the 1st July 2004 by the wide field camera and showing that the ring is composed of at least four finer sub-rings. It is also broken up throughout its length by dark striations. The body responsible for this break up is the tiny moon Prometheus which can be seen just inside the ring at the top left of the image. As it orbits, it passes through the ring, cutting it into numerous sections. The dynamic stability of such a complex system remains a mystery to researchers throughout the world. The finest details in the image are about nine kilometres across. Image credit: NASA/ESA. Below: An astonishing view of Saturn's F ring taken on the 29th October 2004 by the Cassini narrow field camera. The disturbance caused by the tiny moon Prometheus (visible in the centre of the image) is drawing streamers of material to form bridges between the ring and the moon. Even when these bridges have dispersed, there remains a scar in the form of a series of dark stripes in the area of the encounter. The Cassini images do, however, show that all traces of the encounter disappear in less than three months, as though the ring has a strange ability to heal itself. The smallest visible details in this image are around 940 metres in size. Image credit: NASA/ESA.

Stellar Plasmas and Nuclear Astrophysics

This period has known the development of new activities dedicated to the dynamical properties of stellar plasmas. Up to recently, stars were described uniquely like static objets evolving with gravity, pressure and nuclear reaction processes.The objective of the Laboratory of Plasmas and Nuclear Astrophysics is now to build a more realistic representation of stars where effects of rotation, turbulence and magnetic field are properly introduced. These processes are present in all celestrial objects (planets, stars, interstellar medium galaxies, ...) so it is now crutial to introduce them both in 1D stellar models and 3D simulations of stars to better describe these objects.

This revolution in stellar evolution comes from the association of helio and asteroseismic observations in space (SoHO, COROT, PICARD) producing first internal constraints on these processes and the emergence of super computing systems using a very large numbers of processors which stimulate the development of 3D MHD simulations of stars.

Our laboratory contributes strongly to this important progress and has oriented its activity to cover complementary aspects of the field. It plays now an effective role in instrumentation, observations, theory, modelling and simulations. This is a good way to extract the best from SoHO because the different parts are strongly intricated. We try to add also a new direction of investigation in preparing laboratory experiments which could contribute to solve problems associated to the non ideal characteristics of the stellar plasmas.

This strong and very specific effort done during the last 3 year period will hopefully continue in the future. The present orientation has been explicitly expressed in the report of the CEA Prospective of the Research Directors for 2006-2016[1] where a strong relationship emerges between astrophysical plasmas and fusion plasmas. It partly motivates the orientation of our stellar research and the courses teached by some of us for an upper class formation of a new generation of young physicists.

The GOLF/SOHO helioseismic important results

The SoHO satellite was the first milestone of the programme ESA Horizon 2000. Launched in December 1995 for the L1 Lagrangian point and still in operation, it plays today a strong role in this revolution. Effectively this mission cannot be only considered as a unique opportunity to understand how the Sun is working. SoHO has also largely enriched this transition period leading to a more dynamical, complex and complete view of stars. The success of this mission is partly due to helioseismic instruments which have revealed the properties of million of modes not yet reachable in any other type of stars. It results a new, strong and large scientific return with some problems solved (some of them already mentioned in the previous report) and totally new emerging questions (see chapter 9). After more than 10 years of observation, we summarize here the lessons of this mission and enlighten the most recent results we have obtained with the GOLF instrument that DAPNIA has largely contributed to build and analyze the results (Garcia, Turck-Chièze et al. 2005).

The Doppler velocity measurement for revealing the deep internal dynamics of the Sun

Among twelve instruments aboard SoHO, three of them measure internal solar oscillations and consequently probe the solar interior. The American Michelson Doppler Instrument (PI: P. Scherrer) looks to the Sun locally which allows to detect a large number of acoustic modes. This instrument has been particularly successful in investigating for the first time some motions in the convective zone and the way the differential rotation profile disappears inside the Sun, showing the importance of the transition region between radiation and convection in the understanding of the dynamo effect connected to the 22 year solar cycle (see below). It has also contributed to confirm and identify some low degree acoustic modes which were at the detection limit of the GOLF instrument. The European VIRGO instrument (PI: C. Frolich) has been mainly dedicated to the time evolution of the total irradiance. It is a photometric instrument with limited capability for detecting low degree low frequency modes due to the effect of the turbulence at the photosphere level. The French Spanish collaboration has built the GOLF instrument which means Global Oscillation at Low Frequency (PI: A. Gabriel). It was effectively designed for the measurement of low degree low frequency modes, i.e., the modes which penetrate deeper in the radiative zone. This instrument measures the variability of the Doppler velocity by the resonant spectrometer technique on the three sodium D1, D2a and D2b lines. This method was previously used in IRIS and BiSON ground networks. The Fourier transform of the velocity signal is shown on Figure 1 and compared to the intensity VIRGO technique. Despite the malfunctioning of the quarter wave plate motor, this measurement has

[1] www-intranet.cea.fr: 8000/fr/lecea/documents/prospectiveHC.pdf

been possible on one wing (left or right depending on the period of observation) along the 12 years of the SoHO mission. This has been possible thanks to the presence of a small modulation of the magnetic field. Figure 1 shows the superiority of the GOLF instrument compared to the VIRGO photometric technique. One has noticed up to a factor 10 to 30 increase in sensitivity in the Fourier transform at low frequency and in particular in the range of gravity modes located between 10 to 400 microHz. This is due to two factors. First the GOLF velocity is extracted in the solar atmosphere at an height of 300 to 500 km and this region is less turbulent than the photosphere. Secondly, the GOLF instrument has been specifically designed to detect very low amplitude signal at low frequency (down to at least 1 mm/s which was supposed to be before the launch the amplitude of the first gravity modes). This performance was reached in using 2 photomultiplers counting up to 1.2 10^7 ph/s associated to a very stable electronics built to get an instrumental noise totally dominated by the statistical noise chosen in relative value as low as possible.

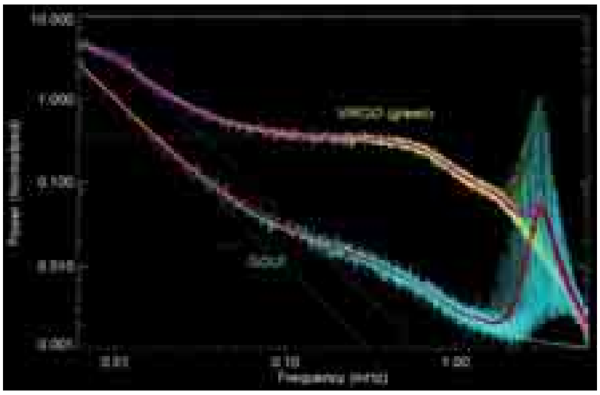

Figure 1. *Comparison of velocity versus intensity measured simultaneously aboard SoHO. The superiority of the velocity technique established with GOLF is also noticed in asteroseismology.*

The GOLF instrument has been successful in solving the questions for which it has been designed. There are three domains where it has given very positive information: (1) the description of the solar core and the neutrino puzzle thanks to the detection of previously unknown low degree acoustic modes, (2) a good understanding of the solar variability with the solar cycle, and (3) the capability to detect gravity modes with Doppler velocity technique.

The GOLF instrument has detected for the first time all the low degree acoustic modes (orders n from 7 up to 40) for degrees l= 0, 1, 2, 3 and has followed most of them along a complete solar cycle (Garcia et al. 2004, 2007). This important fact allows a study of the Sun like a star for which only these modes could be available. The understanding of the properties of these modes and their evolution along the 11 year solar cycle allows us to separate the range of frequency in at least 2 parts dedicated to different scientific information.

- The range of frequencies between 2.3 and 4 mHz is extremely useful to characterize the surface layers down to 0.98 solar radius. The variability of their frequency along the solar cycle is now properly established and their properties (intensity, width) well determined (Jiménez-Reyes, Garcia et al., 2004). These informations put some limit on the mean magnetic field of these layers and its varying component along the solar cycle (Nghiem et al. 2006). Nevertheless one needs yet to disentangle the effect of the solar radius variation from the effect of turbulence and magnetic field to properly establish the active behaviour of these layers, this is the main objective of the PICARD mission which will be launched in 2009. The use of these modes to extract information of the deep Sun have led to confusing interpretation in the past. It is why these modes have been avoided in most of our inversions of the sound speed and the rotation.
- A large range of frequencies below 2.3 mHz (about n < 16) has been measured for the first time by the GOLF/SoHO instrument. They represent the best way to extract some information from the deep radiative zone even they penetrate less deeply than higher order modes. Effectively, these modes are very stable (long lifetime) and not perturbed by the variation of the superficial magnetic field along the solar cycle. Their use has led to the best constraints on the sound speed in the core and to a precise extraction of the flat rotation profile down to 0.2 solar radius (see previous publications). The detection of these modes (Garcia et al. 2004, 2007) shows long lifetime modes and do not favor any deep variation during the period of observations (10 years) except may be a 1.3 yr period (Jiménez-Reyes et al. 2004) already mentioned in some other studies and attributed to the tachocline region.

The quest for gravity modes: the detection established ?

The GOLF instrument has been specifically designed to try to detect some gravity modes. Nevertheless the publication of Kumar et al. ApJ 1996 just after the SoHO launch on their probably very low surface amplitude coupled to the malfunctionning of the polarisor motors have put some doubts about the capability of GOLF to detect any useful signal. Nevertheless, intensive studies have been dedicated to this field since the first years and a search strategy has been defined in our laboratory: first to look for multiplets (it improves the capability of detection of very low signal) in the region above 150 μHz where the velocities are the greatest and then to examine the low frequency region if the first research was successful.

The first search has led to candidates which have been followed in time and reported in previous activity report. A significant pattern (more than 90% confidence level not to be pure noise) has been observed from the beginning (Turck-Chièze et al. 2004). His shape has evolved from a triplet to a quintuplet with more than 98% CL (Turck-Chièze et al. 2006, Mathur, Turck-Chièze, Couvidat & Garcia 2007). We have labeled the observed triplet as a potential quadrupole gravity modes l= 2, n=-3. Then its evolution in the form of a quintuplet has led us to examine three possibilities: such a quadrupole gravity mode showing a rapid rotation core with an oblique axis, a mixture of noise and of this gravity mode with a flat rotation in the core or a mixture of different modes. Recently an analysis of 10 years of the VIRGO data has shown a continuous signal at the position of 220.7 µHz corresponding to one of the highest component of the GOLF candidate confirminging the solar origin of this signal.

Then a second analysis below 150 µHz has been done. In this range of frequencies, it is not possible to look for individual peak or multiplet (they have a too small amplitude and the mode spectrum is too dense for hoping any identification). So this search has used the asymptotic behavior of the modes (they are spaced in period) and the cumulative effect of 20 modes has been analyzed. Such search has put in evidence a pattern compatible with the sum of dipole gravity modes at more than 99.7% confidence level, illustrated by Figure 2 (Garcia, Turck-Chièze et al. 2007). This detection favors also a higher rotation rate in the solar core (Figure 3) than in the rest of the radiative zone.

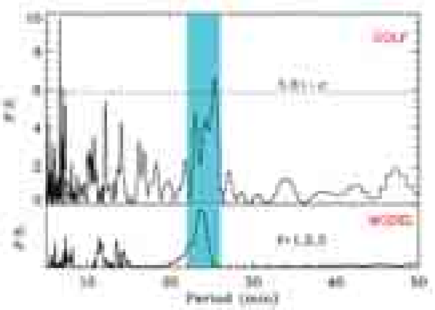

Figure 2. *Detection of a GOLF signal at a very high CL at the precise place where is waiting a large pattern identified like the superposition of the theoretical dipole modes of the seismic solar model. This result is obtained in using the properties of the gravity modes which are spaced in period between 2 to 11 hours. See figure 3.*

Considering these two analyses, it seems rather clear that GOLF has detected some solar gravity mode signatures. Nevertheless the information on the core rotation stays rather poor. It is interesting to note that the two analyses are only compatible if the core of the Sun turns quickly and the axis of the core rotation is oblique in comparison with the rotation axis of the rest of the radiative zone (Mathur, Eff Darwich, Garcia & Turck-Chièze 2007). But due to the very low amplitude of the signals, this conclusion needs to be confirmed by improved observations. Presently, the analysis of the other instruments has shown the superiority of the GOLF instrument and of its technique for the gravity mode detection so it is important to build an instrument even more performant (see the description of GOLF-NG Chapter 8). Today, we consider that all the objectives of GOLF have been reached, unfortunately the knowledge of g-modes is not yet sufficient to properly describe the dynamics of the solar core and its consequences on the deep magnetic field but this door is open and the potentiality of such information to reveal the dynamics of more than half the solar mass well established.

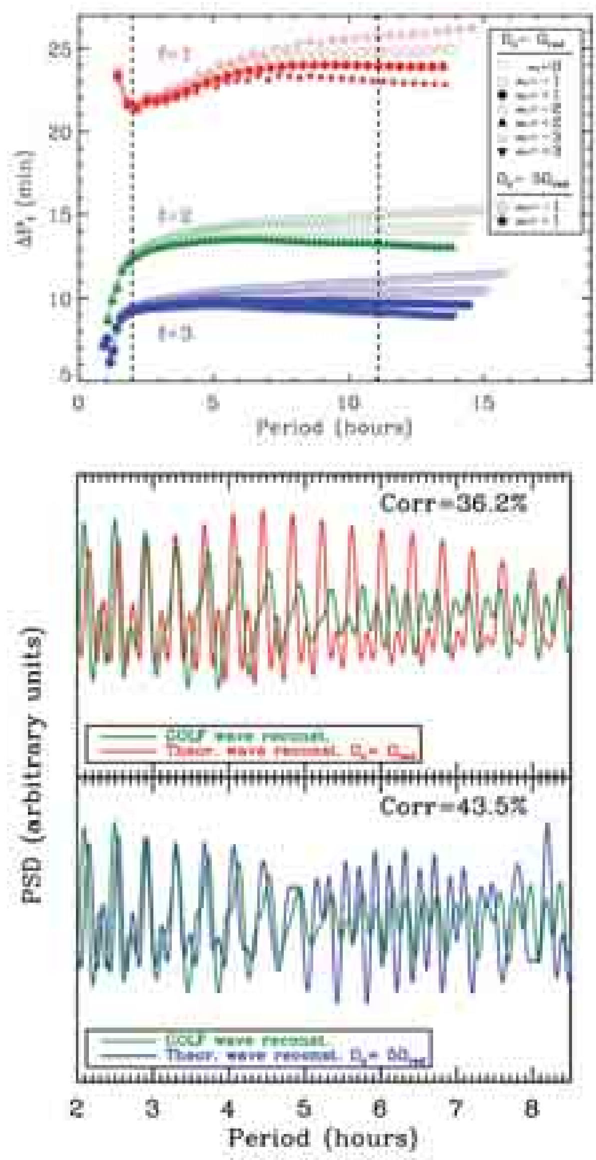

Figure 3. *Top : Separation in period between adjacent radial orders (n, n+1) gravity modes for l= 1, 2, 3 using theoretical frequencies extracted from the seismic model versus the period of the modes. Superimposed are the rotation splittings for different core rotation profiles. Bottom : GOLF wave reconstruction and correlation with models supposing different rotation rates in the core. We have noticed a systematic increase of the correlation for a higher core rotation rate than in the rest of the radiative zone.*

1D modelling approach for the gravity mode search

An intense activity of solar modelling has been pursued during this period for the interpretation of the GOLF seismic observations. In fact the interpretation and labelling of seismic observations needs a comparison with theoretical acoustic and gravity mode frequencies.
These values are extracted from precise solar (stellar) models through an oscillation code. It is why a special effort has been dedicated to the solar model along the last decade for a proper extraction of gravity mode frequencies in particular for high order n modes which are very sensitive

to the central region. After the establishment of the solar seismic model, which is a classical model including the sound speed profile, we have continued to discuss any progress which impact on the thermodynamics of the plasma.

Some works devoted to the 3D representation of the solar superficial convection and atmosphere, have led to a reduction up to 30% of the CNO photospheric composition proposed by different authors (Holweger 2001, Asplund et al. 2003). As these elements play a strong role in the opacity coefficients of the radiative zone, this important result has led to a lot of questions on the consequences of this reestimate. Effectively the solar CNO composition affects the galactic evolution of the solar environment, the initial helium composition and the sound speed profile (Turck-Chièze, Couvidat, Piau, 2004).
This new study and the previous ones on the influence of microscopic effects on modes were used to quantify the sensitivity of the gravity modes to the physics of the radiative zone (Mathur, Turck-Chièze, Couvidat, Garcia 2007) and these predictions have been compared to the GOLF data and to other predictions done by other authors.
Figure 4 is an example of this study. One notes that a 2 μHz, difference observed between the gravity mode candidate and the theoretical estimate deduced from the seismic model, is not larger than the effect of the abundance change. The seismic model has been used to calculate the information of

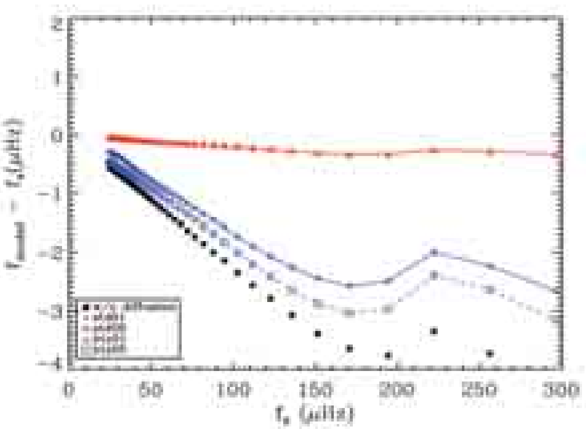

Figure 4. *Difference between the gravity mode frequencies obtained for standard models with the new composition of Asplund without and with turbulence in the radiative-convective transition region (std05, btz05), idem with the old composition (std01, btz01) and the frequencies obtained with the seismic model for the quadrupole modes l= 2.*

Figure 3 top where the asymptotic behaviour of the gravity modes (spaced in period) is shown. One notices that the different degrees l =1, 2, 3 appear well separated in $\Delta P_l = \nu_{n,l} - \nu_{n-1,\,l}$ which helps in the identification of the observed pattern. We have shown that it is true for all the calculated models. The pattern at the bottom of Figure 2 is the sum of the 20 gravity modes having period between 2 and 11 hours. We have also estimated the impact of magnetic field and rotation on the absolute values of the gravity mode frequencies (Rashba ... Turck-Chièze.. 2007).

Dynamical physical processes in stellar plasmas

We have developed during this period, new expertises in magnetohydrodynamics both on the theoretical side and on the modelling and simulation sides. In the 1D model, we contribute to develop the algorithms inserted in the stellar evolution CESAM code to follow the evolution of the momentum transport due to rotation, gravity waves or magnetism (this part will be develop in the next report). Today the implantation of the momentum transport by rotation is operational and several comparisons have been done between CESAM and STAREVOL in the case of the Sun.

Asteroseismology is developing on ground using the velocity technique and in space with two missions: the canadian microsatellite MOST and the european minisatellite COROT in December 2006, which both measure the variability of stellar luminosity. So the expertise obtained in helioseismology has been applied to analyze and interpret the coming observations. We have contributed to prepare the algorithms useful for COROT targets and soon for the KEPLER american mission.We have mainly concentrated our studies on diagnostics of the extension of the convective zone (Ballot, Turck-Chièze, Garcia 2004) or some indicators for open clusters (Piau, Ballot, Turck-Chièze 2005) . During the thesis of P. Lambert, it has been shown also that a curvelet analysis of the echelle diagram could be extremely useful to extract the maximum of identified modes (Lambert, Ballot, Garcia, Turck-Chièze 2006).

Simulation of the magnetism and dynamics of stars

Understanding the origin and the influence of magnetic fields on the evolution and the dynamics of celestial objects is crucial. Today dynamo action is believed to be the physical process at the origin of intense and multi-scale magnetic fields in the Universe. The universal character of the dynamo effect allows theoreticians and modellers of different astrophysical objects to compare their approach and to progress on the precise description of this process. In that spirit, stars, and the Sun in particular, represent a modern physical laboratory for developing our understanding of this complex and non-linear physical process. We have thus, over that period, developed 3D magnetohydrodynamics (MHD) numerical simulations of dynamo action of different stellar spectral types in order to describe the diverse manifestations of stellar magnetic activity (see Brun 2005). These numerous experiments have been developed around the Fortran 90 spectral MPI code named ASH (anelastic spherical harmonic; Brun et al. 2004) presented in the previous report. This code is now implemented on different sites in Europe: in CCRT at CEA, IDRIS Orsay and in the framework of DEISA in Europe for the STARS (Simulation of the Turbulence, Activity and Rotation in Stars) project.

3-D stellar models of magnetized convection

Several simulations have been realized at very high resolution (>5003) in spherical geometry to study the dynamo effect in a simplified model of the Sun where convection, rotation and magnetic field are introduced in a consistent way. The introduction of a « tachocline »[2] and of a stable region below the convective zone strongly improves the solar model of the convective zone in 3D and the generation of intense toroidal magnetic structures (Brun et al. 2004, Browning et al. 2006).
Other models have been developed to study the convective core and its radiative envelope for 2 solar masses stars with values of rotation rate between 1/10 and 8 times the solar rotation. These simulations show that the convective cores are very efficient at exciting a dynamo (Brun 2005, Browning et al. 2004, Brun et al. 2005). The ratio magnetic energy (ME) over kinetic energy (KE) increases with the rotation rate to get an equipartition and may be a superequipartition (ME>KE).

In our effort to modelling with 3-D numerical simulations the various stars found in the Herztsprung-Russell diagram, we have examined the dynamics of young stars that are know to be fast rotators (Ballot 2004, Ballot, Brun, Turck-Chièze 2007). The initial conditions have been chosen from the CESAM code for a Sun of 10 Myr, this age is interesting because it corresponds to the epoch where the lithium (excellent indicator of internal dynamical processes)

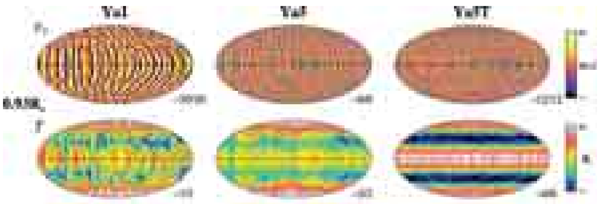

Figure 5. *Radial convective velocity Vr (in m/s) and temperature fluctuations T (K) near the surface (r=0.93 Rstar) and near the convective limit (at 0.75 Rstar) realized in 3-D models of young suns rotating at 1 or 5 times the solar rotation rate. Note the clear change of spatial extension of the convective cells as the rotation rate and the degree of turbulence is increased (from left to right), as well as the appearance of banded thermal structures associated with the strong differential rotation realized in the simulation.*

is largely destroyed. The corresponding hydrodynamical simulations have been calculated for rotation rate between 1 to 5 solar rotation rate. It is find that the convective patterns are very sensitive to the rotation rate of the star (Fig 5). At 5 time the solar rotation some models reveal a strong spatial and temporal intermittency that could lead to modulation of the star's luminosity. These simulations also indicate that the angular velocity latitudinal contrast $\Delta\Omega$ does not vary significantly with stellar rotation in agreement with recent observations.

[2] Tachocline: transition region between the surface solar convection zone and the radiative interior revealed by helioseismology where the differential rotation changes into an almost solid body rotation

Simulation of the solar radiative region and of the tachocline

A new series of simulation has studied the deep magnetism potentially present in the solar radiative zone (Brun & Zahn 2006). These first 3D simulations consider a flat rotation above the nuclear core and the presence of a differential rotation at the level of the tachocline imposed by the convection zone above (but for now not modelled).

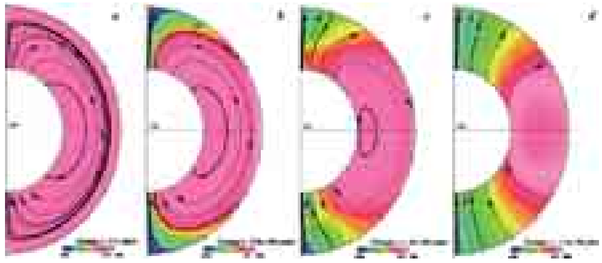

Figure 6. *Temporal evolution of the angular velocity Ω (r, θ) (color contours and white lines) and of the mean axisymmetric poloidal field (superimposed black lines), which initially is buried below the convection zone. a-d) sequence spanning 4.7 Gyr (in solar equivalent units) of the dipolar magnetic field in the presence of rotation and shear. The field lines gradually connect with the imposed top shear, thereby enforcing differential rotation at all depths above latitudes greater than ~ 40°, at the (equivalent) age of the Sun. Note also in frames (c-d) the distortion near the poles of the lines of constant Ω, which is associated with the Tayler instability discussed in the text.*

They have demonstrated that the inward spread of the solar tachocline cannot be stopped by an inner fossil field, since such a field would lead to state of differential rotation that is not observed (see Fig 6). Thanks to their 3-D character, they have also confirmed the existence of non axisymmetric instabilities of the poloidal field (m>20) and of m=1 instabilities of the toroidal structures formed by Ω effect (i.e the large scale shearing of polar field into azimuthal field) predicted by pure theoretical work done by Tayler and collaborators in the seventies. This deep magnetism may have important consequences on the structure of the solar interior and may influence the dynamo generated field.

The 2D solar dynamo

A new 2D axisymmetric code STELEM (STellar ELEMent), has been developed, using the numerical method of finite elements to solve the induction equation in the approximation of the mean field theory in order to study more quantitatively the 22-yr solar cycle and compute for example butterfly diagrams. This work is part of the thesis of L. Jouve on solar magnetism. This code can simulate all sort of dynamos (α2, $\alpha\Omega$, Babcock-Leigthon) as well as flux transport models including a meridional circulation. The role of multi cellular flows in the convective zone has been studied in detail to assess their influence of the longevity of the cycle and on the parity of the butterfly diagram. These simulations show that when the number of cells increases, the duration of the cycle increases also. SoHO has shown that the number of cells and the velocity of the meridional circulation seem to vary with time along the solar cycle.

Opacity measurements with lasers

A new activity has been initiated during this period. It consists to use high energy lasers to check opacity calculations useful for explaining stellar pulsations or radiative transfert in low mass stars. The new generation of high energy lasers like LULI, LIL or LMJ (Rochester or NIF) could produce plasmas of the same kind than those found in stars. So we have proposed a laboratory experiment to reproduce some characteristics of the conditions at the base of the convective zone in LIL or LMJ, these conditions are presently difficult to reach and a path will be defined in the future in order to approach the best conditions on different installations to validate stellar opacities which stay a fundamental ingredient for asteroseismlogy interpretation of dynamics in stellar interiors.

Finally, in parallel to these scientific activities, technical activities have been developed to prepare the next generation of instruments. In Chapter VIII, the GOLF-NG prototype is described and in Chapter IX we show what kind of mission is useful for definitively understand the Sun as a whole, two missions have been proposed to ESA : the DynaMICCS and HIRISE missions to answer to the new important questions in this field

High energy cosmic phenomena

The High Energy Cosmic Phenomena Laboratory (LEPCHE), collecting the heritage of the historical SAp involvement in cosmic-ray, X-ray and gamma-ray astrophysics, develops research programmes devoted to the study of the most extreme sources and violent phenomena of our universe. Such studies allow scientists to explore fundamental physical processes under conditions that cannot be obtained in laboratories.

The major questions at the centre of the LEPCHE research programmes concern the validity of the theory of gravitation in strong fields, the origin of cosmic rays, the nature of the accelerating processes of particles and their maximum energy limit, the physics of accretion of matter and of the emission of jets in compact objects, the nucleo-synthesis processes in the galaxy, the formation and evolution of black holes and neutron stars, the origin and mechanism of gamma-ray bursts, and the nature of dark matter.
To tackle these issues the laboratory has developed two main research domains that play a major role in modern astrophysics today: the physics of compact objects and the physics of relativistic particle acceleration. Compact objects (black holes, neutron stars and white dwarfs), surrounded by extremely powerful gravitational and magnetic fields, appear as luminous and variable X-ray and gamma-ray sources and are usually associated with some of the most exotic environments and violent phenomena of the Universe. The study of particle acceleration on the other hands is conducted by exploring and modelling the strong shocks generated by the supernova remnants, the particle winds produced by pulsars, and the interactions of particles with the interstellar medium, in the attempt to resolve the 100-year-old mystery of the origin of galactic cosmic rays. These two domains involve each their specific targets and specific tools but are also strongly linked since particle acceleration processes often take place in the extreme environments around compact objects or are generated by their birth.

The LEPCHE research programmes are mainly based on observations carried out with the high energy observatories to which the SAp has provided significant contribution for the science driver, the hardware development, the data analysis systems and the scientific operations. The programmes carried out over the 2004-2006 period made use in particular of the XMM-Newton X-ray (0.1-12 keV) and the INTEGRAL soft gamma-ray (3 keV-10 MeV) space observatories along with the very high-energy (VHE) gamma-ray (100 GeV – 10 TeV) ground based HESS telescope that started operations in 2004 opening a totally new astronomical window for the study of the cosmos. These programmes, the associated multi-wavelengths campaigns, and the parallel theoretical and modelling work have yielded many important results (published in ~230 refereed papers including 5 letters to Nature) some of which will be reviewed here along with the future perspectives.

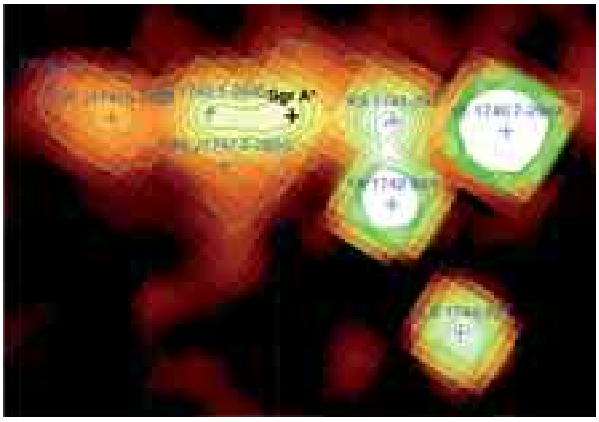

Figure 1. *View of the galactic centre region at low-energy gamma-rays (20-40 keV), as seen from the INTEGRAL observatory (Bélanger et al. 2006). The image includes several accreting X-ray binary systems (the brightest of which is the black hole microquasar 1E 1740.7-2942) and the central source at the position of the super-massive black hole Sgr A*.*

The more than 30 members of the laboratory are indeed also actively working to develop new projects in collaboration with the space agencies CNES and ESA. The laboratory activities at the borderline between particle physics and high-energy astrophysics naturally overlap with the emerging domain known as astroparticle physics. Some of the LEPCHE scientists are members of the new laboratory AstroParticle and Cosmology founded in 2005 at the University of Paris 7 with the support of the CEA.

High energy phenomena at the galactic centre

An important scientific programme of the laboratory concerns the study of the super-massive black hole at the centre of our galaxy and of the high-energy phenomena occurring in its vicinity (the 300 pc × 150 pc of the so

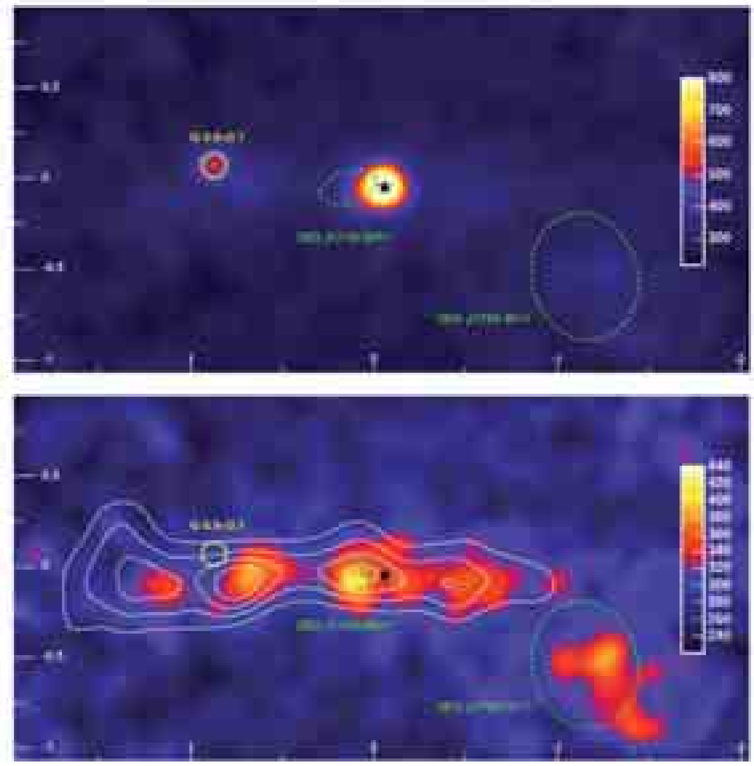

Figure 2. *The galactic centre region at very high-energy gamma rays (100 GeV - 10 TeV), as seen from the HESS observatory (Aharonian et al. 2006). Top panel: the two bright point-like sources, the central one coincides with the super-massive black hole of the Galaxy. Bottom panel: diffuse emission is clearly seen after removal of the two bright sources.*

called galactic centre region). Identified with the compact radio source Sgr A*, this black hole of about 3 millions solar masses is the nearest and most extensively studied of all the massive black holes. Two new, bright Sgr A* X-ray flares, originating close to the black hole's horizon, were discovered and closely studied as a result of a vast campaign of simultaneous observations performed in 2004, in X-rays with XMM-Newton, in gamma-rays with INTEGRAL and at lower energies with several other observatories (Bélanger et al. 2005). One of the bursts was also observed at infrared frequencies (IR) with the Hubble Space Telescope (HST), making it possible to place strong constraints on the emission mechanisms (Yusef-Zadeh et al. 2006). In addition, a quasi-periodicity of about 22 minutes was detected in the longest X-ray flare. This phenomenon could be related to a periodic modulation at the last stable orbit of an accretion disk around a rotating black hole. In this case, the measured period allows one to obtain, for the first time, an estimate of the black hole spin.

Using all 2003-2004 INTEGRAL data of the galactic center, LEPCHE research teams succeeded in making the most comprehensive and accurate gamma-ray map ever made of this complex region of the Galaxy in the range 20-100 keV (Fig. 1), and discovered a central source (IGR J17456-2901) well located at the position of the black hole (Bélanger et al. 2006). This source does not exhibit temporal variation and cannot be identified with Sgr A*, nor with any of the other objects of this complex region. Its nature is still a mystery but it is certainly the signature of a significant non-thermal high energy component that, if diffuse, could explain the nature of the hot X-ray diffuse emission that permeates the central regions of the Galaxy. Till now this emission has been interpreted as thermal radiation from hot plasma, however the estimated temperature (~10 keV) is too high to have the gas confined in the region. The presence of a non-thermal component, dominant above 10 keV and not detectable with XMM-Newton and Chandra observatories, would now explain this inconsistency. An alternative model for the hot gas, invoking significant presence of Helium has also been proposed to allow the hot gas to be confined in the region (Belmont et al. 2005).

Scientists of the laboratory have also contributed to the study and interpretation of the different other components of the complex X-ray emission seen with XMM-Newton in the galactic center region, including those associated to the Sgr A East supernova remnant, the Arches star cluster, and several weak transient sources discovered with XMM-Newton in the region.
On the other hand the INTEGRAL source could be instead related to the TeV gamma-ray source detected at the centre of the Galaxy by HESS in 2004 (Fig. 2, top). The discovery of this TeV source (Aharonian et al. 2004) is one of the major results of the new generation of Cherenkov based TeV telescopes today in operation. This source also coincides with Sgr A* but cannot be clearly identified either. Its spectrum is not compatible with that expected from the annihilation of dark matter particles (expected to concentrate in the very centre of the Galaxy), and it rather reveals the presence of very high-energy particle acceleration.

Another key discovery of the HESS telescope is that of diffuse TeV emission well correlated to the distribution of the dense and massive molecular clouds of the galactic centre region (Fig. 2, bottom) (Aharonian et al. 2006). This radiation is likely due to the interaction of particles, probably protons, accelerated at relativistic energies that propagate and interact with the neutral molecular gas of the clouds. The spectrum of the emission indicates that acceleration was recent, possibly associated to the central source located at the super-massive black hole position. Again the origin of the particles is not known but a single supernova in the cloud environment is enough to supply the energy required to accelerate these protons.

Figure 3. *An all-sky image of all hard X-ray (>20 keV) sources detected with the INTEGRAL IBIS/ISGRI telescope. Colour indicates the hardness: blue for hard and red for soft sources (Credit: CEA /DAPNIA / SAp-APC).*

Diffuse gamma-ray emission from the Galaxy and population studies

More broadly, the study of gamma emission from the galactic bulge and the disk using the INTEGRAL spectrometer SPI has provided a detailed map and spectrum of the mysterious diffuse emission at 511 keV, the electron-positron annihilation line (Knödlseder et al 2005). The remarkable results of INTEGRAL indicate that the annihilation take place in a warm ionized medium but the origin of the positrons, in particular those that give rise to the emission of the galactic bulge, is still not understood. An important theoretical work on this issue led astrophysicists of the laboratory first to consider that positrons could be generated by galactic hypernovae, supposed to give rise to GRBs, (Cassé et al. 2004) and later to suggest that positrons could result from light dark matter particle annihilation (Sizun et al. 2006). If this latter hypothesis is correct the INTEGRAL image would be the first map ever of the dark matter distribution in our Galaxy. INTEGRAL observations with the SPI telescope also led to the detection of the gamma-ray lines of the ^{26}Al (Diehl et al. 2006) and ^{60}Fe (Harris et al. 2005) radionuclides along the galactic disk, which testify the nucleosynthesis carried out by the supernovae in the Galaxy and constrain the production rate of supernova in our galaxy.

With the IBIS/ISGRI telescope of INTEGRAL instead we have solved the long-term mystery of the diffuse galactic emission in the 20-200 keV band, resolving a good fraction of it as point-like sources (Lebrun et al. 2004), most of which are made up of binary systems with an accreting compact object. The second IBIS catalogue of hard celestial sources (> 20 keV) includes now more than 400 objects (Fig. 3), most of which are of galactic nature and associated to compact objects (Bird et al. 2006).
The presence of huge dark gas clouds in the solar neighbourhood was revealed from archival gamma-rays of the GRO/Egret emitted during their bombardment by cosmic rays (Grenier et al. 2005). This result implies that, on galactic scale, there is as much mass in dark clouds as there is in the visible molecular clouds. Taking this into account may lead to significant revision of the population of unidentified galactic gamma-ray (> 100 MeV) sources. Meanwhile HESS have redesigned the map of VHE gamma ray sky, with more than 40 sources detected at more than 100 GeV, and in particular about 10 sources along the central 60 degrees of the galactic disk.

Stellar black holes and microquasars

Accreting black holes of stellar mass (between 2 and 50 times the solar mass) in close binary systems are the most intense sources of low-energy gamma rays (Fig. 1) and are often observed beyond 300 keV. In these systems, the black hole captures matter from the companion star. The accreting material falling in the deep gravitational well of the compact object provides the energy to feed – via a disk or a hot corona – the X-ray and gamma-ray emission and sometimes (in microquasars) a radio jet of relativistic particles. Black holes X-ray binary systems are INTEGRAL's priority targets. They are studied to model the accretion disk, the hot corona and the jet, as well as their mutual interactions.

One of the outstanding results of the LEPCHE research efforts in this area was the detection of a high-energy (400-1000 keV) component in the X-ray/gamma-ray spectrum of Cygnus X-1, the prototype of galactic black hole binary systems (Cadolle Bel et al. 2006). This component cannot be explained by the hot plasma corona and indicates the presence of relativistic non-thermal electrons.
INTEGRAL observations and associated multi-wavelength observational campaigns have been performed for a number of transient or highly variable binary sources supposed to host a black hole. In particular detailed observations were carried out for the galactic black hole GRS 1915+105 (which was the first microquasar to show

apparent superluminal – or faster-than-light – motion) in which the accretion rate varies significantly during the main outbursts (Rodriguez et al. 2004) and for several newly discovered transients that appeared in the galactic bulge region, remained active for few months and then went back to quiescence (Cadolle Bel et al. 2004). This made it possible to study the behaviour and the interplay between the disk, the hot corona and the jet, as the sources evolved in different spectral states.
Another key result obtained by members of the laboratory was the discovery of a new X-ray jet from a microquasar (H 1743-322) with the Chandra X-ray observatory (Corbel et al. 2005), while for the first time a well known microquasar (LS 5039) with an orbital period of ~ 4 days and associated to a massive star was detected with the HESS observatory in the VHE gamma-ray band (Aharonian et al. 2005). This detection provides unambiguous evidence for particle acceleration to multi-TeV energies in a microquasar.

These observational results have contributed to the development of the hydro-magnetic instability model (also known as accretion-ejection model) of the disk around black holes, which SAp researchers have proposed (Tagger & Verniere 2006). This model, which also explains how the accretion disk releases energy towards the hot corona and ultimately feeds the jet, was improved, compared with data from various sources, and then successfully applied also to Sgr A* flares (Tagger & Melia 2006).

Neutron stars in binary systems and isolated pulsars

Unlike black holes, neutron stars have their own magnetic field which can be extremely powerful. In this case, the observed emission is characterised by a coherent

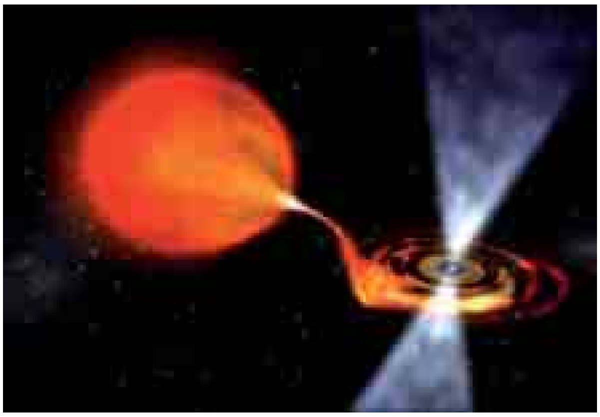

Figure 4. Artist's view of an X-ray pulsar in a close binary system like the INTEGRAL source IGR J0029+5934. (Credit: NASA/Dana Berry).

pulsation, due to the radiation cone generated at the magnetic poles of the star crossing the line of sight as the star rotates. LEPCHE astrophysicists have studied several pulsars in binary systems, where the accretion flow close to the compact object is dominated by the magnetic field (Fig. 4).

The most significant results in this field have been obtained for "millisecond" binary pulsars, which provide a link between the neutron stars in binary systems and fast spinning isolated neutron stars. Three of these objects were detected and studied for the first time in the hard X-ray range (> 20 keV) with INTEGRAL, and a decrease in the rotation period (i.e. acceleration of the rotation) was discovered in one of these systems (Falanga et al. 2005). This strengthens the hypothesis whereby fast-spinning isolated pulsars are "cannibals" neutron stars, formerly in a binary system, that have completely devoured their companion star.
When the magnetic field is not too strong, accreting neutron stars in low mass binaries with moderate accretion rates do not display pulsation but they may reveal their nature showing X-ray bursts with typical durations from seconds to tens of minutes and a characteristic spectral softening during the event. X-ray bursts are the result of explosive thermonuclear burning of the accreted material at the surface of the neutron star. These sources have hard spectra and are often bright at energies > 20 keV. A number of studies have been carried out on these systems using INTEGRAL observatory in particular to characterize and model their persistent and bursting hard X-ray emission (e.g. Falanga et al. 2006).

Accreting neutron stars with a high mass companion star are the majority of the new sources discovered by INTEGRAL. They are highly absorbed at low X-ray energies (Rodriguez et al. 2006) and were not detected by X-ray observatories. A vast program of X-ray, optical and IR monitoring of these highly obscured INTEGRAL sources has shown that they are often associated to early type supergiants with an extended dense circum-stellar envelope (Filliatre & Chaty 2004).
LEPCHE's research teams also work on the X- and gamma-ray emissions from the so-called magnetars, a class including the 'soft gamma-ray repeaters' and the 'anomalous X-ray pulsars'. These isolated neutron stars are powered by their extremely intense magnetic fields (~ 10^{15} G) rather than by accretion of matter or by rotational energy like in classical radio pulsars. INTEGRAL detection of persistent hard X-ray emission from these classes of objects (Gotz et al. 2006) was a surprise and opens the door to a wealth of important theoretical development in neutron star modelling.

Sources of cosmic rays

Observational efforts are concentrated on searching, in potential sources of galactic cosmic rays, for the signatures of the particles (notably electrons, protons) that have been accelerated to the highest energies. Observing in X-rays and gamma-rays is crucial to the study of accelerated particles with energies of up to $3 \cdot 10^{15}$ eV. This range characterizes the following: synchrotron emission from ultra-relativistic electrons, inverse Compton scattering of these electrons in the ambient photon field and gamma-ray emission associated with neutral pion decay as accelerated protons interact with protons from the interstellar medium. This last process produces an amount of neutrinos comparable to (or, in the event of gamma-ray absorption at the source, superior to) the number of gamma-rays.

Key science results were obtained by LEPCHE scientists using the XMM-Newton and INTEGRAL satellites, and the HESS telescope. From a modelling perspective, only the diffusive shock acceleration theory has been sufficiently developed to be used for quantitative calculations and to account for a large number of observational constraints. Since these models have reached a certain maturity, they can now be used to assess the physical parameters of acceleration by comparing them to observations of supernova remnants. However, other available models will be compared to X-ray and gamma-ray observations.

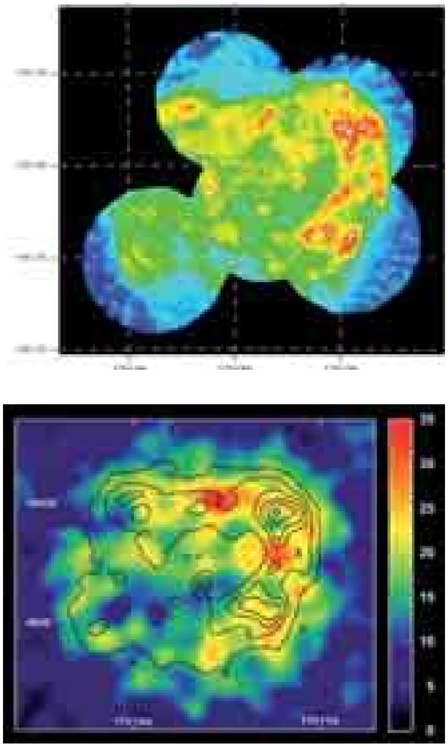

Figure 5. *The supernova G347.3-0.5 (or RX J1713-3946), displayed in X-rays by XMM-Newton (top) (Cassam-Chenaï et al. 2004), and in gamma-rays by HESS (bottom) (Aharonian et al. 2004b).*

Acceleration in supernova remnants: observations, modelling and simulations

A major breakthrough in gamma-ray astronomy was achieved using HESS to map the supernova remnant G347.3-0.5 in the TeV range (Aharonian et al. 2004b), followed by a second remnant, Vela Junior. This produced the first images at these energies using the stereoscopic system in HESS telescopes. These observations (Fig. 5), along with those obtained in X-rays using the XMM-Newton satellite (Cassam-Chenaï et al. 2004), made it possible to map the regions where particles are accelerated to energies in the range of 100 TeV and to characterise their spectrum.

In soft gamma-rays, INTEGRAL was used to observe emission from Cas A - the youngest supernova remnant in our galaxy - that reached up to 100 keV (Figure 6). The presence of two radioactive decay lines implies that the ^{44}Ti mass synthesized by the supernova is much higher than predicted by spherically symmetric supernova nucleosynthesis models (Renaud et al. 2006). The nature of the continuum emission - up to 100 keV - remains undetermined.

Numerous observations of young supernova remnants using the XMM-Newton and Chandra satellites have shown that the emission at the shock is of synchrotron origin. Its filament-like morphology is explained by significant radiative synchrotron losses on TeV-accelerated electrons and induces a strongly amplified magnetic field at the shock. Moreover, the morphology of the thermal X-ray emission from young supernova remnants can only be explained by significant back-reaction of cosmic rays on the shock structure.

These results are in line with models of cosmic-ray modified hydrodynamics, developed from the start of the new millennium by LEPCHE researchers (Ellison et al. 2004). These models can consistently calculate both thermal and non thermal (synchrotron) emission (Cassam-Chenaï et al. 2005), and they have also been integrated in a numeric hydrodynamic code. Furthermore, it has been proven that as the ejecta expand magnetic field weakens (unless some mechanisms amplify the magnetic field) and prevents any efficient acceleration in the internal shock (that propagates through the ejecta). This is consistent with the observed high temperature of shocked ejecta that is not compatible with efficient acceleration.

Acceleration in pulsar wind nebulae: observations and modelling

Observations in X-rays and gamma-rays of pulsar wind nebulae are highly complementary and provide key information to understand electron acceleration in the vicinity of pulsars. X-ray emission comes from ultra-relativistic electrons with TeV energies spiralling in the nebula magnetic field, while the very high-energy gamma-rays are more likely to come from the inverse Compton scattering of these relativistic electrons on low-energy ambient photons.

To date, the Crab nebula was the only known case of very high-energy gamma-ray emission in a nebula where the energy is provided by a young neutron star. HESS discovered several nebulae of this type, opening a new window through which this population of sources can be observed. The first spatially resolved gamma-ray spectral studies revealed a softening of the spectrum towards the edges of the nebula. This effect, already observed in the X-ray range with XMM-Newton, is a result of the cooling of ultra-relativistic electrons in the nebula. Observations of one of these nebulae with the INTEGRAL satellite up to 100 keV made it possible to estimate the maximum energy reached by electrons at values between 400-700 TeV (Forot et al. 2006).

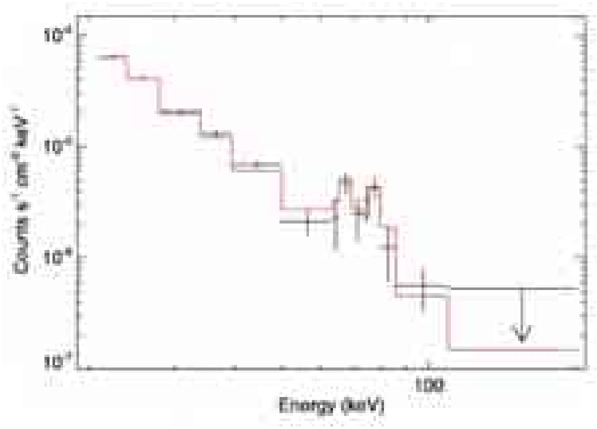

Figure 6. *Soft gamma-ray spectrum in energy from Cas A supernova remnant obtained by INTEGRAL/ISGRI, showing ^{44}Ti decay lines and high-energy continuum emission (Renaud et al. 2006).*

Extragalactic sources and gamma-ray bursts

Extragalactic sources such as active galactic nuclei (AGN), clusters of galaxies and gamma-ray bursts (GRB), emit hard X-rays and high-energy gamma-rays and are some of the targets of the research programmes of the laboratory.

The most interesting results in this area have been obtained with the IBIS telescope on INTEGRAL that has provided a catalogue of more than 60 AGN (mostly Seyfert galaxies) emitting at energies > 20 keV (Bassani et al. 2006), demonstrating its capability to probe the extragalactic gamma-ray sky by finding absorbed active galaxies. INTEGRAL observations also led to the detection of hard X-ray diffuse emission from the Coma cluster, well correlated with the X-ray morphology seen with XMM-Newton (Renaud et al. 2006).

Gamma-ray bursts are the most powerful events observable in our universe with typical energy comparable to 100 supernovae emitted in less than few tens of seconds; they occur in external galaxies and can be observed at very high red-shifts. They are probably the signature of direct collapse of very massive stars in black holes (hypernovae) or the coalescence of two neutron stars. With the detection of about one GRB per month, INTEGRAL and its automatic GRB detection system installed at the INTEGRAL science data centre, continued to provide the community with prompt (< 30 s) and precise (at better than 2') localisation of GRBs and made possible the study of afterglows (and in some cases even of prompt emission) at low energies for some of them with ground based telescopes. The fast triggering on the precursor of one event allowed the first detection of IR prompt emission in a GRB while detection of very faint afterglows for other two events showed the presence of a GRB population with dark afterglows (Filliatre et al. 2006).

The laboratory will increase his involvement in extragalactic high energy astronomy with the participation to dedicated projects for GRB science in the future years.

Future programmes and perspectives

The study of compact objects and cosmic ray sources will continue with the use of data from XMM-Newton and INTEGRAL missions, that are expected to be extended till 2010 and beyond, and data from the HESS observatory, that will be upgraded (HESS 2 project) to cover the range 10-100 GeV starting from 2008. LEPCHE physicists have also high expectations for others future experiments in which the laboratory is actively involved, in particular for the GLAST mission, whose launch is planned for beginning of 2008, and that will be used to better identify gamma-rays produced by the interaction of accelerated protons with those in the interstellar medium.

Looking further ahead, the laboratory is actively involved in two new high-energy space missions planned for the period 2011-2014. The SVOM/ÉCLAIRs project, a mission approved for phase A study as part of a French-Chinese bilateral agreement, is dedicated to the study of gamma-ray bursts, a domain that will also benefit from the laboratory's participation to the UV-visible-IR X-SHOOTER spectrograph project, an instrument to be installed at the ESO's VLT in 2008. The SIMBOL-X project, the first telescope capable of focusing hard X-rays (> 10 keV) through the use of multi-layer X-ray mirrors and the operation of two satellites in formation flying, is also in Phase A study, as part of a French-Italian mission. SIMBOL-X main scientific objectives are again at the core of the laboratories research topics the physics of compact objects and of the particle acceleration processes in the universe

Cosmology and Evolution of Galaxies

The Laboratory of Cosmology and Galaxy Evolution studies the formation and evolution of structures in the Universe from galaxies to galaxy clusters and large-scale structures. Our main expertise concerns the cold and dusty infrared Universe, the hot X-ray Universe, the weak gravitational lensing and other statistical signatures of large-scale structures and dark matter/energy.

Over the past years, a consensus has emerged as to the values of cosmological parameters (Hubble's constant, baryonic density of the universe, non-baryonic dark matter, dark energy, etc.). However, the physical processes that led to structure formation in the universe since the dark ages (before the birth of the first stars) are still poorly understood within the framework of the so-called "concordant model" and represent a major research area in astrophysics. Within this context, our team has focused its efforts on **three main areas associated with the scientific expertise in direct connection with the space experiments developed at the Department of Astrophysics (SAp)** or where we participate in major programmes:

- **Galaxy clusters and their contribution to cosmology (XMM-Newton, MegaCam, PLANCK):** dark matter profiles, role of non-gravitational processes in cluster formation, large-scale structures as traced by galaxy clusters.
- **Dark matter, dark energy, and cosmological origin of large-scale structures (DUNE, PLANCK):** Study of dark energy by measuring the gravitational lensing due to the large-scale structures of the universe, search for non-Gaussian signatures in the cosmic microwave background, statistical analysis of the spatial distribution of galaxies.
- **Cosmological evolution of galaxies and relationship with the environment (ISO, SPITZER, HERSCHEL):** Role of luminous infrared galaxies and collisions between galaxies, origin of cosmic infrared background, influence of local galaxy density, origin of local 'bimodality', role of accretion by supermassive black holes at the centre of distant galaxies, study of nearby galaxies as local analogies of distant galaxies.

It must be noted that an excellent synergy has developed between numerical simulations, signal processing, observations and instrumentation. In this respect, one of the objectives is to define observables directly comparable with theoretical models and numerical simulations so as to facilitate the synergy between theory and observations.

Galaxy clusters and cosmology

Galaxy clusters are composed of mostly dark matter, 20% X-ray emitting hot gas (intracluster medium, or ICM), and galaxies (a few %). They are the largest gravitationally bound objects in the Universe. In the standard hierarchical structure formation scenario, most groups of galaxies started to form at approximately z=2. This is followed by the formation and growth of clusters through continuous accretion of surrounding matter and through sporadic merger events. The observed X-ray properties of this evolving population provide crucial information on the physics of structure formation and the constraints associated with cosmological parameters. SAp researchers have been particularly active in this area of research for many years and have made abundant use of data from the XMM-Newton satellite since it was first launched.

Structural properties and scaling laws of cluster populations

The most simple, purely gravitational structure formation scenario predicts that galaxy clusters form a self-similar population. The internal structure of galaxy clusters is universal, with scaling laws linking each physical property

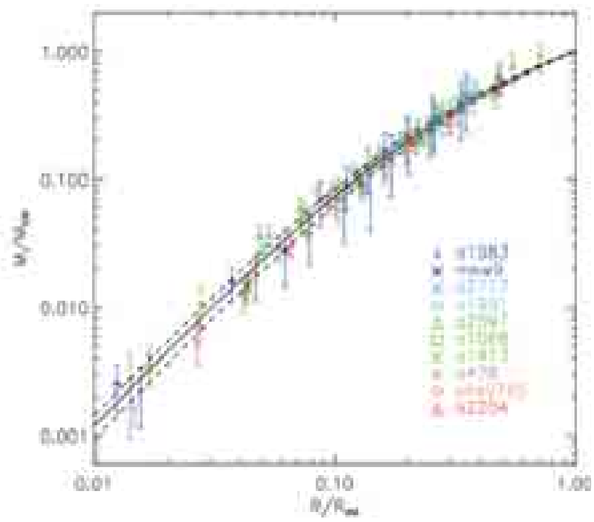

Figure 1. *Integrated mass profiles of 10 relaxed clusters covering a mass range from [1 – 12] 10^{14} h_{70} $M_{\odot}$ (with kT ranging from 2 [blue] to 9 keV [red]), observed with the XMM-Newton satellite (Pointecouteau et al., 2005). The mass and radius of each cluster are scaled to the virial mass M_{200}, and virial radius R_{200}, respectively. The solid line corresponds to the mean NFW model yielding the best adjustment, and the broken lines indicate the standard deviation.*

with the total mass M of the cluster or temperature T of the intracluster gas (ICM) and with the redshift. M. Arnaud, E. Pointecouteau and G. Pratt have studied the structural and scaling properties of a sample of local relaxed clusters (z<0.2) on the basis of accurate XMM-Newton observations covering a vast temperature range (2-9 keV). The analysis of Pointecouteau, Arnaud & Pratt (2005) provides a direct observational proof that the dark matter profile of nearby galaxy clusters is universal, with a central cusp as predicted by numerical simulations (see Pointecouteau et al. 2004). When compared with the virial radius (R_{200}) and virial mass (M_{200}), the mass profiles show a dispersion of less than 15% at 0.1 R_{200} (Figure 1). In addition, the shape of the profiles is in agreement with model predictions. Moreover, the concentration parameters are consistent with the mass-concentration ratio (c-M) derived from numerical simulations within the framework of a ΛCDM-type cosmology (Figure 2). This excellent quantitative agreement with theoretical predictions provides solid evidence in favour of a cold dark matter (CDM) cosmological scenario and shows that the physics of the gravitational collapse of dark matter is properly understood, at least at the scale of galaxy clusters.

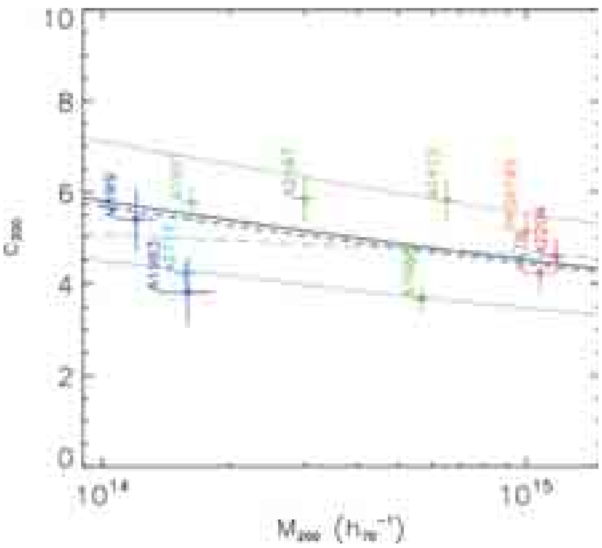

Figure 2. Concentration parameter c_{200}, based on cluster mass. The solid line represents the variation of c_{200} for clusters at z=0, derived from the numerical simulations of Dolag et al. (2004). The dotted lines indicate the standard deviation from this relation. The broken line represents the same relation for a redshift of z=0.15 (maximum redshift for this sample).

On the contrary, we have known for quite sometime that the properties of the intracluster gas show a deviation from the predictions of purely gravitational structure formation models. Pratt & Arnaud (2005) and Pratt, Arnaud & Pointecouteau (2006) have confirmed that the gas entropy S is in excess as compared to the value based on gravitational heating, not only for the core but also for the entire cluster (Figure 3). The S-T relation is flatter than the predictions of self-similar models at all radii. This is also the case with the S-M relation, as observed for the first time by our team. More surprising still, once scaled appropriately, the entropy profiles appear to be similar beyond $0.1R_{200}$, with an intrinsic dispersion of 15% and a shape consistent with gravitational heating. However, the dispersion increases at small radii, reaching up to 60% at R <$0.05R_{200}$. These results allow us to reject models that explain the entropy excess as due to preheating (prior to cluster collapse), but they are in qualitative agreement with models that increase entropy production (due to the effects of impacts during accretion). However, localised entropy modification (e.g. due to radiative cooling and AGN feedback) is probably needed to explain the dispersion in the inner regions.

The M-T relation is a fundamental scaling law. Since the other scaling laws are expressed in terms of temperature, the M-T relation provides the missing link between the gas properties and the mass. In addition, estimates of cosmological parameters derived from cluster abundance and spatial distribution rely heavily on this relation to relate the mass to the observables available from X-ray surveys. Arnaud et al. (2005) have measured the slope and scaling of this relation with unequalled precision. The scaling value is 30% higher than predicted by purely gravitational

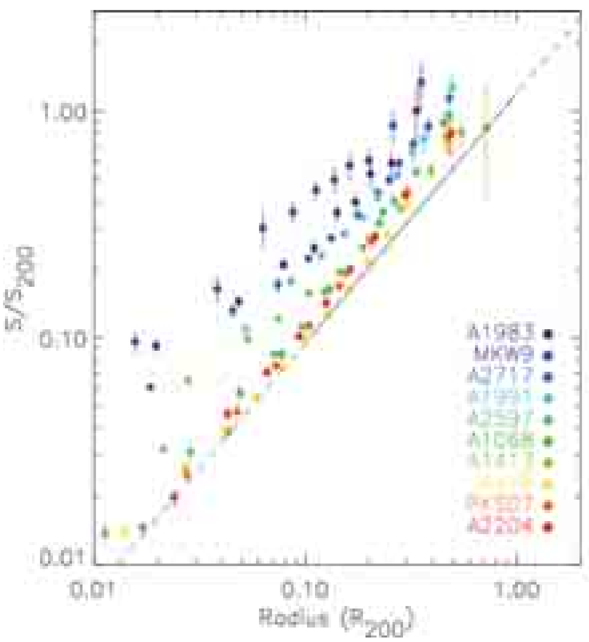

Figure 3. Entropy profiles of 10 relaxed clusters covering a mass range of [1 – 12] 10^{14} h_{70} $M_{\odot}$ (with T ranging from 2 [blue] to 9 keV [red]), observed with the XMM-Newton satellite (Pratt et al., 2006). The profiles have been scaled using the characteristic halo density S200 and the virial radius R200. The solid line represents the universal profile derived by Voit et al. (2005) from simulations including only gravitational processes. Note the entropy excess observable at all radii and its increase at small masses.

models, but agrees to within 10% with the most recent models taking into account cooling and galaxy feedback. We now need to consider larger, non-biased samples (e.g. covering a representative variety of dynamic states) in order to statistically study the properties of clusters in the local universe. This is the objective of REXCESS (Böhringer et al. 2007), a large-scale XMM-Newton observation programme conducted by H. Böhringer (MPE). An initial analysis of the temperature profiles (Pratt et al. 2007) has shown that they have similar shapes beyond the core region, with possibly a slight dependency on the dynamic state of the cluster. The central regions exhibit the largest dispersion, mainly due to the presence of cold-core clusters.

M. Arnaud is simultaneously conducting another large-scale XMM-Newton observation programme to study a non-biased sample of distant clusters (0.4<z<0.6) and accurately determine the redshift evolution of the scaling laws (in comparison with the project devoted to nearby clusters). This is of crucial importance in order distinguish and understand the relative roles played by the various non-gravitational processes. Independent estimates of the total mass of the clusters are currently being made using the gravitational lensing technique and the MegaCam camera (PI: G. Soucail, Midi-Pyrénées Observatory). In both of these programmes, the gas density profiles are derived from imaging data (with no prior assumption about the shape of the profiles) using an improved deprojection and PSF-deconvolution technique developed by Croston et al. (2006).

Cluster formation in the local and distant universe

The formation of large-scale structures follows a hierarchical scenario: groups form first, followed by increasingly massive clusters. Our team has developed numerical tools used to study the physics involved in cluster merging. These types of studies are important not only for the analysis of clusters, but also as tools for cosmology.
With the advent of X-ray spectral imaging (made possible by the CCD detectors onboard the Chandra and XMM-Newton satellites), it has become clear that the key analyses for the study of cluster dynamics (merging clusters in particular) are the gas temperature and galaxy density and velocity distribution maps obtained by spectroscopy and optical imaging (optical data collected by Maurogordato et al., Nice Observatory, OCA).

A new algorithm (X-ray Wavelet Spectral Mapping, or XWSM) based on a multiscale approach and intended to generate temperature maps from raw XMM data has been developed through a collaboration between OCA and SAp (Bourdin, Sauvageot et al. 2004). This algorithm takes into account instrumental effects and can be used to reconstruct significant temperature structures with no prior assumption on their location or geometry, which is a great advantage. Almost all of the results presented in this section were obtained using this algorithm.

A tool is currently being developed to compare observations and numerical simulations with high spatial resolution (J.L. Sauvageot). Starting from a set of predefined initial collision conditions, two 'ideally' relaxed clusters are allowed to evolve under the effect of their own gravity. Each cluster is in perfect hydrostatic equilibrium and initially follows a mass profile of the type described by Navarro, Frenk & White, represented by approximately 40000 non-collisional dark matter particles making up 90% of the mass, with the remaining 10% consisting of gas. These clusters are positioned inside a large-sized simulation box according to the speed and position parameters desired for the collision, and the evolution due to gravity is calculated using the RAMSES code (R. Teyssier). The X-ray emission is then calculated for each point of the simulation box, and XMM observations are simulated (also taking into account instrumental effects). This enables direct comparison (using the same simulation tools) between the simulations (whose collision parameters are known) and the real observations to be interpreted.

Three cases studied by our team which illustrate the efficiency of a combined X-ray and optical analysis for the interpretation of merging scenarios are presented below.
XMM observations show that the group that appears to fall

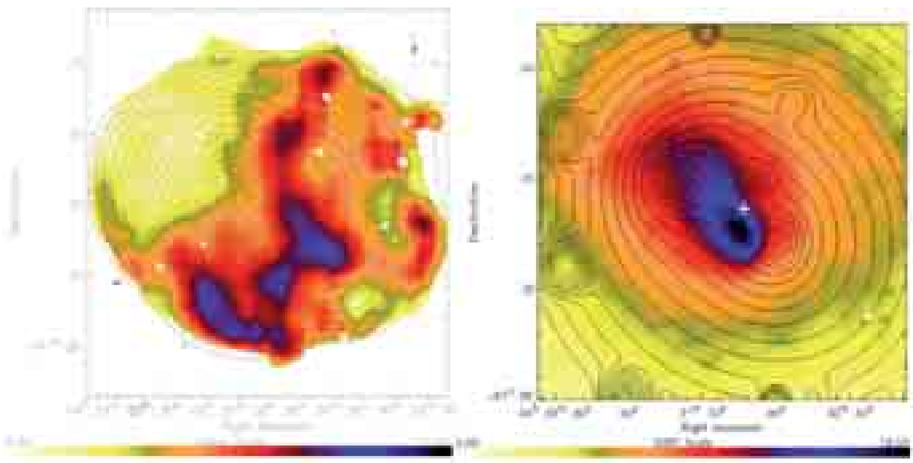

Figure 4. *Cluster A3266 observed by XMM-Newton. To the left: temperature map established using XWSM, with X-ray emissivity contours superposed. Note the spherical appearance of these isocontours and the shape of the hot region (in blue) corresponding to the shockwave. To the left: X-ray luminosity map with galaxy cluster density contours. This galaxy cluster is interpreted as due to merging during the maximum collapse phase (hence the apparent regularity of the X-ray luminosity). Note the bimodal appearance of the galaxy density distribution, due to the difference in relaxation time between the collisional gas and the galaxies.*

into cluster A3921 had actually already passed through the main cluster (Belsole, Sauvageot et al. 2005), contrary to the initial time-based interpretation of the ROSAT satellite. This is confirmed by the fact that the galaxies present in the wake of this group show an excess of star formation (Ferrari et al. 2005, A&A 430, 19).

Ferrari et al. (2006) have used Chandra observations to show that cluster A521 was composed of several subclusters and groups converging towards the centre of the main cluster and observed at different phases of the merging process.

Finally, cluster A3266 has been studied in detail using the beautiful mosaic of XMM observations (Sauvageot et al. 2005). Figure 4 shows the hot gas temperature map (to the left) and the X-ray luminosity map (to the right). A combined analysis of X-ray and optical data based on the bimodal galaxy density distribution (whose contours are shown in Figure 4 to the right) and the X-ray temperature map has led to the conclusion that this cluster consists of a main cluster into which a group is merging. Clearly evidence was obtained of the shockwave predicted by numerical simulations during the maximum collapse phase.

The purely gravitational physics involved in cluster merging now appears to be clearly understood. Of course, a large number of phenomena remain to be quantified, such as the entropy supplied to the cluster during merging (according to the mass ratio and progenitor impact energy) or the relationship between the radio relics present and the merging clusters (observationally established but still vaguely understood).

The XMM-LSS survey

The European XMM-LSS programme (XMM Large-Scale Structure Survey) is the largest cosmological X-ray survey of galaxies beyond the local universe (PI: M. Pierre).

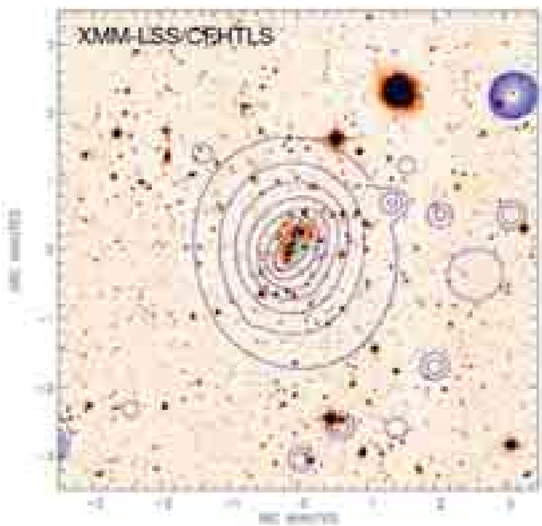

Figure 5. Hottest cluster detected in the XMM-LSS survey, with temperature T=4.8 keV and located at redshift z=0.43.
This study has led to the measurement of the temperature (T) and luminosity (Lx) of the intracluster gas, and the total mass (M) of the clusters. The temperature of the intracluster gas was measured for all clusters of the sample with an accuracy of up to 20% (including groups) for temperatures ranging from 1 to 5 keV. The spatial profile of the X-ray emission was used to measure the total mass by assuming a hydrostatic equilibrium of the gas in the gravitational potential pits of the cluster dominated by dark matter.

It aims to map the distribution of matter in the distant universe using galaxy clusters and active galactic nuclei (AGN) to investigate the physics of formation of these objects and to constrain the cosmological parameters (normalization factor, $\sigma 8$, and slope, Γ, of the power spectrum of primordial density fluctuations). Galaxy clusters are located at the nodes of cosmic structures and grow through accretion of galaxy groups along the filaments. The state of the intracluster medium is therefore subject to a succession of accretion and relaxation phases modulated by possible interactions with the cluster galaxies. The evolution of the spatial distribution and number of clusters as a function of time depends strongly on the cosmological parameters, the nature and quantity of dark matter, and the dark energy equation of state. The survey is designed to measure this evolution using the unequalled sensitivity of the XMM-Newton space experiment. With an XMM sensitivity (point-like sources) of ~ 5×10^{-15} erg/s/cm2 in the [0.5-2] keV range, it is possible to detect most of the galaxy cluster population at redshifts of up to z~0.6 (z=2 for massive clusters), and that of AGNs up to z~4.

In 2005, the XMM evaluation committee added 5 square degrees to cover the entire SWIRE field (Spitzer coverage) and CFHTLS field (CFHT MegaCam coverage). As a result, the XMM-LSS survey now covers 10 square degrees. The survey is specifically intended to allow a statistical analysis of clusters and AGNs selected only according to X-ray criteria. The central region of 5 square degrees has been studied in detail, leading to the publication of a complete catalogue of X-ray sources (extended and point-like sources, Pierre et al. 2006 and 2007) and an electronic database (http://cosmos.iasf-milano.inaf.it/~lssadmin/Website/ LSS/Query/).

The XMM-LSS survey has led to the compilation of the only complete X-ray sample of galaxy clusters with well-controlled selection effects and less than 1% contamination by point-like sources (Pacaud et al. 2007), using a dedicated method based on wavelet filtering (J-L Starck ; see Pacaud et al. 2006). This sample is publicly accessible via the database developed by DAPNIA (http://l3sdb.in2p3.fr:8080/l3sdb).

The luminosity-temperature, L-T, relation (and its redshift evolution) is one of the cosmological constraints derived from galaxy clustering. Until now, it had been measured in cluster samples selected by pointed observations (not systematically, based on a complete survey such as XMM-LSS). Pacaud et al. (2007) have shown that previous studies on clusters selected in this manner presented a systematic bias causing an artificial evolution of the L-T relation. In particular, it has been demonstrated that it is more efficient to constrain this relation by studying a large number of clusters with 30% temperature accuracy than by studying a few tens of clusters with high accuracy.

When studied according to the complete XMM-LSS sample, the redshift evolution of the L-T relation is compatible with a self-similar evolution law (see Figure 6). This, in combination with the cluster count according to redshift, contradicts the scaling value of the WMAP1 fluctuation spectrum (σ8=0.85), but is in agreement with that of WMAP3 (σ8=0.74) (Figure 7, Pacaud et al. 2007). The increase to 10 square degrees of coverage should reduce the grey zone in Figure 6, thereby placing more effective constraints on the evolution of the relation as a function of the redshift, and therefore σ8.

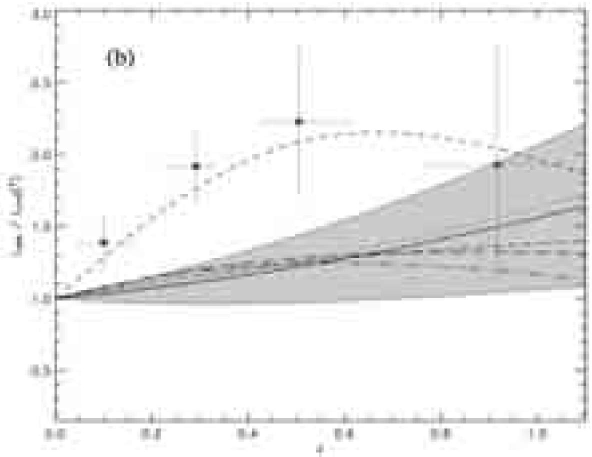

Figure 6. *Redshift evolution of the L-T relation in XMM-LSS (Pacaud et al. 2007). The points correspond to observations. After correction of selection effects, the data behave like the solid line, with the associated uncertainty represented by the grey area. Various models are compared: model of self-similar evolution (dotted line, very close to observations after correction of selection effects) and two models taking into account non-gravitational physics (dash-and-dot lines, not so close to observed values).*

The XMM-LSS survey has also produced a sample of ~ 3000 AGNs in the central five-square-degree field, allowing the angular self-correction function of AGNs to be measured for the first time in such a large field of view (Gandhi et al. 2006). There is apparently a stronger correlation for type II AGNs than for type I's, but over 5 square degrees the result is at the limit of detection and requires confirmation. If confirmed over 10 square degrees, the result of this study could question the unified AGN model, according to which the difference between type I AGNs (blue optical colour, soft X-ray spectrum, presence of broad emission lines) and type II AGNs (red optical colour, hard X-ray spectrum, only narrow emission lines) would be due to their different orientation (i.e. central dusty torus seen close edge-on in the case of type II AGNs, and close to face-on in the case of type I). In such a scenario, type II AGNs have no reason to exhibit a stronger self-correlation than type I's.

Moreover, the analysis of the AGN multiwavelength properties detected in the XMM-LSS survey has led to a better constraint of AGN spectral energy distributions through the application of the three criteria to distinguish between the two types of AGNs (X-ray, infrared and optical; Polletta et al. 2007, Tajer et al. 2007).

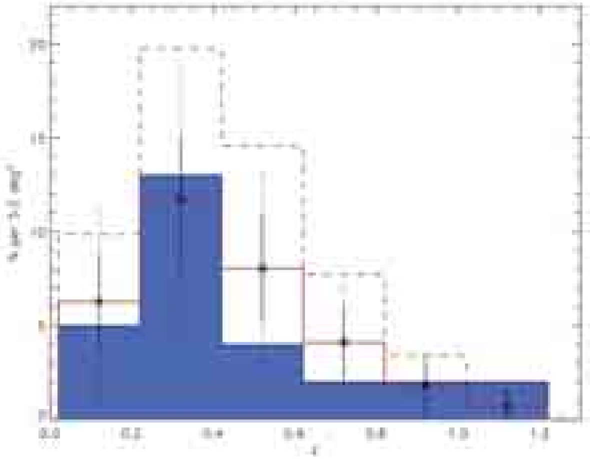

Figure 7. *Redshift (z) distribution of galaxy clusters in the central 5.2 square degrees of the XMM-LSS survey. The histogram of observations is shown in solid colour. The cosmological predictions for a primordial fluctuation spectrum normalization value σ8=0.74 (WMAP3) and a self-similar evolution of the L-T relation are shown as lines. The case where σ8=0.85 (initially proposed in the WMAP1 version) shows a systematic excess of 35% with respect to the observed values (shown here without evolution of the L-T relation, but even more significant in case of self-similar evolution).*

Dark matter, dark energy and cosmological origin of large-scale structures

Study of dark energy by measuring the gravitational lensing due to the large-scale structures of the universe

In 2005 and 2006, A. Réfrégier et al. (SAp) developed a new space mission concept called DUNE (Dark Universe Explorer; Réfrégier et al. 2006). DUNE is a wide-field imager whose main objective is to study dark energy and dark matter with unequalled precision using weak gravitational lensing (see Figure 8). The mission consists of a 1.2-metre mirror with a field of view of one square degree in the near visible and infrared ranges placed in geosynchronous orbit (Réfrégier et al. 2006; Grange et al. 2006). DUNE will allow all the sectors of cosmological models to be tested simultaneously, e.g. dark energy, dark matter and effects of large-scale structures. In particular, it will reach a 1% and 5% precision on the equation of state parameter and its evolution with redshift, respectively. Weak gravitational lensing can be used to characterise dark energy because of its effect on both the distance-luminosity relation and the cosmological growth of structures. As a result, DUNE will also make it possible to distinguish between dark energy models and models suggesting a modification of Einstein's gravitational theory.

SAp researchers have worked on how to optimise a gravitational weak lensing survey with DUNE in order to achieve maximum accuracy of the cosmological parameters (Amara & Réfrégier 2007). The immediate secondary objectives of the project concern the evolution of galaxies (to be studied with significant statistical power), the detailed structure of the Milky Way and nearby galaxies, and the demography of planets with terrestrial mass. DUNE will survey the entire sky in a visible band and three near infrared bands to produce a unique astrophysical and cosmological database. Further to a predesign phase (phase 0) conducted at CNES (including a focal plane analysis performed by Olivier Boulade, SAp), the satellite has recently been proposed as a medium-class mission for the ESA Cosmic Vision programme. SAp is the PI of this proposal and the DAPNIA has a leading role in the payload instrument of the mission.

Figure 8. *DUNE (Dark Universe Explorer) is a wide-field imager that will conduct a complete sky survey of large-structures. SAp is the project leader. DUNE will allow unique constraints on dark energy by studying its effects on the distribution of matter in the universe.*

Search for non-Gaussian signatures in the cosmic microwave background

The statistical properties of the CMB temperature anisotropies provide us with information on the physics of the primordial universe. If their distribution is Gaussian, they are generated by simple inflation models. Otherwise, they result from topological defects such as cosmic strings. We have developed a new type of statistical test based on the wavelet transform to detect cosmic strings (Jin, Starck et al. 2005 ; Starck, Aghanim & Forni 2004).

Preparation of the PLANCK mission

Component separation analysis: a new component separation method called GMCA and based entirely on parsimonious representation has been recently developed (Bobin, Starck et al. 2007 ; Bobin et al. 2006 ; Moudden et al. 2005) and proposed for the reconstruction of the cosmic microwave background.

Development of the MR/S software tool (MultiResolution on the Sphere): this software tools contains a set of sphere data analysis methods [Starck et al. 2006a] (wavelet and curvelet transform, Gussianity test, component separation, etc.). It has been made available to the scientific community.

Statistical analysis of the spatial distribution of galaxies

Galaxies are distributed along connected filaments and walls of various sizes forming a vast cosmic web encompassing huge, nearly empty regions. We have developed new methods to describe this distribution and compare it with the different cosmological models (Martinez et al. 2005 ; Starck et al. 2005), and we have applied them to 2DF data (Saar et al. 2007).

Cosmological evolution of galaxies and environmental effects

The extragalactic data obtained by the ISOCAM camera onboard the Infrared Space Observatory (ISO) had already provided us with evidence of the major role played by infrared luminous galaxies in the cosmological history of star formation and the production of the infrared cosmic background. During the period from 2004 to 2006, the observations made by NASA's Spitzer satellite not only confirmed these results, but also allowed for more in-depth analysis of infrared galaxies, particularly within the framework of major legacy-type programmes (GOODS, COSMOS, SWIRE) offering a combination of complementary multiwavelength observations.

Effect of the environment on star formation

The local density of galaxies reflects their environment and constitutes a significant observable providing a direct link with numerical simulations of hierarchical structure formation in a ΔCDM-type cosmology (i.e. composed of dark matter and energy). In this context, it is possible to test the relationship between the formation of dark matter halos and the formation of galaxies (through their star formation activity), as well as the star formation quenching mechanisms implemented in these simulations to reproduce the bimodal distribution of local galaxies into blue, active galaxies and red, dead galaxies (without star formation). Figure 9 shows the results of the MareNostrum simulation (Teyssier et al. 2007, under preparation), a large-scale numerical simulation of the universe with a resolution allowing the study galactic disc dynamics (1 billion dark matter particles, 10 billion gas cells).

Our team has achieved several significant results based on observations from the GOODS cosmological survey (Great Observatories Origins Deep Survey, PI: M.

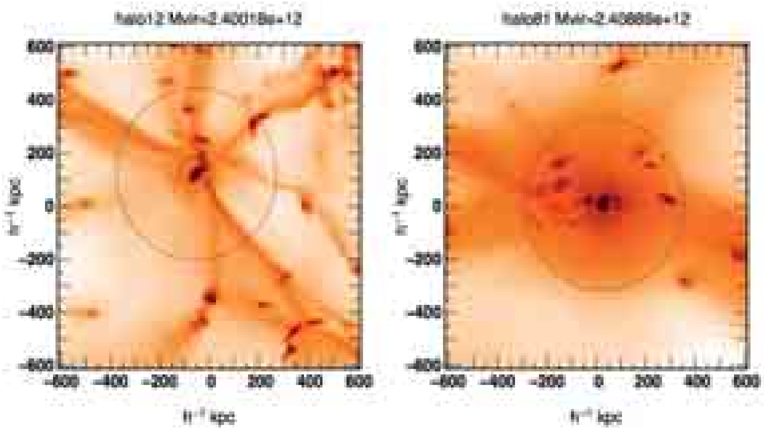

Figure 9. *Images obtained from the MareNostrum simulation performed in Barcelona within the framework of the Horizon project. The images shown are the result of 4 weeks of calculations performed by 2000 processors for 10 billion particles. These figures present the distribution of the baryonic matter. The large circle plots the contour of a halo of 2.4×10^{12} solar masses of dark matter at z=4 (left) and z=2 (right). Note the disappearance of the cold gas accretion filaments between the two redshifts.*

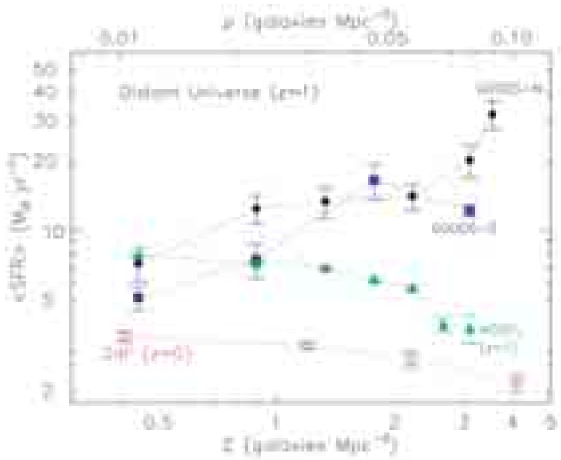

Figure 10. *Average star formation rate (SFR) of galaxies as a function of their environment, measured according to the local galaxy density (Elbaz et al. 2007). At z~1, the SFR was higher in the dense regions, whereas the opposite is observed today (z~0). At still higher densities, this study has shown that the SFR decreases again, suggesting that the formation of stars in the densest regions of the Universe occurred in more remote periods.*

Dickinson), a multiwavelength survey covering two 150 arcmin^2 regions and using a unique sample of redshifts allowing 3D mapping of the galaxy environment. By associating star formation rate measurements based on infrared luminosity (using techniques developed in the past; Chary & Elbaz 2001, Elbaz et al. 2002) with the 3D galaxy environment when the universe was half its present age (z~1), we have been able to show, for the first time, the reversal of the activity-density relation of galaxies in the past (Elbaz et al. 2007; see Figure 10). Contrary to what is observed today, galaxies in the past were more active in denser regions.

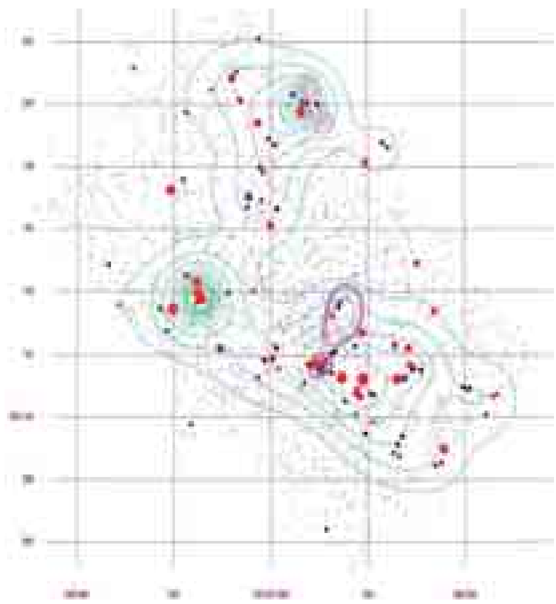

Figure 11. *Map of a proto-galaxy cluster at z~1.016, with galaxies having the highest star formation activity indicated by red dots of increasing size (Elbaz et al. 2007). The blue squares indicate the position of active galactic nuclei. The isodensity contours (shown in green) were obtained by wavelet filtering.*

The history of the formation of galaxies is therefore influenced by their environment (and by the formation of large-scale structures in particular). Although such a result could be intuitively expected within the scope of the hierarchical model, numerical simulations (e.g. Millenium simulation) predict the exact opposite, i.e. a decrease in SFR with increasing density. The influence of the formation of large-scale structures (and galaxy clusters in particular) is directly illustrated in Figure 11 which shows that the galaxies with the highest star formation activity are concentrated in the centre of groups of galaxies within a proto-cluster structure (Virgo-type cluster). The origin of this influence remains poorly understood. The study of the auto-correction function of infrared galaxies confirms that infrared luminous galaxies exhibit excess correlation with respect to infrared galaxies in general, and therefore that there is a relationship between the star formation activity and the environment (Gilli, Daddi et al. 2007). Based on measurements of the stellar masses of these galaxies, Elbaz et al. (2007) have shown that the activity-density relation is not only due to the presence of more massive galaxies in the dense regions, since the specific star formation rate (SFR/M*) also increases with the density.

Elbaz et al. (2007) have demonstrated the existence of a strong relationship of proportionality between the stellar mass of blue galaxies and their star formation rate. The most massive galaxies are either red and no longer forming stars, or they are blue and very active. The large fraction of galaxies with high star formation rates among the massive galaxies at z~1 (Elbaz et al. 2007) and z~2 (Daddi et al. 2005) suggests that the star formation activity extends over long periods and is a general phenomenon among galaxies. In addition, the majority of these massive galaxies with high star formation rates exhibit a morphology typical of massive spiral galaxies and not of interacting galaxies (HST/ACS imaging, see Figure 12). Moreover, galaxies that have undergone a recent interaction exhibit a specific star formation rate (SFR/M*) only slightly higher than that of an isolated galaxy. These studies suggest that interactions between two nearly equal mass galaxies do not play a dominant role to explain these effects, contrary to what had been proposed in the past.

Figure 12. *Three-colour images (BVI) acquired by the Advanced Camera for Surveys (ACS) onboard the Hubble Space Telescope, showing infrared luminous galaxies with high star formation rates corresponding to the 4 types of morphologies (z~1, 50 kpc): (a) spiral galaxy, (b) major merger of 2 galaxies, (c) irregular galaxy, (d) compact galaxy.*

Preparation of Herschel guaranteed time cosmological programs

We have significantly contributed to the development of two far-infrared photometers, PACS (70, 100 & 160 μm) and SPIRE (250, 350 & 500 μm), and we play a key role in Herschel GTO programmes devoted to cosmological surveys, i.e. PEP (PACS Extragalactic Probe, 650 hours) and HERMES (Herschel Multi-tiered Extragalactic Survey, 900 hours).

We have adapted our model of the evolution of the average infrared luminosity of galaxies (Chary & Elbaz 2001) so as to reproduce the count values obtained with Spitzer (Le Borgne et al., under preparation). This model has allowed us to calculate optimal sizes and depths for complementary surveys, as well as the confusion limit (Herschel is limited by diffraction).

3D mapping of the three components of galaxies

The COSMOS survey is an international multiwavelength observation programme aiming to study the impact of the environment on the evolution of galaxies, their star formation history and their active nucleus activity, within a field of two square degrees. It is based on a visible imaging survey from space (Hubble Space Telescope) and the ground (SuprimeCam (Subaru), MegaCam and Wircam (CFHT)), an infrared survey with Spitzer, an X-ray survey with XMM-Newton and Chandra, and spectroscopic survey with VLT (ESO) and Magellan. We have actively participated in the analysis of ground-based data obtained from this survey (Aussel, Daddi), and in the detection of the weak lensing signal in the HST data (Réfrégier).

Ground-based data is used to grossly measure the 3D spatial distribution of galaxies (by means of the photometric redshift technique), as well as their stellar mass. It can therefore be used to measure the stellar mass density in three dimensions. That is precisely what the COSMOS survey has done, as shown in figure 1, where the galaxy density is plotted in blue and green. X-ray data can be used to plot the hot gas of the clusters and galaxy groups (plotted in red in figure 13). These two tracers are visible matter tracers.

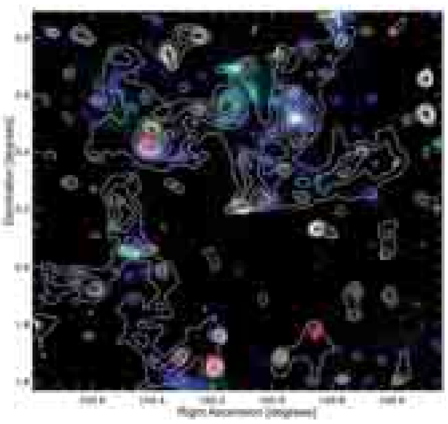

Figure 13. *Distribution of matter in the field of view of the COSMOS survey (Massey et al. 2007). The contours represent the distribution as plotted by the gravitational distortions of the background galaxies in the HST image. The image represents the distribution as plotted by the hot gas of the clusters and galaxy groups (shown in red) and by the stars of the galaxies (shown in blue).*

The presence of matter in the foreground of distant galaxies slightly distorts their shape (weak lensing effect). By statistically measuring this deformation in the HST image, we can measure the quantity of matter present in the foreground. This technique allows us to directly measure all the matter present in large-scale structures, i.e. both visible matter and dark matter. We have developed a new wavelet-based method to reconstruct dark matter maps (Starck, Pires & Réfrégier 2006b), as well as a statistical detection tool called False Discovery Rate (FDR). The codes developed have been integrated into a software tool (MR/Lens) and made available to the scientific community.

During the period from 2004 to 2006, our team participated in the first 3D mapping of the dark matter in the field of view of the COSMOS survey (Massey et al. 2007). This was achieved by combining the three tracers of matter in the universe. We also participated in 20 articles for the special edition of the Astrophysical Journal devoted to the COSMOS survey (scheduled for publication in 2007). From 2007 to 2009, we will analyse Spitzer data to obtain an unbiased measurement of star formation activity in galaxies covered by the COSMOS survey. We will then be able to study the effects of the environment on the star formation activity using the environment measurements taken during the period from 2004 to 2006.

Galaxy collisions and dark matter

The conservation of angular momentum is a classical law of physics perfectly illustrated during the collision of two galaxies. When they merge, the galaxies diffuse their angular momentum in the form of gigantic antennas or tidal tails. Numerical simulations have shown that these tails give birth to dwarf galaxies that contribute to the satellite galaxies observed in the close vicinity of massive galaxies (Bournaud & Duc 2006).

The theoretical models had predicted that, unlike conventional galaxies, these recycled galaxies should not contain dark matter. A kinematic analysis combined with a numerical model has allowed Bournaud, Duc et al. (2007 ; see Figure 14) to show that, on the contrary, these galaxies contain twice as much dark matter as visible matter. This visible matter is probably a baryonic dark matter component in the form of cold molecular gas generally present in the discs of spiral galaxies, and not in the spheroidal halo surrounding them (as expected for non-baryonic dark matter).

Figure 14. *Numerical simulation of NGC5291 (Bournaud et al. 2007): the visible galaxy in the centre (white) collided with another galaxy 360 million years ago. The collision formed a large ring of gas (visible in blue). This led to the formation of new dwarf galaxies (young stars visible in pink) in which an unexpected dark matter mass has been detected.*

Role of accretion by supermassive black holes

We now know that every local galaxy has a supermassive black hole at its centre, with a mass proportional to the stellar mass of the central bulge, but the origin of these black holes remains an open problem. The shape of the cosmic microwave background radiation in the X-ray spectrum suggests that most of the radiation produced during the accretion of matter that gave birth to these black holes must have been absorbed by very high density interstellar gas. The deepest images from the XMM-Newton and Chandra satellites have led to the identification of the galaxies responsible for this background at energies of less than 8 keV, whereas the cosmic microwave background attains a peak value of approximately 30 keV and nearly half of these galaxies with active nuclei remain to be discovered.

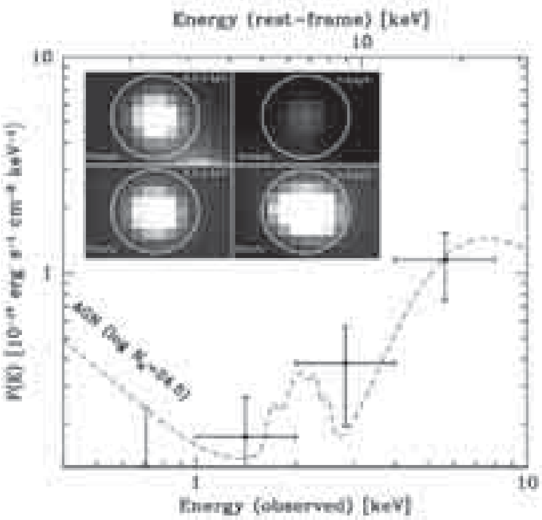

Figure 15. *Spectral energy distribution in the X-ray range obtained by stacking galaxies with an average infrared emission excess detected by Spitzer at 24 µm. The strong emission of hard X-rays suggests strong X-ray absorption, which explains why these galaxies were not individually detected by Chandra. The image shows the soft-band (0.5-2 keV) and hard-band (2-8 keV) stacking of 'normal' galaxies with an infrared excess (i.e. buried AGNs).*

Based on combined observations from the Spitzer and Chandra satellites, our team (Daddi et al. 2007a,b) has identified over 200 AGNs at a redshift z~1.5-2.5 (i.e. when the universe was 2.5 to 4.5 billion years old) by studying a complete sample of 2000 galaxies in the deepest images of the GOODS survey. These AGNs, which had not been detected in X-ray observations, were confirmed by stacking X-ray images at the positions of sources with an infrared emission excess. In addition, the spectral energy distribution of the detected galaxies was measured (see Figure 15) and corresponded to that of Compton thick AGNs, i.e. undergoing extreme extinction (hydrogen column density > 10^{24} atoms/cm2).

As a result of this study, the number of AGNs known at z~2 has been multiplied by 2 to 3. With a density of 3200 AGNs of this type per square degree (100 millions in the entire sky at z~2), these galaxies represent the entire missing population at z~2 according to current models (see Figure 16). Generally speaking, over 25 % of the galaxies as massive as the Milky Way (and 50% of those 2 to 3 times more massive) are AGNs at z~2.

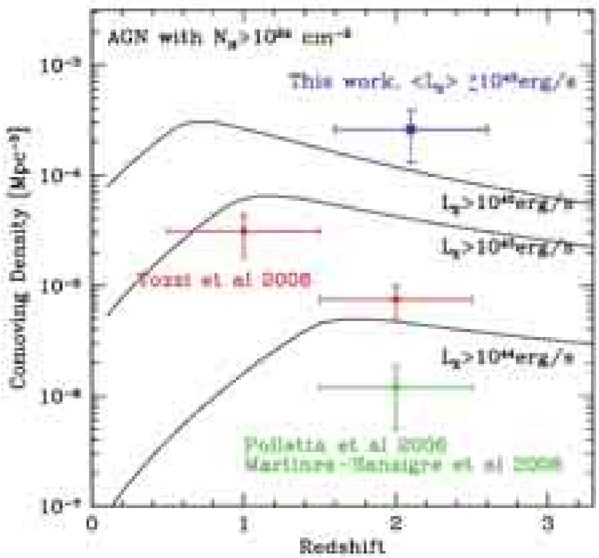

Figure 15. *Spectral energy distribution in the X-ray range obtained by stacking galaxies with an average infrared emission excess detected by Spitzer at 24 µm. The strong emission of hard X-rays suggests strong X-ray absorption, which explains why these galaxies were not individually detected by Chandra. The image shows the soft-band (0.5-2 keV) and hard-band (2-8 keV) stacking of 'normal' galaxies with an infrared excess (i.e. buried AGNs).*

Nearby galaxies as local analogs of distant galaxies

Through the detailed modelling of the observational signatures of the gas and dust in galaxies, we are laying the groundwork for understanding star formation activity in the wide variety of ISM (interstellar medium) conditions in the local universe, thus providing benchmarks against which distant, unresolved galaxies can be compared. The big issues we are confronted with center around one general question: What properties of the galaxy as a whole and processes within it control its observational signatures, such as the dust spectral energy distribution and the vast array of molecular and atomic emission lines? This is especially challenging for the distant unresolved galaxies, where we are limited by spatial information as well as luminosity.

The sensitivity, spatial resolution and wavelength coverage of Herschel will give us unprecendented capability to disentangle the effects of dust size distribution and composition, ISM structure, star formation activity, metallicity, density and temperature within the various phases of galaxies. Sauvage & Madden, using ISO and Spitzer data as well as ground-based data are examining the dust properties of elliptical galaxies, spiral galaxies and low metallicity and dusty starburst galaxies. Doing this for the different local galaxies, such as dwarf galaxies, spirals, starbursts and elliptical galaxies, will allow us to look toward the distant universe and study the evolution of these properties.

Low metallicity dwarf galaxies, which are bountiful in the local universe, are ideal laboratories to study the effects of star formation under primordial conditions and the process of metal enrichment in galaxies. We have found that their global dust properties are dramatically different in comparison to dusty starburst galaxies, with polycyclic aromatic hydrocarbons (PAHs), otherwise very prominent in dusty starburst galaxies (Vogler, Madden, Sauvage et al 2005; Förster Schreiber, Sauvage et al 2003), destroyed on large scales due to the hard, permeating radiation field and the energetic effects of shocks from supernovae (Galliano, Madden, et al 2003, 2005; Madden et al 2006). These effects seem to be related to the low metallicity ISM. Zooming into these kinds of environments, very young massive super star clusters with strong stellar winds can be found which emit optically thick radiation at radio wavelengths, even in galaxies as metal poor as 1/50th of the solar metallicity (Plante, Sauvage et al 2002; Thompson, Sauvage et al 2006). These winds, seen in galaxies which resemble those formed near the epoch of reoinisation, can have a dramatic effect in the galaxy's evolution by quenching the photoionisation very close to the stars thus delaying the onset of negative feedback by photoionization and photodissociation on star formation in the clusters. Our recent Spizer Legacy Program (1,100 h) focusing on our 2 nearest neighbors, the large and small magellanic clouds (LMC and SMC), now allows us to resolve molecular clouds, star formation sites, and supernovae remnants in 1/10 to ¼ solar metallicity galaxies.

Gas and dust flowing in and out of galaxies plays an important role in the energy balance and chemical evolution of galaxies. Knowledge of the physical conditions of outflowing matter in nearby galaxies can provide important constraints on galaxy formation scenarios, since outflows are crucial to these models. Evidence is accumulating for the presence of extended galactic halos, thick discs, and discrete connecting features between the disc and the halo in many spiral galaxies, both star forming and quiescent. Thus if we want to understand the origin and evolution of galaxies, we must study the chemistry and physics of the halos in galaxies. To address this question, we have taken the route of studying the character of the dust emission in edge-on galaxies in order to relate the dust components to a physical model. We made the first discovery of PAHs in the halo of a low star formation (1 to 2 Msolar/year) galaxy, NGC5907 (Irwin & Madden 2006) and have more recently detected PAHs in the halo of NGC5579 (2 Msolar/yr) out to more than 8.5 kpc, the most extensive galaxy halo yet detected (Irwin, Madden et al 2007). The halo shows substructure and that the PAHs likely originate from a disk outflow. This suggests that the ejection in NGC5529 likely did not occur more than about 100 million years ago; otherwise the galactic rotation would destroy these structures. PAHs are long-lived in a halo environment. Continuous replenishment from the disk is not a requirement. The optical and FUV photons must leak from the porous disk into the halo to excite the PAHs. Studying these processes can help understand what physical phenomenon are involved with the enrichment of the intergalactic medium.

Pinpointing the role of elliptical galaxies in galaxy formation and evolution models remains an outstanding astrophysical issue. One cosmology scenario supports the idea that elliptical galaxies have formed from more recent galaxy-galaxy mergers events. Evidence of recent merging or accretion have indeed been noted, primarily from obscuration in the optical, where fossil footprints in the form of dust ripples and dust lanes are sometimes detected. Another scenario has them forming early-on in the universe, leaving them as quiescent objects, evolving passively into old age. They are also thought to contain almost half of the stellar mass in the local universe. Despite their importance, relatively little is known about the ISM in these systems, yet the relatively simple dust life-cycle in elliptical galaxies should offer us an excellent laboratory to test the origin of the dust and structure. Early studies from ISO (e.g. Athey, Sauvage et al 2002; Xilouris, Madden, Sauvage et al 2004), and more recent Spitzer observations have seen that many ellipticals have excess mid-infrared emission that can be attributed to PAHs and very small grains. The survival of such small grains in the X-ray emitting plasma of these galaxies is surprising

Study of the initial phases of stellar cluster formation

We have recently established the existence of a population of young and very massive stellar clusters in the immediate environment of the AGNs of NGC1365 and NGC 1808 (Galliano et al. 2005, 2007). They are still buried in a cloud of cold matter and therefore only visible in the radio spectrum (cm/VLA) and thermal infrared spectrum (VLT/VISIR). We have developed an original method to date them (using the shape of their radio spectrum). These clusters have several characteristics that make their study interesting: (a) they are subject to strong gravitational fields due to the host-galaxy stellar bulge and the massive black hole in the AGN – their lifetime is therefore affected, and this impact can be quantified through numerical simulation (in progress), (b) they appear in a high-metallicity environment with an intense radiation field (AGN) – two highly specific and unique conditions. They therefore constitute a precious source of information on stellar formation in an environment encountered nowhere else.

Search for CO molecules in high-redshift AGNs

We are currently investigating the emission of molecular gas (IRAM data) in quasars amplified by the gravitational lens effect. The differential gravitational effects allow us to indirectly 'measure' the size and kinematics of the molecular material near the AGN with an effective resolution of less than one millisecond of arc. This requires an excellent lens model. We have therefore modelled gravitational lenses and searched for possible contributions from galaxy clusters or groups for an entire set of amplified quasars. Recently, in the course of the analysis of CO emission in MG0751, a quasar at z = 3.2 amplified by the lens effect was used to 'measure' the size of the molecular toroid (a few hundred parsecs, see Alloin et al. 2007). With the advent of ALMA, this pioneering method has a bright future

Theory and Modelling

A large panel of high performance numerical tools is developed in the Laboratory Theory and Modelling for Astrophysics, along with a sustained effort on the complementary theoretical and analytical approaches. The diversity of the issues so addressed, such as cosmology and galaxy formation, interstellar medium, supernovae or solar eruptions, discs and protoplanets, solar corona, and also laboratory experiments on high energy density plasmas, generated by intense lasers, ensures a large diffusion of these tools inside and outside the Astrophysics Division.

Cosmology

1-The Horizon Project: cosmological simulation and galaxy formation

In 2004, a group of astrophysicists, expert in computational cosmology and galactic dynamics has gathered to form a nation-wide project whose goal is to run, promote and exploit cosmological simulations of international standard. We have applied for an "ANR Blanche" grant and received 500 k€ funding (post-docs and hardware mainly) for the 2005-2008 period. This last few years, the Horizon team, led by Romain Teyssier (SAp), has developed mainly simulation and analysis codes, whose most notable realizations are the RAMSES N-body and hydro code, the MPGRAFIC initial conditions software and the ADAPTAHOP halo and dub-halo detection software. These are now freely available on the web. The Horizon project has also collectively conducted two computational "grand challenge" projects: the largest galaxy formation simulation ever performed (5 billions resolution elements) using MareNostrum at Barcelona Supercomputing centre and the largest N-body simulation ever performed (70 billion particles) using platine, the new BULL computer at CCRT (CEA Supercomputing centre). Ongoing work will give rise to several large databases where our results will be made available to the scientific community.

Figure 1. *True color image of a simulated deep sky survey using G, I and K filters (from the Mare Nostrum simulation; credit Christophe Pichon, AIM and IAP).*

2-Cosmic star formation history

For the PhD thesis of Yann Rasera, we have decided to tackle the problem of understanding the cosmic star formation history (the so-called Madau plot) in the universe using the currently favored model of hierarchical clustering. We have developed a new and quite simple analytical model to compute the star formation rate in the universe as a whole, but also in individual halos (Rasera & Teyssier 2006). This model was calibrated on very-high resolution simulations performed at CCRT. The star formation efficiency in galactic discs and the wind efficiency in dwarf galaxies are the two most important ingredients of the model. Using a compilation of observational estimates of the CSFR gathered by David Elbaz (SAp), we have determined the magnitude of these two parameters using an original "fitting" procedure. Our results show that although the CSFR can be well reproduced with reasonable values, individual halos SFR show a strong discrepancy at high-mass, where the observational SFR drops much faster at late time than predicted by the model (Rasera, Teyssier & Chièze 2003; Rasera & Teyssier 2006).

3-Gamma ray background from light dark matter annihilation

One interesting application of the previous analytical model is the possibility to compute self-consistently the amount of dense gas sitting in the center of each dark matter halo. Since the discovery of a thin 511 keV line by the INTEGRAL satellite, the idea of a light dark matter candidate annihilating in electron-positron pairs emerged. First calculations were performed based on the halo model

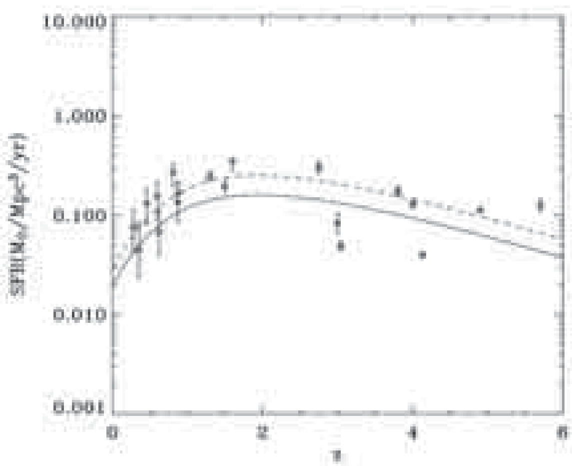

Figure 2. *Star formation rate predicted by the hierarchical model (line), compared to the observations (dots).*

to predict a possible soft gamma-ray background due to the collective 511 keV emission of all halos at all redshifts. An important point was missed at that time, namely that this emission is strongly dependant on the presence of dense magnetized ISM in the halo centre, so that electron-position annihilation can occur. We have therefore extended the previous calculations taking into account the effect of baryons, and found that the previous estimates were too large by a factor of 10 (Rasera et al. 2006).

4-Galactic winds in low mass halos

For the PhD thesis of Yohan Dubois, we have decided to study in more details the physics of galactic winds, since they are key ingredients of the galaxy formation theory. We have performed isolated halo simulations with self-consistent cooling, resulting to the formation of quiescently star-forming discs.

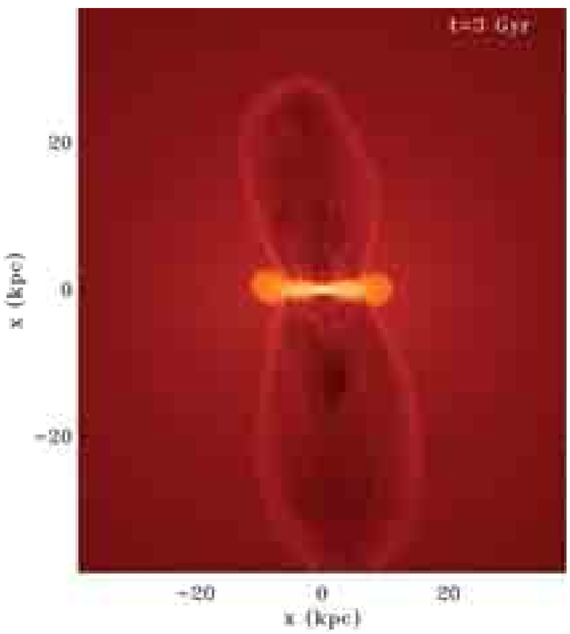

Figure 3. *A vertical slice showing an edge-on view of a galactic disc and the cavity created by the galactic wind emanating from the disc.*

We have determined that the main factor controlling the formation of galactic winds is the ram pressure of infalling material from the surrounding halo. It turned out that according to our simulations (Dubois & Teyssier 2006; 2007), only halo with circular velocity lower than 80 km/s can develop winds, and in that case, the wind efficiency is very low (less than 10%). Possible ways out of this conundrum are the effect of starbursts, the influence of a realistic, filamentary cosmological environment and some unknown physics in the dynamics of supernovae driven super-bubbles.

5-Self-regulation in AGN feedback

While supernovae feedback is likely to have an effect for low mass halos, we still need to explain why star formation proceeds at such a low rate, if any, in large elliptical galaxies or even in galaxy clusters. Among many possible mechanisms, one has received a strong interest from the community in the recent years: AGN feedback. The presence of AGN-driven bubbles in X-ray clusters is now firmly established by XMM and Chandra. We have studied the dynamics of such bubbles under the influence of thermal conduction (Benoit Commercon training period). It turns out that if the AGN power is too large, most of the energy escapes out of the hydrostatic cluster core, and if it is too low, it cannot prevent cooling and subsequent star formation. With Andrea Cattenea, we have performed high-resolution hydrodynamics simulation of a typical Perseus-like cluster core, with a central supermassive black hole accreting at the Bondi-Hoyle rate. We confirmed that, when the resulting jet interacts with the core, most of the energy escapes, leading inevitably to the so-called "cooling catastrophe". After this catastrophe, however, we have discovered that because of the resulting collapsing flow, the jet turns unstable, and the energy is much more efficiently deposited in the core, leading to self-regulation (Cattaneo & Teyssier 2006).

6-MHD scheme for the RAMSES code

This past 4 years have also been an intense period of code development, with the release of a new MHD solver for AMR codes. This solver has been first applied to the induction equation only. The idea is that any proper "up-winding" of the induction equation should rely on the solution of 2D Riemann problems at the intersection of 4 neighboring cells (Teyssier, Fromang & Dormy 2006). We have then implemented this solver for the ideal MHD equations in RAMSES (Fromang, Hennebelle & Teyssier 2006)

7-Theoretical cosmology

The work of R. Lehoucq in the field of cosmic topology, initiated in 1995, led to a publication in Nature of a new cosmological model, with no other free parameter than those already involved in the standard model. In this model of cosmic topology, the spatial section of the universe is multiconnected and described by the Poincaré dodecahedral space. This proposal allowed us to derive two predictions about the value of the total density parameter (1.018, within the error bars of the cosmological standard model) and about particular correlations to be found in the diffuse cosmic microwave background. This work has been extended, especially by developing a general method to calculate the normal modes in any spherical multiconnected space. M. Lachièze-Rey has calculated the eigenmodes of spherical spaces (topological variations of the three-sphere), in particular of the Poincaré dodecahedric. (Lachièze-Rey 2004 a, b, c, d; Lachièze-Rey and Caillerie 2005), applied to cosmic Topology (Caillerie et al. 2007, Riazuelo et al. 2007). The influence of topology on the polarisation of the microwave background has been studied. In the case of the Poincaré space, the temperature fluctuation power spectrum has been calculated, which allowed us to improve the fitting of the power spectrum measured by the WMAP satellite. They showed that the correlation between matched points is always positive and higher than the one obtained from temperature fluctuations maps, which is slightly blurred by Doppler and Sachs-Wolf effects. This work allows a search of an imprint of topology on cosmic microwave background polarization maps produced by the awaited Planck satellite. It is also the main part of S. Caillerie PhD thesis, defended in 2005.

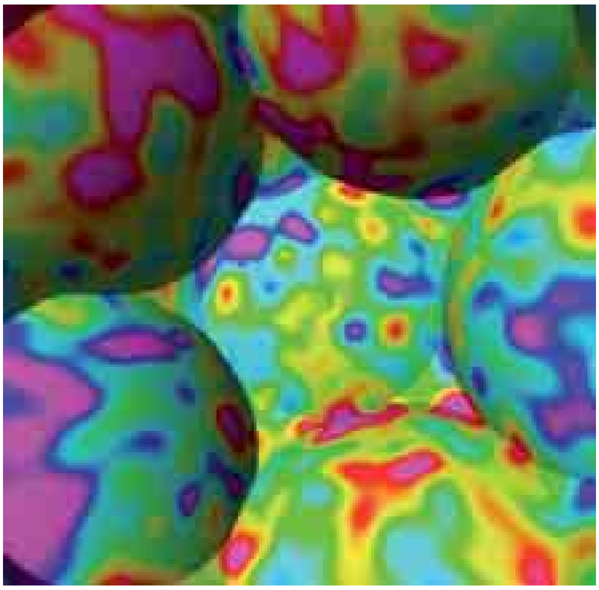

Figure 4. *The last scattering surface (LSS) as viewed from outside in the Poincaré space. Since the physical space is only a fraction of the volume encompassed by the LSS, it intersects itself along six pairs of correlated circles.*

In the field of quantization methods, M. Lachièze-Rey and collaborators studied the quantum field theory on de Sitter space-time (Gazeau, Lachièze-Rey & Piechocki 2005; Gazeau & M. Lachièze-Rey, 2006), and introduced the coherent state quantization method, establishing a very general protocol; they also compared with other quantization methods. They finally established the link (for the sphere) with non commutative geometry (Gazeau et al., 2007).
They also shown the existence of a system of (osculating) coordinates, adapted to the study of a local system in a cosmological context (Mizony and Lachièze-Rey, 2004, Lachièze-Rey, 2005). M. Lachièze-Rey proposed and analyzed a system of measurable and covariant coordinates which provides a reference system in general relativity (Lachièze-Rey M. 2006). By applying it, he showed that the Pioneer effect is not cosmological (Lachièze-Rey M., 2007)

Simulations of the Interstellar Medium

The neutral interstellar medium, which consist mainly of neutral atomic hydrogen (HI), is of primordial importance to understand the formation of structures such as molecular clouds and to determine the onset of the stellar formation process. HI was therefore subject of numerous studies both from the observational and theoretical point of view. However, due the multiphase nature of HI flows and to the very large span in the spatial scales that needs to be resolved, it is only recently that the complex dynamical properties of HI have been investigated through numerical simulations.

It is now well established, both from the observational and theoretical points of view that HI is a thermally bi-stable medium which at thermal equilibrium can be in two different thermodynamical states: a warm and diffuse phase (WNM) and a cold and dense one (CNM) roughly in pressure equilibrium.
We have used 2 and 3 dimensional high resolution simulations of thermally unstable HI flows in order to study the dynamical coupling between thermal instability and turbulence. The bidimensional simulations have a resolution up to 10 000 × 10 000, which is marginally sufficient to describe all the physical scales present in the flow. The three dimensional runs have a lower spatial resolution (i.e. up to 1200^3) but allow a better description of the topology and distribution of cold structures.

A density map of a high resolution 2D turbulent simulation is presented in figure 5. We can see that the flow is indeed very turbulent. Small dense CNM clumps are formed (in red) surrounded by warm WNM and unstable gas (in green). We can see that the two phases are tightly interwoven and that the flow exhibit very complex structures. In spite of this strong turbulence, the sharp front separating the warm from the cold phase is still present and locally the situation is quite similar to the two-phase equilibrium model. Even for

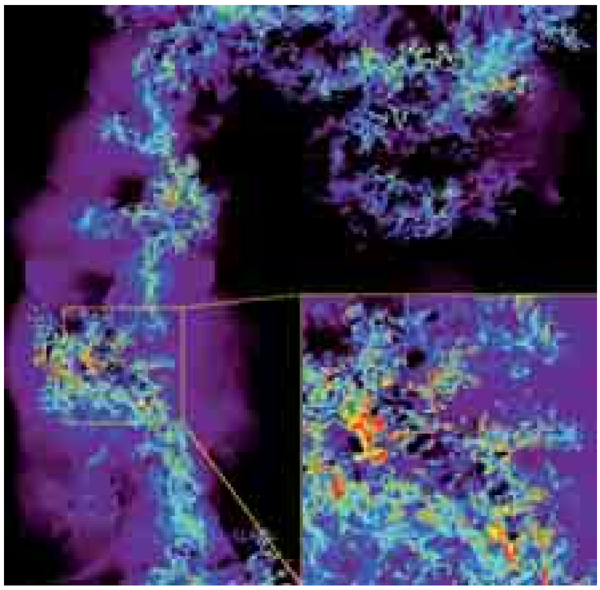

Figure 5. *Density map of a very high resolution (10000^2) turbulent simulation of the ISM fragmentation. Black corresponds to WNM with density less that 1 cm^{-3} and red to CNM structures above 100 cm^{-3}.*

this very dynamical medium the pressure fluctuations are rather small (i.e. about one order of magnitude compared to more than three for the density fluctuation).

This study have shown that the number of cold structures formed was closely related to the degree of turbulence (i.e. the higher the turbulence the lower the number of structures). We have also shown that the masse spectrum of the CNM structures was: $N(M) \sim M^{-1.7}$. We have proposed analytical model to explain both these phenomena. A study of the spectrum of various quantities (density, velocity ...) has also permitted to highlight the differences between the ISM turbulence and the Kolmogorov theory.

Jets structure

A study of the interaction between a jet and the ambient interstellar medium, using the HERACLES code for radiation hydrodynamics, has shown that radiative effects can have important consequences when the jet is well embedded in a dense, opaque molecular cloud. Taking into account, for the first time, the feedback of the re-absorption of cooling photons by the gas, it has been shown that a radiative precursor may form upstream of the jet. The resulting pressure increase tends to collimate the jet over its axis, leading to the formation of a dense and thin secondary jet.

Theory and Modelisation of Supernovae Explosions

A tight coupling between theory and modelisation is carried out to explore the nature of both gravitational and thermonuclear supernovae.

1-Instabilities and the Asymmetric explosion of Core-Collapse Supernovae

The discovery of the advective-acoustic instability by Foglizzo (2001, 2002) led him to understand why the accretion of gas on a black hole moving supersonically is unstable. By studying the interaction of acoustic waves and entropy/vorticity waves after an accretion shock, he was able to distinguish physical effects from numerical artefacts in the numerous adiabatic numerical simulations of this classical problem named Bondi-Hoyle-Lyttleton accretion (Foglizzo et al. 2005). This work is based on the use of perturbative methods for the calculation of eigenfrequencies and wave coupling efficiencies, and a strong interaction with the leaders of numerical simulations, in Great Britain and Japan.

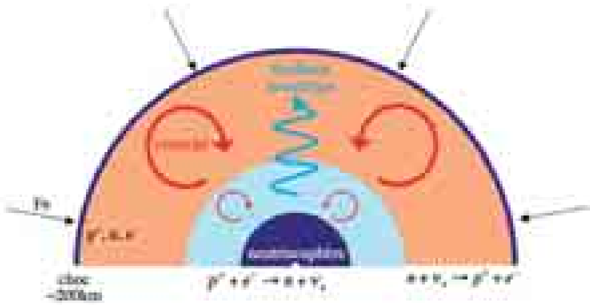

Figure 6. *The advective-acoustic cycle in the core-collapse supernovae is based on the linear coupling between vorticity waves, advected downward, and acoustic waves propagating outward.*

Following the same method, T. Foglizzo investigated the consequences of the advective-acoustic instability on the problem of core-collapse supernovae, where a standing accretion shock is stalled during a few hundred milliseconds in the iron core above the surface of the proto-neutron star, before explosion. First recognized in the numerical simulations of Blondin et al. (2003), this instability, also named SASI, has become a major object of research by many other groups in the USA, Germany and Japan. T. Foglizzo supervised the PhD thesis of P. Galletti (2003-2005) on this subject.

A close collaboration with the specialists of the MPA group in Garching enabled Foglizzo et al. (2006) to first characterize the effects of the convective instability associated to neutrino heating, and distinguish them from the development of SASI. Neutrino driven convection favours unstable motions on a smaller scale than the global l = 1,2 oscillations of SASI. A perturbative analysis using WKB approximations were used to demonstrate the instability of the advective-acoustic cycle in a simplified set up (Foglizzo et al. 2007) and interpret more realistic numerical simulations of core collapse (Scheck et al. 2007).

The consequences of SASI on the core-collapse problem are spectacular. It seems to be a key ingredient in the success of neutrino powered explosions (Marek & Janka 2007) as well as in the new acoustic mechanism of Burrows et al. (2006). Its asymmetric character could be the key to the long standing "pulsar-kick" problem (Scheck et al. 2004, 2006), and the develoment of a spiral mode could also affect the pulsar spin (Blondin & Mezzacappa 2007).

In order to establish the theoretical foundations for these promising effects, T. Foglizzo has developped the "Vortexplosion" project, based on the complementarity of perturbative and numerical approaches. This project involving 2 postdocs (T. Yamasaki and J. Sato) and an active collaboration with Germany and Japan, is funded by CEA, the French Research Agency (ANR), and Egide.

2-Thermonuclear supernovae

The study of thermonuclear supernovae at SAp/LTM began as part of the project « Combustion and Supernovae », initiated by J.-P. Chièze, under the auspices of the Institut Lasers & Plasmas. With the collaboration of Y. Busegnies and L. Siess (both from Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles), and B. Dubroca (CELIA and IMB, Université Bordeaux 1), we first established a robust equation of state for the plasma of a white dwarf, with arbitrary relativistic degeneracy. This has been included, altogether with the treatment of the plasma cooling by neutrinos, convection and radiative transport, in the 1D hydrocode ASTROLABE, developed by J.-P. Chièze. This code offers an extremely high resolution capability, due to the adoption of a « moving grid » technique. It has been used to study ignition of the C+O mixture of a sub-Chandrasekhar white dwarf through accretion from a companion. A series of models have been calculated by J.-P. Chièze, to study the ignition process in an accreting white dwarf. The results suggest that for a wide range of accretion rate, ignition proceeds at the surface of the accreting white dwarf, at the bottom of the accretion layer. Combustion then propagates both inwards and outwards, as two strong detonation waves (Figure 7).

In parallel to this approach, a 2D simulation of the cellular

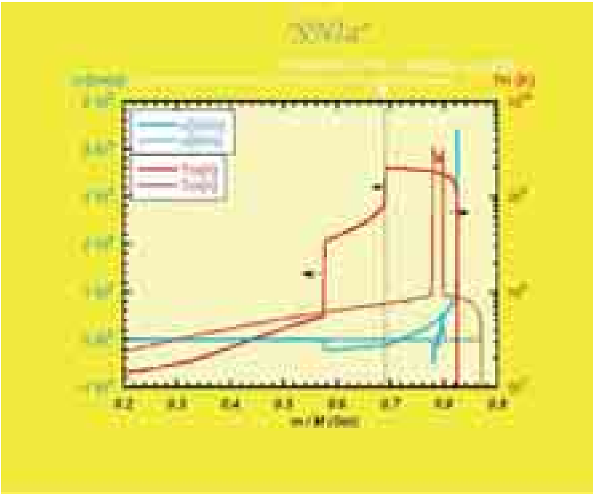

Figure 7. One dimensional simulation of the ignition of the C+O plasma of an accreting sub-Chandrasekhar white dwarf, occurring at the bottom of the accretion layer. Two strong detonations, moving in the opposite directions are formed.

propagation mode of detonations has been performed by E. Audit and J.-P. Chièze, in order to prepare a more general study of the detonation behaviour against density gradients, as encountered in the envelopes of SNIa progenitors.

Discs and protoplanets

During the period 2004-2006, the research work of F. Masset on discs and protoplanets was mainly focused on two points.

1-The development and release of numerical codes dedicated to planet-disk interactions.

F. Masset made a public release of the FARGO code, available at the following address: http://fargo.in2p3.fr After its release, this code has been used independently by several groups in the world. In addition to the features developed in the main, stable release, some new features have been implemented in the form of beta releases: the inclusion of the disk's self-gravity and of an adiabatic equation of state have been undertaken by Clément Baruteau, who is doing his PhD under my supervision, and mesh 1D extensions to follow the disk's global evolution have been implemented by A. Crida, as part of his PhD thesis work, at the Côte d'Azur Observatory (Crida, A.et al. 2007). F. Masset have also worked on the 3D, nested grid parallel code named JUPITER, in which he implemented a technique that enables a proper description of the disk's hydrostatic equilibrium, based on a zone splitting technique developed by LeVeque. The public release of this code is now in progress. Its salient features are its versatile geometry (spherical, cylindrical or Cartesian), its ability to work in a rotating frame, and a number of characteristics aimed at an efficient scheme in the case of an embedded protoplanet (such as an automatic time-step splitter for a recursive subcycling on levels of increasing resolution).

2-Tidal interaction of forming planets with their protoplanetary disk

With Gordon Ogilvie (DAMTP, Cambridge), F. Masset has investigated the saturation properties of several, overlapping corotation resonances (Masset & Ogilvie, 2004). They found that these properties are very similar to the saturation properties of an isolated resonance, which offers a step forward in the understanding of the eccentricity excitation of giant protoplanets by the tidal interaction with the disk. F. Masset then turned to the study of the coorbital corotation torque and the so-called horseshoe drag, and their impact on the migration of low to intermediate mass planets. In particular, with A. Morbidelli and A. Crida (OCA) and J. Ferreira (LAOG), it has been shown (Masset, Morbidelli, Crida, Ferreira, 2006) that a surface density jump in a protoplanetary disk can efficiently act as a planet trap, due to the action of a boosted corotation torque. As a consequence, incoming planetary embryos should halt their migration at the edge of cavities, even shallow ones.

In collaboration with G. D'Angelo (NASA-ARC) and W. Kley (University of Tuebingen), the transition of the topology of the horseshoe region has been investigated (Masset, D'Angelo, Kley, 2006). This region extends between the low horseshoe region width, and the high mass regime, which resembles the classical restricted three body problem. They have found that in the intermediate mass regime (around 5-15 $M_{\oplus}$) the horseshoe region is overwide, which boosts the

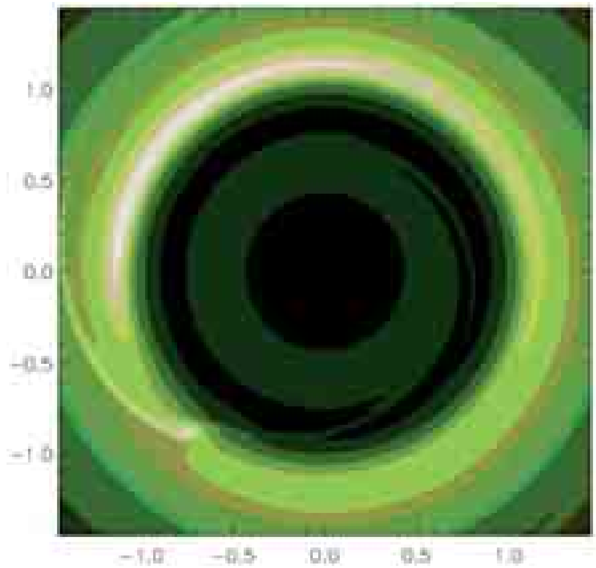

Figure 8. This figure shows the wake of a protoplanet trapped at a cavity edge (dark circular area) in a protoplanetary disk. Its migration is stopped, and it keeps a fixed circular orbit at this location.

action of the corotation torque and may cause migration to stall. With Clément Baruteau, they have investigated the impact of the disk's self-gravity on type I migration, for which contradictory statements existed in the litterature. They confirmed analytical expectations that self-gravity slightly speeds up migration (rather than slowing it down, as suggested by some previously published simulations), and we have designed a fast method, based on the use of an anisotropic pressure, to mimic the effects of self-gravity. As a side result, they also confirmed the fact that the corotation torque is almost insensitive to the disk's self gravity.

At the end of 2006 they began to get interested in the effect of the equation of state on the type I migration rate (for low mass objects), as it had been claimed a few months before (Paardekooper & Mellema, 2006) that the type I migration of planets could be halted or reversed in non-isothermal disks. We contemplated the limiting case of an adiabatic flow and found that a contact discontinuity appears in the corotation region, which adds a component to the corotation torque that scales with the radial entropy gradient, and which can indeed stop or reverse the migration of low mass objects. The results have led to a publication in the Astrophysical Journal (accepted), which will appear at the end of 2007.

Astrophysical Plasmas in Space and Laboratory

1-The solar coronal magnetic field

A long term analytical and numerical study of the evolution of the solar coronal magnetic field is pursued by J.J. Aly. The main goal is to understand the triggering of large scale eruptive processes like coronal mass ejections by the changes occuring at the photospheric level (shearing of the foot points, injection or disappearance of flux, etc.). On the analytical side, the current work is essentially devoted to the particular question of the determination of a force-free equilibrium with an a priori prescribed topology. Exact upper and lower bounds on the energy of a solution to that problem have been derived, and some results regarding existence and uniqueness of solutions have been established. Also, some new 3D analytical solutions of the magnetostatic equations (including the plasma pressure force) have been obtained, and their properties studied in details.

On the numerical side, a collaboration with T. Amari and J.-F. Luciani (CPhT, Ecole Polytechnique) is carried on. Efforts have been done for developing a model allowing a self-consistent description of both an active coronal region and the upper part of the underlying convection zone. In particular the evolution of a magnetic flux tube, initially present below the photosphere, has been computed by using a MHD code. At some stage the tube emerges into the corona, and after a quiet phase during which it stays in quasi-equilibrium, it is found to expand at a fast rate, while a large amount of energy is released by a reconnection process (see Fig. 9).

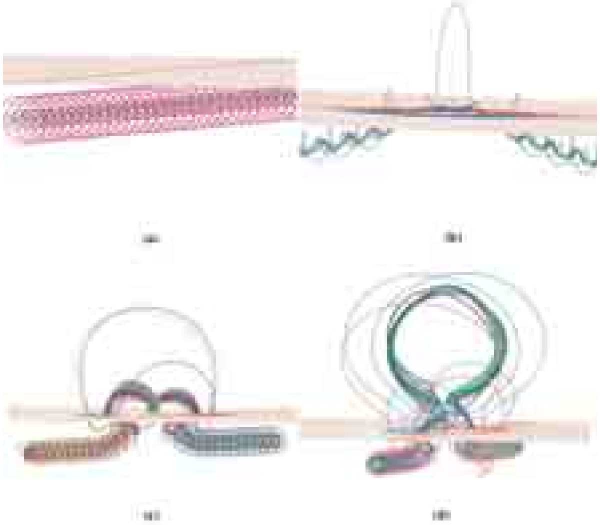

Figure 9. *Emergence of a flux tube through the photosphere and evolution in the corona. (a) Initial configuration. (b)-(c) Quiet phase of the evolution. (d) Beginning of the fast expansion phase. (From T. Amari, J.-F. Luciani & J.-J. Aly, ApJ 629 (2005)).*

2-Structure of the magnetosphere of a pulsar

J.-J. Aly has reconsidered, from an analytical point of view, some aspects of the axisymmetric model of pulsar magnetosphere, initially introduced by F. C. Michel, in which the charges occupy only a domain of finite size, consisting of two domes extending above the poles and an equatorial belt. He obtained in particular a general result concerning the 'force-free surfaces' separating a charged region from an empty one (a vacuum), and established several results of confinement and nonlinear stability.

3-High Energy Laser Plasmas

High energy lasers allow producing plasmas with temperature, density or velocity characteristics which join those met in various astrophysical objects. Our group develops a triple approach of designing, modelling and interpretation of experiments. A special effort has been stressed on the modelization of coupled hydrodynamics and radiation flows, with an effective feedback from laboratory radiative shocks experiments.

Radiative shocks

In strong radiative shocks, the structure of the flow is controlled by radiation. It may be so due to the high radiative energy density itself, which can not be neglected relative to the gas thermal pressure, or through the high energy flux radiated from the shock front. Strong radiative shocks are ubiquitous in various phases of the stellar evolution, as accretion shocks in the star formation process (TTauri accretion funnels), in the structure of jets launched from young stellar objects, in the pulsating envelopes of stars, or in supernovae explosions. Difficulties in the numerical description of these shocks arise from the huge dynamics of the spatial and temporal scales. Dedicated plasma laser experiments are used for code validation.

The HERACLES code

In his PhD work, M. González developed a 3-D, parallel radiation hydrodynamics code, with visualisation modules. (González et al. 2007). Coupled radiation-hydrodynamics moment equations (the so called model M1, initially developed in Dubroca & Feugeas 1999) are solved by a combination of the parallel implicit solvers Gauss-Seidel and GMRES, well suited to the general regime encompassing the diffusive and the free streaming regimes. It has been shown that HERACLES compares well with Monte Carlo codes.

Experimental validation on a laser driven radiative shock in xenon

HERACLES has been used for the modelling and the interpretation of an experiment held at the high energy laser facility PALS (Prague, Czech Republic) on December 2005. F. Thais (also at CEA/DSM/DRECAM/SPAM). E. Audit and M. Gonzalez have participated in this experiment, with C. Stehlé (Observatoire de Paris-Meudon, LERMA) as principal investigator. The shadowgraphy diagnosis of the plasma indicates that multidimensional effects and radiative lateral leakage do affect the propagation of the radiative precursor of the shock wave. With the HERACLES code, the influence of the lateral radiative losses on the slowing down of the radiative precursor has been pointed out, and quantitatively assessed (such as the influence of the albedo of the xenon container, and the dependence of the curvature of the radiative shock on the ratio of the photon mean free path and the width of the container). Simulations have been performed on the CCRT parallel computers, with a few hundreds processors.

4-The SiNERGHy project

In 2006 the project SiNERGHy (Simulations Numériques EN Rayonnement, Gravitation et Hydrodynamique) led by E. Audit was accepted by the ANR and received a 600 k€ funding. This project is a large collaboration between the SAp, the SEDI at CEA, the CELIA at the University of Bordeaux 1, which has specialists of laser generated plasmas and inertial fusion, and Laboratoire de Mathématiques Appliquées de Bordeaux (Institut de Mathématiques de Bordeaux). This project aims at satisfying simulation needs in the fields of Astrophysics, Hot Dense Matter and Inertial Confinement Fusion. A large part of the scientific production in these fields relies upon simulations of complex unsteady hydro flows, coupled to non equilibrium transport and chemical kinetics. As the characteristic time scales of transport may be much shorter than the fluid time scale, implicit numerical methods are required. Some of the numerical codes developed in the presently co-working institutions may be now regarded as mature. Nevertheless, the large scale exploitation of these codes exceeds the isolated capabilities of the developing teams. A coordinated action was thus necessary. The main issues that will be tackled in the coming years are:

1. Numerical methods for multi-material, three dimensional compressible, unsteady flows.
2. Parallel algorithms. Specifically, efficient implicit solvers for non linear transport or diffusion equations.
3. Data management and visualisation.
4. Constitution and efficient access to large shared data bases for equations of state and transport coefficients.
5. Source code management and software design in order to ensure
   - Cross validation of codes
   - Stability and long term maintenance of software.
   - Interoperability : portability of physical packages, exchange of numerical data, code linking.

In this context, an opacity database server, named ODALISC (Opacity Database for Astrophysics, Laboratory astrophysics and Inertial Fusion SCience) was developed. This server gathers spectral opacities computed by various teams. These opacities are all in the same format and tools are provided to visualize and use these opacities in radiation-hydrodynamics codes such as HERACLES.

Teaching and Scientific Diffusion

Several physicists of LTM are deeply involved in the academic formation, at the Master 2 and Doctoral levels. J.-P. Chièze and E. Audit, are respectively professor and associate professor at Institut National des Sciences et Techniques Avancées (INSTN). They give lectures in three Masters (2nd year M2) in astrophysics (Astronomie & Astrophysics d'Ile-de-France, Observatoire de Paris, Paris VI, Paris VII and Paris XI) and plasma physics (Optique, Matière et Plasmas, Université de Paris XI, Université de Paris VI, Université Paris VII, Université de Versailles Saint-Quentin, Institut d'Optique, École Polytechnique, École Nationale Supérieure des Télécommunications, and Sciences de la Fusion, a federations of ten institutions : Université de Provence Aix-Marseille I, Université de la Méditerranée Aix-Marseille II, Université Paul Cézanne Aix-Marseille III, Université Bordeaux I, Université Nancy I Henri Poincaré, Université Paris VI Pierre et Marie Curie, Université Paris XI Paris-Sud, Ecole Polytechnique, Institut National Polytechnique de Lorraine (INPL), Institut National des Sciences et Techniques Nucléaires (INSTN). In the frame work of the Ecole Doctorale d'Astronomie et d'Astrophysique d'Ile de France, J.-P. Chièze also organized a post-doctoral teaching module of 30 hours devoted to the contribution of large lasers to High Energy Density Physics and E .Audit a similar module dedicated to high performance computing in Astrophysics.

E. Audit and J.-P. Chièze also gave lectures in various schools at the pre- and post- doctoral levels (Ecole prédoctorale des Houches [J.-P. C.], September 2005, Ecole d'Aquitaine on plasma physics and fusion, September 2005 [J.-P. C.] and September 2006 [J.-P. C., E. A.], "Formation Plasmas créés par lasers", Bordeaux 1 University [J.-P. C. 2004, 2005, 2006]). Every year, F. Masset gives a post-master lecture on "Planet-Disk interactions" for students of the "Ecole Doctorale d'Astrophysique d'Ile de France". In september 2005, he also gave this lecture at the Summer School organized in Oléron by J.P Zahn and M.J. Goupil on "Interactions in composite systems": stars, disks and planets, Since September 2006, R. Lehoucq is part-time professor at Ecole polytechnique in charge of two courses (Nuclear Physics and Astrophysics ; Special Relativity and Variational Methods). He also teaches an Introduction to Stellar Physics at ENSTA, within the frame of European exchanges between high schools (ATHENS).

R. Lehoucq maintained his editorial activities (articles in specialized magazine and books) and also gave public lectures (about 30/year). He was scientific advisor for various exhibitions produced by scientific museums (Mission Biospace, at Cité de l'Espace of Toulouse ; Le monde de Franquin et Star War, l'Expos, at Cité des Sciences et de l'Industrie of Paris). Year 2005, declared World Year of Physics by UNESCO, was particularly active from this point of view. He was in charge of the whole editorial process of 4 booklets, 20 pages each, whose issues were the Universe, the Earth and its environment, Physics of Life, Matter and Light. 60 000 copies of theses booklets were freely distributed in all French undergraduate schools.

F. Masset has written, in collaboration with Wilhelm Kley (University of Tubingen) a chapter of the book "Planet Formation: Theory, Observation, and Experiments" (Cambridge University Press 2006), on "Disk-planet interaction and migration"

The JWST and the MIRI project

The JWST[1] space observatory, a NASA led mission intended as a replacement for the HST[2], is due to be launched on an Ariane rocket in 2013. The programme is an international collaboration between the US space agency (NASA), the European Space Agency (ESA) and the Canadian Space Agency (CSA). One of the major scientific aims is to observe the very first objects to shine in the universe.

Background

The JWST has a planned lifetime of between 5 and 10 years. It will be located at the L2 Lagrange Point between the Earth and the Sun at a distance of 1.5 million kilometres from the Earth.
The 6.5 metre diameter primary mirror will have a light gathering area almost ten times that of the HST. The on-board instrumentation will be sensitive to infra-red and will enable the JWST to detect radiation emitted up to 13 billions years ago.

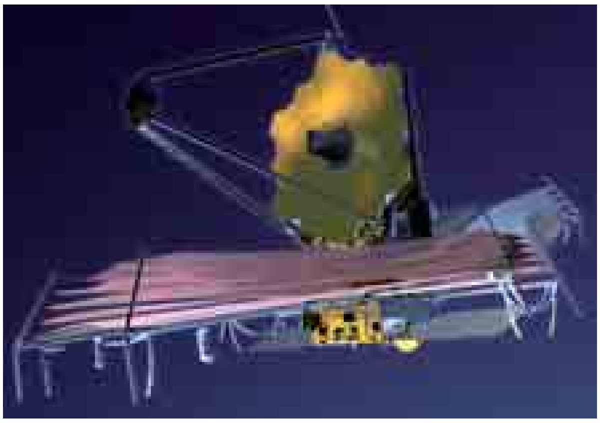

Figure 1. *The JWST (artist's impression); credit NASA.*

The MIRI[3] mid infra-red spectrometer-imager (5µm to 27 µm) is one of the four instruments carried on board the JWST. This instrument has been designed by a joint European and US consortium. The European contribution has involved research institutes in Germany, Belgium, Denmark, Spain, Ireland, France, the Netherlands, Great Britain, Sweden and Switzerland, coordinated by Gillian Wright at the Royal Observatory, Edinburgh (ROE).
The CEA, in partnership with the CNES and with the participation of the LESIA[4], IAS[5] and LAM[6] laboratories within the CNRS, is responsible for supplying the entire optical bench assembly (MIRIM-OB) for the imager with the exception of the detector which will be supplied by the JPL[7].

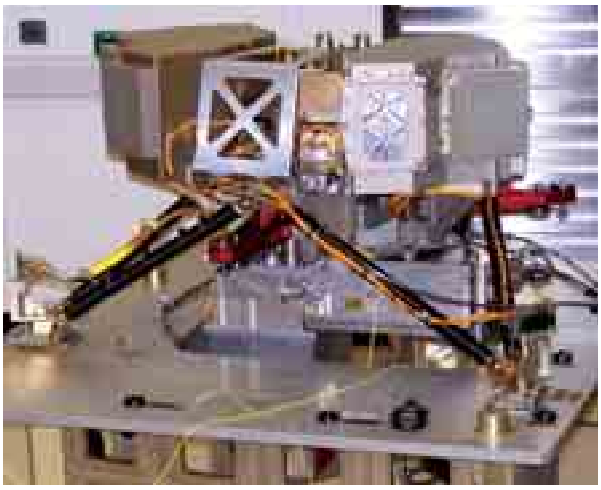

Figure 2. *MIRI: Verification Model assembled at the RAL.*

The role of the Astrophysics Division

The Astrophysics Division is responsible for delivering the French contribution which itself includes contributions from other European laboratories. These include the MPIA[8] (Germany) supplying the cryomechanism for the filter wheel, the CSL[9] (Belgium) responsible for manufacturing the mirrors and the double prism and for checking for the absence of stray light, and the UoS[10] (Sweden) who are supplying the optical filters.
The Astrophysics Division, in conjonction with the DAPNIA SIS and SEDI divisions, is responsible for the optical and mechanical design, manufacture and integration, and testing of MIRIM-OB. The Astrophysics Division is also contributing to the test specifications and calibration monitoring procedures for the entire MIRI instrument.
The French MIRI team consisted of between 40 and 50 people during 2004-2006.

MIRIM, the MIRI imager

The MIRI imager (MIRIM) provides imaging functions at wavelengths between 5 µm and 27 µm, coronagraphy[11] at wavelengths between 10 µm and 23 µm, and low-resolution spectroscopy.

1 JWST James Webb Space Telescope
2 HST Hubble Space Telescope
3 MIRI Mid InfraRed Instrument
4 LESIA Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique
5 IAS Institut d'Astrophysique Spatiale
6 LAM Laboratoire d'Astrophysique de Marseille
7 JPL Jet Propulsion Laboratory (USA)
8 MPIA Max Planck Institut für Astronomie (DE)
9 CSL Centre Spatial de Liège (BE)
10 UoS University of Sweden (SU)
11 Method enabling the immediate environment of a star to be observed without the detector becoming saturated by the light from the star itself. Used in the search for exoplanets, dim companion stars, dust discs, etc.

Figure 3. *3-D view of the MIRIM-OB.*

The MIRIM-OB is an optical bench assembly consisting of a supporting framework on which is mounted an optical path with five mirrors, a filter wheel, and three phase masks and a Lyot mask for coronagraphy (supplied by the LESIA) at the input plane. The system also includes an optical system for calibration. The assembly is designed to operate at a temperature of around 7 K.
Following delivery to the RAL[12] for integration and tests in conjunction with the MIRI instrument, the MIRIM-OB will be mounted on the MIRI support deck and coupled to the IOC[13] which supplies the incoming light beam for imaging and calibration. The focal plane detector module will then be attached to the output window.

The main MIRIM sub-assemblies

The optical system

The MIRIM optical system consists of five mirrors. Three of these mirrors form a TMA[14] system for an improved image quality. The mirrors have been designed by the Astrophysics Division and manufactured by the CSL.

The

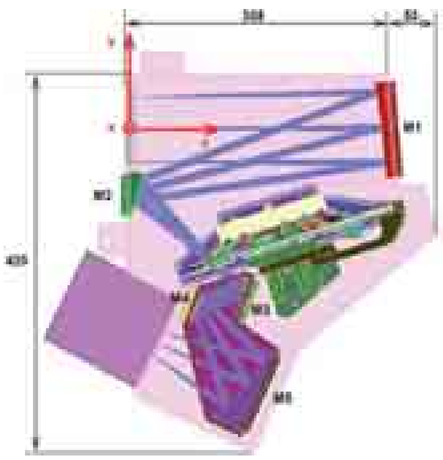

Figure 4. *The optical path and mirrors.*

Figure 5. *The M3 mirror.*

mechanical structure

Machined from a single block of aluminium, the mechanical structure supports the optical elements and provides the optical, thermal and mechanical interfaces. It also features bafflets to prevent from stray light.

The filter wheel

The filter wheel incorporates 18 positions. Four of these are used to support pupil masks for coronagraphy, while one position holds a double prism for low-resolution spectroscopy and another is fitted with a blanking shutter. The remaining 12 positions are fitted with filters suitable for imaging at wavelengths between 5 µm and 27 µm.

Figure 6. *The VM filter wheel.*

The VM filter wheel

No less than six laboratories contributed to the design and manufacture of this sub-assembly:

- The Astrophysics Division and the Dapnia/SIS were responsible for the design of the disc and the optical ports.
- The Dapnia/SEDI provided the optical equipment.
- The LESIA designed and manufactured the coronagraphy pupil masks.

12 RAL Rutherford Appleton Laboratory (UK)
13 IOC Interface Optics & Calibration unit (resp. CSL)

14 TMA Three Mirror Anastigmatic

- The MPIA supplied the cryomechanism.
- The UoS supplied the optical filters.
- The CSL supplied the double prism.

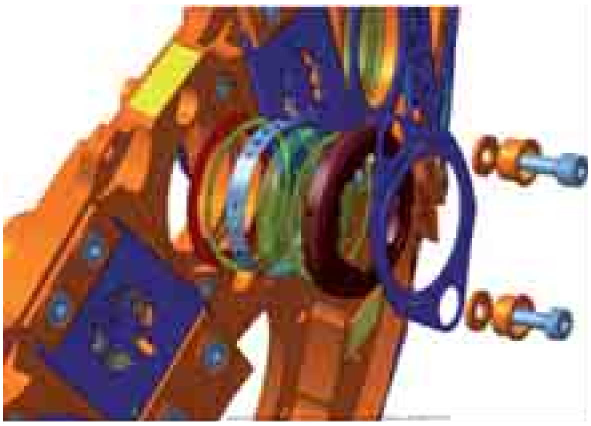

Figure 7. *Filter mounting (detail).*

Coronagraphy focal plane

This focal plane masks part of the MIRIM input window. It consists of a framework supporting three phase masks and a Lyot mask. The system also includes a slit for the low-resolution spectroscopy mode.

Figure 8. *Coronagraphy focal plane: Verification model.*

The coronagraph function is provided by combining the phase masks and the pupil masks on the filter wheel. The specification for the alignment of these two components is very demanding as they must be positioned to within a few microns relative to each other.

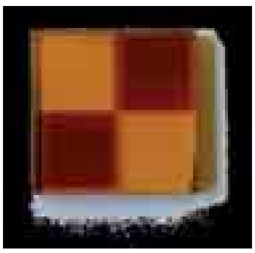

Figure 9A. *Coronagraph phase mask.*

Figure 9B. *Coronagraph pupil mask.*

This sub-assembly was designed and manufactured by the LESIA. The design and manufacture of the phase masks was sub-contracted by the LESIA to the DRECAM[15] Condensed Matter Physics division.

The models

The development of space instruments requires the manufacture of a number of intermediate models to confirm the functional performance of the design and to qualify the Flight Model in the environments it will have to withstand before, during and after launch.
At least six models will be built in addition to the mechanical and thermal computer simulation models. A number of intermediate demonstration models will also be built as part of the approval process for the most critical components.

Mass Model

The purpose of the Mass Model is to confirm the mechanical and thermal design in the area of the MIRIM imager and the MIRI instrument.
The model has been built and tested and was delivered in mid-2004 to be integrated with the MIRI instrument Structural and Thermal Model.

Verification Model

This model was built in 2006 in order to validate the following:

- The mechanical and optical design.
- The manufacturing processes.
- The integration schedule and procedures including ambient temperature tests.
- The integration of MIRIM into the MIRI instrument (interfaces and procedures).

The model was delivered in May 2007 and was successfully integrated with the MIRI Verification Model.

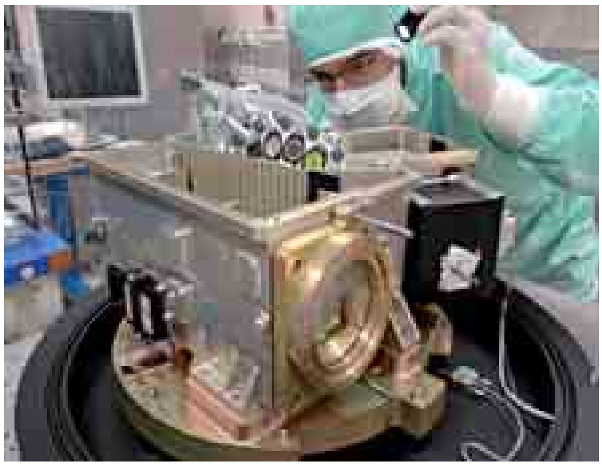

Figure 10. *The Verification Model during inspection.*

[15] DRECAM **D**épartement de **R**echerche sur l'**É**tat **C**ondensé, les **A**tomes et les **M**olécules, CEA/DSM

Figure 11. *Cryogenic test bed.*

The existing resources available to the Astrophysics Division (clean rooms, thermal cycling enclosures, etc.) have been used and modified where necessary to meet the specific requirements of MIRI.
Other resources, including integration tooling, ambient temperature and cryogenic test facilities have been specially developed.
A cryogenic test bed has been developed specifically for the MIRI project. This test bed was developed in collaboration with three other DAPNIA departments. The SACM was responsible for the cryogenics, the SIS provided the control and data acquisition systems, and the SEDI developed the telescope simulator specified by the IAS.
The use of a detector supplied by the JPL has required specific studies and tests, the construction of a cryogenic test bed, and the design of a suitable mechanical and thermal enclosure.

Engineering Model

This non-deliverable model is identical to the Verification Model. It will be used for functional and performance tests at both ambient and operational temperatures (~7K). This model will be used to validate the design, characterisation and test procedures for the Flight Model.

Mechanical Qualification Model

This model is mechanically representative of the Flight Model and will be used for mechanical tests in the operating environment with the aim of qualifying the design and calibrating the computer simulation models.

Flight Model

This model is due to be built in early 2008. Following low-temperature characterisation and testing, it will be delivered during the fourth quarter of 2008.

Spare Model

The model is identical to the Flight Model and will be used as a replacement in the event of a late failure.

Manufacture, Acceptance, Integration and Validation

Most of the manufacturing operations will be carried out by industrial sub-contractors.
Most of the integration, test and qualification of the models will be carried out by the Astrophysics Division. These development phases have required the design and construction of equipment to meet space standards, together with the development of highly rigorous procedures.

Assurance product

The preparation and implementation of a Product Assurance Plan and associated resources are an absolute necessity, especially in the case of space projects. Such a Plan has been incorporated in the project and includes the requirements of both the ESA and the MIRI instrument. The Plan covers the monitoring of modifications and anomalies, the continual checking against specific quality requirements (cleanliness, materials, and processes), and the conformity of the deliverable documentation.

Schedule for 2004-2006

June 2004	Delivery of the Mass Model.
October 2004	Preliminary MIRI design review.
June 2005	JWST scientific evaluation review.
June 2006	Critical MIRIM design review.
December 2006	Critical MIRI design review.

ARTÉMIS

*SAp has positioned itself as a leading player in the eyes of the astronomic community by offering unique DRT/Léti technology to produce several thousands of absorbing pixels in the far-infrared (60 to 200 µm) range. The ArTéMiS project aims to strengthen this technological progress by extending developments with a view to producing large focal planes for very large, 12 m ground telescopes. These will be thus equipped with several thousands of absorbing pixels in the [200 – 1,200 µm] range. This is the objective of the ArTéMiS programme (bolometer **Ar**chitectures for ground **Te**lescopes with a wide field of view in the sub**Mi**llimeter domain).*

The results detailed below were obtained at the end of the project's first year.

Scientific objectives

The programme was put forward as part of an ANR (French national research agency) initiative and will receive funding for three years (2006, 2007 and 2008). In addition to various CEA departments, it brings together the Centre for Research into Very Low Temperatures (CRTBT) in Grenoble, the French Institute of Spatial Astrophysics (IAS) in Orsay and the Institute of Astrophysics in Paris (IAP).

Submillimetric astronomy (submm) is the principal observation technique used to study the creation and early development stages of a wide range of astrophysical objects. This range of wavelengths makes it possible to observe the Cold Universe (typically between 10 – 30 K) since the emission spectrum of such cold objects has a maximum size of between 100 µm and 1 mm. Using the largest ground telescopes, the angular resolution of these ranges can be significantly improved, which, in turn, makes it possible to identify any fragmentations of dust and gas clouds during gravitational collapse. The angular resolution of the ArTéMiS-1 camera installed on a 12 m telescope, such as the APEX in Chile, will make it possible to access the mass spectrum of massive protostars.

Submm astronomy is also used to study the far-off Universe by observing the properties of distant galaxies that have been shifted towards the infra-red (or rather submm) range as the universe expands. Here again, the use of instruments with higher angular resolution than those that can be deployed in space, makes it possible to envisage resolutions for the diffuse cosmic infrared background into individual objects, which would eventually shed light on the mystery of the origins of this background. The use of several thousands of pixels paves the way to wide fields of views and makes it possible to select zones that are rich in primordial galaxies, which could then be detailed in highly sensitive surveys as part of the ESO's ALMA programme.

Figure 1. *P-ArTéMiS installed in the focal plane of the KOSMA telescope*[1].

Technological objectives

The project's key objective is to produce an automatic camera (**ArTéMiS-1**), providing a wide field of view in three wavelength bands : 200, 350 and 450 µm. A secondary objective is to develop bolometer technology (using grids or antenna) with a view to producing a second camera (**ArTéMiS-2**) devoted to the [800 – 1,200 µm] band. The bolometric pixels sensitive to these wavelengths must be cooled to sub-Kelvin temperatures. Their use in limited-access sites - such as the upper plateaux of the Atacama Desert (5,000 m) in Chile - requires the development of automatic cryogenic systems, representing the project's third objective.

Demonstration prototype

The first year of the project (2006) consisted of implementing a prototype camera (**P-ArTéMiS**) that aimed to validate the principle of bolometric detection at 450 µm. This camera was first installed on KOSMA, a 3 m telescope situated at an altitude of 3,100 m in Switzerland (see Figure 1, Talvard et al, 2006). This initial session provided a wealth of information and the preliminary results were used to optimise a first test run conducted on the APEX telescope in Chile at the beginning of 2007. The first mapping of a region of star formation was thus obtained.
In parallel, studies into the design of a cryostat for the ArTéMiS-1 camera have made progress. A system based on the use of a pulsed-gas tube providing a 4 K cooling capacity, coupled with a Helium 3 + Helium 4 adsorption cryocooler from the DRFMC/SBT in Grenoble is currently being produced.

First 450 µm images of a region of star formation

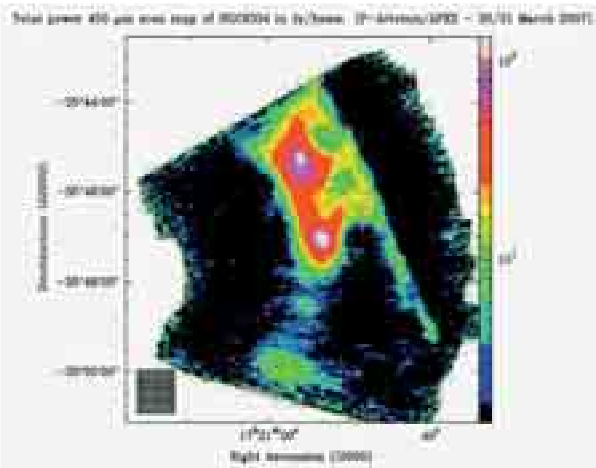

Figure 2. *450-µm image of the 6334 NGC region obtained using the APEX telescope[2]. The square in the bottom left-hand corner indicates the size of the 256-pixel matrix used to produce the mapping*

[1] KOSMA 3 m telescope situated at 3,100 m on the Gornergrat site in Switzerland, in collaboration with the University of Cologne.
[2] APEX 12 m antenna situated at 5,100 m on the Chajnantor plateau in Chile, collaboration with the Max Planck Institut fur Radioastronomie (Germany), the ESO and ONSALA Space Observatory (Sweden).

GOLF-NG

An association between SAp, SEDI and SIS, are presently developing a prototype that takes benefit of SoHO results. The GOLF-NG (Global Oscillation at Low Frequency New Generation) instrument will measure, like GOLF, the global Doppler velocity variations in the sodium line NaD1.

A new solar resonant spectrometer demonstrator

We are presently building in CEA/France in collaboration with IAC/Spain a demonstrator which results from a 30-year expertise on resonant scattering spectrometers (Brookes et al. 1978) used on ground (IRIS and BiSON networks) and in space (GOLF/SoHO).
Such effort is motivated by the superiority of the Doppler velocity technique demonstrated in space (see chapter 4) by the GOLF/SoHO instrument (known 15 days after the first analysis of the different instruments in 1996). Such instrument has reached its main objectives to probe the nuclear core of the Sun. SoHO has shown the capability of this technique to reveal the totally unknown dynamics of the solar core. The rotation in this important part of the Sun seems different than in the rest of the star but it appears clear that the measurements must be pursued (Mathur et al. 2007) to put valuable constraints on the rotation profile and on the magnetic field for a strong development of complete modelling and simulations of the whole Sun (see also chapter 9).

The composition of the team and the characteristics of the instrument are described in Turck-Chièze et al. (2006). The improvements of this new concept consist of trying to

- measure the velocity at 8 positions in the solar atmosphere between the photosphere and the chromosphere to reduce the effect of the solar granulation in the range of g-modes. This orientation uses the fact that the observed patterns of the solar granulation differ, consequently we must improve the signal over noise in the gravity mode range of frequencies by this innovative method.
- increase the number of photons detected by a factor 10 for a reduction of the instrumental noise by a factor 3 or 4 to reduce the instrumental noise in this region when the solar noise is reduced. Figure 1 shows from GOLF that the gravity mode region is first polluted by the granulation noise, the red part of the spectrum showing a particularly low instrumental noise. his second point must be maintained in relative value,
- (3) measure both intensity and velocity to separate vertical and latitudinal variation of the line.

The scientific objectives of GOLF-NG are extremely difficult to reach. GOLF has probably detected some gravity mode signals with a velocity in the atmosphere of the order or smaller than 1mm/s for period between 1 hour and 10 hours. Doing better by a factor between 5 or 10 needs to solve real technical and scientific challenges. But different studies show that the aim is now reachable in considering the fact that GOLF has not worked nominally and that the velocity has been extracted on only one wing of the lines.

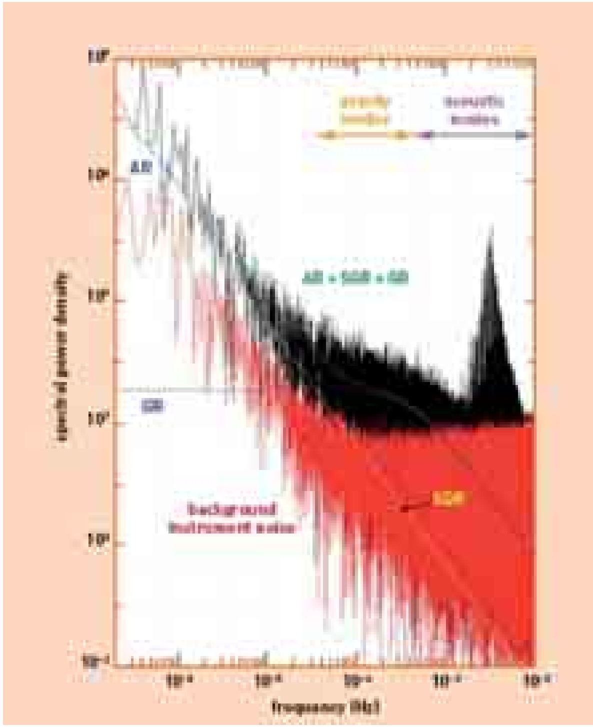

Figure 1. *GOLF spectrum (Turck-Chièze et al. 2004) where the different sources of noise appear very clearly.*

GOLF-NG measures the Doppler shift of the solar D1 sodium Fraunhofer line by a comparison with an absolute standard given by the sodium vapour cell, the heart of the experiment. The corresponding photons are absorbed by the sodium and reemitted in a very narrow band. A small portion of the line is probed by the resonant photons and split into its Zeeman components by means of a longitudinal magnetic field whose strength varies along its axis to explore different heights of the atmosphere. By changing the circular polarization of the incoming flux, one selects 8 points on the right wing of the line or 8 points on the left wing, including one common point.

Figure 2. *Top The cell equipped with the heaters and prepared with its 31 outputs. Bottom: the same cell inside the intermediate piece with the 31 outputs to guarantee the thermal equilibrium of the cell and the magnet.*

The analyzed flux has been increased by a factor 10 thanks to a high quantum efficiency of the detectors and 4 outputs by position, altogether 31 detectors are considered. This will contribute to decrease the instrumental noise and to allow consecutive measurements of portions of the Sun. A second crystal polariser could be installed to get a spectrum of the mean magnetic field.

The important work of the last 3 years has been devoted to solve the technical problems that we need to face to measure 8 points along the line (never done in any instrument before). It supposes : (1) a linear permanent magnet between 0-12 kG of small size, (2) good thermal conditions along the cell heated around 170°C inside a magnet at 25°C, (3) a realisation of a cell filled of sodium without attack of the sodium on the window, (4) a great number of outputs along the cell to amplify the counting rates by a large factor : in fact 31 on a very small volume (8 mm* 60 mm) with a temperature stability of 1°C, (5) any important loss of counting rate between the cell and the detector, (6) a high performance of the final detectors to be sensitive only to the statistical noise (see Fig 2). Most of the hard points have been solved and the complete instrument has been checked in laboratory in space conditions, that means in vacuum with articial light and with the Sun.

The feasability has been demonstrated in March 2007 in getting the 31 resonances with a good efficiency of the whole instrument and a low level of parasite light and the improvement will be checked for the granulation noise rather soon.

Two problems stay important to solve before getting a scientific instrument:

- the capability of the cell to use sodium for a long time (we look for another glass than pyrex, in GOLF we were using a galeniet glass),
- the development of a CCD detector to reach the necessary performances of counting about 0.25 10^8 ph/s continuously with an electronic noise smaller than the statistical noise. It is not the case today with the photodiode modules of Hamamatsu which are used

The Gamma-ray burst telescope ECLAIRs

In 2012, the Sino French SVOM mission will perform multi-wavelength observations of the Gamma-ray burst (GRB), Its main instrument, the space borne gamma-ray telescope ECLAIRs is expected to provide accurate GRB localizations on the sky in near real-time, necessary for ground based follow-up observations. Developed by a consortium of French laboratories (CESR Toulouse & APC Paris) under the responsibility of DAPNIA/SAp, the ECLAIRs project is currently in its technical design phase.

Scientific Objectives

Gamma-ray bursts (GRB) are cosmic events, which are seen in space borne gamma-ray detectors as count rate increases during short periods of time, from tens of milli-seconds to tens of minutes. They are the signature of very energetic explosions in the Universe, mostly occurring at cosmological distances, and believed to be linked to the formation of black holes. The most popular models assume the collapse of a rotating massive star (for long duration GRB) or the merger of two neutron stars (for short GRB). Following the Gamma-ray event, afterglows are often detectable in other wavebands (visible, radio, X-rays). Those provide crucial additional information to study the physics of the event itself (constrain the GRB models, study their relativistic jets and shocks, study the link between GRB and supernovae), to determine the distance of the event (measuring the redshift of its host galaxy), to use the event as a background light source to study the foreground universe, or to use collections of those events as tools for cosmology (study the star formation history, the very first stars, constrain the cosmological parameters), or to solve questions of fundamental physics (GRB as sources of ultra-high energy cosmic rays or gravitational waves).

Figure 1. *The X- and Gamma-ray Camera of the ECLAIRs telescope aboard the SVOM satellite detects Gamma-Ray Bursts in real-time and localizes them on the sky with an accuracy better than 10 arcmin.*

Currently the satellites INTEGRAL, HETE-2, and SWIFT deliver most of the GRB triggers to the ground-based observers, among which robotic follow-up telescopes which refine the space-given localization to a precision matching the small fields of view of the large spectroscopic 8-m class telescopes. In 2012 the ECLAIRs gamma-ray detector, foreseen to fly on a low-earth-orbit satellite, is expected to carry on the hunt and deliver ~80 GRB triggers per year.

Concept of ECLAIRs

The ECLAIRs project, managed by DAPNIA/SAp, is currently in its detailed technical design phase, with the development phase expected to start in 2008. ECLAIRs is a part of the SVOM payload developed in collaboration between the French space agency and Chinese partners, the launch being scheduled in 2012.

The ECLAIRs flight hardware is composed of a 2D-coded mask aperture telescope (CXG, camera for X- and gamma-rays), with a detection plane of 80×80 CdTe pixels covering 1024 cm^2. It provides localizations of point sources with accuracy better than 10 arcmin in a 2 sr field of the sky in the 4 – 50 keV energy band, using a mask deconvolution technique similar to the one used in INTEGRAL. A second set of four 1D-coded mask aperture telescopes (ESXC, soft X-ray camera) operating from 1 – 10 keV observes the same 2 sr field in the sky, and permits to refine the localization accuracy to better than 1 arcmin for most of the GRB detected by the CXG. The low energy thresholds of its detectors render ECLAIRs more sensitive than previous missions to high-redshifted GRB, which are potentially the most interesting ones.

A real-time data link to ground is foreseen, inherited from HETE-2, with a data transfer rate of up to 600 bit/s. It uses a VHF on-board emitter and a network of about 30 VHF ground receiver stations, deployed under the satellite track. This messaging system is used among others to transmit to ground in real-time, within tens of seconds, the localization of GRB detected by ECLAIRs.

The on-board scientific processing and trigger unit (UTS) of ECLAIRs uses the CXG data in order to discover the appearance of a gamma-ray source in the sky, determines the precise localization of the source, and sends as quickly as possible (within seconds) the trigger information to the VHF network, from which it is forwarded to the observer community. For a detailed on-ground analysis, all detected photons are also stored in an on-board mass memory which is dumped to ground after a delay of up to one day via high-bandwidth X-band transceivers.

The ECLAIRs UTS (scientific trigger unit) is an on-board digital processing unit, comprising the GRB trigger and other functions. The ECLAIRs UTS electronics and software is developed at DAPNIA, based on radiation tolerant components, among which a large Xilinx Virtex-II QPro FPGA coupled to an AT697 Leon-II processor (86 Mips, running the RTEMS operating system) and about 100 MB of radiation protected SD-RAM.

A dedicated set of ground based robotic telescopes, operating in the visible and near-infrared bands, will be used to further refine to arcsec accuracy the localization of a GRB, based on the detection of its afterglow, and to obtain a photometric redshift estimate.

The overall pointing strategy of the satellite carrying ECLAIRs is to observe the part of the sky roughly opposite to the direction of the sun (for thermal constraints), with avoidance of the galactic plane and bright X-ray sources as Sco X-1 (to reduce background). With this scheme, the Earth will be entering the field of view of the instruments every orbit, reducing the overall efficiency by about 30%. However the benefit of this strategy is that almost all detected GRB are potentially observable by large spectroscopic telescopes, because located above horizon in the Earth tropical zones harboring those telescopes

Figure 2. *The SVOM satellite (Space-based Variable astronomical Objects Monitor) is developed in the frame of a French-Chinese collaboration.*

SIMBOL-X

The Simbol-X mission will be the advent of the telescope in hard X-rays energies, allowing to gain several orders of magnitude in observation power in this domain dominated by the most powerful phenomena in the Universe. This mission, studied in bilateral collaboration between France and Italy, uses for the first time the formation flight technology. It is scheduled for a launch in 2013. The CEA/SAp, which initiated the project, has the scientific leadership of the mission for France, and is responsible for the development and realization of the focal plane detection unit.

Scientific and technological context

Observing the sky in hard X-rays (above ~ 10 keV) is of fundamental importance for revealing and studying processes which occur in the most extreme environments, particularly around black holes. So far, the instrumentation in this domain is based on instruments with collimators or coded mask optics (as IBIS on INTEGRAL), with performances well below that at other wavelengths, in particular the adjacent soft X-rays band. This limits the observations to bright objects, as well as the capabilities of mapping extended objects and performing multi-wavelengths studies.

Simbol-X, which operates between ~ 1 and ~ 100 keV, will be the first instrument to use focusing optics in the hard X-ray range, bringing hard X-ray astronomy into the telescope era. This gives 2 to 3 orders of magnitude improvement in the observational power (sensitivity, angular resolution) compared to the current instruments.

This revolution is made possible today thanks to the emergence of the formation flight technology. This allows to have instruments distributed on several spacecrafts; in the case of Simbol-X this capability is used to build a telescope made of a "classical" X-ray mirror, as in the soft band, but with a very long focal length (20 m) which allows

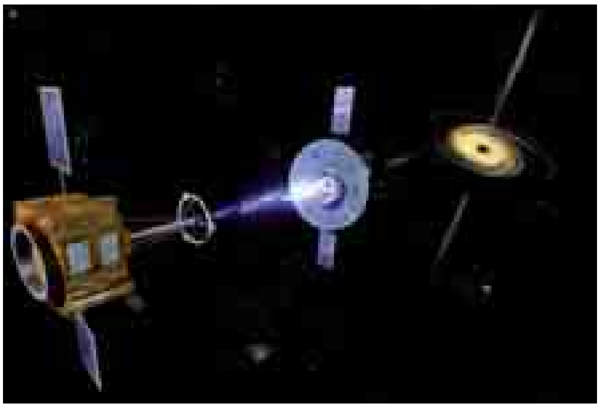

Figure 1. *Artist view of the Simbol-X configuration in flight, with mirror and detector spacecrafts. The focused radiation from the high energy source is highlighted in blue.*

to extend the focusing capabilities into the hard domain. The mirror is on one spacecraft, the focal plane detector on the second one (Fig. 1).

Simbol-X has been proposed by CEA/SAp (mission P.I. P. Ferrando) to CNES following the 2004 call for ideas of scientific payloads to be flown on a formation flight demonstrator. After a competitive assesment phase, it has been selected for a phase A study, which ends in december 2007. The feasability of the mission has been demonstrated within the allowed technical and budget enveloppes. The programmatic context is that of a bilateral mission, conducted jointly by CNES and ASI. German laboratories are participating to the scientific payload. The Simbol-X launch is scheduled for late 2013.

Scientific objectives and requirements

Offering "soft X-ray" like angular resolution and sensitivity in the hard X-ray range, Simbol-X will provide a dramatic improvement for investigating key issues in high energy astrophysics and will allow to perform detailed studies on a very wide range of sources, such as Galactic and extra-galactic compact sources, supernovae remnants, cluster of galaxies, or young stellar objects. In phase A, the Joint Scentific Mission Group has defined more in details the core objectives that must be reached by the mission. They are shortly given below.

The very wide discovery space uncovered by Simbol-X is particularly significant for the two large and crucial areas in high energy astrophysics and cosmology: the physics of black holes and their census, and the understanding of particle acceleration mechanisms. In these domains, Simbol-X will i) find out and characterize the population of obscured AGNs which are responsible for the Cosmic X-ray background at the enegies where it peaks, and constrain evolution models ii) solve the puzzle of the hard X-ray emission from the Galactic centre which harbours the closest Super Massive Black Hole, iii) constrain acceleration processes in relativistic jets of blazars, around pulsars, and in gamma ray bursts, iv) measure the maximum energy of electrons in supernovae remnants and put constraints on hadron acceleration, v) map the controversial non-thermal emission of clusters of galaxies and determine its impact on clusters evolution.

Besides these top priority objectives, which are driving the instrument and mission requirements, Simbol-X will be capable of performing breakthroughs studies in several other areas, like for example the nucleosynthesis in young SNRs or the importance of X-ray activity in star formation, both of particular interest for the SAp.

To reach these objectives, the requirements on the mission have been set. The most salient ones are a large energy range (< 0.5 to > 80 keV) with excellent spectral resolution at the Fe and Ti lines, a field of view larger than 12 arcmin, a sensitivity better than 0.5 μCrab in the 10-40 keV band, an angular resolution better than 20 arcsec with a source localization better than 3 arcsec, and a timing accuracy better than 100 µs. The nominal mission shall give at least 2 years of science observation time and allow to perform more than 1000 observations.

Scientific payload and CEA responsability

Simbol-X carries a single telescope, made of a mirror and a focal plane. A collimator, visible as the long tube in Fig. 1 is added on top of the focal plane to protect the detectors from unwanted sky background.
The mirror is a grazing incidence angles Wolter I optics. It is built with the same technology used in former missions as XMM-Newton, with the exception of the coating. In Simbol-X the shells will be covered with multi-layers in order to reach the required field of view. The mirror is under Italian responsability.
The focal plane is a highly packed assembly as shown in Figure 2. Its is made of two 8 × 8 cm^2 spectro-imaging detectors with 625 µm size pixels each on top of each other (Fig. 2). The two different detectors are needed to cover the full energy range of Simbol-X with the required spectral resolution. The Low Energy Detector, on top, is a monolithic Silicon wafer with implementation of APS type pixels. It is under German responsability. The High Energy Detector (HED) is described below. Both detectors operate at moderately low temperature (~ -40°C), an advantage for this mission. They are surrounded by a combination of passive and active (anticoincidence) shieldings which reduce the particle induced background to a minimum.
The HED is constructed with 4-sides buttable 2 mm thick pixelated Cd(Zn)Te crystals, ~ 1 cm^2 each. Each 256 pixels crystal is connected to a low noise front end electronics, developped in DAPNIA, located below the crystal. The full system forms a "Caliste" module. The development of these modules is the object of a research and development program conducted at SAp and funded by CEA and CNES (see R&D chapter). Very impressive laboratory results on crystals and electronics do show that the Simbol-X requirements will be met by these Caliste modules.

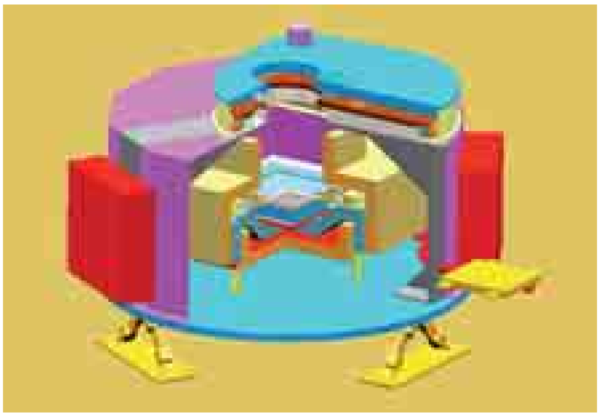

Figure 2. *Cut view of the Simbol–X focal plane assembly. In the center are placed the 64 Caliste modules forming the HED detector. The LED detector is just above. They are enclosed in the anticoincidence detector. A calibration wheel is on top.*

In phase A, CEA has been responsible for the definition and preliminary design of the full detector payload, including the collimator. It has been managing the work of the other laboratories participating to the hardware development (APC/Paris, CESR/Toulouse, MPE/Garching and IAAT in Germany). In the following phases, CEA will be responsible for the integrated focal plane assembly with its three detectors, which will be further integrated by CNES with the remaining parts of the payload.

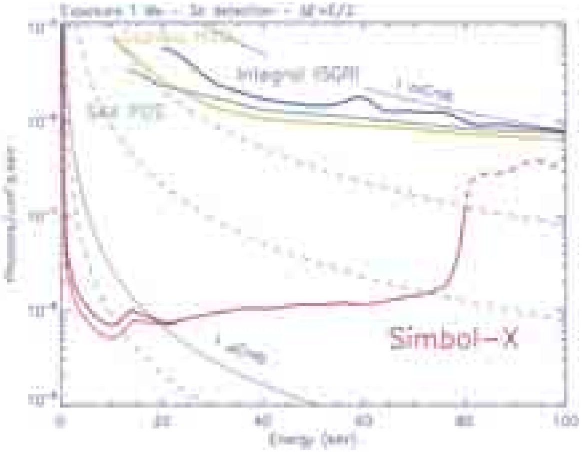

Figure 3. *Simbol–X continuum sensitivity to point source detection, compared to past and present hard X–rays instruments. The dotted line part above ~ 80 keV depends on the exact implementation of the optics which will be decided in phase B.*

Simbol-X performances and operations

The Simbol-X performances calculated from the phase A design are shown in Figure 3 for what concerns sensitivity. They are several orders of magnitude better than existing instruments up to ~ 80 keV. In addition to this sensitivity gain Simbol-X will bring angular accuracy into hard X-rays, going from the ~ 10 arcmin of today to 20 arcsec.
Simbol-X will be launched late 2013 for about 3 years of guaranteed operations, with at least ~ 1000 targets. In addtion, there is a provision for a possible 2 years extension. It will be placed onto a High Elliptical orbit, with a 4 days period, which will allow close to 300 ks long uninterrupted observations.
In order to fully exploit the discovery space offered by this instrument, Simbol-X will be operated as an observatory. It is anticipated that Simbol-X will have a core science program, and guaranteed time for the participating countries. In addition, a large fraction of the time will be opened to the worldwide community. All the data will be made public after an adequate proprietary time. The contact with the scientific community regarding observation proposals, data processing software, and data distribution will be made by a dedicated Scientific Ground Segment which is in the process of being defined. It is proposed that a collaboration based on APC/Paris and CEA/SAp takes a leading role in this ground segment

DUNE : the Dark UNiverse Explorer

In recent years, measurements from very diverse cosmological probes have led to the establishment of a standard model of the Universe. In this cosmological model, 96% of the density of the Universe is in the form of two mysterious components: dark energy and dark matter (Figure 1). Dark Matter is outside the realm of the standard model of particle physics and drives the formation of structures in the universe. Dark energy causes an acceleration of the expansion of the universe, and poses a major challenge to fundamental physics which does not offer a natural explanation for its nature.

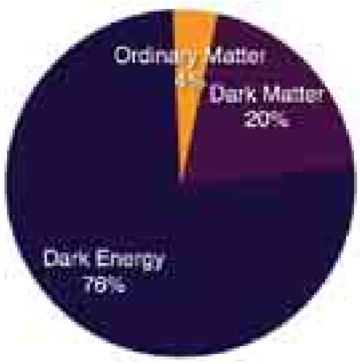

Figure 1. *Composition of the Universe today according to recent cosmological measurements. The Universe density is dominated by dark matter and dark energy, while ordinary matter makes up only a small fraction.*

Science Objectives

The Dark Universe Explorer (DUNE) is a wide-field space imager whose primary goal is the study of these two components with unprecedented precision using weak gravitational lensing (Figure 2). Immediate secondary goals concern the evolution of galaxies, the detailed structure of the Milky Way and nearby galaxies, and the demographics of Earth-mass planet. DUNE will carry out an all-sky survey in one visible and three Near InfraRed (NIR) bands which will form a unique legacy for astronomy.

DUNE is optimised for weak lensing, a unique technique to map the distribution of dark matter and to probe dark energy through its impact on the large scale structure of the Universe (Figure 2). To do so, DUNE will measure the shape distortion of distant galaxy images over the full extragalactic sky (20,000 deg^2). The required accuracy of these measurements needs the stability of the Point Spread Function (PSF) and image quality offered by DUNE. Furthermore, reliable redshift estimates need NIR photometry to the same depth, which cannot be obtained from any existing or planned ground-based facility.

DUNE will complement its weak lensing measurement with three other independent cosmological probes: Baryon Acoustic Oscillations, the Integrated Sachs-Wolfe effect, and clusters of galaxies. DUNE will simultaneously challenge all the sectors of the standard model of cosmology and thus offers wide potential for discovery of new physics. In particular, DUNE will yield unprecedented information on the clustering properties of dark matter and the initial conditions for structure formation, and test modifications of General Relativity.

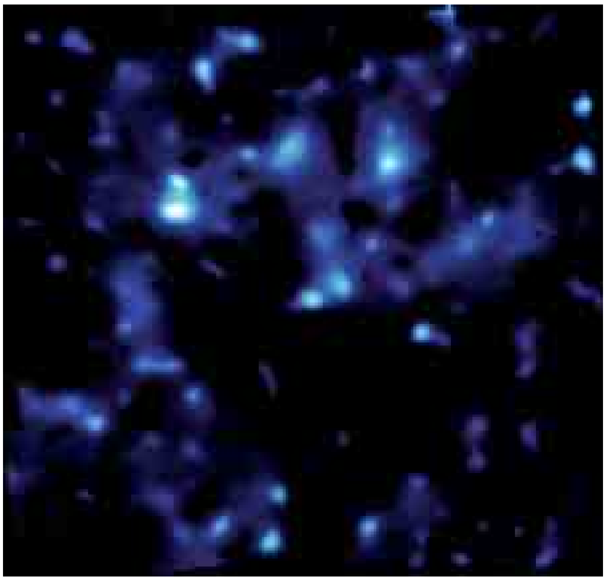

Figure 2. *Dark matter map derived using the weak gravitational lensing technique with COSMOS, the largest survey performed with HST (Massey et al. 2007, Nature cover). This mass map covers 2 deg^2. DUNE will provide space-based weak lensing measurements over 20,000 deg^2.*

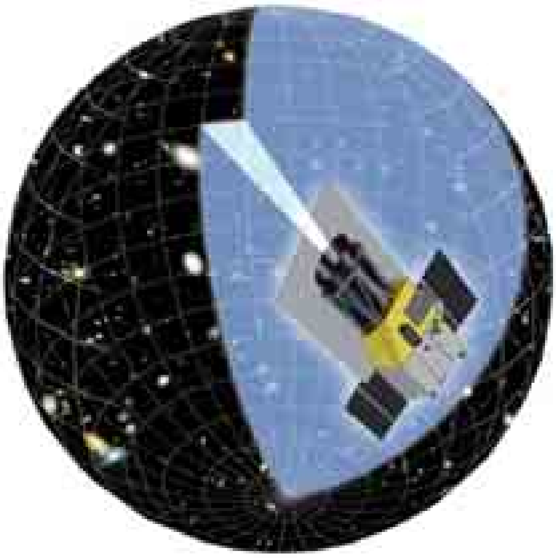

Figure 3. *The Dark Universe Explorer (DUNE) mission is a wide-field space imager which will make a full sky map of large scale structure. DUNE will place definite constraints on dark energy through its effect on the distribution of matter in the Universe.*

DUNE Mission

The DUNE concept is a medium class mission with limited risks and costs. It consists of a 1.2m telescope with separate visible and near-Infrared (NIR) focal planes, with a combined field of view of 1 deg^2 (Figure 3). Fixed filters provides observations in one visible (broad I) and three NIR (Y,J,H) bands, together covering the wavelengths in the range 550-1600nm. The resolution is 0.23'' (FWHM) with pixels of 0.10'' (in the visible band). The satellite will be placed in a geosynchronous orbit (GEO), affording thermally stable observing conditions. This will be achieved by a Soyouz S-T Fregat launch with a circularization boost by the spacecraft whose wet mass is about 2000kg.
The DUNE mission has been the object of a pre-study phase (phase 0) led by the CNES and has recently (october 2007) been selected by ESA as one of the mission concept to be studied in its Cosmic Vision programme

DUNE Survey Legacy

The wide extragalactic DUNE survey complemented by a 100 deg^2 medium-deep survey will also provide a unique resource for the study of galaxy evolution, its relation to structure growth, and the discovery of high- redshift objects. An additional survey of the galactic plane will address various areas of galactic structure and low-temperature objects, and complete the sky coverage to yield a unique 4π legacy for astronomy. A microlensing survey (DUNE-ML) in the galactic bulge will search for Earth-mass extra-solar planets. Synergies with other missions include the mass and photometric redshift measurements of about 10000 clusters of galaxies discovered by Planck and eROSITA, complementarity with GAIA, as well as target finder for future ELTs and JWST.

The solar DynaMICCS perspective

The Saclay team has proposed a new perspective for a 3D picture of the Sun from the core to the corona, first during the Cosmic Vision meeting at ESA and second, through the DynaMICCS[1] formation flying mission as an answer to the call for tender at the horizon 2015-2025.

The success of SoHO invites the European community to pursue its investigation of the Sun as a whole because the Sun is the only star which can deliver a complete information on all the processes in action and also because SoHO has revealed strong interaction between Sun and Earth which needs a continuous and permanent observation of our star (impact of particles, impact on technology, prediction of variability, human and climat...).

After the SoHO mission, totally new questions emerge from our progress which will not be solved by the already engaged missions:

- What is the dynamical influence of the internal rotation and magnetic field on the external activity?
- Which processes are at the origin of the solid body rotation in part of the radiative zone? What is the respective role of the agents responsible for the redistribution of the angular momentum: rotation, gravity waves, magnetic field? Presently theoretical works do not agree with the suggested observed rotation profile. What are the consequences of a more rapid core? Is there another dynamo in the core?
- What is the topology, strength and influence of a fossil field? How the progressive internal waves modify the overall internal dynamics? Could we determine the nature of the nonlinear interactions between the convective dynamo and the fossil field if it exists?

Figure 1. *The DynaMICCS formation flying mission with seismology, irradiance, permanent pobservation of the corona and measurements of the solar wind*

- How can we check the presence of large scale flows, their amplitude and their mixing properties in the radiative zone? Could we put some constraints on the presence of magnetohydrodynamical instabilities in the radiative zone and their coupling with the convection zone

These questions show the need to understand the solar magnetism in its different forms. The mission called DynaMICCS for Dynamics and Magnetism from the Core to the Corona of the Sun would like to reveal the different sources of the solar cyclic variability. To reach this objective, crucial internal regions of the Sun must be scrutinized: (1) the previously unexplored dynamics of the inner core thanks to gravity modes, (2) the time evolution of the radiative/convective zone interface layer thanks to a large number of acoustic modes, (3) the emergence of the flows from the photosphere to the chromosphere layers thanks to different lines and heights. Moreover the formation flying concept of the mission allows to follow simultaneously (4) the evolution of the low corona never explored continuously thanks to a permanent eclipse, (5) the total and spectral irradiance and finally (6) in-situ measurements of plasma/energetic particles/magnetic fields of the solar wind. This mission delivers simultaneously all the global quantities no other known mission has already provided. This information is important for understanding Space Weather and Space Climate and for advancing stellar and fundamental physics (neutrino properties, atomic physics, gravitational moments...). To fully achieve these objectives, the DynaMICCS mission must provide uninterrupted observations of the Sun for about a decade.

This mission uses an original concept studied by Thalès-Alenia Space in the framework of the CNES call for formation flying missions. The concept has been built upon the ASPIICS coronagraph study. It consists in obtaining an external occultation of the solar light by putting a small discal occulter supporting the main spacecraft located in front of the second spacecraft. The two spacecrafts reuse a LEO platform of the "mini sat" class, e.g. PROTEUS type which allow to define a distance of 150 m between the two satellites. The first one carries the helioseismic and irradiance instruments and the formation flying technologies. The latter spacecraft of the same type carries a visible and infrared coronagraph for a unique observation of the solar corona down to less than 1.1 solar radius and

Figure 2. *The SOYOUZ dual launch vehicule containing the two spacecrafts : the occulter spacecraft equipped with 3 helioseismic instruments + 3 irradiance other instruments, and the second one equipeed with coronograph, imagers and solar wind instruments.*

instrumentation for the study of the solar wind. The payload of each spacecraft has a mass of about 170 kg and a power consumption around 100 W. This mission must guarantee long (one 11-year solar cycle) and continuous observations (duty cycles higher than 94 %) of signals that can be very weak (the gravity mode detection supposes the measurement of velocity smaller than 1mm/s). This assumes no interruption in observation and very stable thermal conditions. The preferred orbit therefore is the L1 orbit, which fits these requirements very well and is also an attractive environment for the spacecrafts due to its low radiation and low perturbation (solar pressure) environment.

From this study has emerged just before the deadline of the call another proposal HIRISE for High Resolution Imager and Solar Explorer. This mission puts the accent on the ultrahigh spatial spectral and temporal resolution of the solar atmosphere with some insight on the solar interior. It is also a formation flying mission but using an Herschel platform for the occulter spacecraft, it allows more capabilities, an increase flow of data sent to the earth and consequently also a mission around the L1 Lagrangian point.

In fact we believe that the main objectives of DynaMICCS and HIRISE can coexist on the same mission. The increased distance of 300 m between the two spacecrafts due to the size of the Herschel platform improves significantly the study of the low corona. So, we have presented to ESA the formation flying added to the reuse of european platforms mission at relatively low cost, putting together all the instruments necessary for the 3D vision of the Sun with global and local information covering most of the questions of the whole european solar community.

The complementarity of DynaMICCS and HIRISE leads to the most promising and exciting mission that we ever think for the solar exploration. It will definitively establish the complete 3D vision of the Sun and its real impact on the earth environment. Such a mission could not been selected for the first class M mission due to the launch of Solar Orbiter in 2014 just before the beginning of the Cosmic Vision period but we hope that such mission, supported by a very large european, american, indian and chinese collaboration will be realized as soon as possible

[1] Dynamics and Magnetism of the inner core to the Corona of the Sun

The R&D programs in spectro-imagers for astronomy

Within the Sap, the Laboratory of Space Detectors houses development and characterization activities in the frame of the realization of scientific instruments devoted to astronomy, especially in the field of mid infrared, far infrared, X and gamma rays. All these developments are possibly used in space missions in order to prepare the future. This laboratory is also involved in R&D works, sometimes funded together by CNES and CEA, CEA only or CEA and ANR (National Agency for Research). The research topics are focused i), on X and gamma ray detectors based on CdTe semiconductors ii), on ultra high spectral resolution X¬-Ray detectors based on micro calorimeter arrays and iii), on high spatial resolution and high sensitivity of sub millimetre bolometer arrays.

R&D activities on CdTe based detectors

This project is inherited from previous developments of the ISGRI space CdTe gamma camera on board the ESA INTEGRAL satellite, in orbit for 5 years without failure.
The aim of the R&D program, triggered jointly with Dapnia/SEDI since 2003, is to push further the performances of X and gamma-rays spectro-imagers based on moderately cooled semiconductor sensors for space missions. Therefore, we realize CdTe segmented electrodes detector arrays equipped with pixels of 0.5 up to 1 mm by side, together with their associated low noise front-end integrated circuits (IDeF-X ASIC family) and hybridization techniques of the two in order to provide elementary detection modules, future brick of large area cameras (~100 cm^2) qualified for space environment, including reliability, radiation hardness, environmental stresses on ground or in space.
During the period 2003 to 2006, we focused on the realization of three versions of the IDeF-X multi channels chips (16 to 32 independent spectroscopy channels). In parallel, detector tests benches have been set up for ultra low current measurements and spectrometric measurements on 64 pixels "flat" prototypes as well as 3D pixel detector modelling software. The combination of these works has enabled the realization of the first prototypes of complete elementary detection modules named CALISTE. The first CALISTE is equipped with 64 pixels (Figure 1) and is ready for functionnal tests in 2007 while CALISTE 256 pixels modules are being built for preliminary technological studies and feasibility. The CALISTE hybrid modules are realized using industrial means of the 3D-plus Company in France.

Figure 1. *The two first prototypes of CALISTE micro camera, equipped with a CdTe detectors superimposed onto a stack of four IDeF-X Chips installed perpendicularly to the detector plane. (CEA-3D-Plus)*

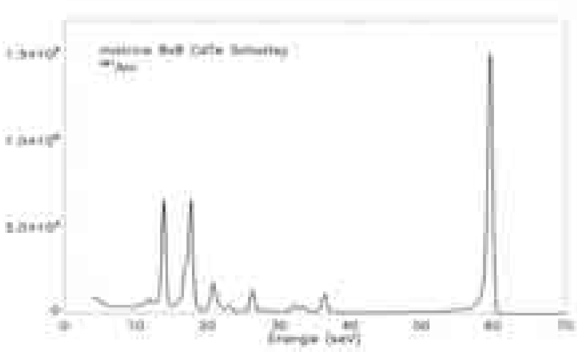

Figure 2. *Pulse-height spectrum obtained by summing the individual pixel response of a CdTe 8x8 blocking contact pixels array. The pixel size is 1 mm^2 and the crystal thickness is 2 mm. The detector is illuminated with a ^{241}Am radioactive source during 45 minutes. The detector array is mounted on a "flat" substrate configuration where four IDeF-X V1.0 ASICs are connected. The operating conditions are 600 V at -36°C.*

Simultaneously with the hybridization developments, detailed detector studies have demonstrated excellent spectrometric performances on CdTe prototypes equipped with blocking contacts when readout by IDeF-X V1.0 chip. Figure 2 shows a spectrum obtained by summing all the 64 pixels responses of our prototype, cooled at -36°C. The spectral response is excellent and better than 770 eV FWHM at 60 keV (Am 241 line). This result is roughly ten times better than ISGRI performances and closer and closer of the theoretical limit (~ 550 eV).
The fruits of these works are now part of two space projects, namely **ECLAIRs** which will fly our IDeF-X V2 chip and **SIMBOL-X** which will fly the CALISTE modules. Both missions are currently in Phase A (see chapter IX).

R&D activities on X-Ray micro-calorimeters

Prior the launch of the XMM-Newton ESA mission, where SAp played a key role with respect to its success, new reflection was initiated at a European level to imagine next generations of X-ray space telescopes: The XEUS concept

was born. According to the technological developments available at CEA for IR bolometer arrays (Herschel / PACs instruments), CEA considers that new generation of ultra high spectral response micro calorimeter in the hard X-ray domain was affordable. The expected performances are spectacular, close to 3 eV FWHM at 6 keV (50 times better than current CCDs in operation in space). This challenge includes the capability of making large area spectro-imagers with 1024 pixels operated at high counting rates.
The R&D activities on X-ray micro calorimeter have started in parallel with the manufacturing of the Herschel / PACS bolometer arrays and was recently reinforced involving CEA/LETI, CEA/DSM/Dapnia/SAp, CEA/DSM/Dapnia/SEDI, CSNSM Orsay and Observatorio G. Vaianna in Palermo within a collaboration. The project is funded by CEA and CNES.

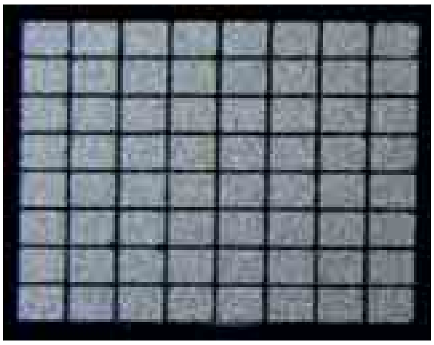

Figure 3. *This prototype has been realized to validate the collective mounting of the absorbers onto the thermal sensor arrays. This technology is natively appropriate for the realization of large area micro*

Even if the X-ray micro calorimeter working principle is very simple (i.e. measuring a temperature raise due to a photon interaction in the absorber), its realization is extremely complex. For instance, the sensor must be operated at very low temperature (T~100mK) to take advantage of the thermal noise suppression combined with the minimization of the absorber calorific capacity.
Many groups in the world are involved in this research field but only one team has successfully operated a 32 pixel array. The ambition of our program relies on the technological process used to realize simultaneously all the pixels of a micro calorimeter array. The pixels are installed collectively on the device, using mainly micro etching on silicon technologies.
Moreover, other challenges have to be faced: superconducting absorber arrays in Ta, low calorific capacity Indium hybridization, cryogenic readout and multiplexing electronics integrated into the focal plane and collective assembly of the absorbers arrays onto the thermal sensors array. Preliminary technological tests of the latter have been successfully achieved in 2006 (Figure 3). The first specific thermometer array will be operated in 2007.
Regarding the ultra low noise cryogenic electronics, integrated in the focal plane, several solutions are explored in parallel. Fast readout of high impedance sensors at 100 mK requires several technologies to work together (CMOS, AsGa, SiGe).

R&D activities on sub-millimetre bolometers

The laboratory achieved recently the integration and final tests of the PACS flight model instrument onboard the Herschel ESA space observatory to be flown by the end of 2008. This imaging photometer is based on sub-millimetre bolometer arrays operated at 300 mK. The instrument development has permitted a breakthrough in this domain: for the first time, large bolometer arrays (2048 pixels), with limited inter-pixel zones are operated in multiplexed mode. These sensors are based on CEA/LETI technology. The self-suspended silicon grids efficiently absorb far infrared photons in the range 50 to 200 µm by means of a quarter wave resonant cavity and a reflecting backshort. Thermal sensors on the pixels are, indium bump, hybridized collectively to the readout circuit. The Indium bumps ensure the electrical and thermal contacts and control the cavity width.
In order to push further the performances of such devices, R&D activities have started and rely on a large and well experienced team. The early R&D works are related to a ground-based program (ArTeMiS) and a balloon born (PILOTE) experiment. Both require high sensitivity at longer wavelength: 200-600 µm.
The new set of detectors built for ArTeMiS is based on the same technology than the PACS one excepted that the absorbing cavities are now to be tuned to longer wavelength. Moreover, the number of channels increases to 4096 making an imager twice the size of PACS. CEA-ANR and CEA-CNES support these activities respectively.
At the moment, the specifications of the ArTeMiS instrument are close to be reached on the prototype used in Chile on the large (12m) APEX sub-millimetre telescope.
Associated extra R&D works are done, due to the integration of the camera into a telescope. This implies specific cryogenic studies with autonomous cooling systems and optical studies dedicated to the sub millimetre domain.
Furthermore, in the ANR project, the team is developing new devices in order to reach much longer wavelength and to build large filled arrays in the millimetre range. This technology is derived from the current detector scheme but new absorbers, based on antennas, and new absorbing materials are being explored. Besides these technological

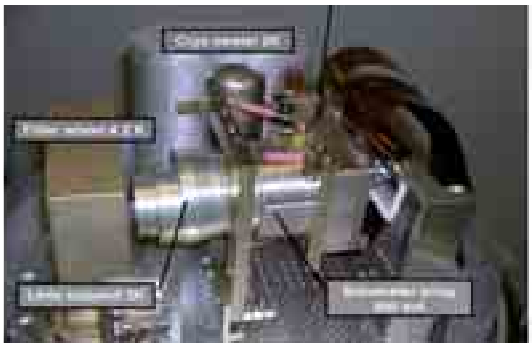

Figure 4. *Inner part of the ArTeMiS camera cryostat prototype with the detector assembly, its cooling system and interconnection for readout.*

studies and design efforts, the challenge is to reach much more sensitive devices, by a factor of 100 with respect to the current technology, in order to fulfil demanding requirements of future space missions proposed in the frame of the ESA Cosmic Vision Program (SPICA). The first step is to evaluate the technology at room temperature on prototypes and to go further at low temperature. The last four years have permitted to prepare this ambitious program that is now ready to start

Permanent staff (2007)

Administration

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Secretaries and documentation	MATHIEU Laetitia, CHAVEGRAND Pascale, MONVOISIN Dominique, RAINOT Elisabeth

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S. MADDEN	M. PIERRE	A. REFREGIER
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High Energy Cosmic Phenomena

Head of Laboratory : GOLDWURM Andréa

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Space electronics

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J. MARTIGNAC	V. MOREAU	S. RONAYETTE
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L. DUMAYE	D. D. HUYNH	I. LE MER

Space Detection

Head of Laboratory : CORDIER Bertrand

Calibration and data processing Group

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D. DUBREUIL	P. GALLAIS	R. GASTAUD
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M. LORTHOLARY	B. MORIN	K. OKUMURA
S. PIRES	A. SAUVAGEON	JL. SAUVAGEOT
S. SCHANNE	J.L. STARCK	

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C. PIGOT	L. RODRIGUEZ	V. SZEFLINSKI
F. VISTICOT		

Manufacture, Acceptance, Integration and Validation

Head of Group : CLOUE Christelle

L. CADELIS	F. DALY	E. GREGOIRE
G. HAMON	Ch. HERVIOU	B. HOREAU
Th. ORDUNA	E. POINDRON	

Non permanent staff (since 2004)

Administration

LEQUEUTRE Perrine		

Astrophysic Interpretation

Cosmology and Galaxy Evolution

AMARA Adam	ANOKHIN Sergei (PhD)	BERGE Joël (PhD)
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YAMASAKI Tatsuya		

Star and Planet Formation

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MENSHCHIKOV Alexander	MINIER Vincent	PANDEY Mamta
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Stellar plasmas and Nuclear Astrophysics

BALLOT Jérôme (PhD)	DUEZ Vincent (PhD)	JOUVE Laurène (PhD)
LAMBERT Pascal (PhD)	LEFEBVRE Sandrine	MATHUR Savita (PhD)
PALACIOS Ana	PIAU Laurent	

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VITALE Vincenzo	ZURITAS-HERAS Juan	

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Space electronics

BRIET Emmanuel		

Space Systems and Architectures

EL KHOULOUDI Samir	GLASSE Alistair	POUPAR Sébastien

Product assurance and Space quality

BOUZAT Mylène	LAFARGE Hélène	MAGNANT Véronique
RAVAL Damien		

Space Detection

Calibration and data processing Group

ABRIAL Pierrick (PhD)	BOBIN Jérôme (PhD)	CHAZALMARTIN Séverin
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GOTZ Diego	HAMADACHE Clarisse	PANUZZO Pasquale
PIRES Sandrine (PhD)	RENAUD Mathieu (PhD)	WOISELLE Arnaud (PhD)

Space detector Group

ALIANE Abdelkhader (PhD)	DIRKS Bob (PhD)	HURTADO Norma
MEURIS Aline (PhD)	PAUL Philippe	PEROT Florian
TAUPIN Maxime		

Manufacture, Acceptance, Integration, Validation

ALOUADI Fetiha	GRANIER Philippe	LE BLEVENEC Florian
RONAYETTE Samuel		

Defended PhDs 2004-2006

Recherche d'effets d'irradiation par les rayons X dans la matière interstellaire VUONG M.H. Université Paris XI - Orsay, 02/04/2004

Etude multi longueurs d'onde de galaxies naines proches: propriétés des milieux interstellaires de faible métallicité GALLIANO F. Université Paris XI - Orsay, 05/04/2004

Modélisation des restes de supernovae observés en rayons X par le satellite européen XMM-Newton CASSAM-CHENAI G. Observatoire de Paris, 06/10/2004

Structure et dynamique des étoiles de type solaire. De l'héliosismologie à l'astérosismologie

BALLOT J. Université Paris XI - Orsay, 16/11/2004

Détermination de la réponse instrumentale du spectromètre INTEGRAL/SPI et application à l'observation des raies gamma nucléaires de la région des voiles ATTIE D. Université Pierre et Marie Curie - Paris VI, 12/01/2005

L'histoire cosmique des baryons dans un univers hiérarchique ou contribution à l'étude des galaxies RASERA Y Université Denis Diderot - Paris VII, 13/10/2005

De l'instabilité advective-acoustique aux explosions asymétriques des supernovae de type II GALLETTI P. Université Paul Sabatier - Toulouse III, 25/10/2005

Aspects dynamiques des phases précoces de la formation d'étoiles en amas PERETTO N. Université Pierre et Marie Curie - Paris VI, 23/11/2005

Effets de la topologie de l'univers sur le fond diffus cosmologique CAILLERIE S. Université de Paris XI - Orsay, 06/12/2005

Chauffage compressionnel de l'environnement des disques magnétisés : des microquasars au centre galactique BELMONT R. Université de Paris XI - Orsay, 07/12/2005

Propriétés physiques des anneaux de Saturne : de CAMIRAS à la mission CASSINI LEYRAT C. Université Denis Diderot - Paris VII, 20/03/2006

The Milky Way's Central Black Hole and its Environment: High Energy Observations with INTEGRAL and XMM-Newton BELLANGER G, Université Denis Diderot - Paris VII, 18/05/2006

Etude multi-longueurs d'onde des galaxies lumineuses en infrarouge distantes MARCILLAC D. Université Paris XI - Orsay, 17/10/2005

Etude des émissions à haute énergie des trous noirs stellaires accrétants CADOLLE BEL M. Université Denis Diderot - Paris VII, 13/09/2006

Les jeunes vestiges de supernova et INTEGRAL: raies du 44Ti et émission non-thermique RENAUD M. Université Denis Diderot - Paris VII, 09/10/2006

Contribution à l'étude numérique de l'hydrodynamique radiative: des expériences de chocs radiatifs aux jets astrophysiques GONZALEZ M. Université Paris XI - Orsay, 26/10/2006

Study and modelling of the new generation Cd(Zn)Te X- and Gamma-ray detectors for space applications DIRKS B. Université Denis Diderot - Paris VII, 23/11/2006

Accélération de particules au sein des vents relativistes de pulsar : Simulations et contraintes observationnelles avec le satellite INTEGRAL FOROT M., Université Denis Diderot - Paris VII, 08/12/2006

Disques protoplanétaires autour d'étoiles de masse intermédiaire: l'apport de l'imagerie en infrarouge moyen DOUCET C. Université de Paris XI - Orsay, 12/12/2006

Sismologie solaire et stellaire LAMBERT P. Université Denis Diderot - Paris VII, 21/03/2007

Etude de l'annihilation électron-positron dans la région du centre Galactique avec le spectromètre INTEGRAL/SPI SIZUN P. Université Pierre et Marie Curie - Paris VI, 23/04/2007

TEACHING (2004-2006)

Name	Year	Matter	Level	University	Hours
ALLOIN Danielle	2005-2006	Physics of Galaxies	Master niveau L,M,D	University of Hanoi	8
ALY Jean-Jacques	2004-2005	Mathématiques pour physiciens et chimistes	Licence et Maîtrise	Université d'Evry	30
	2004-2005	Maths pour chimistes	Maîtrise	Université d'Evry	30
	2004-2005 2005-2006	MHD et physique solaire	1ère année école ingénieur	ENSTA	24
AUDIT Edouard	2004-2005 2005-2006	OMP	Master	Université Paris 11	15
	2005-2006	Simulation en astrophysique, et calculs parallèles	Master Modélisation et Simulation	INSTN , ENS-cachan, Centrale, UVSQ, ENSTA	25
BOULADE Olivier	2005-2006	Imagerie CCD en astronomie	Physiciens et ingénieurs	Ecole IN2P3 du détecteur à la mesure	3
BOURNAUD	Frédéric	Physique	L1, L2, M1	Paris VI	120
BRUN Allan Sacha	2004-2005 2005-2006	Magnétisme dans l'Univers et effet dynamo	M2	INSTN , ENS-cachan, Centrale, UVSQ, ENSTA	10
	2004-2005 2005-2006	Introduction à l'Astrophysique	M1	ENST Bretagne	10
	2004-2005	Magnetohydrodynamique des étoiles	post-doctoral	Ecole d'Aussois 2004	2
	2005-2006	Spectral methods in stellar fluid dynamics	post-doctoral	Ecole de Cargese en dynamique des fluides astrophysiques	2
CHATY Sylvain	2004-2005 2005-2006	Mécanique Physique	L1		94
	2004-2005 2005-2006	Méthodologie Laboratoire	M2		40
	2004-2005 2005-2006	Astrophysique Enseignement	L3		27
	2004-2005 2005-2006	Instrrumentation de l'infrarouge aux hautes énergies	M2		22,5
	2004-2005 2005-2006	Evolution Univers	L2		24
CHIEZE Jean-Pierre	2005-2006	Galaxies et cosmologie	Master M2	Ecole Doctorale de Paris	10
	2005-2006	Plasmas Astrophysiques	M2		9
	2005-2006	Physique de la matière en condition extrêmes	M2		10
CLARET Arnaud	2005-2006	Effet des radiations sur les photodétecteurs	Master M2 PRO Photodétection	Universite Denis Diderot Paris 7	6
DUBREUIL Didier	2005-2006	Optique pour l'infrarouge moyen et lointain	Master M2 Pro Photodétection	Universite Denis Diderot Paris 7	9
ELBAZ David	2004-2005	Formation et l'Evolution des Galaxies	Master M2	Ecole doctorale d'Astronomie et d'Astrophysique de Paris	15
	2005-2006	Propriétés et observations des galaxies non-résolues en étoiles	Master M2	Ecole Doctorale de Paris	15
GALLAIS Pascal	2004-2005 2005-2006	Projets expérimentaux	M2 Astronomie et Astrophysique	Observatoire de Paris P6, P7, P11	50
	2004-2005 2005-2006	Mini projet- Module Analyse de données	Post-Master (doctorant)	Ecole doctorale d'Ile de France	20
	2004-2005 2005-2006	TP Radioactivité naturelle	M2 pro OSAE	Observatoire de Paris P6, P7, P11	20
	2004-2005 2005-2006	Introduction aux méthodes d'observation	M1 Astronomie	Observatoire de Paris	12

Name	Year	Matter	Level	University	Hours
ALLOIN Danielle	2005-2006	Physics of Galaxies	Master niveau L,M,D	University of Hanoi	8
ALY Jean-Jacques	2004-2005	Mathématiques pour physiciens et chimistes	Licence et Maîtrise	Université d'Evry	30
	2004-2005	Maths pour chimistes	Maîtrise	Université d'Evry	30
	2004-2005 2005-2006	MHD et physique solaire	1ère année école ingénieur	ENSTA	24
AUDIT Edouard	2004-2005 2005-2006	OMP	Master	Université Paris 11	15
	2005-2006	Simulation en astrophysique, et calculs parallèles	Master Modélisation et Simulation	INSTN , ENS-cachan, Centrale, UVSQ, ENSTA	25
BOULADE Olivier	2005-2006	Imagerie CCD en astronomie	Physiciens et ingénieurs	Ecole IN2P3 du détecteur à la mesure	3
BOURNAUD	Frédéric	Physique	L1, L2, M1	Paris VI	120
BRUN Allan Sacha	2004-2005 2005-2006	Magnétisme dans l'Univers et effet dynamo	M2	INSTN , ENS-cachan, Centrale, UVSQ, ENSTA	10
	2004-2005 2005-2006	Introduction à l'Astrophysique	M1	ENST Bretagne	10
	2004-2005	Magnetohydrodynamique des étoiles	post-doctoral	Ecole d'Aussois 2004	2
	2005-2006	Spectral methods in stellar fluid dynamics	post-doctoral	Ecole de Cargese en dynamique des fluides astrophysiques	2
CHATY Sylvain	2004-2005 2005-2006	Mécanique Physique	L1		94
	2004-2005 2005-2006	Méthodologie Laboratoire	M2		40
	2004-2005 2005-2006	Astrophysique Enseignement	L3		27
	2004-2005 2005-2006	Instrrumentation de l'infrarouge aux hautes énergies	M2		22,5
	2004-2005 2005-2006	Evolution Univers	L2		24
CHIEZE Jean-Pierre	2005-2006	Galaxies et cosmologie	Master M2	Ecole Doctorale de Paris	10
	2005-2006	Plasmas Astrophysiques	M2		9
	2005-2006	Physique de la matière en condition extrêmes	M2		10
CLARET Arnaud	2005-2006	Effet des radiations sur les photodétecteurs	Master M2 PRO Photodétection	Universite Denis Diderot Paris 7	6

Organization of conferences

ALLOIN Danièle

Organisation avec C.Hummel, d'un micro-workshop sur l'interférométrie optique à ESO/Santiago, 28 Janvier 2004.
Organisation avec K.O'Brien, d'une réunion thématique à ESO/Santiago "Accretion onto compact objects", 15 Avril 2004.
Membre du SOC Symposium UAI S225 "Impact of Gravitational Lensing on Cosmology", Lausanne, Suisse, 19-23 Juillet 2004.
Organisation d'un Atelier international -IAOC2004- "The Cool Universe: Observing Cosmic Dawn", Valparaiso, 4-8 Octobre 2004.
Membre du SOC de l'Atelier International "Resolved Stellar Populations", Cozumel/Cancun, Mexique, 18-22 Avril 2005.

ANDRE Philippe.

Member of the Scientific Organizing Committee : « Cores, Disks, Jets, and Outflows », Banff, Canada, 11/07/2004-16/07/2004
Member of the Scientific Program Committee : « The Young Local Universe », XXXIXth Rencontres de Moriond, La Thuile, Italie, 21/03/2004-28/03/2004
Main Scientific Organizer « Stellar Physics with ALMA » Workshop, Montpellier, France 14/11/2005-15/11/2005 (cf. http://www.dstu.univ-montp2.fr/alma/pnps.html)
Member of the Scientific Organizing Committee : IAU Symposium 237 « Triggered Star Formation in a Turbulent ISM », Prague, Czech Republic 14/08/2006-18/08/2006
Member of the Scientific Organizing Committee : « The Early Phase of Star Formation (EPoS) » Workshop, Ringberg Castle, Germany 28/08/2006-1/09/2006

ARNAUD Monique

Main Scientific Organiser of the Symposium E 1.2 of the 35th COSPAR Scientific Assembly
"Clusters of Galaxies: New Insights from XMM-Newton, Chandra and INTEGRAL", Paris, 19/07/2004 - 20/07/2004
Member of the Scientific Organizing Committee for "The Future of Cosmology with Galaxy Clusters", Hawai, USA, 27/02/2005-2/03/2005
Member of the SOC of the EPIC consortium meeting : "5 Years of Science with XMM-Newton", Ringberg, Germany, 10/04/2005-13/04/2005
Member of the SOC of the IAP colloquium : "Mass profiles and shapes of cosmological structures", Paris, France, 04/07/2005 -08/07/2005
Member of the SOC for "The X-ray Universe 2005", El Escorial, Spain, 26/09/2005 - 30/09/2005
Member of the SOC of the XXVIth Astrophysics Rencontre de Moriond : "From Dark Halos, to Light", La Thuile, Aosta Valley, Italy, 12/03/2006-18/03/2006
Member of the SOC of the Symposium E 1.8 of the 36th COSPAR Scientific Assembly : "Shedding New Light on Dark Matter and Dark Energy", Beijing, Chine, 16/07/2006 - 23/07/2006.
Member of the SOC for "Heating vs. Cooling in Galaxies and Clusters of Galaxies", Garching, Germany, 06/08/2006-11/08/2006

CHAPUIS Claude

Organisation de l'école internationale de printemps ''Observing the X and Gamma-ray sky'', du 3 au 14 avril 2006, Cargèse, France. Membre du SOC et du LOC.

CORBEL Stéphane

Organisation de l'école internationale de printemps ''Observing the X and Gamma-ray sky'', du 3 au 14 avril 2006, Cargèse, France. Membre du SOC et du LOC.

DECOURCHELLE Anne

Member of the SOC of the Symposium E 1.4 of the 35th COSPAR Scientific Assembly : "Young neutron stars and supernova remnants", Paris, 07/2004.
Member of the SOC of the conference "Towards a Network of Atmospheric Cherenkov Telescopes VII", Palaiseau, 04/2005.
Member of the SOC of the school "Observing the X- and Gamma-ray sky", Cargèse, 04/2006.

DUC Pierre-Alain

Workshop "Tidal Dwarf Galaxies" novembre 2006.

ELBAZ David

Principal organisateur des XLèmes Rencontres de Moriond (03/2005) : « When UV meets IR : a history of star formation ».
Co-organisateur des XXXIXèmes Rencontres de Moriond (03/2004) : « The young local universe » 21-28 March 2004.
Co-organisateur des 5èmes Rencontres du Vietnam « New views on the universe », 6-11/8/04

FERRANDO Philippe

Principal organisateur du Workshop SIMBOL-X, 11-12 mars 2004, CNES – Paris
Co-organisateur de "XMM-Newton EPIC Consortium Meeting : 5 Years of Science with XMM-Newton", Ringberg (Allemagne), 10-13 avril 2005,

GOLDWURM Andréa

Principal organisateur du 5ème Atelier scientifique de l'APC sur High Energy Phenomena in the Galactic Center, Collège de France, Paris, 6-24 juin 2005
Principal organisateur de la Conférence Internationale du 5ème Atelier scientifique de l'APC sur High Energy Phenomena

in the Galactic Center, ESPCI, Paris, 15-17 juin 2005
Membre du SOC de l'International Conference on Galactic Center 2006 : From the Center of the Milky Way to Nearby Low-Luminosity Galactic Nuclei, Köln (D), 18-22 avril 2006
Membre du SOC de l'International Conference on Physics and Astrophysics of Black Holes, Santa Fé (NM, USA), 10-14 juillet 2006

GORET Philippe

Membre du comité d'organisation de la conférence internationale NDIP 05: « New Developments in Photodetection, Beaune 2005, France, June 19-24 »

GRENIER Isabelle

Membre du SOC des colloques internationaux suivants :
"How does the Galaxy work?" Granada, 2003
"The Multiwavelength Approach to Unidentified Gamma-Ray Sources", Hong Kong 2004
"4th Four Seas" conference on Bosphorus, Istambul, 2004
"5th Four Seas", Romania, 2006
"Observing the X-ray and Gamma-ray sky", Cargèse, 2006

KOCH Lydie

EuroScience Open Forum 2004, Session on "The Social Responsibility of Scientific Institutions", organisée par J. Finney, L. Koch-Miramond, K. Evers.
Conférence internationale "La science au service de la guerre et la responsabilité des scientifiques", 2005, Ecole Normale Supérieure, Paris, organisée par D. Iagolnitzer, L. Koch-Miramond, V. Rivasseau.

LAURENT Philippe

Membre du comité d'organisation des 6ème Rencontres du Vietnam, Hanoï août 2006

LEHOUCQ Rolland

Commissaire scientifique de l'exposition permanente Le grand récit de l'univers, dont l'inauguration est prévue en octobre 2007 à la Cité des Sciences et de l'Industrie.
Rédaction du livret de la pièce de théâtre pour enfants Kant, écrite par Jon Fosse et mise en scène par Etienne Pommeret, Rouen, 12/2006.
Star Wars, l'expo, Cité des Sciences et de l'Industrie, 10/2005 – 8/2006 (700 000 visiteurs).
Le monde de Franquin, Cité des Sciences et de l'Industrie, 10/2004 – 8/2005 (500 000 visiteurs).
Mission Biospace Cité de l'Espace de Toulouse, 4/ 2004 – 12/2005 (250 000 visiteurs).
Généalogie de la matière, série de trois cours donnés dans le cadre du Collège de la Cité des Sciences et de l'Industrie, janvier-février 2004.
Programmation du Festival d'Astronomie de Fleurance (Gers) 2002-2006
Responsable de l'édition de 4 brochures pour le compte de la Société Française de Physique à l'occasion de l'Année Mondiale de la Physique, 2005. Thèmes : L'univers, Terre et environnement, Physique du vivant, Matière et lumière.

LIMOUSIN Olivier

Membre du comité d'organisation de la conférence internationale NDIP 05: « New Developments in Photodetection, Beaune 2005, France, June 19-24 »

MINIER Vincent

Organisateur de l'atelier PICS France-Australie "High-mass star formation", Paris, IAP, 10-11/05/2005

RODRIGUEZ Jérôme

Principal organisateur avec S. Corbel, C. Chapuis, A. Decourchelle : Observing the X-and Gamma-ray sky, Cagèse, avril 2006.
Co-organisateur du 1st INTEGRAL Data Analysis workshop, Versoix, Suisse, Octobre 2004.

Outreach activities

ALLOIN Danièle

En 2004, préparation d'une exposition sur l'Univers, en liaison avec l'équipe correspondante à l'ESO/Santiago. En place pour plusieurs années.
Introduction à l'astrophysique, conférences et ateliers, au Lycée Français de Barcelone, Mai 2007.

BALLET Jean

Intervention sur l'astronomie à l'école primaire Paul Langevin de Palaiseau en mai 2004.
Mise à jour fin 2004 pour réédition du chapitre « Astronomie X » du « Grand Livre du Ciel » (Bordas).
Conférence grand public « L'astronomie en rayons X », Société d'Astronomie Populaire de Limoges, 07/04/2005.

BRAHIC André

Une centaine d'émissions de radio (France Inter, Europe 1, France Culture, France Info, BFM, Radio Canada, Radio Suisse Romande, RTB, radios américaines, ..., un après midi « Le bon plaisir » sur France Culture et six émissions de plus de 90 minutes) entre 1990 et 2006.
Environ 200 interventions à la télévision (journaux, magazines, documentaires, ...) TF1,FR2, FR3, Canal +, Arte, La 5, M6, LCI, Paris Première, PBS aux Etats-Unis, chaînes suisses, russes et japonaises, RFO et chaînes câblées – sept émissions de plus de 60 minutes - entre 1990 et 2007.
Deux cassettes vidéo entre 1990 et 2005.
Quarante six articles de presse dont cinq fois une double ou triple page entre 1990 et 2006.
Environ 70 articles de vulgarisation entre 1975 et 2007.

CASSE Michel

Soleil Nucléaire, Clé CEA, Printemps 2004
L'Astrophysique Nucléaire, science des étoiles et du cosmos, Brochure CEA, 2004
Lettre International : Himmelskunde, avec Edgar Morin, 2004
L'origine des éléments chimiques avec R. Lehoucq, La Recherche, janvier 2005
Explorer le cosmos, les dossiers de la Recherche, Novembre 2005

Einstein dans le noir, Télécom Interview, Automne 2005
La création vue par l'astrophysique, Théolib : La création vue par l'astrophysique et la théologie, Hors série, juillet 2006
Matière et Quintessence, Institut d'Astrophysique de Paris, 2 mars 2004 (DVD)
L'essentiel est dans l'invisible, festival d'Astronomie de Fleurance, 6 Août 2005
Cosmologie, Bar des sciences 2 février 2005
La cosmologie à portée de tous, avec M. Lachièze-Rey, Bar des sciences 13 septembre 2005
Histoire de la modélisation astrophysique, Quarantième anniversaire du Service d'Astrophysique, 2 décembre 2005
Univers/Plurivers, Université Populaire 92, théâtre de Gennevilliers, 16 janvier 2006
Structure de l'univers, complexité, origine de la matière, origine de l'univers, forces, interactions, « Le siècle d'Albert Einstein », direction d'une table ronde à l'UNESCO, 15 Juillet 2005
Le langage et la science : Poétique, métaphysique, mystique de la physique moderne, « Le siècle d'Albert Einstein », table ronde à l'UNESCO, dirigée par J-M Alimi, 14 Juillet 2005
Univers envolé, Théâtre National de la Colline, 27 Octobre 2006
Exposition Star Wars à la Cité des Sciences et de l'Industrie de la Villette, Octobre 2006 : Interview diffusée sur le portail d'entrée
Conception de 36 vitraux scientifiques exposés au Centre International du Vitrail à Chartres :
Passeurs de Lumière en collaboration avec Hubert Reeves, 2005, émission sur ARTE.
Qu'est-ce que la matière noire et l'énergie noire avec J-P. Luminet, France-Culture/ Le Monde, émission de M. Alberganti, 16 Octobre 2004
Surpris par la nuit (A. Weinstein), France –Culture, 27 Septembre 2004
Un nouvel art de penser : redécouverte de la pluralité des mondes (8 heures d'émission, Fréquence Protestante : Octobre – décembre 2006)
Le partage de minuit, fiction scientifique (3heures), réalisé par J. Taroni. France-Culture, 22 janvier 2006
Conférence pour l'inauguration du Musée des arts premiers (Quai Branly), RFI, 24 Juin 2006

CHATY Sylvain

Réalisation du film du concours 2005 ``Olympiades Nationales de Physique'' (de Sylvain Chaty et Jean-Paul Flourat, Production Studio-Vidéo de Paris 7)
Le ciel, la cordillère et l'astrophysicien, réalisation Jean-Louis Berdot, film de Jean-Louis Berdot, Sylvain Chaty et Jean-Paul Flourat, coproduction CEA et Paris 7, 2005
Entretiens sur Radio Hôp, Escapades Célestes: ``les Trous Noirs''
Un nouveau couple d'étoiles dans notre Galaxie, J. Bourdet, 21/11/2005, Le Figaro
3 conférences invitées au Club d'Astronomie Uranoscope, Université Inter-âges du Val-de-Marne et Géospace Hérault: ``Les secrets des astres X poussiéreux : une nouvelle population d'astres''
Conférences lors de ``Science en Fête'' à Paris 7: ``Comment percer les secrets de l'Univers?'' et ``Promenade dans le bestiaire des sources extrêmes''
Conférences invitées et ateliers aux Festivals d'Astronomie de Fleurance (Gers) sur les microquasars, les mécanismes d'émission et l'observation multi-longueurs d'onde en astrophysique.
Cosmogonies, rencontre ``Art et Science'' entre des étudiants, l'astrophysicien Sylvain Chaty et l'artiste Julien Discrit (Galerie de Noisy-le-Sec et Musée des Arts et Métiers).
Fondation 93, rencontres avec des collégiens du 93 à la

Cité des Sciences: projet de gravitation. Conférence: ``La gravitation dans l'Univers, des naines blanches aux trous noirs''.
Un nouveau couple d'étoiles dans notre Galaxie, J. Bourdet, 21/11/2005, Le Figaro

DUC Pierre-Alain

Participation au festival d'astronomie de Fleurance.
Participation aux rencontres du ciel et de l'espace.
Participation aux rencontres sur le Calcul Intensif, Assemblée Nationale.
Rédaction d'articles de vulgarisation dans les revues "Pour la Science" et "Ciel Espace".

ELBAZ David

Membre du Jury du Prix du Livre de l'Astronomie du Festival de la Haute Maurienne en 2006:

FERRANDO Philippe

Conférence « Astrophysique spatiale et Univers violent », lycée Lakanal (Sceaux), 19 janvier 2006
Participation à l'article « Satellites en escadrille », Science et Avenir n° 3801, novembre 2006

FERRARI Cécile

Conférences grand public dans les collèges, lycées, associations d'astronomie, école d'été du CLEA (Comité de Liaison Enseignants Astronomes)
« La limite de Roche et les anneaux », L'Astronomie, Vol 120, Nov. 2006
« Anneaux et satellites de Saturne: L'héritage de Huygens », Au plus près de Saturne, Vuibert, Ed., Déc. 2005

GOLDWURM Andrea

Ciel et Espace, Février 2005, « Et en plus il tourne, le trou noir central de la Voie lactée » J.F., Hait, 2005.

GRENIER Isabelle

Ciel & Espace, 2005, « de la masse cachée sous nos yeux »
Le Monde, 2005, « un coin du voile se lève sur l'Univers invisible »
Le Figaro, 2005, « de vastes nuages de gaz sombre découverts près du système solaire »
Libération, 2005, « les halos qui comblent notre Galaxie »
Science Now, 2005, « dark matter need not apply »
St Michel l'Observatoire, 2004, « les hautes énergies ou les fureurs de l'univers »
IAP Paris, 2005, « le jacuzzi local, des étoiles, du gaz et des bulles »
Société astronomique de Bourgogne, 2005, « un vibrant univers »
Festival du ciel et de l'espace de Fleurance, 2005, « le jacuzzi local, des étoiles, du gaz et des bulles »
Festival Art – Science – Pensée, Mouans-Sartoux, 2005, « Emergence de la matière »
8ème Rencontre Météo-Montagne, Alpe d'Huez, 2005, « Energies dans l'Univers »
Société astronomique de Bourgogne, 2006, « le jacuzzi local, des étoiles, du gaz et des bulles »
Festival Art – Science – Pensée, Mouans-Sartoux, 2006, « Des pommes au caoutchouc : la gravitation »
Rencontres RCANES des clubs d'astronomie amateur de l'Est, 2006, « Energies dans l'Univers »

LEHOUCQ Rolland

Les horizons en cosmologie, R. Lehoucq, Pour la Science spécial « Frontières floues » 350, 44-50, décembre 2006.
Les robots de Star Wars, R. Lehoucq, Texte et Documents pour la Classe, p. 27-30, mai 2006.
L'univers, R. Lehoucq, rédaction du numéro Hors-série de la revue Wapiti, septembre 2005.
Y a quelqu'un ?, R. Lehoucq, postface de l'anthologie « Premiers contacts » dirigée par Denis Guiot, Editions Mango, collection Autre Monde, avril 2005.
Haddock en orbite !, R. Lehoucq, Texte et Documents pour la Classe, avril 2005.
Ce qui a changé en 1905, R. Lehoucq, Le Monde 2, p. 72, 25 mars 2005.
Compte à rebours, R. Lehoucq, Le Monde Diplomatique, p.18, janvier 2005.
Décryptage : E = mc2, R. Lehoucq, Texte et Documents pour la Classe, p.12-14, décembre 2004.
Le terraformage, R. Lehoucq, Le Monde Diplomatique, p. 24, décembre 2004.
Voyager dans le temps ?, R. Lehoucq, Pour la Science spécial Einstein 326, 140-142, décembre 2004.
Les constantes en dix questions, R. Lehoucq, Science et Avenir Hors Série « Les constantes fondamentales », décembre 2004.

SAUVAGE Marc

14 Février 2006 - Participation a l'article "Les yeux de lynx des astrophysiciens du CEA" - La Croix
17 Février 2006 - Participation a l'article "Le CEA sur Herschel et le télescope JWST" - Air & Cosmos

TALVARD Michel

Exposé ''Thématiques scientifiques et Instrumentation spatiale au CEA'' lors du Colloque ''Les mathématiques du réel'' organisé par la Société de Calcul Mathématique en partenariat avec EDF le 25 mars 2005.

TURCK-CHIEZE Sylvaine

Rencontres du Mardi : Univers Etoiles noyaux et particules, 11 Juin 2004
Préparation et Participation à l'exposition de la Villette du CEA de Mars 2004 à Janvier 2005 intitulée : Soleil, mythes et réalités.
Participation à l'élaboration et Contribution au numéro 40 Clefs CEA : Le Soleil et la Terre

Books 2004 - 2006

ALLOIN Danielle

The Cool Universe: Exploring Cosmic Dawns", 2005, ASP Conf. Series 344, Eds C.Lidman et D. Alloin.
"Physics of AGN at all Scales", 2006, Springer Lecture Notes in Physics 693, Eds D.Alloin, R.Johnson, P.Lira.

BONNET-BIDAUD Jean-Marc

"Star maps and astronomy in ancient China" in 'The Silk Road: Trade, Travel, War and Faith', The British Library, ed. Susan Whitfield, June 2004

BRAHIC André

7 livres de cours et de vulgarisation entre 1999 et 2007 dont l'un vendu à plus de 80 000 exemplaires et traduit en 6 langues.

CASSE Michel

Pequena Estrela, avec Elisabeth Vangioni, édition portugaise, Martin Fontes (Sao Paulo)
Lettres à Dieu, Calman-Lévy, Collectif, 2004
Energie noire, matière noire, Odile Jacob, 2004
Théorie du Ciel, réédition, Payot, 2005,
Théories du Ciel, traduction Coréenne, Bestun Korea Agency, Seoul, 2005
Spin, Roman noir de la matière avec Jacques Paul, Odile Jacob, 2006.
Pavillon noir, collectif, entretien réalisé par Eric Reinhardt, Xavier Barral ed., 2006
Préface du livre de L. Celnikier : « Find a hotter place », a history of nuclear astrophysics, World Scientific Series in Astronomy and Astrophysics, 2006

LEHOUCQ Roland

Faire de la science avec Star Wars, éditions Le Pommier, octobre 2005.
La lumière à la loupe, éditions Le Pommier, collection Mini-Pommes, septembre 2005.
Les secrets de la matière, écrit en collaboration avec Françoise Balibar et Jean-Marc Lévy-Leblond, Editions Le Pommier, avril 2005.
Les constantes fondamentales, écrit en collaboration avec Jean-Philippe Uzan, Editions Belin, mars 2005.
Le Soleil, notre étoile, éditions Le Pommier, collection Mini-Pommes, septembre 2004.

KOCH Lydie

"The Scientific Legacy of Beppo Occhialini", 2006, ed. Springer,
"La Collaboration Milano - Saclay - Palermo", B. Agrinier, L. Koch-Miramond, J. Paul
"La science et la guerre. La responsabilité des scientifiques", 2006, ed. L'Harmattan, sous la direction de D. Iagolnitzer, L. Koch-Miramond, V. Rivasseau

MASSET Frédéric

Disk-planet interaction and migration, F. Masset & W. Kley, dans "Planet Formation: Theory, Observation, and Experiments", ed. Hubert Klahr & Wolfgang Brandner, Cambridge University Press 2006.

Publication list

Afonso C., Glicenstein J.F. ; Hamadache C. ; Vigroux L. et al, 2006. The OGLE-II event sc5-2859: a classical nova outburst? Astronomy and Astrophysics Volume 450, 1, 233-239.

Aguilar J.A. ; Goret P. et al, 2005a. Transmission of light in deep sea water at the site of the ANTARES neutrino telescope, Astroparticle Physics Volume 23, 1, 131-135.

Aguilar J.A. ; Goret P. et al, 2005b. Study of large hemispherical photomultiplier tubes for the ANTARES neutrino telescope. Nuclear Instruments and Methods in Physics Research A-Accelerators, Spectrometers, Detectors and Associated Equipment Volume 555, 1, 132-141.

Aguilar J.A., ; Goret P et al, 2006. First results of the instrumentation line for the deep-sea ANTARES neutrino telescope, Astroparticle Physics, Volume 26, 314-324.

Aharonian F., Goret P. et al, 2004a. Calibration of cameras of the HESS detector, in Astroparticle Physics, Volume 22, 2, 109-125.

Aharonian F., Goret P. et al, 2004b. High-energy particle acceleration in the shell of a supernova remnant, Nature Volume 432 Numéro 7013, 75-77.

Aharonian F., Goret P. et al, 2004c. Very high energy gamma rays from the direction of Sagittarius A Astronomy and Astrophysics Volume 425, 1, L13-L17

Aharonian A., Glicenstein J.F., Goret P. et al, 2005a. Observations of selected AGN with HESS Astronomy and Astrophysics Volume 441, 465-472.

Aharonian F., Glicenstein J.F., Goret P. et al, 2005b. Discovery of extented VHE gamma-ray emission from the asymmetric pulsar wind nebula in MSH 15-52 with HESS, Astronomy and Astrophysics, Volume 435, 1, L17-L20.

Aharonian F., Glicenstein J.F., Goret P. et al, 2005c. Discovery of VHE gamma rays from PKS 2005-489, Astronomy and Astrophysics Volume 436, 2, L17-L20.

Aharonian F., Glicenstein J.F., Goret P. et al, 2005d. Detection of TeV gamma-ray emission from the shell-type supernova remnant RX J0852.0-4622 with HESS, Astronomy and Astrophysics Volume 437, 1, L7-L10.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2005e. Observations of MKN 421 in 20004 with HESS at large zenith angles. Astronomy and Astrophysics Volume 437, 1, 95-99.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2005f. Serendipitous discovery of the unidentified extended TeV gamma-ray source HESS J1303-631. Astronomy and Astrophysics, Volume 439, 3, 1013-1021.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2005g. Discovery of very high energy gamma rays associated with an X-ray binary. Science, Volume 309, 5735, 746-749.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2005h. Multi-wavelength observations of PKS 2155-304 with HESS, Astronomy and Astrophysics, Volume 442, 3, 895-907.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2005i. A possible association of the new VHE gamma-ray source HESS J1825-137 with the pulsar wind nebula G 18.0-0.7, Astronomy and Astrophysics, Volume 442, 3 , L25-L29.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2005j. A search for very high gamma-ray emission from the starburst galaxy NGC 253 with HESS, Astronomy and Astrophysics, Volume 442, 1, 177-183.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2005k. Discovery of the binary pulsar PSR B1259-63 in very-high-energy gamma rays around periastron with HESS, Astronomy and Astrophysics, Volume 442, 1

Aharonian F., Goret P., 2005l. HESS observations of PKS 2155-304, Astronomy and Astrophysics, Volume 430, 3, 865.

Aharonian F., Goret P., 2005m. Very high energy gamma rays from the composite SNR G0.9+0.1, Astronomy and Astrophysics, Volume 432, 2, L25.

Aharonian F., Goret P., 2005n. Search for TeV emission from the region around PSR B1706-44 with the HESS experiment, Astronomy and Astrophysics Volume 432, 1, L9.

Aharonian F., Goret P., 2005o. A new population of very high energy gamma-ray sources in the milky way, Science, Volume 307, 5717, 1938.

Aharonian F., Goret P., 2005p. Upper limits to the SN1006 multi-TeV gamma-ray flux from HESS observations Astronomy and Astrophysics, Volume 437, 1, 135.

Aharonian F., Glicenstein J.F. ; Goret P., 2005q. Discovery of the binary pulsar PSRB 1259-63 in very-high-energy gamma rays around periastron with HESS Astronomy and Astrophysics Volume 442, 1, 1

Aharonian F., Goret P., 2005r. Upper limits to the SN 1006 multi-TeV gamma-ray flux from HESS observations Astronomy and Astrophysics Volume 437, 1, 1.

Aharonian F., Goret P., 2005s. Search for TeV emission from the region around PSR B1706-44 with the HESS experiment Astronomy and Astrophysics Volume 432, 1, L9.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2006a. The H.E.S.S. survey of the inner galaxy in very high energy gamma rays. Astrophysical Journal Volume 636, 2, 777-797.

Aharonian F., Glicenstein J.F. ; Goret P. ; Rolland L. et al, 2006b. First detection of a VHE gamma-ray spectral maximum from a cosmic source: HESS discovery of the Vela X nebula. Astronomy and Astrophysics, Volume 448, 2, L43-L47.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2006c. Evidence for VHE gamma-ray emission from the distant BL Lac PG 1553+113. Astronomy and Astrophysics, Volume 448, 2 , L19-L23.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2006d. Discovery of very-high-energy gamma-rays from the Galactic Centre ridge. Nature, Volume 439, 7077, 695-698.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2006e. A detailed spectral and morphological study of the gamma-ray supernova remnant RX J1713.7-3946 with HESS. Astronomy and Astrophysics, Volume 449, 1, 223-242.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2006f. A low level of extragalactic background light as revealed by \gamma-rays from blazars. Nature, Volume 440, 7087, 1018-1021.

Aharonian F., Glicenstein J.F. ; Goret P. ; Rolland L. et al, 2006g. Discovery of very high energy \gamma-ray emission from the BL Lacertae object H 2356-309 with the HESS Cherenkov telescopes. Astronomy and Astrophysics, Volume 455, 2, 461-466.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2006h. Discovery of the two 'wings' of the Kookaburra complex in VHE \gamma-rays with HESS, Astronomy and Astrophysics, Volume 456, 1, 245-251.

Aharonian F., Glicenstein J.F. ; Goret P. et al, 2006i. Observations of the Crab nebula with Hess, Astronomy and Astrophysics Volume 457, 3, 899-915.

Aharonian F., Glicenstein J.F. ; Goret P. ; Rolland L. et al, 2006j. Energy dependent gamma-ray morphology in the pulsar wind nebula HESS J1825-137, Astronomy and Astrophysics, Volume 460, 2, 365-374.

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Service d'Astrophysique
CEA - Saclay
Bâtiment 709, Orme des Merisiers
Point courrier 131
F-91191 Gif-sur-Yvette Cedex, France
Phone: +33 (0) 1 69 08 52 18
Fax: +33 (0) 1 69 08 65 77
Web site address: http://www-dapnia.cea.fr/SAp