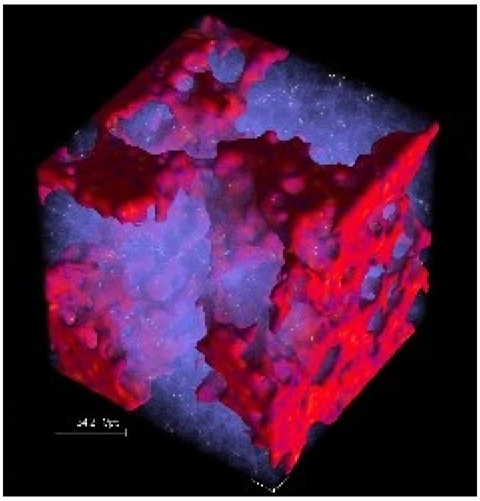
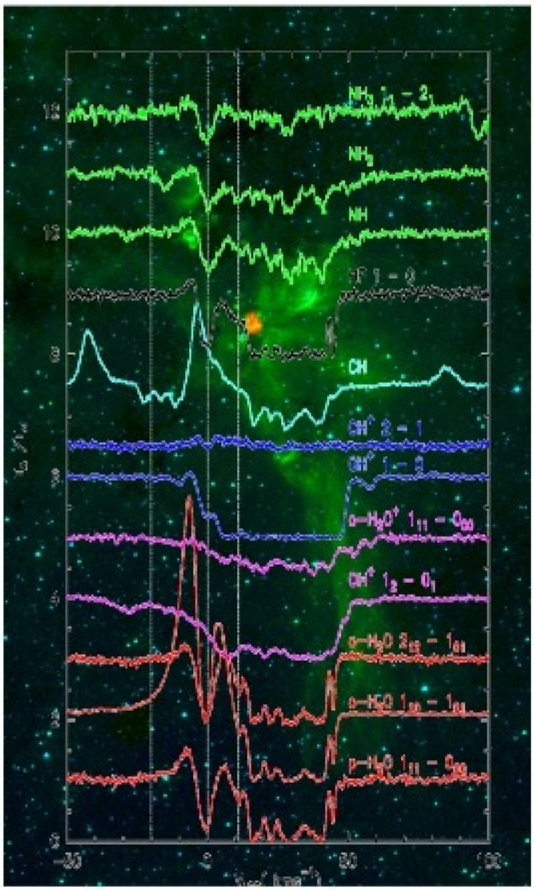
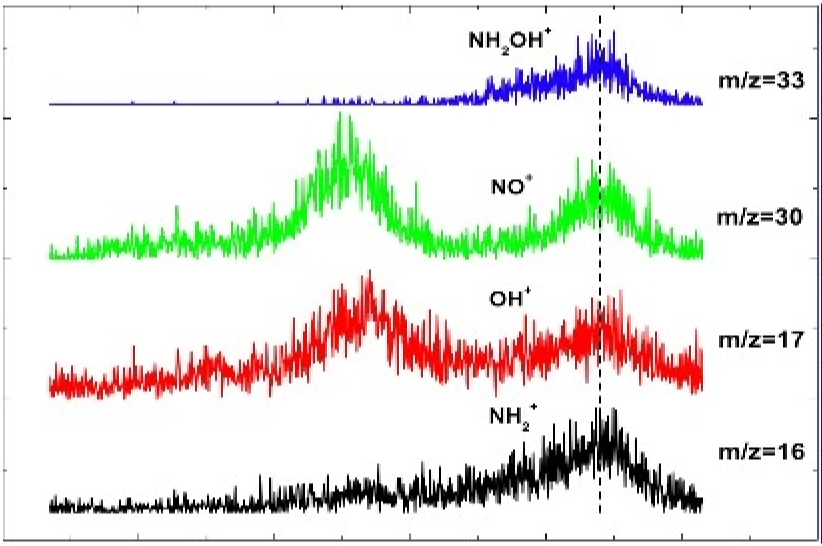
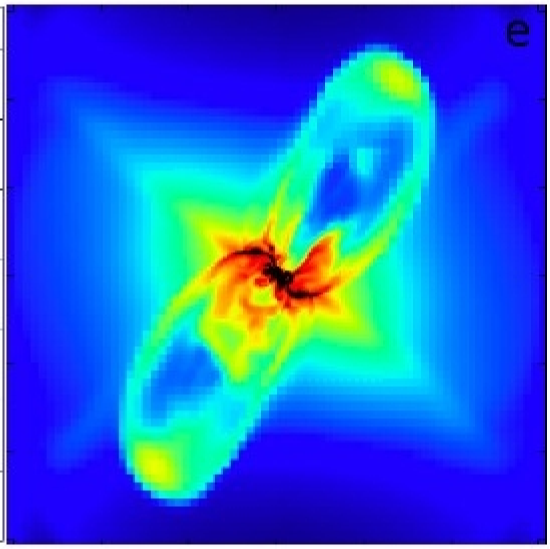
LABORATOIRE D'ETUDES DU RAYONNEMENT ET DE LA MATIÈRE EN ASTROPHYSIQUE





LERMA
Results
2007-2012
Vol.I Scientific Report (version 2.2)





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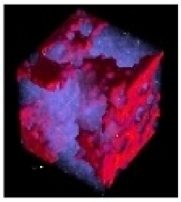
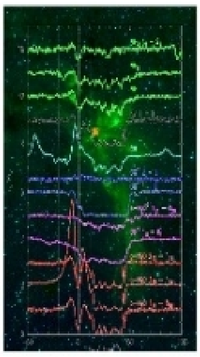
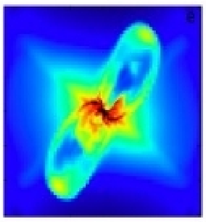
Scanning Electron Microscope (SEM) images of a 2.5 THz HEB mixer made by LERMA



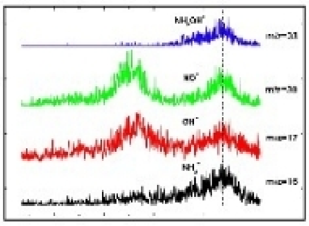
First simulation with Lyman-alpha transfer of intergalactic medium reionization at z~7, in a box of 100Mpc/h
©Baek *et al* 2010



High-resolution Herschel/HIFI absorption spectra of hydrides observed towards W31C in the PRISMAS program
© Gerin *et al.* 2010



3D MHD simulation of protostellar collapse with a 45° angle between initial B-field and spin axis
© Ciardi & Hennebelle 2010



Thermal desorption signal of compounds formed by H atom irradiation of NO ice on a 10K amorphous silicate
© Congiu *et al* 2012.

Conception graphique S. Cabrit

Foreword

This is version 2.2 of the LERMA report on the results obtained during the period 2007 to mid-2012. It has been formally approved by the LERMA Council on January 9th, 2013.

The structure of the document derives from the AERES requirements as expressed in their document S2-1-1-UR-ResultatsAutoEvaluation.pdf.

Following the AERES guidelines given in document S2-1-1-UR-ResultatsAutoEvaluation.pdf, this report contains 3 sections : the main section (Volume I) is a presentation of the results and self-evaluation. It is followed by a short section (Volume II) dedicated to organisation charts and regulations. The last section (Volume III) lists the publications of LERMA members.

The **Results and Self-evaluation section** follows the new scientific organisation of LERMA in four main Research Poles : the corresponding scientific objectives, activities, results and their visibility are documented in the first 4 chapters of this section, one for each of our 4 Research Poles : **Galaxies and Cosmology**, **Dynamics of the ISM and Stellar Plasmas**, **Molecules in the Universe**, **Instrumentation and Remote Sensing**. The other aspects of the report, which involve our common Support Pole at various levels, and an interplay of the various components of the Lab, are described in an additional chapter : **Common Missions and Services**, which summarizes the LERMA productions other than publications, its interactions with the environment, its involvement in training by research and its organisation. Last a short analysis of the Laboratory resources is presented, followed by a summary of the principal achievements, and of the implementation of the 2009 recommendations of AERES.

As requested a second section of the report displays the laboratory organisation charts and internal regulations.

Last, the refereed (ACL) and non refereed conference (ACT) publications, grouped per year, from 2007 to 2012, are listed in the third section. No attempt has been made to list invited talks separately, nor have unpublished communications been judged worth listing.

These documents have been prepared by a small coordination group (S. Cabrit, F. Combes, F. Dulieu, C. Prigent and V. Audon), with the much valued help of many colleagues, which took significant amounts of their time in order to prepare the various inputs to this report. Special thanks to A. Coulais, F. Dayou, E. Falgarone, M. Gerin, L. Girot, A. Maestrini, A.-L. Melchior, L. Pagani, B. Sémelin, C. Stehlé, D. Valls-Gabaud, M. Wiedner, C.-M. Zwölf. I am very indebted to all of them for their continuous support.

Michel Pérault, directeur du LERMA October 15th 2012 in Paris

(updated January 10th 2013)

Structure of the document

Vol. I. Scientific Report.......................................5

Part 1. Executive summary.......................................7

Part 2. Results and self-evaluation 2007-2012.......................................17

Vol. II. Organisation Charts and Regulations.......107

Part 1. Organisation charts.......................................109

Part 2. Rules and regulations.......................................113

Vol. III. Bibliography.......................................125

Part 1. Refereed articles ACL list.......................................127

Part 2. Conference proceedings (ACT).......................................191

Vol. IV. Tabulated data.......................................231

Part 1. List of tables.......................................233

Part 2. Tables.......................................235

Vol. I. Scientific Report

Table of Contents of Volume I

Vol. I. Scientific Report..5

Part 1. Executive summary...7

1.1. Overview...7

1.2. Thematic Poles...8

1.3. Support Pole...8

Part 2. Results and self-evaluation 2007-2012..17

1. Introduction...19

2. Pole 1: Galaxies and Cosmology...23

2.1. Global Presentation...23

2.2. Cosmology and Early Universe...23

2.3. Clusters of Galaxies...26

2.4. Dynamics of Galaxies, Dark Matter...27

2.5. AGN, Star Formation and Feedback in Nearby and High Redshift Galaxies........30

2.6. Summary...33

3. Pole 2: Dynamics of the ISM and stellar plasmas 35

3.1. Overview and Scientific Objectives 35

3.2. Observational characterization of the ISM cycle 36

3.3. Modelling cloud condensation : From diffuse gas to stars and discs.....................39

3.4. Modelling chemical diagnostics of ISM dynamics 41

3.5. Modelling transport mechanisms in circum/stellar plasmas..................................43

3.6. Laboratory Plasma Experiments...44

3.7. Visibility and attractivity..46

4. Pole 3: Molecules in the Universe....49

4.1. Overview....49

4.2. Scientific objectives and results....50

4.3. Technological developments....57

4.4. Production and visibility....58

4.5. Summary....58

5. Pole 4: Instrumentation and remote sensing....59

5.1. Introduction....59

5.2. The THz Instrumentation Group 60

5.3. Earth and Planet Remote Sensing activity....67

5.4. The software instrumental activity....71

6. Additional missions and services....73

6.1. Productions other than publications....73

6.2. Interactions with the non-academic environment....76

6.3. Training by research....78

6.4. Laboratory Life and Organisation....80

7. Analysis of Laboratory Resources....87

7.1. Research environment and its evolution....87

7.2. Main resources....88

7.3. In house facilities....93

8. Summary and Conclusions....95

8.1. Principal achievements....95

8.2. Implementation of the 2009 recommendations....99

Part 1. Executive summary

This summary is composed of a short overview and 5 standardized Fiches Résumés, one for each of the 4 Thematic Poles, and one for the Common Services..

1.1. Overview

LERMA is rooted in the early development of radioastronomy, on one hand, and atomic and molecular physics applied to astronomy, on the other hand. Created in 2002 with the merging of the *Laboratoire de Radioastronomie Millimétrique* and of the *Laboratoire Atomes et Molécules en Astrophysique*, LERMA has grown to a mature research institute, fundamentally dedicated to molecular astrophysics and to the development and exploitation of powerful instruments for spectroscopic and spectropolarimetric imaging.

These fundamentals have triggered active investigations of the dynamics of stellar systems and galaxies, with more and more emphasis on galaxy, star and planetary system formation. Needless to say, these investigations have developed far beyond radio observations, into various parts of the electromagnetic spectrum, into numerical simulations and more recently into laboratory astrophysics. These developments resulted into a great diversity of activities within LERMA and into a very large network of collaborations and partnerships in France and abroad.

An heritage from the early developments of the two historical components of LERMA is the implantation of the lab within 4 institutions, 3 of them are venerable institutions in Paris, namely the Sorbonne (UPMC), the Observatoire de Paris (OP), and the École normale supérieure (ENS). The 4th institution, on the other hand, is a recently created University in the Paris area, at Cergy-Pontoise (UCP).

The resulting geographic dispersion of the research teams over the Paris area much influences our laboratory life. The advantages and drawbacks of this situation will be addressed in the report. But the report is purposely organised according to the scientific structure of our activities, which have been grouped in 4 thematic poles, which happily traverse geographic boundaries. As they stand today, these 4 poles arose from intense internal discussions which started during the March 2011 *Journées du LERMA*, when the whole lab convened at a secluded residence in Sologne, and continued throughout the following year where the future of the lab was very seriously considered.

1.2. Thematic Poles

The 4 thematic poles are: 1. Galaxies and Cosmology 2. Dynamics of the Interstellar Medium (ISM) and Stellar Plasmas 3. Molecules in the Universe and 4. Instrumentation and Remote Sensing. This simple scientific partition also prepares for the future integration of two groups into LERMA: the Laboratoire de Physique Moléculaire pour l'Atmosphère et l'Astrophysique (LPMAA), mostly into Pole 3, with connections to Pole 4 and a reinforcement of the Support Pole, and of members of the LUTh Interstellar Medium team, into Pole 2. This was the last compelling argument for the 4-Pole presentation adopted here.

The summary forms which follow collect essential information from the activity and production of each of our 4 thematic poles. This information is expanded and commented in each of the 4 scientific sections of the main document.

1.3. Support Pole

Almost all administrative and technical personal is attached to the Support Pole. Some of them also carry on research activities, and therefore belong to one of the thematic poles, as primary or secondary affiliation. This shared structure has been progressively installed after the nomination of our technical manager, in charge of the technical section of the pole, in order to facilitate exchanges among specialists of similar fields, to optimize the workload of our administrative and technical staff, and to improve their career perspectives. The resulting links, which developed across our many boundaries, play a constructive role in our lab development.

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1.2. Fiche-résumé du Pôle 1 **du LERMA**

(la fiche ne devra pas dépasser un recto-verso)

Pôle Galaxies et cosmologie

Intitulé de l'unité : Laboratoire d'Études du Rayonnement et de la Matière en Astrophysique
Nom du Directeur de l'unité : Michel Pérault
Nom de la coordinatrice du pôle : Françoise Combes

Effectifs de l'entité (au début du contrat en cours ; préciser si l'entité a été créée au cours de la période d'évaluation)
4 enseignants-chercheurs ; 2 chercheurs ; 2 techniciens, ingénieurs et autres personnels ; 5 post docs et doctorants.

Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de cette période)

0 statutaire (0 mois) ; 2 doctorants (40 mois) ; 4 post-docs (68 mois).

Nombre de recrutements réalisés au cours de la période considérée et origine des personnels (Préciser l'affiliation et le statut précédent.)
1 chercheur statutaire (GEPI chercheur statutaire) ; 1 doctorant (Madrid doctorant); 10 post-docs (4 doctorants : Lyon 1, Montpellier, Paris 7, Moscou ; 6 post-doc : GEPI, CEA, Tsukuba, Princeton, Durham, Harvard) ; 3 techniciens, ingénieurs et autres personnels (1 doctorant-INRIA, 1 post-doctorant-IRAM, 1 étudiant en apprentissage).

Production scientifique au cours de la période écoulée (1er janvier 2007 - 30 juin 2012) :
Indiquer les **résultats majeurs** obtenus par l'entité (une à trois lignes par résultat, au maximum 5 résultats majeurs). Ces résultats peuvent correspondre à tout type de production scientifique ou technique (publications, brevets, licences, logiciels, etc.).

1. Discovery of large amounts of cold molecular gas in large-scale filaments around cooling flow galaxies, with the IRAM 30m and PdBI interferometer. The prototype Perseus A shows a remarkable network of Halpha filaments, and CO emission has been discovered with surprising kinematics (Salome et al 2011). A numerical model has been computed to propose a physical interpretation, in terms of the AGN feedback and moderating actions (Revaz et al 2008)

2. Computation of a remarkably large library of mergers of galaxies, and integration in the theoretical Virtual Observatory (Chilingarian et al 2010). For the first time, a large series of numerical simulations is offered online to the astronomy community, with VO tools to compute on the fly projected quantities, like the morphology, kinematics, dust extinction, spectral energy distributions, or line spectroscopy.

3. Determination of the nature of the sources of light during of the Epoch Re-ionisation (EoR) in the primordial Universe: cosmological simulations with radiative transfer show how the 21 cm signal properties depend on the relative contribution of stars and quasars to the ionizing photon budget (Baek et al 2011).

4. The Planck satellite has been launched in 2009, and a rich accumulation of first results has started to be published, involving foregrounds in the Galaxy, but also on galaxy clusters with the SZ effect, and many other bright results. Several people in our group are involved in these "Planck Collaboration" first papers.

5. Discovery of a unique hyper-luminous galaxy, one billion year only after the Big-Bang : this unique object has been searched with Herschel behind nearby clusters as gravitational telescopes. The redshift has been searched with EMIR at the IRAM-30m telescope with CO/H2O/NII lines, and the source has been mapped in many lines (CII, H2O, etc..) with the PdB interferometer (Combes et al 2012).

Bilan quantitatif des publications de l'entité :

620 publications, of which 370 refereed articles

Indiquer les **5 publications majeures** de l'entité (avec leur titre et en soulignant, dans le cas de publications communes, le nom du ou des membres de l'entité) :

•Salomé, P., Combes, F., Revaz, Y., Downes, D.; Edge, A. C.; Fabian, A. C.
A very extended molecular web around NGC 1275 2011 A&A 531, A85
•Chilingarian, I. V., Di Matteo, P., Combes, F., Melchior, A.-L., Semelin, B.
The GalMer database: galaxy mergers in the virtual observatory 2010 A&A 518, A61
•Baek, S., Semelin, B., Di Matteo, P., Revaz, Y., Combes, F.
Reionization by UV or X-ray sources 2011 A&A 523, 4
•Planck Collaboration; Ade, P. A. R.; Aghanim, N.; Arnaud, M.; Ashdown, M.; Aumont, J.; Baccigalupi, C.; Balbi, A.; Banday, A. J.; Barreiro, R. B.; and 228 coauthors
Planck early results. VIII. The all-sky early Sunyaev-Zeldovich cluster sample, 2011, A&A 536, A8
•Combes, F., Rex, M., Rawle, T.D., Egami, E., Boone, F., Smail, I., Richard, J., Ivison, R.J., Gurwell, M., Casey, C. and 13 coauthors

A bright z = 5.2 lensed submillimeter galaxy in the field of Abell 773. HLSJ091828.6+514223 2012 A&A 538, L4
•Destri C, de Vega H., Sanchez N.
MonteCarlo Markov chains analysis of WMAP3 and SDSS data points to broken symmetry inflaton potentials and provides a lower bound on the tensor to scalar ratio, 2008 Phys. Rev. D, 77(4):043509

Indiquer **au maximum 5 documents majeurs** (autres que publications) produits par l'entité (par exemple : rapport d'expertise, logiciel, corpus, protocole, brevet en licence d'exploitation, etc.)

Web sites GALMER http://galmer.obspm.fr, Projet HORIZON http://www.projet-horizon.fr

---

Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques** de l'entité (par exemple : invitations à donner des conférences, organisation de colloques nationaux ou internationaux, réseaux collaboratifs, cofinancements, prix et distinctions, etc.)

Environ 30 invitations à donner des conférences par an, Organisation de plusieurs colloques, notamment les Ecoles Chalonge, ou symposiums IAU, plusieurs ANR en collaboration (HORIZON, LIDAU, GALHIS, VACOUL, RTIGE, POMME...), réseaux SKA-Design Study Européen, financement ERC-momentum, Prix Européen Tycho Brahe, Médaille d'argent pour Hands-on-Universe européen

---

Indiquer **au maximum 5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel (par exemple : contrat industriel, collaboration à une exposition majeure, émission audiovisuelle, partenariats avec des institutions culturelles, etc.)**

Vice-présidence de Comité AMA09 (Année Mondiale de l'Astronomie 2009) + participation à de nombreuses expositions (Palais de la Découverte, Cité des Sciences). Direction de HOU-France, et EU-HOU (Hands on Universe), financement par Réseau Européen

---

Indiquer **les principales contributions de l'entité à des actions de formation** (par exemple : conception et coordination de modules de formation en master et en doctorat, accueil et suivi des doctorants, conception d'outils à vocation pédagogique, action de formation continue, etc.)

Formation à la parallélisation sur super-computer. Introduction de radio-télescopes sur site (Obs et UPMC) avec mise-au point de logiciels de réduction et d'exploitation, pour observation à distance et TP d'astronomie, et introduction de télescopes optiques pour travaux pratiques. Hands-on-Universe pour formation des étudiants. Participation au CNED pour formation continue. Nombre d'heures d'enseignement par an ~500h.

Le **directeur d'unité** peut indiquer ici brièvement **3 points précis** sur lesquels il souhaite obtenir l'expertise du comité.

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1.2. Fiche-résumé du Pôle 2 du LERMA

(la fiche ne devra pas dépasser un recto-verso)

Pôle : Dynamique des milieux interstellaires et plasmas stellaires

---

Intitulé de l'unité : Laboratoire d'Etudes du Rayonnement et de la Matière en Astrophysique
Nom du Directeur de l'unité : Michel Pérault
Nom de la coordinatrice du Pôle : Sylvie Cabrit

Effectifs de l'entité (au début du contrat en cours ; préciser si l'entité a été créée au cours de la période d'évaluation) : In Jan. 2010, Pole 2 gathered 10 teaching researchers; 11 full time researchers (including 3 emeritus); 4 technicians and engineers ; 9 post-docs and Ph.D. students ; 3 associate researchers (Pineau des Forêts, IAS ; Dormy, IPGP ; Schrinner, ENS).

Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de cette période) : 2 permanent researchers (20 months) ; 3 engineers or technicians (26 months) ; 2 Ph.D. students (38 months) ; 1 post-doc (8 months).

Nombre de recrutements réalisés depuis Janvier 2010 et origine des personnels (Préciser l'affiliation et le statut précédent) : 3 permanent researchers (Heidelberg, Post-doc ; ObsPM-LERMA post-doc; ObsPM-LUTh, permanent) ; 2 post-docs (Max Planck Institutes Heidelberg & Bonn, Post-docs) ; 7 Ph.D. students (France, Greece, Chile).

Production scientifique au cours de la période écoulée (1er janvier 2007 – 30 juin 2012) :

*Pole 2 obtained **major results** in the following 5 areas :*

1) Observations of the ISM cycle: *Herschel* inventory of hydrides, a new probe of cosmic ray flux and of the first steps of molecule formation. Discovery of sheared CO filaments and H_2-bright regions tracing turbulent dissipation. Discovery of grain growth to micron size and sub-critical B-fields in prestellar cores. Innovative studies of disks/outflows at various stages.

2) High-resolution 3D MHD numerical simulations and analytical work elucidating: the key interplay of turbulence, thermal instability, and gravity in defining the structure of molecular clouds and the Initial Mass Function of stars; and the coupled impact of magnetic fields and radiative feedback on the formation of proto-planetary discs, binaries, and massive stars.

3) Chemical diagnostics of gas dynamics: First models of non-equilibrium heating and chemistry in turbulent dissipation regions (TDRs) and in magnetized shocks and jets, able to explain *Herschel*, IRAM and H_2 observations. First deuterium fractionation models including a full treatment of spin symmetries, enabling to infer the age of contracting pre-stellar cores.

4) Modeling of transport processes in astrophysical plasmas, critical for planet formation, stellar structure and abundance determinations: temporal behavior and coupling with dust of the magneto-rotational instability in protoplanetary discs; dynamo and turbulent/convective transport in rotating stars; high-precision calculations of opacities and radiative diffusion.

5) Laboratory astrophysics : Experimental studies of supersonic plasma jets and radiative shocks using pulsed power electric facilities, high power lasers, and numerical simulations, providing new insight on the formation, structure, temporal evolution and instabilities of magnetized protostellar jets and accretion shocks.

Bilan quantitatif des publications de l'entité

Indiquer les **5 publications majeures** de l'entités:

*Pole 2 members published 373 refereed articles in 2007-2012. Selecting only 5 is therefore quite arbitrary. We have chosen to list below, for each of our 5 research themes, the article with a first author from Pole 2 presenting the most citations **per year** with 2 ex-aequos for Theme 3 (note that this creates a bias against 2011-2012 articles, which have not yet reached their peak citation rate). A more complete view can be found in the personal activity files of Pole 2 members.*

1) *Interstellar OH^+, H_2O^+ and H_3O^+ along the sight-line to G10.6-0.4*, **Gerin, M.**; **de Luca, M.**; Black, J.; Goicoechea, J. R.; Herbst, E.; Neufeld, D. A.; **Falgarone, E.; Godard, B.**; and 45 coauthors : 2010, A&A 518, L110 (45 citations)
2) *Analytical Theory for the Initial Mass Function: CO Clumps and Prestellar Cores.* **Hennebelle, P.** & Chabrier, G. 2008, ApJ 684, 395 (138 citations)
3) *Models of turbulent dissipation regions in the diffuse interstellar medium*, **Godard B., Falgarone E.** & Pineau des Forêts G. 2009, A&A 495, 847 (42 citations), and *SiO line emission from C-type shock waves: interstellar jets and outflows* **A. Gusdorf**, **S. Cabrit**, D. R. Flower & G. Pineau Des Forêts 2008 *A&A*, 482, 809 (41 citations)
4) *MRI channel flows and their parasites*. **Latter H., Lesaffre P., Balbus S. A.**, 2009, MNRAS 396, 779 (20 citations)

5) *The evolution of magnetic tower jets in the laboratory*, **Ciardi, A.;** Lebedev, S. V.; Frank, A.; Blackman, E. G.; Chittenden, J. P.; Jennings, C. J.; Ampleford, D. J.; Bland, S. N.; Bott, S. C.; Rapley, J.; Hall, G. N.; Suzuki-Vidal, F. A.; **Marocchino, A.;** Lery, T.; **Stehlé, C**., 2007, Physics of Plasmas, Volume 14, Issue 5, pp. 056501-056501-10 (39 citations)

Indiquer **au maximum 5 documents majeurs** (autres que publications) produits par l'entité (par exemple : rapport d'expertise, logiciel, corpus, protocole, brevet en licence d'exploitation, etc.) :
1) MHD version of the 3D public code RAMSES (co-development and tests of the Riemann solver)
2) public code MESA of 1D stellar structure (integrator, mixing-length prescription, …) 2011 ApJS 192, 3
3) public code IRIS of 3D radiative transfer for the post-processing of numerical simulations
4) public grid of 3D MHD simulations of protostellar collapse with synthetic observations (Astronet EU project STARFORMAT)
5) Interactive tables of opacities and radiative accelerations for stellar models (OP server) 2007 MNRAS 378, 1031

Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques** de l'entité (invitations à donner des conférences, organisation de colloques, réseaux collaboratifs, cofinancements, prix et distinctions, etc.)
1) About **75 invited talks at international conferences and schools,** including 50 on ISM turbulence, magnetic fields, star formation, *Herschel* results, jets and shocks, and laboratory experiments; and **27 invited foreign senior researchers** that visited Pole 2 for 1-8 months over the period.
2) **Organization or SOC membership of about 15 international conferences and schools**
3) **Major participation in international collaborative networks:** *Herschel* Large Programs (PI of PRISMAS, co-Is in HEXOS, WADI, CHESS, WISH, HOP, DEBRIS, PCC); *Planck* satellite Core Team; JETSET Marie Curie RTN (co-PI); STARFORMAT Astronet project (PI-ship); COST action "*The Chemical Cosmos*"; MESA consortium; GdRE *Dynamo*; Projects *Opacity, Iron*, and *IPOPv2* (PI-ship); IAEA program "Spectroscopic and Collisional Data for Tungsten".
4) **Cofinancing ANR grants**: PI of STARSHOCK (Stehlé), SCHISM (Pety), co-PI of MAGNET, COSMIS; co-I of SILAMPA, ProbaGEO
5) **Nominations to national and international scientific responsibilities:** Astronomy Section of CNRS (Gerin, Pagani) and CNAP (Pérault), Scientific councils and committees of INSU (Stehlé, Zeippen, Gerin, Pérault), AERES science delegate (Falgarone), Astrophysics committee of CNES (Falgarone, Pérault, Pagani), Scientific committee of the "Programme National de Physico-Chimie du Milieu Interstellaire" (Gerin (Director), Falgarone, Hennebelle, Cabrit), National ALMA Specific Action (Pety (Director), Pérault), Vice-presidence of URSI-France (Le Bertre), Organizing Committee of IAU Division IV (Cabrit), Governing board of DIAS Dublin (Stehlé), Expert for the European Research Council (Falgarone, Gerin), ESO and ALMA time allocation committees (Heydari-Malayeri, Gerin), *Planck* Editorial Board (Falgarone); **Distinctions:** CNRS bronze medal (2008, Hennebelle)

Indiquer **au maximum 5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel (par exemple : contrat industriel, collaboration à une exposition majeure, émission audiovisuelle, partenariats avec des institutions culturelles, etc.)**
1) Organization in Oct 2008 of an interdisciplinary meeting gathering (bio)chemists, physicists and philosophers: « Origins of life : self-organization and/or biological evolution » and publication of the proceedings book (eds. MC Maurel & M Gerin)
2) Creation of the first Etymological Dictionary of Astronomy and Astrophysics (http://dictionary.obspm.fr; Heydari-Malayeri)
3) Partnership with the association "Les Musiques à Ouir" on a stage show "*Une nuit dans les étoiles*" combining jazz-music and astrophysical readings, played at l'Hexagone in Meylan and Trianon-Transatlantique in Rouen (2007, 2008) (Cabrit).
4) Video and radio interviews for the french TV, the *Herschel* french web site, RFI, and the BBC (Pagani, Cabrit, Heydari-Malayeri), Public conferences for the 2010 Festival "Astronomie en France" (Heydari, Lebertre) and for the International Year of Chemistry 2011 (Pagani). Invited articles for *Encyclopaedia Universalis, L'Astronomie, Pour la Science*.
5) Organisation of a major exhibit on "Le Verrier and the discovery of Neptune" and writing of a related book (Lequeux)

Indiquer **les principales contributions de l'entité à des actions de formation** (par exemple : conception et coordination de modules de formation en master et en doctorat, accueil et suivi des doctorants, conception d'outils à vocation pédagogique, action de formation continue, etc.)

- Creation of 15h-30h modules at M1 and M2 levels on "MHD" (Balbus), "Star and Planet formation" (Cabrit), "Astrophysical plasmas" (Ciardi & Hennebelle); hands-on training for M2 students at Observatoire de Haute-Provence (Cabrit).
- Creation of a new Master "Space and applications" at the University of Science and Technology in Hanoï (Lesaffre).
- over Jan 2007 - June 2012, supervision of ~ 20 master student projects, 17 local PhD students (Chaulagain, de Sa, Godard, Guzman, Islam, Jacquet, Joos, Libert, Momferratos, Morey, Panoglou, Petitdemange, Reynaud, Selier, Štěpán, Yvart, G. Di Molfetta), and co-supervision of 10 PhD students from other national or international institutes (Agra-Amboage, Ben Chaouacha, Commerçon, Dionatos, Gusdorf, Hamdi, Mahmoudi, Marocchino, Masson, Pilleri).
- Writing of 3 books at master level on: Thermodynamics & Statistical physics (Debbasch), Stars and the ISM (Lequeux).
- Continuing education: Scientific Organization of two CNRS schools for young researchers : "The Herschel satellite" (2007; Pagani, Gerin), "Role and transport mechanisms of angular momentum in the formation and early evolution of stars" (2012, Hennebelle), and editing of proceedings. Lecture series on Star formation for "Diffusion des Savoirs" at University Joseph Fourier (Cabrit). Biennal IRAM training schools on millimeter interferometry (Pety).

Le **directeur d'unité** peut indiquer ici brièvement **3 points précis** sur lesquels il souhaite obtenir l'expertise du comité.

Vague D :
Campagne d'évaluation 2012 - 2013

Unité de recherche

1.2. Fiche-résumé du Pôle 3 du LERMA

(la fiche ne devra pas dépasser un recto-verso)

Pôle Molécules dans l'Univers

Intitulé de l'unité : Laboratoire d'Etudes du Rayonnement et de la Matière en Astrophysique
Nom du Directeur de l'unité : Michel Pérault
Nom du coordinateur du pôle : [Jean-Hugues Fillion] François Dulieu and Fabrice Dayou

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Effectifs de l'entité (au début du contrat en cours ; préciser si l'entité a été créée au cours de la période d'évaluation)

10 enseignants-chercheurs ; 3 chercheurs ; 0 techniciens, ingénieurs et autres personnels ; 6 post docs et doctorants.

Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de cette période)

2 statutaires (30,5 mois) ; 4 doctorants (47 mois) ; 1 post-docs (12 mois).

Nombre de recrutements réalisés au cours de la période considérée et origine des personnels (Préciser l'affiliation et le statut précédent.)
1 chercheur statutaire (LPMAA post-doctorant) ; 4 doctorants (State Univ. NY, Univ. Catane, Univ. Strathclyde, INSAT Tunis) ; 1 techniciens, ingénieurs et autres personnels (1 CDD ITA post-doctorant).

Production scientifique au cours de la période écoulée (1er janvier 2007 – 30 juin 2012) :

1) Ultra-high precision HD lines were measured at extreme UV wavelengths by laser spectroscopy and FTS absorption measurements at the synchrotron SOLEIL, providing a database for comparison with high-redshift quasar spectra to probe possible proton-electron mass-variation effects on a cosmological time scale.

2) The survival of plant seeds in space has been studied through the ESA projects EXPOSE-E and EXPOSE-R on the International Space Station from 2006 to 2012. From the partial survival of arabidopsis thaliana seeds, it has been possible to calculate the probability of transfer of life between Mars and Earth for these seeds.

3) Accurate collisional rate coefficents computed for the rotational excitation of SO_2 by o/p-H_2 predcited new absorption and maser line profiles that are useful to trace physical conditions of the ISM. The predicted absorption line profile for the 1_{11}-2_{02} transition was confirmed by observations of dark clouds at the GBT.

4) Experimental synthesis of H2, H2O, CO2 and NH2OH on cold dust grains anlalogs.

5) Sticking measurements of H2, D2 analysis and extension to an analytical formulae for H, D, HD, on amorphous water ice and silicates, unveil a large Isotopic effect.

Bilan quantitatif des publications de l'entité : 68 ACL

Indiquer les **5 publications majeures** de l'entité

1) HD as a probe for detecting mass variation on a cosmological time scale, T. I. Ivanov, M. Roudjane, M. O. Vieitez, C. A. de Lange, W.-Ü L. Tchang-Brillet, and W. Ubachs,Physical Review Letters, **100**, 093007 (2008)

2) Collisional excitation of sulfur dioxide in cold molecular clouds,J. Cernicharo, A. Spielfiedel, C. Balança, F. Dayou, M.-L. Senent, N. Feautrier, A. Faure, L. Cressiot-Vincent, L. Wiesenfeld, and J.R. Pardo, *Astronomy & Astrophysics*, **531**, A103 (2011)

3) Kinetics and dynamics of the $S(^1D_2)+H_2 \rightarrow SH+H$ reaction at very low temperatures and collision energies
C. Berteloite, M. Lara, A. Bergeat, S.D. Le Picard, F. Dayou, K.M. Hickson, A. Canosa, C. Naulin, J.-M. Launay, I.R. Sims, and M. Costes, *Physical Review Letters*, **105** (20), 203201 (2010)

4) Measurement of the adsorption energy difference between ortho- and para-D_2 on an amorphous ice surface
Amiaud, L., A. Momeni, F. Dulieu, J. H Fillion, E. Matar, and J. -L Lemaire. *Physical Review Letters* **100** (5) (2008)

5) NO ice hydrogenation : A solid pathway to NH2OH formation in space , E. Congiu, G. Fedoseev, S. Ioppolo, F. Dulieu, H. Chaabouni, S. Baouche, JL Lemaire, et al. 2012 , *The Astrophysical Journal* 750 (1) (mai 1): L12.

Indiquer **au maximum 5 documents majeurs** (autres que publications) produits par l'entité (par exemple : rapport d'expertise, logiciel, corpus, protocole, brevet en licence d'exploitation, etc.)

1) Document describing the 10 m spectrograph for the ESA GBF (Ground Based Facilities) database (L. Tchang-Brillet).

Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques** de l'entité (par exemple : invitations à donner des conférences, organisation de colloques nationaux ou internationaux, réseaux collaboratifs, cofinancements, prix et distinctions, etc.)

1) Node for LASSIE ("Laboratory Astrochemical Surface Science In Europe"). International Training Network: http://lassie.u-cergy.fr/

2) ANR contract « ONIRISM », 2007-2011, Head : JL Lemaire, in collaboration with ISMO laboratory (V. Sidis)

3) Organisation of Molecules in Space and Laboratory, International conference, 14-18 May 2007, Paris, 264 participants.
http://www3.u-cergy.fr/Mol_Sp_Lab/

4) Chevalier de l'ordre des Palmes Académiques 2007 (Nicole Feautrier) et 2009 (Lydia Tchang-Brillet)

5) Invited conference and contributed talk at the 280 IUA Conference, The molecular Universe » Toledo Spain, 2011

Indiquer **au maximum 5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel (par exemple : contrat industriel, collaboration à une exposition majeure, émission audiovisuelle, partenariats avec des institutions culturelles, etc.)**

1) F. Dulieu is responsible for the Maison Universitaire de Diffusions de Savoir
http://www.u-cergy.fr/fr/orientation-et-insertion/diffusion-savoirs.html

2) Organisation (SOC and LOC) of multidisciplinary research,colloquium « L'égalité des Chances, au delà des mots » Pontoise, March 2010

3) Organisation and participation (testimony and laboratory visits) to « Univ-d-hiver, 2011 and 2012 »
http://www.dailymotion.com/video/xp89ie_univ-d-hiver-4-jours-pour-decouvrir-luniversite_news?start=1#from=embed

4) Partnership with schools (from primary to high degree) to promote and improve astronomy teaching (C. Balança- E. Congiu)

Indiquer **les principales contributions de l'entité à des actions de formation** (par exemple : conception et coordination de modules de formation en master et en doctorat, accueil et suivi des doctorants, conception d'outils à vocation pédagogique, action de formation continue, etc.)

1) Head of Master 2 Contrôle et Qualité en apprentissage (Université de Cergy-Pontoise) (V. Cobut)

2) Invited professor (F. Dulieu), Summer School for doc and post doc, « Chemistry and Infrared Spectroscopy of Interstellar Dust », 4-8 June 2012, Nijmegen, The Netherlands

3) Membre du Conseil de l'ED389 " La Physique de la Particule à la Matière Condensée". Membre de la Commission des Thèses et HDR de Physique à l'UPMC (2007-2012). (L. Tchang-Brillet) ; Membre du Conseil de l'ED 419 « Science et ingénieurie » (F. Dulieu)

4) Livres : L. Tchang-Brillet est co-auteur avec B. Cagnac d'une édition réactualisée du livre "Physique Atomique", Tome I (Dunod, 2005), Tome II (Dunod, 2007). Relecture de la traduction chinoise qui sortira en 2012 (I) et 2013 (II) en Chine.

• Head of « Classe préparatoires aux Grandes Ecoles, PCSI, PSI » with Lycée Jean-Jaurès d'Argenteuil (F. Dulieu)

6) Collaboration in the creation and use of web site for e-learning in astrophysics (C. Balança) http://media4.obspm.fr/public/AMC/

agence d'évaluation de la recherche et de l'enseignement supérieur

Vague D : Campagne d'évaluation 2012 - 2013

Unité de recherche

1.2. Fiche-résumé du Pôle 4 **du LERMA**

(la fiche ne devra pas dépasser un recto-verso)

Pôle Instrumentation et Télédétection

Intitulé de l'unité : Laboratoire d'Etudes du Rayonnement et de la Matière en Astrophysique
Nom du Directeur de l'unité : Michel Pérault
Nom du responsable de l'équipe : Catherine Prigent

Effectifs de l'entité (au début du contrat en cours ; préciser si l'entité a été créée au cours de la période d'évaluation)

3 enseignants-chercheurs ; 5 chercheurs ; 11 techniciens, ingénieurs et autres personnels ; 3 post docs et doctorants.

Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de cette période)

3 statutaires (30,5 mois) ; 2 doctorants (41 mois) ; 1 post-docs (12 mois).

Nombre de recrutements réalisés au cours de la période considérée et origine des personnels (Préciser l'affiliation et le statut précédent.)
0 chercheur statutaire ; 3 techniciens, ingénieurs et autres personnels (LERMA doctorant, poste permanent privé, doctorant UPMC) ; 6 doctorants (2 Observatoire de Paris, 1 Imperial College London, 1 Lulea Technical Univ., 1 Ecole Polytechnique, 1 Purple Mountain Observatory); 1 post-docs (SouthEast Univ. Chine).

Production scientifique au cours de la période écoulée (1er janvier 2007 – 30 juin 2012) :

1. Successful launch and operation of Herschel : the two SIS mixers of HIFI-band 1 (480-640GHz) delivered by LERMA-GEMO have excellent in-flight performance in terms of sensitivity and stability. Band 1 is among the two most used channels on HIFI.
2. LERMA now masters the design, fabrication - in partnership with CNRS-LPN - and characterization of THz heterodyne receivers based on 3 device technologies relevant to astrophysics, planetology and the sciences of the atmosphere : Hot Electron Bolometers, Superconductor-Insulator-Superconductor junctions and Schottky diodes.
3. Theoretical demonstration of the potential of millimeter and sub-millimeter satellite observations for ice cloud and rain characterization, and selection of the corresponding instrumentation for the future generation of European operational meteorological satellite
4. Monthly mean wetland extent at global scale, for the last 15 years, and their analysis that shows a decrease of 6% of the entent over that period.
5. Definition of generic data models (e.g. ALMA), standards for theoretical astrophysics (Sim-DM, Parameter Description Lenguage), semantics vocabulary for astrophysics concepts (Astro-concepts) and Ontological reasoning algorithms for automatic physical interoperability and test generation

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Bilan quantitatif des publications de l'entité

Indiquer les **5 publications majeures** de l'entité (avec leur titre et en soulignant, dans le cas de publications communes, le nom du ou des membres de l'entité) :

- <u>Miao, W.</u>, <u>Y. Delorme</u> <u>A. Feret</u>, <u>R. Lefevre</u>, L. Benoit, <u>F. Dauplay</u>, <u>J.M. Krieg</u>, <u>G. Beaudin</u>, <u>W. Zhang</u>, Y. Ren, and S.C. Shi, "Comparison between hot spot modelling and measurement of a superconducting hot electron bolometer mixer at submillimeter wavelengths," Journal of Applied Physics, vol. 106, no. 10, 103909, 2009.
- <u>Maestrini, A.</u>, <u>B. Thomas</u>, <u>H. Wang</u>, <u>C. Jung</u>, <u>J. Treuttel</u>, Y. Jin, G. Chattopadhyay, I. Mehdi, and <u>G. Beaudin</u>. Schottky diode-based terahertz frequency multipliers and mixers. Comptes Rendus Physique, 11:480–495, Aug. 2010.
- <u>Prigent, C.</u>, F. Papa, F. Aires, <u>C. Jimenez</u>, W. B. Rossow, and E. Matthews (2012), Changes in land surface water dynamics since the 1990s and relation to population pressure, *Geophys. Res. Lett.*, 39, L08403, doi:10.1029/2012GL051276.

- Jiménez, C., C. Prigent, and F. Aires (2009), Toward an estimation of global land surface heat fluxes from multisatellite observations, *J. Geophys. Res.*, 114, D06305, doi:10.1029/2008JD011392.
- Le Gall, A., Hayes, A. G., Ewing, R., Janssen, M. A.; Radebaugh, J.; Savage, C.; Encrenaz, P.; Cassini RADAR Team, Latitudinal and altitudinal controls of Titan's dune field morphometry , Icarus, 217, 231-242, 2012.

Indiquer **au maximum 5 documents majeurs** (autres que publications) produits par l'entité (par exemple : rapport d'expertise, logiciel, corpus, protocole, brevet en licence d'exploitation, etc.)

1. Patent on the use of Josephson junction array with high Tc superconducting materials as sub-millimeter source jointly filed in 2010 with the High Tc Superconductors and Signal processing group of Thales-CNRS (UMR 137) (reference: Boussaha, F.et al., Fundamental and harmonic submillimeter-wave emission from parallel Josephson junction arrays. Journal of Applied Physics, 105(7):073902, Apr. 2009.)
2. Software TELSEM to estimate land surface microwave emissivities, implemented in the European radiative transfer community model.
3. Transfer of a licence of know-how between C. Prigent and F. Aires from CNRS and a start-up Estellus
4. Distribution of geophysical datasets (inundations, emissivities, roughness length ...)
5. The Parameter description language (IVOA standard working draft) http://www.ivoa.net/Documents/PDL/20120516/index.html C.-M. Zwölf

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Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques** de l'entité (par exemple : invitations à donner des conférences, organisation de colloques nationaux ou internationaux, réseaux collaboratifs, cofinancements, prix et distinctions, etc.)

1. Creation of the GdR 'Microwave radiometry for the Earth atmosphere' (C. Prigent)
2. Two members of Pôle 4 received a price of the Académie des Sciences (Grand Prix Emilia Valori, 2010 for Catherine Prigent and Prix Arago, 2009 for A. Maestrini)
3. Organization of a major scientific and technical meeting in Paris in 2009 for the future russian THz space observatory "Millimetron", with about 80 attendees (the technical group)
4. Member of the GEWEX international GDAP panel and leader of the GEWEX LandFlux activity (C. Jimenez)
5. Co-I of the NASA Global Precipitation Monitoring group (C. Prigent)

Indiquer **au maximum 5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel (par exemple : contrat industriel, collaboration à une exposition majeure, émission audiovisuelle, partenariats avec des institutions culturelles, etc.)**

1. Members of LERMA actively participated to the deployment of a 2.3m and 3M radio-telescope working at a wavelength of 21cm for higher education. They worked on the assembly, hardware tests and calibration of the telescope and its receiver.
2. Member of the scientific committee of the Expo permanente du Musée des Sciences de La Vilette ('Objectifs Terre') .
3. Participation in several ESA and EUMETSAT contract related to atmospheric studies using satellite ibservations (for instance, contrat ESA No. 20927/07/NL/JA, 2010, « Study of a sub-millimetre wave airborne demonstrator for observations of precipitation and ice clouds »)

Indiquer **les principales contributions de l'entité à des actions de formation** (par exemple : conception et coordination de modules de formation en master et en doctorat, accueil et suivi des doctorants, conception d'outils à vocation pédagogique, action de formation continue, etc.)

1. 4 PhD. thesis have been defended in the technical group. 6 started (two in the technical group and 4 in the remote sensing group.
2. LERMA participates to the creation of a master degree in "Space and Application" at the Université des Sciences et Technologies d'Hanoi (USTH), Vietnam. Pierre Encrenaz is one of the leader of this initiative. Two other members of Pôle 4 lead two different Teaching Units (UE in French) and will give a total of 30h (A. Maestrini) +20h (C. Prigent) of courses and practice classes, starting in January 2013.
3. LERMA technical group signed a contract with UPMC to design, fabricate and maintain several electro-mechanical devices for practice classes for students in electrical-engineering (Licence and Master levels)

Le **directeur d'unité** peut indiquer ici brièvement **3 points précis** sur lesquels il souhaite obtenir l'expertise du comité.

Part 2. Results and self-evaluation 2007-2012

1. Introduction

The *Laboratoire d'Études du Rayonnement et de la Matière en Astrophysique,* created in 2002 from the earlier *Laboratoires de Radioastronomie Millimétrique* and *Atomes et Molécules en Astrophysique* has founded Molecular Astrophysics in France and played a key role in the creation of IRAM in the late 70's. Its dedication to millimetre wave Astronomy developed into the sub-millimetre wavelength range with major contributions to the definition of the FIRST (Herschel Space Observatory) project in the 80's, and later on to the defence of the ALMA project. In a period of gloom, these giant undertakings at world scale have reached a very enthusiastic point today, where IRAM is again more than doubling the capacity of its large interferometer with the NOEMA extension project, where the Herschel Observatory is completing an impressive program of discoveries from Lagrange point L2 together with its companion the Planck Surveyor, while ALMA starts operations with an already astounding configuration. Because LERMA provided some of the key contributors to these major international projects, and a few of their key components, while investing much of its members' energy into ambitious observing programs using their facilities, it is no overstatement to write that our laboratory has entered a new golden age of molecular astrophysics.

Molecules, along with single atoms and dust grains, these tiny solid particles, which are inescapably linked to molecules in space, play key roles in the dynamical evolution of their environments. Through their cooling and absorption lines they also provide powerful diagnostics of their embedding environments, provided *(i)* one can measure them accurately and extensively, and *(ii)* adequate tools are available to invert the radiative transfer equations. Because these environments turn out to be intermixed components with complex sub-structures, their modelling is a formidable physical and mathematical problem, requesting highly advanced tools in order to deal with it. The High Performance Computing era that we have entered provides adequate instruments for exploiting such tools. This domain has become increasingly active within LERMA in the last decade. The underlying necessity to understand the dynamical evolution of the systems observed, whether at galaxy cluster or at protoplanetary system scales, has triggered much advanced developments within LERMA in the dynamics of self-gravitating systems, hydro- and magnetohydrodynamics, as well as their more advanced radiative and reactive complements.

The wealth of capabilities opened up by these observational and theoretical developments encouraged investigations in many adjacent areas, whether in fundamental physics, at microscopic or macroscopic scales, in neighbouring fields of higher energy phenomena, like stellar and active galaxy nuclei physics, or in technological areas, like detector physics, or, more recently, in analogous fields, like atmospheric physics. This explains the apparently large diversity of topics addressed in our Laboratory, as well as the strong and complex interconnections between them, which will be exemplified all along this report.

With the evolution of these activities and the new perspectives opened in this new era of observing and computing facilities, it was felt necessary to redefine the internal structure of our Laboratory. The issue is made trickier by our multiple hosting institutions and geographical sites, which traverse our various activities in many ways. The resulting network of links and relations is complex : it simultaneously is an asset, and a difficulty. The purpose of the exercise undertaken a year and a half ago during our March 2011 *Journées du LERMA* in Sologne, is to provide an easily understandable structure, both internally and externally, which enables us to also develop a site specific policy, well connected to the hosting institutions scientific policy. We ended up with 4 major thematic poles, which are now shaping our Laboratory, and will back its organisation in the next contractual period 2014-2018.

Pole 1 is dedicated to **Galaxies and Cosmology**. It is coordinated by Françoise Combes, and is principally located in the Paris premises of the Observatory, avenue Denfert-Rochereau, with links under development with UPMC in Jussieu, where several Pole members are teaching, and in relation with the *Institut Lagrange de Paris* (ILP) and *Institut du Calcul et de la Simulation* (ICS) *LabEx projects of UPMC*, of which LERMA is respectively a member and a partner.

Pole 2 mostly addresses dissipative processes at the underlying scales, under the heading of **Dynamics of the Interstellar Medium (ISM) and Stellar Plasmas**, and coordination by Sylvie Cabrit. Its main component is located at ENS rue Lhomond, where it is part of the *International Centre for Fundamental Physics (ICFP)* LabEx project of the Physics Department. The participation of the ENS group to the project is mostly focused on non-linear Physics, namely the non-linear dynamics developing in diffuse gas complexes, which condition their structuration and evolution into stellar and planetary systems. The 2 other components, which address various aspects of star-formation and stellar environments and interiors are located at the Observatory; the higher energy component is led by Chantal Stehlé, who also drives the UPMC *Plasmas in Paris (Plas@Par)* Labex project. C. Stehlé's team will join our Jussieu site as soon as the renovated office space is made available, in late 2014.

Pole 3, **Molecules in the Universe**, is fundamentally a molecular physics component. It also deals with molecular physics applications. It is presently co-chaired by François Dulieu and Fabrice Dayou, and will soon grow considerably with the adjunction of the *Laboratoire de Physique Moléculaire pour l'Atmosphère et l'Astrophysique* (LPMAA), at the beginning of the next contractual term, in 2014. The joint Pole 3 project is lead by Jean-Hugues Fillion, and will be mainly centred in Jussieu (UPMC), with components at Cergy University and at the Observatory. This Pole is a member of the Multiscale Interactions in Chemistry (MIChem) LabEx project lead by UPMC.

Pole 4, **Instrumentation and Remote Sensing**, is intended to bring all the LERMA actors in instrumentation research and development activities, both hardware and software, together with an application group specialized in Earth and planet observation from satellites, which has developed a tight connection with both instrumentation research in the mm and sub-mm wavelength range, and research on massive data processing and inversion methods. The constituting groups of this Pole, led by C. Prigent, are located at the Observatory. The THz instrumentation group is a membre of the *Exploration Spatiale de Environnements Planétaires* (ESEP) LabEx project led by OP. The major involvements of this Pole are in the Engineering of components, detector chains and signal processing, on one-hand, and Physics of the Earth envelopes, on the other hand. Its activities are diversely coupled to the activities of the 3 other Poles, complementing the range of expertises needed for ambitious projects in Molecular Astrophysics.

While the scientific structure has undergone a slow evolution from the 9 thematic groups in place at the beginning of the ongoing contract to this broader structure in poles, also preparing for the future enlargement of our laboratory, all support functions made available to us by our hosting institutions and CNRS as well, for the largest part, have been gathered inside a common Support Pole, headed by the director. This Pole has 2 main components, the administration team, jointly lead by the administrative manager, Valérie Audon, and the financial manager, Laurent Girot, and the technical team, lead by the technical director, Jean-Michel Krieg, itself composed of the computing team, lead by our senior computing engineer, Michel Caillat, the THz instrumentation support team, led by Yan Delorme, and the experiment support team, with its main component located in Cergy and led by Saoud Baouche.

The next 4 chapters (2-5) report on the research activities of each thematic pole separately, and in places underline the inter-pole interactions.

Chapter 6 jointly reports on all other aspects of the Lab activities: productions other than scientific publications, interactions with the environment, training by research, and laboratory resources and organisation. The Support Pole is much involved into these various aspects, and its staff more and more works on a mutuality principle. On the other hand the 4 thematic poles intermingle in the corresponding activities. This was the justification for a shared presentation within a common chapter.

The report ends with a wrap up of what we feel are the principle achievements of the reporting period, how the recommendations of the 2009 visiting committee were implemented, and how the lab specificities translate today into strengths and weaknesses.

2. Pole 1: Galaxies and Cosmology

Permanent staff: *C. Barbachoux, F. Boone, F. Combes, F. Debbasch (1/2), J.-M. Lamarre, A.-L. Melchior, P. Salomé, N. Sanchez, B. Sémelin, M. Signore, D. Valls-Gabaud, F. Viallefond (50%), M. Wiedner (50%)*

Non permanent: *S. Baek, M. Bahi, M. Bois, V. Casasola, I. Chilingarian, K. Dasyra, R. Grouchy, A. Halle, K. Hasegawa, P. Jachym, V. Lattanzi, B. L'Huillier, C. Mastropietro, J. Novak, Y. Revaz, G. Roudier, M. Stringer, O. Tiret, J. Uson, J. Vega Ferrero, P. Vonlanthen, I. Zolotukhin (1/2)*

2.1. Global Presentation

The group "Galaxies and Cosmology" has a branch working on the cosmic microwave background (CMB), and is very active in the Planck mission, another branch working on the standard model of the Universe, the inflation theory compared to observations. Another group studies through numerical simulations the epoch of reionization of the Universe (EoR), and in particular the preparation of SKA (Embrace prototype, key projects on pathfinders, etc..). Pioneering work has been done on cooling flows and the presence of cold molecular gas near the brightest cluster galaxies. The nature of dark matter, and investigation on alternative theories of modified gravity have been probed through galaxy dynamics and observations. A thorough study of AGN fueling and feedback has been carried out, addressing black hole growth history and galaxy evolution.

Another team works both on the observation of local galaxies, the physics of galaxies in clusters, galaxies at high redshift, and on the dynamical theories for the evolution and formation of galaxies, on large-scale star formation and the cosmic star formation history.

Multi-wavelengths observations are used extensively, in the millimeter and centimeter with the instruments of IRAM, the VLA and the beginning of ALMA in 2011-12, Spitzer and Herschel, the optical satellites with infrared and near-infrared, with the CFHT and ESO. Team members are leaders in key programs, such as the NUGA consortium on the IRAM interferometer, the consortium PrimGal on the VLT, or major program at IRAM on distant galaxies, and the observation of galaxies at large z with APEX, Plateau de Bure and ALMA. One speciality of the group is also heavy numerical simulations, and the team competed at a very high level in the HORIZON project program of formation of galaxies in a cosmological context. Among the major results obtained in the last 5 years, are the following:

2.2. Cosmology and Early Universe

2.2.1. CMB observations with Planck-HFI

Lamarre

The Planck satellite was launched in 2009, and encountered a large success. One of the member of Pole 1 is the HFI Instrument Scientist. In January 2012, the temperature of the High Frequency Instrument (HFI) has started to warm-up above the nominal 103 mK needed for their operation. The Low Frequency Instrument will continue its observations for at least 9 months, with a slightly different scanning mode.

The Helium 3 and Helium 4 reserve used by the dilution cooler provided 31 months of cooling instead of the 14 months required. Five complete sky surveys were taken with a sensitivity better than the most optimistic expectations. The activities of the team also include scientific interpretation of the results inside several working groups of Planck.

2.2.2. CMB, Inflation, Theory versus Observations

Sanchez, de Vega

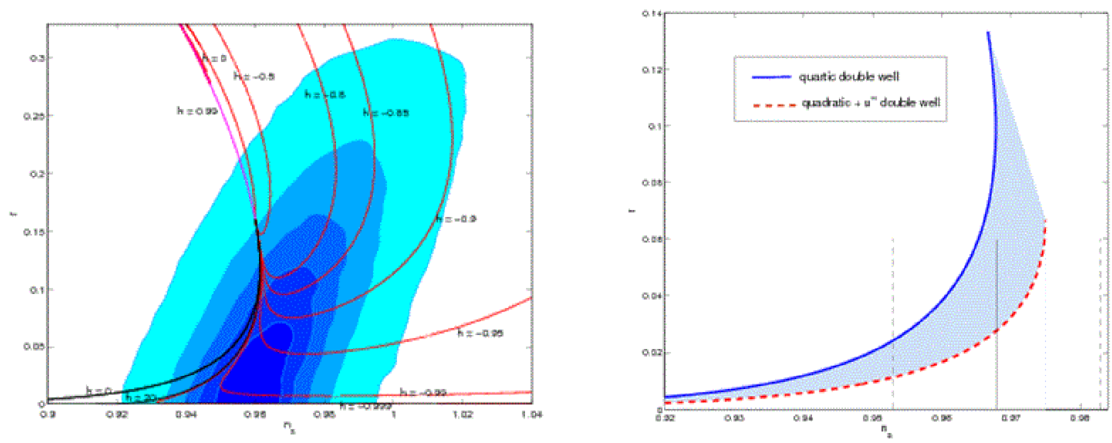


Fig. 2.2.1: Trinomial inflation. Plot of the ratio of r between tensor and scalar fluctuations versus the spectral index of density fluctuations, for fixed values of the asymmetry parameter h of the potential. Right: banana shape of the best model, in the same diagram.

In the framework of the Standard model of the Universe the team develops highly predictive theoretical approaches that can be compared with real astrophysical/cosmological data. The main developments by the team are the formulation of the effective theory of inflation, in the Ginsburg-Landau spirit of phase transitions, making explicit the relevant physical scales in the problem and contrasting it to the CMB+LSS data. The main results are an universal form for the inflationary potential in the slow-roll, that the inflationary couplings turn to be naturally very small, and that the scale invariance deviations of the CMB observables are determined. The energy scale of inflation M is completely determined by the amplitude of the CMB detected scalar adiabatic fluctuations and turns out to be $M \sim 0.7\ 10^{16}$ GeV at the GUT energy scale. The preferred inflaton potential is a double well (new inflation). The analysis seems to favor the existence of primordial gravitational waves. This is not yet determined by Planck and motivates present and future searches and next dedicated CMB polarization experiments (cf Destri et al 2008, 2010, 2011).

2.2.3. Reionization and radiation transfer in the EoR

Semelin, Baek, Combes, Revaz, Vonlanthen

The team is performing competitive simulations of the period of reionization of the universe, corresponding to the formation of the first stars, which puts an end to the dark ages. In the frame of the ANR HORIZON and LIDAU, cosmological simulations of a portion of universe of 50 to 100 Mpc large, taking into account the formation of stars and the subsequent ionization of the surrounding environment, were performed. A Monte - Carlo code (LICORICE), coupled with an SPH code has been developed to treat the radiative transfer in 3D. Radiative transfer has been probed, both for the continuum and its coupling to the dynamics, and for the Lyman-alpha transfer (Baek et al. 2009, Iliev et al., 2008, Sémelin, Combes, Baek 2007). The radiative transfer code is parallelized by OpenMP. The degree of ionization is followed as a function of redshift, between z = 11 to 6.

On the other hand, predictions were made of the temperature and the emission of the neutral hydrogen line at 21cm rest wavelengths, to calculate the brightness maps of this line,

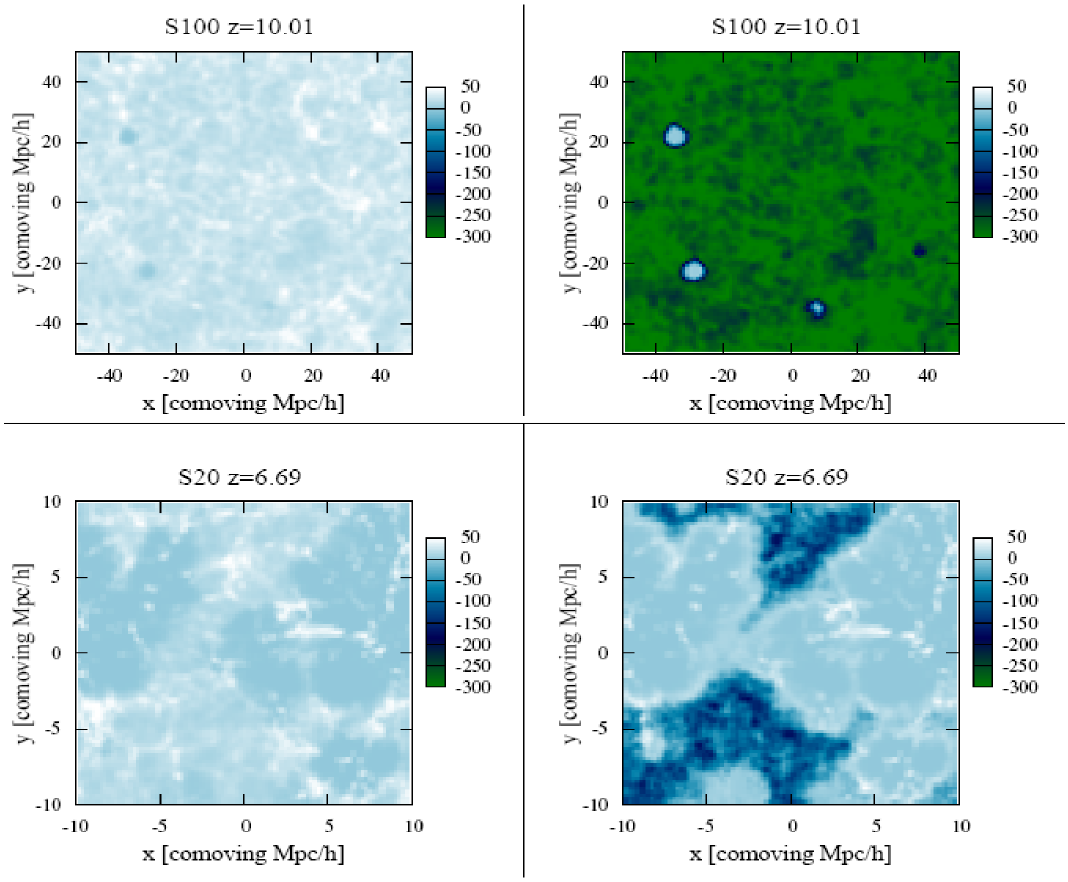


Fig. 2.2.2: Simulations of the HI-21cm emission during the Reionization Epoch (EoR). The colour wedge on the right of each image indicates the brightness temperature of HI in mK.Two simulation boxes were studied: 20/h Mpc = S20 (bottom), and 100/h Mpc = S100 (top). The degree of reionization is 0.5 for S20 (or z=6.69) and 1 for S100 (or z=10.01). Left : results of the approximation Tspin >>Tcmb, and right Tspin = Tgas (Baek, di Matteo, Semelin, Combes, & Revaz 2009).

redshifted to meter wavelengths which will be observed by LOFAR and SKA. In particular were highlighted specific effects in the excitation of the HI gas by the Lyman-alpha photons. The Wouthuysen-Field effect allows these photons to decouple the gas from the cosmic background radiation, in order to align the spin temperature to the kinetic temperature of the gas. The HI-21 cm signal can then appear either in absorption or emission. Because of the multiple scatterings of the Lyman-alpha photons, these stay concentrated around the sources, instead of traveling large distances before entering in resonance with the intergalactic gas. Therefore the predicted signals have a significantly larger contrast with the background and should be more easily detectable with the upcoming generation of radio telescopes. (cf Figure 1). Also, Vonlanthen et al (2011) predict distinctive rings in the 21cm signal due to a series of discontinuities in the Lyman flux. These works are very useful in the frame of the European SKA Design Study.

2.3. Clusters of Galaxies

2.3.1. Observations and modelling of the cooling flows

Salome, Combes, Revaz

The hot gas in clusters of galaxies, emitting in X-rays, is the component that dominates the baryonic mass, especially in rich clusters where it represents ten times the mass of the galaxies. The cooling time of this hot gas is greater than the age of the universe, except at the center of the cluster, where the gas density is the highest. Cooling flows are then predicted at the center of some rich clusters, and in general concentrated on the brightest cluster galaxy (BCG), which is frequently the central cD galaxy. The X-satellites Chandra and XMM have highlighted this phenomenon, and also showed that the quantities of gas in cooling were smaller than expected, because of a negative reaction or feedback phenomenon: the gas falling towards the center feeds an active nucleus in the cD Galaxy, which then emits radio jets, heating up the medium and stopping or regulating the cooling.

Our group has performed the first detections and mapping of molecular gas in BCGs (Salomé et al., 2003, 2004). When resolved, the cold gas lies in very extended filaments (50 kpc), see for instance Salomé et al., (2006, 2011). For the first time, the association of cold molecular gas with the cooling flow, and the ionized gas seen in Halpha, was demonstrated in one of the closest cluster of Perseus (Salome & Combes 2004, Salomé et al. 2006, 2008, 2011). The cold CO gas is kept at large distance from the centre, in general on the edge of the cavities formed in the hot gas by radio jets. Numerical simulations of the process of cooling (cf Figure 2), regulated by the central AGN radio jets, have been proposed. The phenomenon under consideration here is the rise of bubbles of hot plasma, through buoyancy, and the compression of the gas at the edges of the formed cavities, which helps the gas to form cooling flows into thin filaments towards the center of the cluster. These hydrodynamic simulations with high spatial resolution, succeed to explain the observations of CO and Halpha (Revaz et al. 2008). They show a new effect of the AGN feedback, not only negative but positive this time.

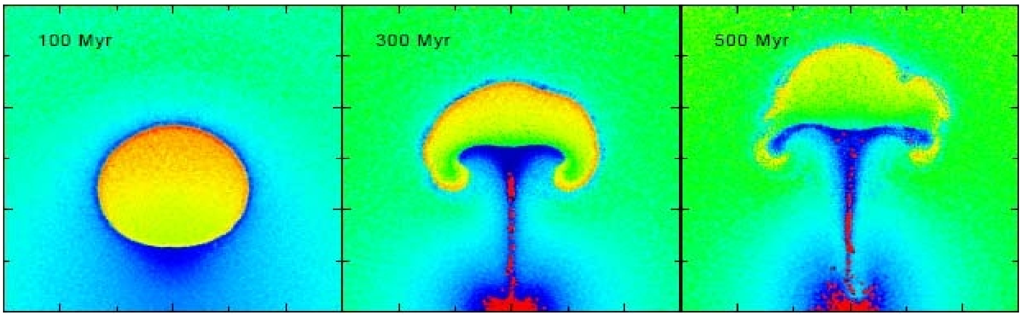


Fig. 2.3.1: Evolution of a plasma bubble in the hot intra-cluster medium. The red points indicate the presence of cold gas (<104 K) formed by compression, in the wake of the hot bubble. Each box corresponds to 150 kpc (Revaz et al. 2008

Filaments around BCGs have a peculiar optical spectrum. They are also very bright H2 emitters with high H2/PAH ratios. The source of excitation cannot by the UV-radiation from young stars. Two scenarios are mostly being studied: (i) kinetic energy dissipation by shocks, like in MOHEG (Molecular Gas Emitting Galaxies) radio-galaxies, see Nesvadba et al. (2011) and (ii) accelerated particles (cosmic rays, hot X-rays gas) ionization and heating. Recent work observed molecular gas around AGN in radio-galaxies where the first scenario seems to stand. The team also observed the Crab Nebula Supernova remnant that is a nearby place where highly energetic particles could heat the cold gas (second scenario). The H2 molecule has recently been detected in the Crab but not the low-J CO emission lines (Loh et al. 2011, 2012; Salomé et al. 2013).

2.3.2. Galactic dynamics in clusters

Jachym, Combes

In clusters of galaxies, evolution phenomena are accelerated by the ram pressure of the intra-cluster hot gas, by tidal interactions between galaxies, and by force gradients of the cluster itself. The physics of galaxies significantly depends on the environment, and namely of the mean density of galaxies. Hydrodynamic simulations using the SPH code, were made as part of the thesis of P. Jachym (in tutorship with Jan Palous, Czech Republic), to simulate the effects of the ram pressure and compare them with the simple predictions of the overall formula of Gunn & Gott. Conversely, studies of galaxies completely isolated, helped to provide a reference to the dynamics of interacting galaxies (Jachym et al. 2007, 2009).

2.4. Dynamics of Galaxies, Dark Matter

2.4.1. Nature of dark matter, Dynamics of galaxies in modified gravity

Tiret, Combes, Sanchez, de Vega

The dynamics of galaxies has been studied under modified gravity frame and MOND in particular, during the PhD thesis of Olivier Tiret. A multi-grid code was developed to treat this non-conventional and non-linear dynamics. Numerical simulations have shown that the formation of bars in this model was easier than in Newtonian dynamics with dark matter. The frequency of bars corresponds then better to observations (Tiret & Combes 2007, 2008). However the dynamical friction is much lower in this new model, and the merger time-scale between galaxies is much longer. Simulations of interactions of galaxies show that it is however possible to form tidal tails and even some tidal dwarfs, which reproduce satisfactorily the observations (cf Figure 3). Dynamics of satellites, and the phenomenon of 'External Field Effect' in MOND, have also been studied in detail and resulted in several publications (Tiret et al 2007). It was shown that the MOND model was consistent with the hypothesis of dark baryons in the form of cold molecular gas, with a H2/HI gas mass ratio of 3 (Tiret & Combes 2009). On the other hand, the motion of the satellites at large scale in the SDSS can be reproduced by MOND (e.g. Combes & Tiret 2009).

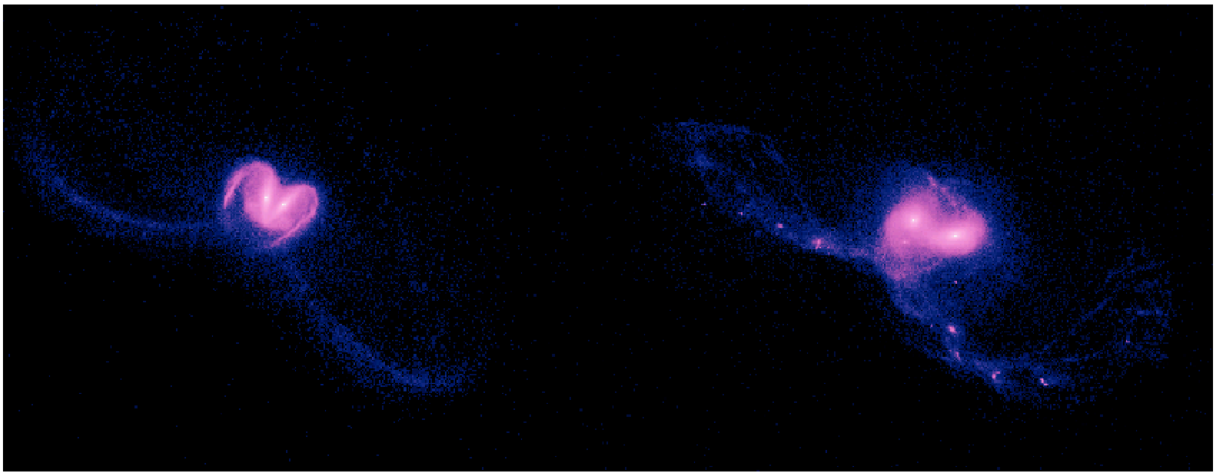


Fig. 2.4.1: Simulations of the interacting galaxies "The Antennae" with CDM-Newton at left, and MOND at right. Morphological details have not been fitted, but the main characteristics of tidal tails are reproduced (cf Tiret & Combes 2008).

Another alternative to the standard model of Cold Dark Matter (CDM) has been developed by members of the group: the hypothesis of Warm Dark Matter (WDM, with masses at the keV scales). The mass of the DM particle and the decoupling temperature Td are obtained by matching the theoretically computed galaxy surface density to its observed value. The decreasing of the phase-space density since the onset of the non-linear regime till today and the type of the galaxy density profile (cored or cusped) are obtained in this way. The dark matter particle mass turns to be between 1 and 10 keV, the decoupling temperature Td turns to be around 100 GeV. The obtained values of the halo radius, the halo central density and the halo velocity reproduce the observations within one order of magnitude while wimps present discrepancies with the observations of up to eleven orders of magnitude. These results are independent of the particle model and vary very little with the statistics of the dark matter particle (de Vega et al 2012).

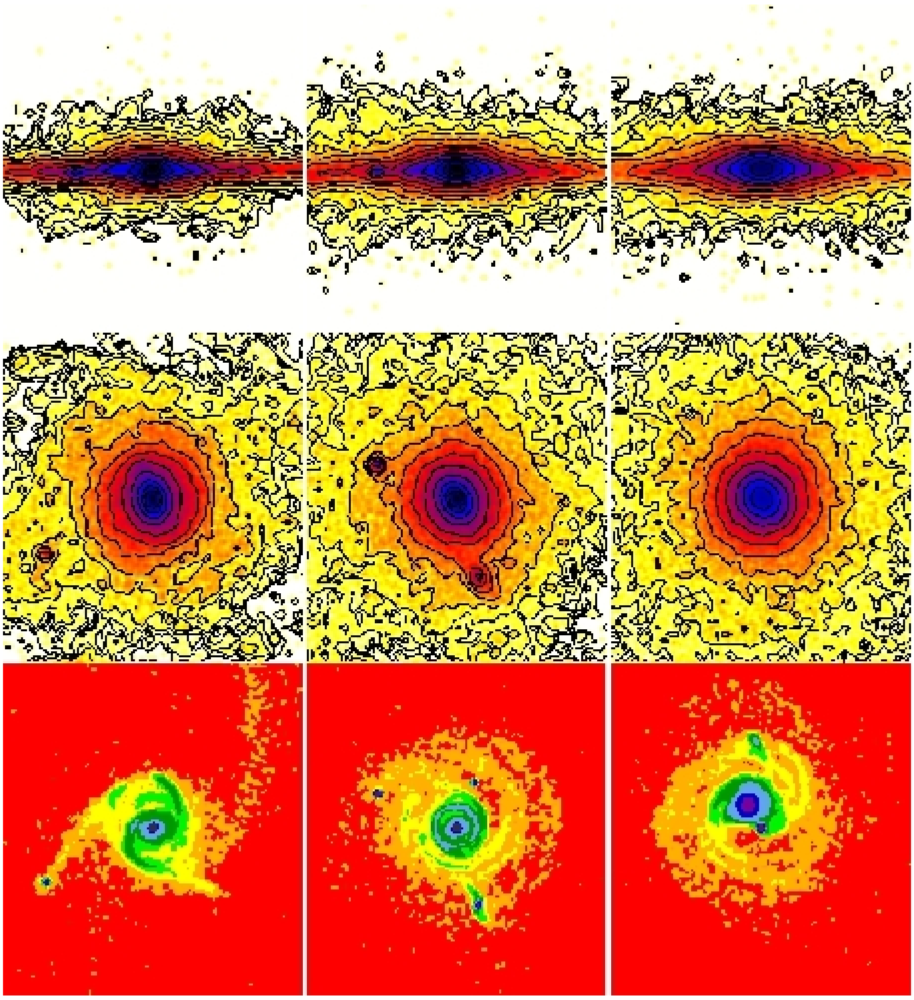


Fig. 2.4.2: 200Myr 1Gyr 1.5 Gyr *after the merger. Interaction in the direct sense, between two Sb spiral galaxies.Top: stellar component, edge-on, Middle: stellar component, face-on; Bottom: gas component with new stars formed, face-on. (Di Matteo et al 2007, 2008)*

2.4.2. Construction of a library of galaxy mergers: project GALMER Database of VO-Paris

Chilingarian, Combes, Di Matteo, Melchior, Semelin

By multiple numerical N-Body simulations (cf Figure 4), taking into account the self-gravity of stars, gas and dark matter, and modeling a wide range of physical phenomena (star formation, feedback from supernovae, stellar mass loss, metallicity), a wide variety of mergers of galaxies was computed. Fundamental results on the efficiency of galaxy interactions in triggering star formation were established, such as the fact that starbursts are more intense for retrograde and non-direct encounters (Di Matteo et al. 2007, 2008). The construction of counter-rotating systems has also been studied (Di Matteo et al. 2009), as well as the dilution of metals in starburst galaxies (Montuori et al 2010), or radial migration in spiral galaxies (Minchev and al 2011, 2012). The GALMER database has been implemented in the theoretical Virtual Observatory on the site of the Observatoire de Paris, and made available to observers (Chilingarian et al. 2010). A synthesis of stellar populations (derived from the PEGASE code) allows to build spectra in each pixel of the formed images. The models can then be built to predict the observations with Herschel or ALMA. This data base of simulations has no equivalent in the literature. Website: http://galmer.obspm.fr

2.5. AGN, Star Formation and Feedback in Nearby and High Redshift Galaxies

2.5.1. Molecular gas in the center of the Andromeda Galaxy (M 31)

Melchior, Combes

Until the observations of the team, no molecular gas was found in the center of our near neighbour Andromeda (M31), and in particular in the IRAM key survey, which was done during several years. The team has highlighted the presence of molecular gas in the centre of M31, which is crucial for the fueling of the central massive black hole, discovered with a lopsided asymmetry. Specific regions were found with double spectra with velocity components separated by more than 260 km/s, for a spatial resolution of 40pc (Melchior & Combes 2011). Several scenarios were considered for this surprising phenomenon, which can provide information on the formation of the Galaxy. After having eliminated the hypothesis of gas flows due to a possible bar, it was discovered that the involved regions were the meeting of two streams of material: one from the primary disk in the centre of M31 (already inclined), and the other from a ring of dust seen almost face-on and clearly delimited by the infrared emission of its PAH molecules detected by Spitzer. The scenario is based on the model of interaction with M32 previously proposed by our team (Block et al 2006).

2.5.2. Panoramic survey of M31 with Megacam

Valls-Gabaud

A panoramic survey of the Andromeda galaxy (M31) was done in the optical by the wide-field camera MEGACAM at CFH (cf McConnachie et al 2009). Loops and streams of stars are detected far from the visible galaxy; those coherent structure are almost certainly remnants of dwarf galaxies destroyed by the tidal field of M31. An improved census of their surviving counterparts implies that three-quarters of M31's satellites brighter than Mv = -6 await discovery. The brightest companion, Triangulum (M33), is surrounded by a stellar structure that provides persuasive evidence for a recent encounter with M31. This panorama of galaxy structure directly confirms the basic tenets of the hierarchical galaxy formation model and reveals the shared history of M31 and M33 in the unceasing build-up of galaxies.

An improved distance to M31, with high precision, has been obtained with Cepheids by Riess et al 2012. The Cepheids, mostly detected from the Canada-France-Hawaii Telescope POMME Survey, were observed in the near-infrared by the Panchromatic Hubble Andromeda Treasury Program using the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST). The combination of HST's resolution and the use of near-infrared measurements provide a dramatic reduction in the dispersion of the period-luminosity relation over the present optical, ground-based data. The M31 distance can then be determined within 1%. The result is also in good agreement with independent distance determinations from two detached eclipsing binaries allowing for an independent calibration of the Cepheid luminosities and a determination of the Hubble constant.

2.5.3. Observations with the Herschel satellite

Combes, Salome, Boone

The team participates in three key-programs on the Herschel satellite, which since 2009 brought a great harvest of results. The nearby galaxy M33 allows to better understand the physics of dust in a galaxy poor in metals, the rate of star formation, the small scale of the interstellar structure (Kramer et al 2010, Boquien et al. 2010, 2011, Verley et al. 2010, Combes et al. 2012). In particular, the analysis of the power-spectrum of the emission by Herschel over the whole galaxy allowed to discover the threshold scale at which the 2D dynamics of the plane leaves place to the 3D turbulent behaviour.

The program on cooling flows allowed to highlight gas cooling through the lines of CII, OI, and compare them to the CO component. The brightest cluster galaxies have very little dust (Edge et al 2010, 2010, Mittal and al 2011). The derived line diagnostics are like typical star forming galaxies. Large scale mapping of Perseus and Centaurus were even possible and showed different line excitation conditions for those two objects (Mittal et al. 2011, 2012). In the case of Centaurus, in order to explain the atomic and optical spectra, another source of heating than the one provided by PDR and HII regions is required (ie cosmic rays, shocks or reconnection diffusion). Important masses of dust have been detected with Spectral Energy Distribution and total IR luminosities typical of local star forming galaxies, with SFR ~1-50 Msun/yr (Edge et al. 2010a, Tremblay et al. 2012a).

Finally, the team is observing galaxy clusters as gravitational telescopes, which amplify background galaxies, and allow the study of 'normal' galaxies at large redshift, impossible to observe in an other way (Egami et al. 2010, Zemcov et al 2010, Rex et al. 2010, Boone and al 2011). The group has in particular recently discovered high-z galaxies, with spectral energy distribution highly shifted to the red, invisible in the optical, and were able to determine their redshift only with CO lines (Combes et al 2012). This work will actively continue with ALMA.

2.5.4. Molecular component of galaxies: NUGA, Sauron, High-redshift galaxy evolution

Casasola, Combes, Salomé, Lattanzi

New observational results were obtained with the IRAM telescopes: observations of molecular gas in elliptical galaxies of the SAURON sample (Combes et al 2007), gas supply to the low luminosity AGN (black hole fueling of the NUGA project), mapping of the center of M81 and decomposition in giant molecular clouds (GMC) in order to study their virial equilibrium and the CO-to-H2 conversion factor, observation of starburst galaxies at intermediate redshift, and determination of the cosmic evolution of the gas fraction, molecular gas in absorption in front of quasars, or in galaxies host of supernovae. In particular, several publications have been made on individual galaxies of the NUGA project, in relation to the atomic gas observed at the VLA, and HST images (Hunt et al. 2008, Garcia-Burillo et al. 2009, Combes et al. 2009, Casasola et al. 2008, 2010, 2011, van der Laan et al. 2011).

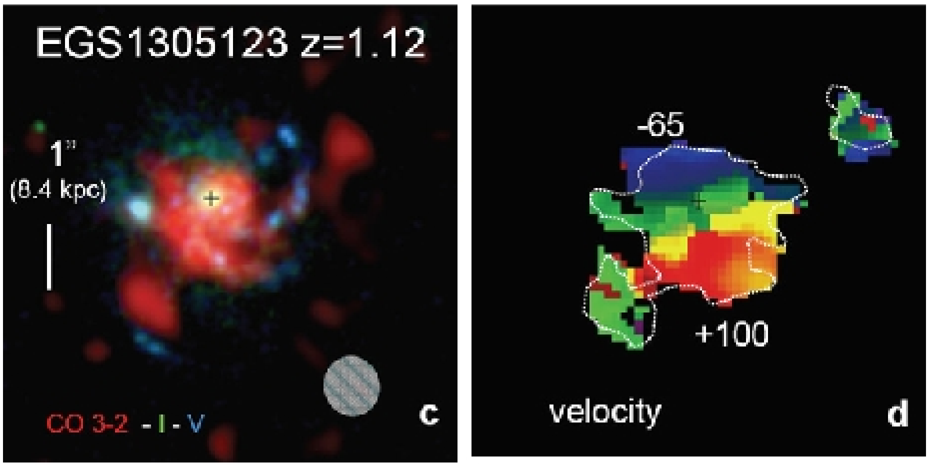


Fig. 2.5.1: One of the objects of the sample in the Large Program at IRAM PdB at z=1.2Left: Superposition of the CO map (in red, obtained with the interferometer of IRAM), with the images in band I (in green) and band V (in blue) obtained with the Hubble Space telescope. The CO(3-2) line, redshifted to 2mm, was observed with an angular resolution of 0.6" x0.7" (beam indicated by the grey hatched ellipse). Right: Velocity field of the galaxy: blue indicates negative velocity (approaching side), and red positive velocity (recessing side). From Tacconi et al 2010.

The brightest starburst galaxies (ULIRGs) were selected in the redshift range 0.2 to 1, particularly poor in observations of the CO molecule for technical reasons. This epoch is extremely important, because it is in this second half of the age of the universe that the cosmic star formation drops by an order of magnitude, and the star formation efficiency declines, without their causes being identified. Through a large survey of 70 galaxies, both with the 30m and PdB, it has been established that the gas fraction of galaxies evolve very quickly in this intermediate redshift (Combes et al. 2011, 2012), The decrease in star formation and efficiency may be related to the loss of gas, together with the decrease of galaxy interactions, as is observed in more local starbursts.

Members of the team actively participate (co-PI) to a Large Program at IRAM (30 m and PdB) in order to better study “normal” massive galaxies forming stars in the main sequence (and non-ULIRGs), in intervals of redshift around 1 and 2 in HST-AEGIS (+ CANDELS) fields. The first results showed that the fraction of gas was on average 34% and 44% at z = 1.2 and 2.3 respectively, which explains the very large star formation rate (see Figure 5, from the corresponding Nature paper).

The current and future mm-submm facilities give a direct access to the molecular content of the first galaxies in the Universe. Those objects are very dusty and have very high star formation rates (100-1000 Msun/yr). Recently the very famous object BR1202-07 was resolved and appears to be a merger of at least 2 objects at a redshift of 4.7 (Salomé et al. 2012). This object is very likely composed of even more sources. BR1202-07 is thus probably one of the first cluster/protocluster of galaxies in the Universe.

2.6. Summary

The teams of pole 1 have achieved very competitive projects in the past years, about the CMB, the inflation, the epoch of reionization, the cooling flows, clusters, the dark matter, high-z galaxies, galaxy interactions and mergers, and their consequence on galaxy formation and evolution, through the hierarchical scenario of through inter-galactic accretion. Breakthroughs were done in the AGN fueling and AGN feedback observations and theory.

The teams have exploited the recent instruments launched in 2009, Herschel and Planck, and also actively the existing competing instruments at ESO, CFH, and also IRAM (which will be completed by NOEMA in the future). ALMA data are now arriving in the various groups, and one group is preparing for the SKA.

Always larger and more impressive simulations are now going on with the supercomputers at GENCI (Curie at CEA, IDRIS, CINES). Locally, the PSL mesocenter and the MOMENTUM cluster are used for the exploitation and post-processing of the simulations.

3. Pole 2: Dynamics of the ISM and stellar plasmas

Pole 2 members between January 2007 and June 2012:

21 permanent researchers: *10 CNRS* (E. Falgarone, M. Gerin, T. Le Bertre, P. Lesaffre, J.-F. Lestrade, L. Pagani, M. Pérault, L. Petitdemange, C. Stehlé, C. Zeippen), 6 *university teaching staff* (S. Balbus, A. Ciardi, F. Debbasch (50%), F. Levrier, J.-F. Panis, L. Tchang-Brillet (50%)), *5 CNAP "astronomes"* (S. Cabrit, F. Delahaye, P. Hennebelle, M. Heydari-Malayeri, J. Pety)

3 emeriti: *M.* Guélin, J. Lequeux, S. Sahal-Brechot

4 engineers & technicians: *C.* Blaess (50%), N. Champion (50%), B. Ooghe (CDD), B. Delforge (CDD)

3 external associates: G. Pineau des Forêts, IAS; E. Dormy, IPGP; M. Schrinner, ENS

27 (co)supervised Ph.D. students: *17 at LERMA* (U. Chaulagain, L. de Sa, B. Godard, V. Guzman, T. Islam, E. Jacquet, M. Joos, Y. Libert, G. Momferratos, E. Morey, D. Panoglou, L. Petitdemange, Reynaud, R. Selier, J. Štěpán, W. Yvart, G. Di Molfetta), *10 at other national or international institutes* (V. Agra-Amboage, H. Ben Chaouacha, B. Commerçon, O. Dionatos, A. Gusdorf, R. Hamdi, W.F. Mahmoudi, A. Marocchino, J. Masson, P. Pilleri).

9 Post-docs: *A.* Ciardi, B. Commerçon, M. De Luca, J. Goicoechea, A. Gusdorf, L. Ibgui, A. Latter, J. Steinacker, F.-O. Waffeu.

3.1. Overview and Scientific Objectives

Pole 2 gathers LERMA researchers located at ENS (ISM-MHD group), Obs-Paris (Circumstellar group), Obs-Meudon and UPMC-Ivry (Stellar Plasmas group), and IRAM-Grenoble, working on three closely related scientific objectives: (1) to understand the key mechanisms controling the ISM condensation path leading from turbulent diffuse gas to dense prestellar cores, stars and planetary systems, (2) to assess the dynamical, chemical and radiative feedback of accretion-ejection processes onto the global ISM cycle and the star formation rate, (3) to understand the structure and evolution of protoplanetary accretion discs and stellar interiors subject to complex turbulent and radiative transport processes. The following report has been structured into five sections, corresponding to the diverse research methods used by Pole 2 to address these questions, namely: (i) Observational characterization of the ISM cycle; (ii) MHD modelling of cloud condensation from diffuse clouds to stars and discs; (iii) Chemical modelling of diagnostics of ISM dynamics; (iv) Theory of transport processes in circum/stellar plasmas; (v) Laboratory plasma experiments.

3.2. Observational characterization of the ISM cycle

The millimeter (mm) and infrared (IR) ranges offer key tracers of the chemistry, dynamics, physical conditions and energy balance in the ISM, through molecular lines and the thermal radiation of dust grains. The period 2007-2012 has seen a huge progress in sensitivity, spectral coverage, and/or angular resolution in these wavelength ranges thanks to the *Spitzer* satellite in the mid-IR, the new receivers and extended IF bands and interferometer baselines at IRAM, and lately the *Herschel* and *Planck* satellites in the sub/mm range (launched in 2009). The LERMA participated in building and calibrating the HIFI heterodyne spectrometer on board *Herschel* and the HFI bolometers on board *Planck,* and our researchers are associated as PI or co-Is to several large projects on these satellites, which are obtaining fantastic results (on *Herschel:* PI of PRISMAS; co-Is of HEXOS, WADI, CHESS, WISH, HOP, DEBRIS; PCC, on *Planck*: PI of CO Survey, co-PI of Foreground Polarization, co-Is of Cold Cores and Dark Gas).

3.2.1. Diffuse ISM : Chemistry, turbulence, and UV irradiation

The PRISMAS key project, led by M. Gerin, is a survey with HIFI/*Herschel* of interstellar hydrides along lines of sight towards eight massive star forming regions in the Galactic Plane.

Because hydrides are the building blocks of most interstellar molecules, their detection has opened new avenues for studying the ISM. For instance, HF and CH have proven to be excellent tracers of the diffuse, partly molecular gas, that could be used in the future for high redshift systems. The molecular ions OH^+, H_2O^+, H_3O^+, H_2Cl^+, HCl^+, first detected (or confirmed) with *Herschel*, enable a thorough analysis of the main reaction pathways in oxygen and chlorine chemistry. OH^+ and $H2O^+$ are also good probes of the cosmic ray flux in diffuse gas ; the analysis of the Herschel dataconfirms the high rates recently obtained from H_3^+ infrared lines. The reactive ions CH^+ and SH^+ show broader absorption lines than CN and HCO^+, supporting an origin linked to intermittent turbulent dissipation as proposed by B. Godard, E. Falgarone et al. (see Section “Modelling chemical diagnostics”).

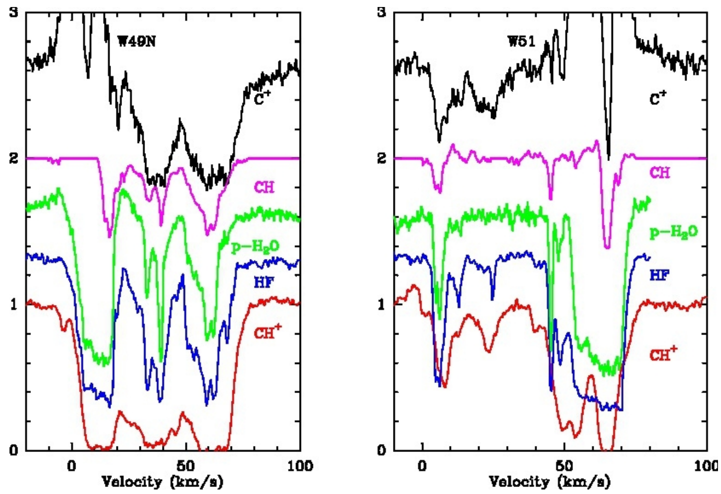


Fig. 3.2.1: HIFI/Herschel spectra of the ground-state transitions of C+ (1.9THz), CH (0.53THz), para-H2O (1.1 THz), HF (1.2 THz), and CH+ (0.83 THz) observed in absorption against W49N (left) and W51 (right) as part of the PRISMAS key program. Spectra are normalized by the continuum and shifted for clarity (Gerin et al. 2012).

In a complementary approach, E. Falgarone, J. Pety and P. Hily-Blant (IPAG) identified structures of high velocity shear in diffuse molecular gas, using statistics of large scale CO maps with very high sensitivity and spectral resolution obtained at IRAM (30m and PdBI). They are shaped in thin filaments coherent on scales of 0.03pc to 1pc, roughly parallel to the magnetic field, and with sharp edges tracing thin CO-rich layers. Those structures may be the first resolved manifestations of intermittent ISM chemistry. By mapping the CO emission of the diffuse gas, J. Pety & H. Liszt (NRAO) also identified regions of enhanced CO brightness per unit magnitude of extinction that cover about 20% of the surface, while the remaining 80% of the gas is under-luminous in CO. These large spatial fluctuations may be another manifestation of turbulent chemistry and, when averaged over the surface, explain the similar overall CO to H_2 luminosity ratio observed in diffuse and dense gas.

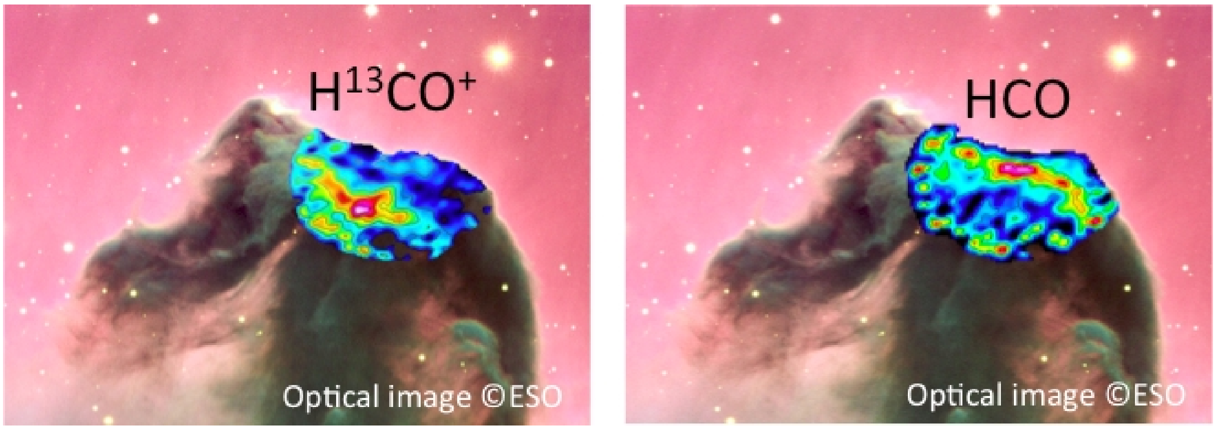


Fig. 3.2.2: Maps of the Horsehead nebula in H13CO+(1-0) (Left) and HCO(1-0) (Right) obtained with the IRAM PdBI. at an angular resolution of 5" (Goicoechea et al 2009, Gerin et al 2009). While H13CO+is concentrated in the cold dense core, the HCO radical is confined to the UV-illuminated edge.

Finally, in the frame of the ANR SCHISM (2009-2013) led by J. Pety, in collaboration with the LUTh-ISM group, J. Goicoechea (Madrid), and H. Liszt (NRAO), a new Ph. D. student V. Guzman is mapping the Horsehead nebula in various species at IRAM(PdBI,30m), to provide a benchmark for the photon-dominated region (PDR) model developed at LUTh. The study of H_2CO has shown that it can be formed purely by gas phase reactions in the dense core, but that formation on ice mantles is required in the PDR. A spectral survey of the 1mm, 2mm and 3mm bands was also performed, and allowed the first detection of C_3H^+ in the ISM, a key species in the gas-phase synthesis of carbon chains and rings, which had escaped detection so far due to its unknown spectroscopic frequencies.

3.2.2. Dense cores: Temperature, magnetic field, dust growth

Dense cores (the densest, coldest regions of molecular clouds) are the birthplace of stars. Their temperature structure is a key parameter, controlling both their stability (Jeans length) and the rates of chemical processes such as gas depletion on ice mantles and deuterium enrichment. L. Pagani, S. Cabrit, and co-workers used multiple lines of N_2H^+ and N_2D^+ observed at IRAM to constrain the gas temperature across the L183 prestellar core, and showed that it was reaching a lower value than believed so far (7K at the center, like dust). L. Pagani and E. Falgarone are now contributing to the “cold core” project, a combined *Planck* and *Herschel* study of cold dense cores identified in the *Planck* sky survey. The data confirm that the dust reaches a minimum of ~7K, and that cores form in filamentary environments. L. Pagani also participated in the first detection of water vapor in a dense core (L1544) with *Herschel*/HIFI, as part of the WISH program. The inverse P-Cygni line profile indicates that water vapor is present throughout the core despite its low temperature, requiring photodesorption of water ice by FUV H_2 fluorescence following cosmic ray ionization. The magnetic field intensity is another critical core parameter. E. Falgarone in collaboration with R. Crutcher performed the most sensitive Zeeman field measurements to date in dense gas, using CN lines at the IRAM-30m. Their Bayesian analysis suggests that dense cores display a broad range of magnetic fields but are in general magnetically super-critical, which favors core formation from turbulence rather than from ambipolar diffusion. Finally, using *Spitzer* archival images, L. Pagani et al. found that dust grains in several dense cores have already grown to micron sizes and scatter light up to 5µm (« coreshine » effect, see Figure below). This may have important consequences for gas-grain chemistry, the ionization balance and magnetic field diffusion before and during the collapse.

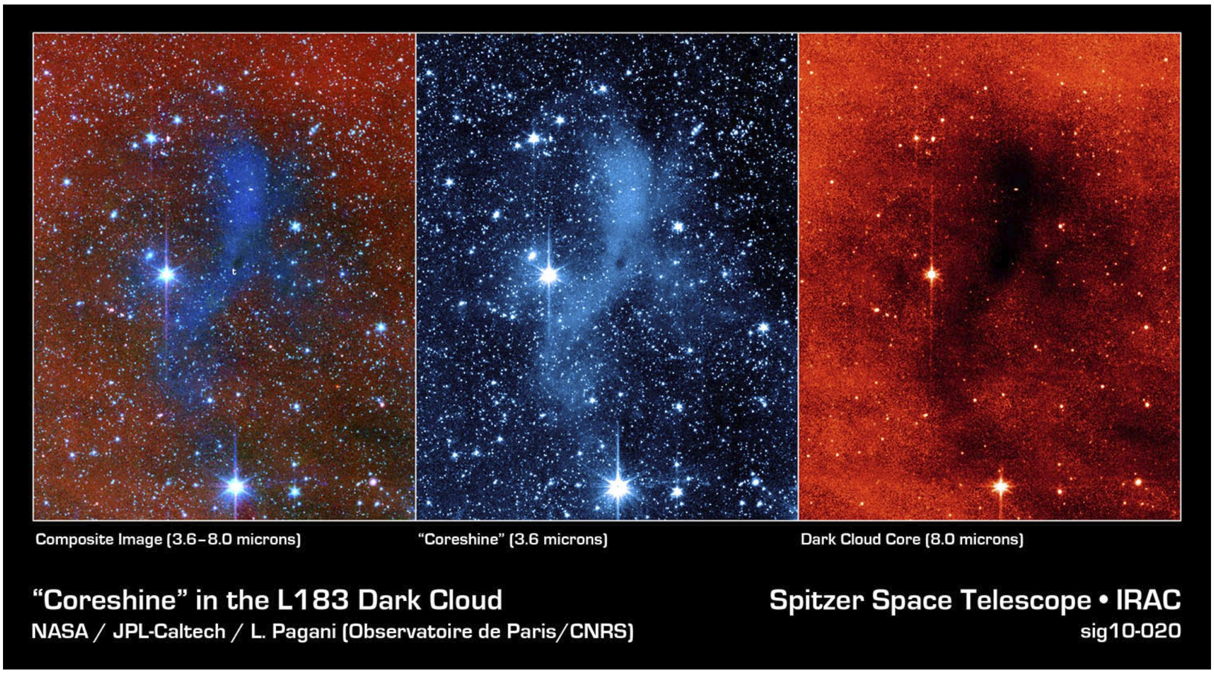


Fig. 3.2.3: The "coreshine" effect in L183: this dense cloud appears dark at 8mic (right) due to dust absorption, but is still bright at 3.6mic (middle), requiring scattering by large micron-sized grains (Pagani et al. 2010).

3.2.3. Star and planet formation :

The formation of massive stars is still not well understood, nor its dependence on metallicity. This question was addressed by M. Heydari-Malayeri, J.-L. Lemaire, and their Ph.D. students R. Selier (2009-2012) and L. Kristensen (2004-2007) in the LMC and SMC using *Spitzer* and VLT/NACO data and optical NTT spectra. Several young clusters were identified, and protostars with masses up to 10-20 Mo and accretion rates of up to 10^{-4} Mo/yr, as well as one candidate isolated massive star, suggesting different modes of star formation as in our Galaxy. The evolution of gas accretion and dust growth in discs is another important issue, related to planet formation. S. Cabrit participated in statistical studies of low-mass accreting stars using the NTT and IRAM-PdBI, which showed that accretion slowly declines from 0.1 to 10 Myr while grain growth is very rapid; J.F. Lestrade conducted deep searches for debris discs (Kuiper belt analogs) around 50 M-dwarfs with the IRAM-30m and found that they seemed less frequent than around more massive stars, possibly because of stripping by stellar fly-bys in the first 100 Myr (Ph.D. thesis of E. Morey). On the other hand, early results of the *Herschel* DEBRIS program suggest a positive correlation between the presence of debris disks and low mass orbiting planets (less massive than Saturn). In the course of this survey, a bright source has been serendipitously discovered and identified as a high redshift galaxy (Lestrade et al 2010,2011).

3.2.4. Stellar feedback : Protostellar jets, shocks, and AGB envelopes

Protostellar jets offer indirect diagnostics of the magneto-centrifugal processes operating in young stars and/or discs, that could provide a key test of current star formation theories (see Section “Magnetized star formation”). Sub-arcsecond observations of jets are required to address this issue. From PdBI maps of the protostellar jet HH212 at 0.3” resolution, S. Cabrit et al. showed that jet collimation requires an intrinsic MHD process. The Ph.D. thesis work of V. Agra-Amboage at IPAG (2006-2010), co-directed by C. Dougados and S. Cabrit, showed that T Tauri jets keep a similar ejection/accretion ratio up to 2Mo and may contain dust, favoring a disc origin. Protostellar jets also drive large molecular bowshocks in their parent cloud that may have a strong feedback on ISM chemistry, turbulence, and star formation rate. The *Herschel* CHESS and WISH programs are now providing a wealth of new information on molecular outflow emission in CO up to J = 40, H_2O and [OI] 63mic. S. Cabrit was involved in the CHESS study of the L1157-B1 bowshock, with B. Lefloch & C. Ceccarelli (IPAG), C. Codella (Arcetri) and J. Cernicharo (Madrid) that revealed a dissociative “reverse shock” tracing the jet impact, and an opposite abundance gradient of H_2O and NH_3 with velocity that is challenging simple 1D shock models. Stars also strongly interact with the ISM in the AGB and post-AGB phases of their evolution, when then expell their newly synthetized elements through expanding dusty circumstellar envelopes. Using combined HI and CO observations, T. Le Bertre et al. mapped the wakes created by AGB envelopes rapidly moving through the ISM, revealing for the first time the history of mass loss for the past 100 000 years, and its interaction and mixing with ambient gas.

3.3. Modelling cloud condensation : From diffuse gas to stars and discs

3.3.1. Formation of molecular clouds by thermal instability in turbulent diffuse gas

It is well known that the ISM is subject to a thermal instability between two stable phases: a warm atomic diffuse phase (WNM, a few cm^{-3}) and a cold and dense phase (CNM, a few 100 cm^{-3}), where molecules can form. Our group has opened a new, more dynamical (and realistic) vision of this phase transition by exploring its coupling to turbulent motions. 2D and 3D hydrodynamical simulations performed by P. Hennebelle and E. Audit (CEA/IRFU) revealed that the mass spectrum of cold clumps is related to the exponent of the density power-spectrum of ISM turbulence; the simulated clump mass-spectrum and hydrogen 21cm spectra agree remarkably with observations. To follow condensation up to prestellar core densities, numerical simulations including magnetic fields and gravity were then performed in the context of the ASTRONET project STARFORMAT, with R. Klessen and R. Banerjee (Heidelberg) and E. Vazquez-Semadeni (Mexico). The new MHD version of the RAMSES code, developed by P. Hennebelle with R. Teyssier and S. Fromang (CEA /IRFU), was used to model colliding flows in a turbulent bi-stable diffuse ISM. The simulations reproduce the empirical “Larson’s relations”, which relate over several decades the observed (turbulent) velocity dispersion and mass of self-gravitating molecular clumps to their size. This work strongly suggests that both the turbulence and the hierarchical scaling structure of molecular clouds could be sustained by the continuous energy input from accretion of diffuse gas onto the cloud.

3.3.2. The IMF and Star Formation Rate from gravoturbulent fragmentation

Pre-stellar cores are the densest structures in molecular clouds, and eventually collapse into stars. The core mass spectrum is thus believed to be at the origin of the stellar initial mass function (IMF). P. Hennebelle and Gilles Chabrier (CRAL, Lyon) applied the Press & Schechter formalism to turbulent molecular clouds, in order to predict their core mass spectrum. This analytical approach is complementary to heavy numerical simulations, as it helps to elucidate the key physical mechanisms at work. The model IMF agrees remarkably well with the observed (and numerically simulated) one, and explains in particular its universal slope at large masses, first measured by Salpeter, as arising from an interplay between turbulent support and gravity. The time-dependent extension of this theory predicts a density dependence of the star formation rate (SFR) in good agreement with observations, supporting the notion that turbulence is the key agent controlling star formation in the ISM.

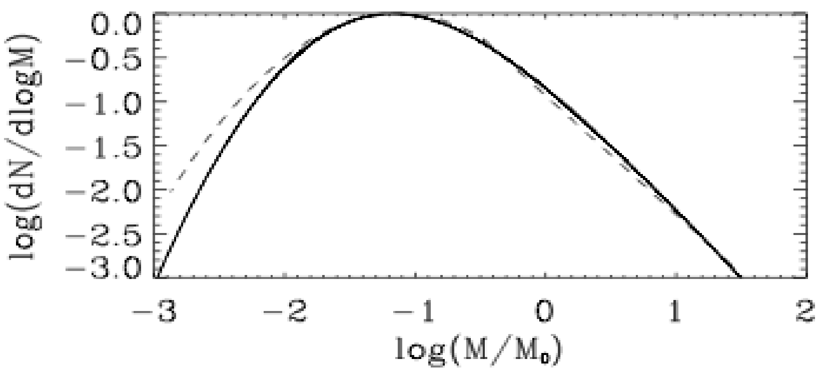


Fig. 3.3.1: Solid curve: IMF predicted by the analytical model of Hennebelle & Chabrier (2008). Dashed curve : fit to the observational IMF of Chabrier (2003).

3.3.3. Magnetized protostellar collapse : discs, fragmentation, and outflows

Our group was among the first to exploit the advent of parallel computing and adaptive-mesh refinement techniques to study the influence of magnetic fields on star and disc formation during rotating gravitational collapse. An extensive series of 3D MHD simulations were performed with the RAMSES code, reaching many orders of magnitude in density contrast. It was shown that even a modest magnetic field completely alters the collapse of solar-mass cores by efficiently removing angular momentum, decreasing the disc size and stabilising it against gravitational fragmentation. These results challenge the standard scenario of disc and binary formation studied in the hydro-dynamical context over two decades. On the other hand, the Ph. D. work of M. Joos (2009-2012; supervised by A. Ciardi and P. Hennebelle) showed that massive discs can still form when the magnetic field is misaligned with the rotation axis, or when the turbulence is strong.

In the Ph.D. thesis of B. Commerçon (2006-2009; co-directed by G. Chabrier and P. Hennebelle), the criteria on spatial resolution and robustness of the solver were carefully characterized, and radiation-hydrodynamics was implemented to study self-consistently for the first time the collapse of massive cores (100 $M_\odot$). It was shown that **radiative feedback and magnetic braking are both** required to inhibit early fragmentation and allow the formation of massive protostars. We thus speculate that highly magnetized massive dense cores are good candidates for isolated massive star formation, while less magnetized ones would form OB associations or small stellar clusters.

Finally, A. Ciardi & P. Hennebelle dedicated particular efforts to understand the MHD outflows that are launched in simulations of rotating, magnetized collapsing cores. It was shown that the initial angle between magnetic field and spin axis is a crucial parameter, and that mass ejection is less efficient and more unstable as this angle increases, with more mass being accreted on to the adiabatic first core. Outflow and jet properties are thus intimately related to the formation conditions of stars and discs.

3.4. Modelling chemical diagnostics of ISM dynamics

3.4.1. Turbulent mixing at cloud interfaces

P. Lesaffre, M. Gerin, and P. Hennebelle calculated the effect of turbulent mixing on the thermal profile and chemical abundances at a 1D interface between the atomic (warm) and molecular (cold) phases of the ISM. Multifluid, high-resolution 1D hydrodynamical simulations were performed, with a simplified chemical network and an enhanced (turbulent) coefficient of thermal and chemical diffusion. Diffusion brings cold H_2 into contact with warm C^+ and H in the atomic gas, leading to enhanced CH^+, H_3^+, OH and H_2O at the interface; the thermal transition is also broadened, modifying selectively the line profiles of various species, and providing a means to diagnose such turbulent fronts. However, the predicted CH^+ columns are still well below the observed range in the ISM

3.4.2. UV-driven chemistry in an inhomogeneous turbulent cloud

To assess the impact of line-of-sight density fluctuations caused by turbulence on UV-driven chemistry, F. Levrier et al. developed an interface between the Meudon PDR code, developed by the LUTh-ISM team, and the results of 3D numerical simulations of MHD turbulence in the ISM. Molecular abundances are found to be enhanced by a factor 2-4 with respect to uniform density PDR models, and correlations between species are also significantly closer to observations. However, the observed CO column densities in the diffuse gas are still not well reproduced, pointing to the need for an extra (probably kinetic) energy input to drive this rich chemistry.

3.4.3. Turbulence dissipation in regions of large velocity shear

Since 1998, our group has been developing the first model of non-equilibrium chemistry triggered by local bursts of turbulent dissipation; we follow the gas heating by viscous shear and ion-neutral drift, and the ensuing chemistry, as it flows through a magnetized "Burgers vortex". The Ph.D. thesis work of B. Godard (2007-2010), supervised by E. Falgarone and G. Pineau des Forêts, recently took this model to a new degree of realism by using a full chemical network, exploring a wide range of shear, densities and UV fields, and simulating a realistic mix of active vortices, relaxing gas, and quiescent gas along the line of sight, taking into account the different chemical relaxation times of the various species. This "turbulent dissipation region" (TDR) model is found to reproduce remarkably well the abundances of many species observed in diffuse gas such as CH^+, HCO^+, CO and rotationally excited H_2, with only a few percent of warm gas distributed on the line of sight. Given the very limited number of free parameters, this success is remarkable and strongly supports our basic concept that "warm" chemistry in the ISM is ultimately linked to turbulence decay.

3.4.4. Deuteration and the age of molecular clouds and pre-stellar cores:

H_2 initially forms on grains with an ortho-to-para ratio (OPR) of 3, and then slowly converts at low temperature to the lower energy para form by proton exchange reactions. Therefore, **the value of the H_2 OPR is a crucial clue to the formation timescale of molecular clouds and dense cores.** Although H_2 itself is too cold to emit, its OPR may be estimated indirectly from observations of deuterated species, whose fractional abundance is influenced by the H_2 OPR via endoenergetic reactions. L. Pagani and his collaborators showed that a proper understanding of deuteration chemistry in dense cores requires individual reaction rates between the various symmetry states (ortho, para, meta) of H_2, H_3^+ and their deuterated counterparts. By fitting observations of the L183 prestellar core, they inferred a minimum core age of a few 0.1Myr, and a more recent increase in central density. With P. Lesaffre and E. Roueff (LUTh), he also showed that the lack of widespread DCO^+ in molecular clouds implies an H_2 OPR > 0.1, which sets an upper limit of 6 Myr to their formation time.

3.4.5. Protostellar outflows and shocks

The youngest protostellar jets are observable only at moderate resolution (>100-1000 AU; *Spitzer*, PdBI…) through their bowshocks (H_2 knots, swept-up CO cavity) or in optically thick lines (SiO, H_2O). Hence even their most basic parameters (mass-flux, thrust, power, magnetization…) are still too uncertain to clarify their origin and feedback. Our group has been undertaking a long-term shock / chemical modelling effort to improve this situation.

T.P.. Downes (Dublin) and S. Cabrit used long duration (1500 yrs) 2D simulations, with a simplified treatment of dissociation, to calculate the biases in estimating jet thrust from CO (2-1) observations of the swept-up cavity. They found that CO momentum could be well estimated but that the age (and jet thrust) was very uncertain. To better constrain flow properties, extensive calculations of H_2 and SiO emission in planar MHD molecular shocks were performed in the Ph. D theses of L. Kristensen (2004-2007; supervised by J -L. Lemaire) and of A. Gusdorf (2005-2008 ; co-supervised by G. Pineau des Forêts, D. Flower, and S. Cabrit), respectively. The effects of density, speed, magnetic field, age, and curvature in 2D and 3D were explored, and it was verified that C-type (bow)shocks could fit SiO and H_2 observations in L1157 and Orion-KL for an age, shock speed and magnetic field in agreement with independent estimates. This tool was applied to *Spitzer* observations of the HH211 flow in the Ph.D. thesis of O. Dionatos in Rome, co-directed by B. Nisini & S. Cabrit.

The thermo-chemistry of the jet itself was modeled for the first time in the Ph. D. thesis of D. Panoglou (2005-2009 ; codirected by S. Cabrit and G. Pineau des Forêts), in the case of an MHD centrifugal disc wind. It was shown that H_2 molecules launched from > 0.2-1 AU in the disc survive against collisional dissociation and photodissociation by UV-Xray stellar photons, and that ambipolar diffusion produces hotter jets at lower mass-fluxes (later stages), W. Yvart (new Ph.D student of S. Cabrit and G. Pineau des Forêts) is now calculating synthetic H_2O and CO line profiles for comparison with *Herschel* and ALMA Cycle 1 data.

3.5. Modelling transport mechanisms in circum/stellar plasmas

3.5.1. MHD instabilities and dust transport in protoplanetary discs

All young stars surrounded by gaseous discs are accreting material at a rate exceeding by orders of magnitude that expected from molecular friction alone. Some kind of "anomalous turbulent viscosity" is invoked to transport angular momentum outwards, but it was only in 1991 that a plausible mechanism was identified by S. Balbus, in the form of the magneto-rotational instability (MRI), which develops even at very low magnetization. However, this instability requires sufficient ionization of the medium, which in the disc midplane depends on the very heat produced by the dissipation of the MRI motions. Therefore, only two states are possible: a hot ionized MRI-active state where gas is turbulent and accretes onto the star, and a cold neutral quiet state (often called 'dead zone'), that might be crucial for dust growth and the formation of planets.

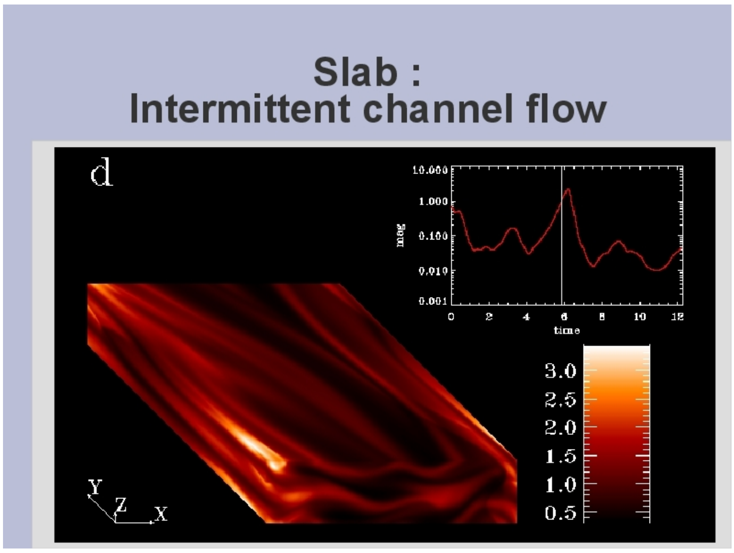


Fig. 3.5.1: Compressible, resistive 3D MHD shearing-box simulations of MRI. Isosurfaces show the Vx component; top right panel displays the time evolution of magnetic energy divided by thermal energy (Lesaffre et al. 2009)

The 'dead-zone' is often believed to lie in a well-defined region between ~ 1 and 10 AU. However, in shearing box 3D MHD simulations, P. Lesaffre, H. Latter (post-doc) and S. Balbus showed that an eruptive behavior could occur where both states alternate: this could explain some of the observed extreme variability of young stellar objects. They also detailed the dynamical role of parasitic instabilities feeding on MRI modes, and found an oscillatory property of the interface between the dead and active zone. Finally, E. Jacquet (Ph. D. student, 2009-2012) and S. Balbus investigated the feedback of dust on MRI turbulence, and how turbulence could radially redistribute the small solid particles seen today aggregated into chondrite meteorites. All of this work clearly has important implications for the first stages of planet formation.

3.5.2. Rotating stellar interiors : dynamos and convective instability

Other astrophysical objects, such as the Earth and Sun, also provide the necessary conditions for MRI, namely magnetic fields and differential rotation. L. Petitdemange and S. Balbus showed that MRI could indeed be present inside the Earth in the form of a magneto-strophic instability. In other developments, W. Herreman (CNES postdoc) and P. Lesaffre showed that time-averaged magnetic fields in a plasma behave as if advected at an effective speed which corresponds to the average drift speed of lagrangian tracers, previously known as the « Stokes drift ». This was used to explain the behavior of dynamos in a set of illustrative flows.

A convective instability may also be triggered, that transports heat by upward/downward motions. The turnover timescale is so short (a few minutes or hours) that stellar evolution codes must resort to a “mixing length theory” to model the transport of heat and chemical elements. This theory was implemented in MESA, currently one of the most widely used stellar evolution code (for which P. Lesaffre developed part of the engine). However, it is 1D, while helioseismology recently revealed that the sun’s rotation profile is intrinsically 2D, with no spherical or cylindrical symmetry. How angular momentum and heat are transported in a rotating star is a long-lasting puzzle. S. Balbus in a series of papers recently reproduced to an impressive degree of accuracy the observed rotation profile of the sun, by assuming that the stratification of entropy is only a function of the local rotation rate. With a few extra assumptions, the correct behavior near the tachocline and the surface was also retrieved.

3.5.3. Microscopic transport : radiation-matter interaction, and stochastic diffusion

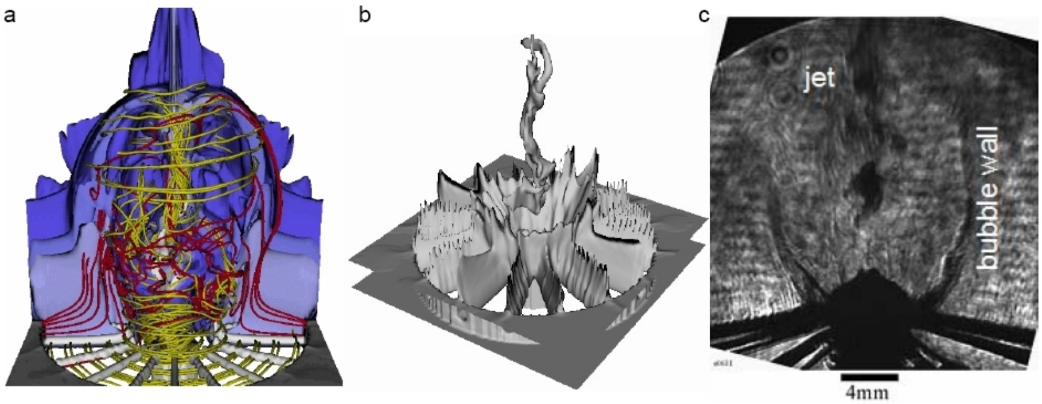


Fig. 3.5.2: a) distribution of magnetic field (yellow lines) and current density (red lines) inside the magnetic cavity as modeled by resistive 3D MHD simulations with GORGON. the isodensity contours (shades of blue) are sliced vertically. With the onset of the kink instability the magnetic field wraps tightly around the jet. The denser, central jet is shown in (b). (c) Experimental shadowgraph showing the bubble wall and the clumpy jet launched along the axis (Ciardi et al.)

Energy transport in most of the Sun is dominated by radiation absorption and diffusion. In this context, the averaged Rosseland opacity plays a crucial role. Observational constraints (solar oscillations and chemical abundances) now require a very high precision in computing this quantity. As part of this process, C. Zeippen is a lead member of the international projects OPACITY and IRON (and its sequel IPOPv2), that produce accurate quantum calculations of atomic/ionic structure (energy levels) and elementary absorption mechanisms (line strengths, photoionisation cross-sections) distributed to a worldwide community (http://cdsweb.u-strasbg.fr/topbase/topbase.html, http://opacity-cs.obspm.fr:8080/opacity/). Based on such calculations, F. Delahaye incorporates in stellar evolution codes the opposing effects of radiative acceleration and gravitational sedimentation of heavy elements, which are crucial to interpret chemical anomalies. Stark broadening and shift of spectral lines by collisions are another key ingredient for plasma opacities. In collaboration with Serbian and Tunisian teams (3 Ph.D. theses), S. Sahal-Bréchot is performing extensive calculations of Stark parameters, made available in the STARK-B database (http://stark-b.obspm.fr). She also develops models of collisional depolarization that were applied to Hα line polarization of solar flares, in the Ph.D. thesis of J. Štěpán (2005-2008) co-supervised with P. Heinzel (Prague). In a different vein, F. Debbasch is developing a theory of relativistic transport involving a relativistic Boltzmann equation and stochastic processes. The model admits non-relativistic counterparts, and could be applied to diffusion on biological interfaces with fluctuating geometries.

3.6. Laboratory Plasma Experiments

Laboratory experiments combined with numerical simulations allow to tackle astrophysical problems from a new angle, and to benchmark theoretical calculations. These studies are at the interface between plasma physics, fundamental physics and astrophysics, and have some applications for fusion plasmas.

3.6.1. Magnetized Jets

In a collaboration with Imperial College (London), A. Ciardi et al. studied the launching and propagation of laboratory magnetized jets using the MAGPIE Z-pinch (1 TW, 1 MA); The experiments and numerical simulations show how a toroidal magnetic field can collimate and accelerate the plasma to super-magneto-sonic speeds (see Figure below). Thanks to our massively parallel, 3D resistive MHD code GORGON (co-developed by A. Ciardi), we were able to study in detail the coupled effects of episodic ejections and current-driven instabilities, which transform the jet from a continuous beam into a series clumps that remain well collimated. These results present striking similarities with our MHD simulations of protostellar outflows (see Section “Magnetized star formation”) and of magnetic tower jets (done in collaboration with A. Frank at the University of Rochester), indicating that the magnetic field topology expected from jet launching models naturally leads to episodic, inhomogeneous – instead of continuous - stellar jets.

3.6.2. Accretion shocks

In the framework of the ANR STARSHOCK (PI C. Stehlé), and in collaboration with J.P. Chièze et al. (CEA/IRFU), T. Lanz (OCA) and I. Hubeny (Tucson), our group has been conducting an experimental and numerical study of accretion shocks where matter from the disc falls onto the photosphere at speeds of several hundreds of km/s. The project aims at clarifying the shock structure and the expected spectral signatures, in order to get accurate diagnostics of the accretion rate in young stars from their UV-Xray emission.

The experiments (PI. C. Stehlé) carried out on the PALS laser facility in Prague (1kJ, 0.3 ns) concern highly hypersonic shocks (~50 km/s) propagating in low-density gas, and exhibiting a radiative precursor in a partly absorbing medium (Xe, at few 0.1 bar). We develop the targets, manufactured at Observatoire de Paris (GEPI), and specific diagnostics. Our main results include the first image at 21 nm showing both the shock front and the precursor, the deformation of the shock ionisation structure by the 2D behaviour of the radiation flux, and the slow convergence (~50 ns) towards a quasi-stationary regime.

In parallel, 1D hydrodynamical simulations carried out by L. de Sa (Ph. D. student, under the supervision of J.P. Chièze and C. Stehlé) have shown that a high opacity modifies the position of the accretion shock in the atmosphere, and quenches the oscillatory radiative instability (which is in fact not observed in young stars). C. Stehlé et al. modeled the expected spectral signatures with the 1D radiative transfer code SYNSPEC, which they upgraded to handle the vast range of temperature (a few 1000 K up to a few 10^6K) found in shocks.

Finally, L. Ibgui (ANR postdoc) developed, in collaboration with I. Hubeny, T. Lanz, and C. Stehlé, a new generic 3D radiative transfer code, IRIS, to post-process snapshots of 3D simulations or experiments. The radiative transfer is solved with the short-characteristics method and can handle arbitrary velocity fields, and periodic media.

3.6.3. Benchmarking of opacity calculations

For some elements, especially those of the iron group, quantum opacity calculations are made very difficult by the large number of ions, and of electrons for each ion. Therefore it is of primary importance to validate theoretical results against experimental measurements. This is done by the consortium OPAC (lead by S. Turck-Chièze (CEA/IRFU) and of which Delahaye and Zeippen are participants), using the LULI2000 laser (Palaiseau, 2kJ, 2.5 ns) and various theoretical codes. The 2010 measurements show better agreement with the OP project opacities than with many other theoretical opacity sets.

3.6.4. High resolution VUV emission spectra of multicharged ions

The high resolution 10m spectrograph in Meudon (see Pole 3) allows analysis of dense and complex VUV spectra from heavy element ions. L. Tchang Brillet et al. focus on transition metals and rare earths observed in chemically peculiar stars. Some of these elements are also present as impurities in fusion plasmas, where they contribute to radiation loss. Their work provides accurate line wavelengths, level energies, transition probabilities, and Landé factors, which are made publicly available on the website MOLAT http://molat.obspm.fr.

3.7. Visibility and attractivity

3.7.1. International and national visibility

Over the period, Pole 2 members published 373 refereed articles in international journals of high standards in their field (A&A, ApJ, MNRAS, Nature, Nature Physics, Science, J. Stat. Phys., Physica A, J. Quant. Spec. Radiat. Transf., High En. Dens. Phys., Laser and Particle Beams, Geophysical Research Letters,...). The results were presented in numerous international conferences, with at least 75 invited talks over the period, including 50 on ISM turbulence, magnetic fields, star formation, *Herschel* data, accretion disks and outflows, and laboratory experiments. Several results related to ALMA, *Herschel, Planck* and IRAM were selected to appear as "Head News" on the web portal page of the Observatoire de Paris, and/or highlighted in Press Releases (NASA/Spitzer, ESA/Herschel, CNRS/INSU).

Pole 2 members also participated in the scientific organization (SOC) of about 15 international conferences, and organized the first European conference on Laboratory Astrophysics (ECLA, Paris, 26-30 septembre 2011, ecla.obspm.fr). They were nominated as scientific experts in numerous committees (see full list in Pole 2 Executive Summary).

3.7.2. Attractivity

Pole 2 is involved in numerous collaborations, either as PI or following an invitation as co-PI or co-I. They include **10 Large international consortia (3 as PI) and 6 ANR grants involving several French institutes (2 as PI)** (see full list in Pole 2 Executive Summary). Pole 2 is also participating in two Labex structures: ENS-ICFP and Plas@par with UPCM (coordinated by a Pole 2 member, C. Stehle).

As another measure of our attractivity, we list below our **senior external collaborators that visited LERMA for at least 1 month over the period** 2007-2012:
At ENS, 18 visitors: K. Chitre (CEBS, India), R. Izzard (AIA, Bonn), C. Reynolds (Maryland), C. McKee (Berkeley), H.T. Ji (Princeton), N. Weiss (DAMPT, Cambridge), J. Cho (Queens, London), M. Arnold (), E. Bergin (Michigan), A. Fuente (Madrid), P. Goldsmith (JPL), M. Houde (Western Ontario), D. Johnstone (Vancouver), R. Klessen (Heidelberg), E. Ostriker (Princeton).

At Meudon and Ivry: 15 visitors: C. Mendoza (Venezuela), M. Pinsonneault (Ohio State), G.X. Chen (CfA, Harvard), T. Lanz (U. Maryland), I. Hubeny (U. Arizona), D. Hammer (Cornell), M. Bocchi (Imp. College, London), M. Dimitrjevic (Belgrade), N. ben Nessib, H. Elabidi, and Y. Azzouz (Tunis), S. Churilov, R. Kildiyerova, and A. Ryabtsev (Troitsk, Russia)

Over the same period, **5 new young permanent researchers were recruited** in Pole 2, after several years of postdoctoral work at other institutes: P. Lesaffre (2007, CNRS), F. Levrier (2009, teaching position at ENS), A. Ciardi (2010, teaching position at UMPC), F. Delahaye (2010, CNAP), L. Petitdemange (2011, CNRS). In addition, **one senior researcher**, C. Zeippen (CNRS) transferred in 2011 from the LUTH, **11 students** started a Ph.D. thesis at LERMA and **7 postdocs** were recruited for durations of 8 months to 3 years.

4. Pole 3: Molecules in the Universe

Thematic Pole 3

Have contributed to Pole 3 research between 2007 et 2012 :

12 research and teaching staff incl. 2 emeriti: *C. Balança, H. Chaabouni, V. Cobut, F. Dayou, F. Dulieu, N. Feautrier, S. Leach, J.-L. Lemaire, A. Momeni, A. Moudens, A. Spielfiedel, L. Tchang-Brillet.*

10 PhD students: *M. Accolla, M. Chehrouri, L. Gavilan, E. Matar, H. Mokrane, M. Minissale, J. Noble, I. Oueslati, M. Roudjane, L. Vincent and 1 postdoc : E. Congiu (hired as assistant prof. in 2011)*

2 long duration visitors: *M. Eidelsberg, F. Rostas*

and 6 technicians and engineers: *S. Baouche, C. Blaess (50%), N. Champion (50%), S. Diana, F. Lachèvre (50%), E. Somson (50%)*

4.1. Overview

Science developed within Pole 3 aims at studying fundamental properties of atoms and molecules relevant to astrophysical media. A common thread to our investigations is to understand how molecular systems interact with their environment, being light, other isolated species or solid materials. The precise knowledge of radiative and collisional properties is essential to properly infer the chemical composition and physical conditions of astrophysical media from the observed spectra. Complementary to the diagnostic, detailed informations on reactions taking place in the gas-phase and on dust grains are necessary to trace matter evolution and understand the origin of the observed molecular complexity. All these fundamental issues have been addressed along the activities of Pole 3 during the last five years, which have been structured around four themes:

- Theme 1: Gas-phase collisional processes
- Theme 2: Gas-phase reactive processes
- Theme 3: VUV spectroscopy an photophysics. Exobiology
- Theme 4: Gas-solid interactions and heterogeneous catalysis

The activities of Pole 3 are strongly interdisciplinary, connecting the fields of physics, chemistry, astrophysics and engineering technology. These activities are based on long-standing and continuously growing expertise in both quantum chemistry and collision theory, as well as on the development of sophisticated experiments for studying gas-grain interactions, and on the use of complementary spectroscopy from mid-IR to vacuum-UV. This wealth of instrumental and theoretical skills allowed us to unravel microscopic mechanisms of increasing complexity, and to determine fundamental parameters which are actually used as reference data. The species and processes under study are of interest to a variety of astrophysical environments, ranging from interstellar and circumstellar media to stellar physics and planetary atmospheres. Joint efforts with astrophysicists are commonly performed to assess the relevance of our results in improving the modelling of these regions. In addition to astrophysical issues, the study of such fundamental molecular properties may benefit to a wider range of scientific thematics (atmospheric chemistry, surface physics, ITER nuclear fusion reactor, biology,...).

4.2. Scientific objectives and results

The huge improvements of observations supplied by new generation space and ground-based telescopes call for new and challenging developments in molecular physics. With a continuously growing number of detected species, molecular properties of higher accuracy and molecular processes of increasing complexity need to be known. Our main objective during the reporting period was to tackle these challenging issues for specific systems especially relevant to astrophysical modelling, pushing the limit of state-of-the-art instrumental and theoretical methodologies.

Significant successes could be achieved over the last five years, yielding to the publication of 162 refereed papers (ACL) shared between physics and chemistry (Physical Review letters, Journal of Chemical Physics, Faraday Discussions...) and astrophysical (ApJ, A&A, MNRAS...) communities, revealing the strong interdisciplinary character of our research activities.

4.2.1. Theme 1. Gas-Phase Collisional Processes

a) *Collisional excitation of molecules by He and ortho/para-H2*

Scientific Context : The abundances and excitation conditions (temperature, density) of molecular species in astrophysical environments can be inferred from detailed modelling of spectral lines intensities at sub-millimetre and infrared wavelengths. Under non-LTE conditions, this analysis requires accurate data for radiative and collisional processes that compete to drive the statistical equilibrium population in each molecular quantum state. Whereas significant advances in spectroscopy techniques allow the measurement of radiative Einstein coefficients with great precision, the measurements of state-to-state collisional excitation rate coefficients (with He and ortho/para-H_2 as the main colliders) remain very scarce. Over the past ten years, the expectation of high resolution and high sensitivity spectra supplied by Herschel and ALMA instruments led to concerted efforts of the scientific community to determine such fundamental parameters by means of theory. This was first undertaken through the network FP6-RTN « Molecular Universe » (2004-2008). Since then, we pursued our investigations for key species through joint efforts with the teams of A. Faure (LAOG, Grenoble), F. Lique (LOMC, Le Havre), J. Cernicharo (CAB. INTA-CSIC, Madrid), M.-L. Senent (IEM-CSIC, Madrid) and Z. Ben Lakhdar (LSAMA, Tunis). These studies received continuous support from the national CNRS PCMI program.

Results : We focused our work mostly on silicon- and sulphur-bearing key species which are used to probe a variety of interstellar and circumstellar environments. We obtained results for rotational excitation of SO (Lique et al., 2007a), CS (Lique et al., 2007b), SO_2 (Spielfiedel et al., 2009; Cernicharo et al., 2011), SiS (Vincent et al., 2007; Lique et al. 2008), and, more recently, small carbon chains C_2H (Spielfiedel et al., 2012) and C_2H^- (Dumouchel et al., 2012). As a major result, we have shown that accurate excitation rate coefficients for collisions with ortho/para-H_2 molecules could not be inferred from rate coefficients with He atoms as the perturbing collider. Differences exist by large factors, up to ten according to the rotational states considered, that may lead to significant errors on astrophysical modelling.

Highlight : The highly accurate rate coefficients for SO_2-H_2 collisions were used to model the lowest rotational lines of SO_2 (Cernicharo et al. 2011). It was predicted that the 1_{11}-2_{02} transition will move from absorption to emission within a range of densities relevant to the ISM (Fig. 1a). The predicted absorption line profile was confirmed by observations of cold molecular clouds at the GBT (Fig. 1b), allowing to trace properly the physical conditions of these regions. The new rates also predict a maser line profile for the 4_{04}-3_{13} transition which could provide strong constraints on the SO_2 abundances inferred from observations.

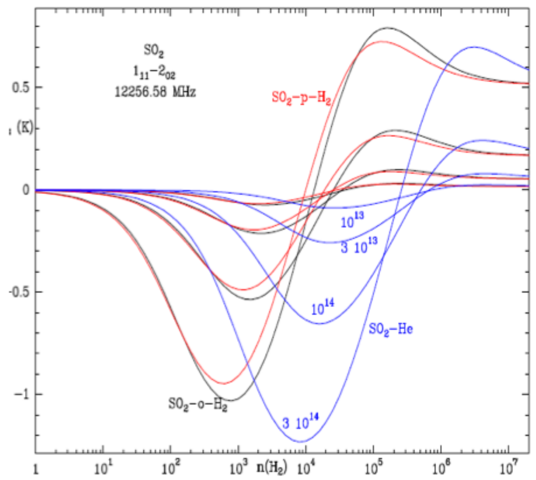


Fig 1a : Predicted brightness temperature of the 1_{11}-2_{02} line as function of $n(H_2)$ for different density columns of SO_2 and different sets of collisional rates.

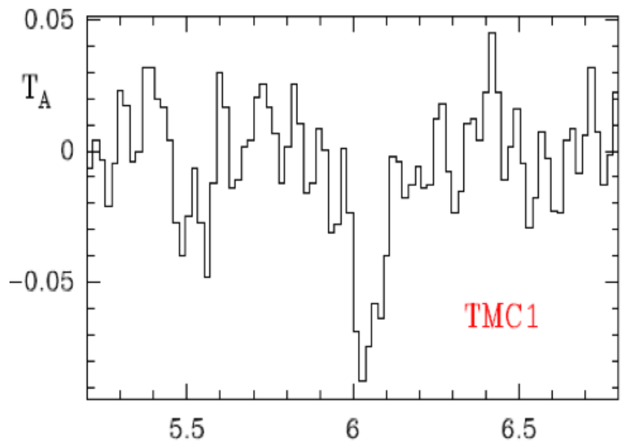


Fig 1b : Observed 1_{11}-2_{02} absorption line profile towards TMC1 (GTB, 2010). Coordinates of x-axis correspond to LSR velocity and the y-axis to the observed antenna temperature

Fig. 4.2.1

b) *Collisional excitation of atoms by H*

The preparation of the Gaia mission generates the development of extremely performant tools for the analysis of stellar observations. However, model atmospheres suffer from LTE approximations that may induce systematic errors in the results. The ability to accurately interpret the lines requires to combine hydrodynamics and radiative tranfer in a non-LTE approach. Collisions with H atoms are dominant in photospheres of late-type stars, even more in metal poor stars, and it is known from past studies that the commonly used approximate Drawin-formula overestimates the cross sections by typically several orders of magnitude. Hence, using state-of-the-art quantum chemistry and dynamics methods, we determined H-collision rates for some neutral and ionised elements (Mg, Ca, O) of major interest for Gaia. Our results (Guitou et al, 2010; Barklem et al, 2011a; Guitou et al., 2011b; Belyaev et al., 2012; Barklem et al., 2012) showed in particular the importance of collisional ion-pair production and mutual neutralisation. These studies, continuously supported by the PNPS (Stellar Physics National Programme) and by the AS GAIA (Specific Action for GAIA), are developed in collaboration with M. Guitou (LMSME, Paris-Est), A. Belyaev (Herzen University, St Petersburg) and P. Barklem (Uppsala University).

c) Collisions between oxygen molecules

Collisional removal processes involving electronically and vibrationally excited species of molecular oxygen O_2 are highly relevant to the chemistry of the upper Earth's atmosphere. Our objective was to take benefit from a wealth of experimental measurements to assess the validity of new theoretical developments. High-dimensionality systems involving coupled electronic states are indeed extremely difficult to treat by usual quantum dynamics methods. We developed in collaboration with J. Campos-Martinez/M. Hernandez (IFF-CSIC, Madrid) and R. Hernandez-Lamoneda (CIQ, Cuernavaca) original approaches based on reduced dimensionality (RD) models to tackle such challenging issues. The results obtained on the collisional removal of oxygen species in their ground $X^3\Sigma_g^-$ and excited $b^1\Sigma_g^+$ states achieved to reproduce, for the first time, the puzzling features observed in experiments (Dayou et al., 2007; Dayou et al., 2010). They provided supported evidence for the key role played by electronic energy transfer mechanisms in such removal processes, as well as their relevance to explain the non-LTE vibrational distributions of O_2 in the upper Earth's atmosphere.

4.2.2. Theme 2. Gas-Phase Reactive Processes

Scientific Context : Chemical models that are based on reaction networks serve to trace matter evolution in interstellar and circumstellar media (ICM). The kinetic databases for astrochemistry (UMIST, OSU, KIDA) incorporate a wealth of reactive processes, most of them related to gas-phase chemistry. However, for many key species, the formation/destruction mechanisms suffer from large uncertainties that may yield an improper description of molecular synthesis in astrophysical environments. Due to the experimental constraints, some classes of reactions are difficult to measure (e.g. reactions involving unstable radicals), and the products formed can generally not be probed. In this context, we have investigated by means of theory a series of poorly known reactions involving small neutral species playing a key role for the ICM chemistry. These studies were conducted in collaboration with the theoretical teams of M. Monnerville (PhLAM, Lille), J.-C. Rayez (ISM, Bordeaux), J.-M. Launay (IPR, Rennes), P. Honvault (ICB, Dijon), T. Gonzalez-Lezana (IFF-CSIC), and the experimental teams of I. Sims (IPR, Rennes) and M. Costes (ISM, Bordeaux). Studies relative to reactions involving larger species began in 2011 with the Ph.D. thesis of I. Oueslati, co-supervised by L. Tchang-Brillet and B. Kerkeni (LPMC, Tunis) and with support of the FP7-ITN « Laboratory Astrochemical Surface Science in Europe » (LASSIE, 2010-2013). Taking benefit from experimental facilities available at the laboratory (see Theme 4), the aim is to perfom joint experimental and theoretical studies of the formation of H_2 molecules on cold silicate surfaces. Preliminary studies are conducted, in collaboration with B. Kerkeni (LPMC, Tunis), S. Bromley (ICREA, Barcelone) et T.P.M. Goumans (LIC, Leiden), on gas-phase reactions between H-atoms and silicate cluster molecules (to be published).

Results : Our studies focused mostly on atom-diatom reactions corresponding to the formation and destruction pathways of the SiO and OH species. The relative low dimensionality of the systems (3D) allows to apply state-of-the-art quantum chemistry and quantum dynamics methods. Complementary approaches were also considered, quantum dynamics still being difficult to handle for systems containing heavy species. This is particularly true for the $Si+O_2 \rightleftharpoons SiO+O$ reaction, for which quasi-classical and statistical treatments of the dynamics provided detailed informations on the reaction mechanisms (Dayou et al., 2008). The close agreement with experiments for the rate coefficients showed the reactants fine-structure partition function to be at the origin of the decreasing reaction rates at high temperatures. Similar features were obtained very recently for the $Si+OH \rightleftharpoons SiO+H$ reaction, investigated in the Ph.D. thesis of A. Rivero-Santamaria (PhLAM, Lille) co-supervised by M. Monnerville (PhLAM, Lille) and F. Dayou. Due to the lack of measurements, only a rough estimate rate coefficient is actually reported in kinetic databases, and the constant value differs significantly from our strongly temperature dependent results. In the last five years, we put a particular emphasis on low temperature reactivity issues. Original theoretical models were developed in collaboration with B. Bussery-Honvault (ICB, Dijon) with the aim at providing an highly accurate description of long-range interactions between open-shell species. The use of such models to study the series of radical-radical reactions $X+OH \rightleftharpoons XO+H$ (with X=C, Si, O, S, N atoms) served to probe the influence of the interaction potentials on the temperature dependence of rate coefficients (Bussery-Honvault et al., 2008; Bussery-Honvault et al., 2009; Stoecklin et al., 2012).

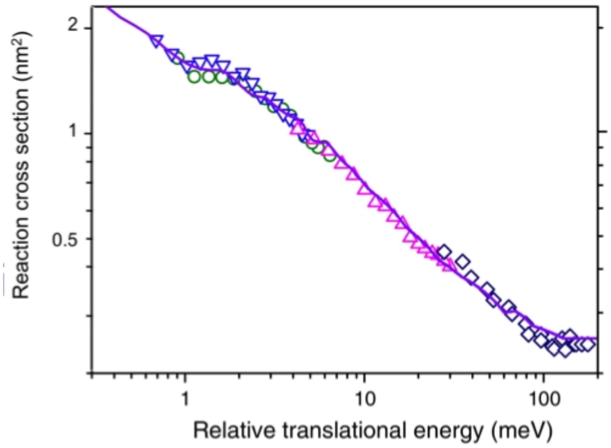


Fig. 4.2.2: Comparison between the integral cross-sections measured from crossed-beam experiments (ISM, Bordeaux) and theoretical results for the $S(1D)+n\text{-}H2 \rightleftharpoons SH+H$ reaction.

Highlight : A thorough study of the $S+n\text{-}H_2 \rightarrow SH+H$ reaction has been performed, including kinetics and crossed-beams experiments by I. Sims (IPR, Rennes) and M. Costes (ISM, Bordeaux) groups which could yield rate coefficients and integral cross-sections measurements down to very low temperatures (6K) and collision energies (<1meV). A close agreement with experiments could be achieved (Fig. 2) by means of quantum dynamics calculations and an accurate treatment of long-range interactions (Berteloite et al., 2010; Lara et al., 2011a). Crossed-beams experiments with specific para-H_2 beams were also performed, showing more pronounced oscillatory features in the cross sections that could be traced back as the signature of a sequential opening of quantum partial wave channels (Lara et al., 2011b). This work has been conducted in the frame of the ANR project "Cold Reactions Between Neutral Species" (2006-2009) led by M. Costes.

4.2.3. Theme 3. VUV Spectroscopy and Photophysics. Exobiology

Scientific Context : The VUV wavelength range corresponding to space observations by HST, FUSE and SOHO is relevant for electronic spectra of small molecules of astrophysical interest (ISM, stellar, solar and planetary atmospheres, exobiology). In the laboratory, we carry out their experimental study by using complementary techniques : high resolution 10m spectrograph of the Meudon Observatory, synchrotron radiation, VUV laser spectroscopy. We also perform the necessary theoretical studies to support interpretation of experimental results. The investigated systems include molecular hydrogen and isotopologues, CO, and exobiological relevant molecules such as aminoacids and nucleic acid bases. Results of VUV

Spectroscopy of atomic ions are presented within activities of Pole 2.

a) High resolution VUV spectroscopy of H_2/HD/D_2

The high resolution (150,000) 10 m spectrograph with concave grating of the Meudon Observatory is used for emission studies of the D_2 and HD molecules over a broad wavelength range (78 - 170 nm) with either photographic recording or detection by photostimulated phosphor image plate. Due to their large rotational constants, the spectra of these light molecules appear as complex line spectra. To speed up the analysis, we made use of visualization tools developed for atomic ion spectroscopy. The D_2 analysis was achieved with support of our theoretical calculations of level energies and transition probabilities taking into account up-to-date *ab initio* potentials and non-adiabatic couplings between the excited electronic states. A large part of D_2 emission data (78-124 nm) were published reporting D^1P_u -$X^1\Sigma^+_g$, D'^1P_u -$X^1\Sigma^+_g$ and $B'^1\Sigma^+_u$ - $X^1\Sigma^+_g$ transitions (Roudjane et al., 2007). For absolute calibration of wavelengths, a number of HD and D_2 lines were measured (Ivanov et al., 2008, Roudjane et al., 2008) with ultra-high precision ($\Delta\lambda/\lambda=10^{-8}$) by VUV laser spectroscopy in collaboration with W. Ubachs (LCVU, Amsterdam). The emission studies and laser measurements were presented in Mourad Roudjane's Ph.D. thesis (UPMC, 2007). Absorption studies at the synchrotron SOLEIL were carried out in collaboration with W. Ubachs on the D^1P_u -$X^1\Sigma^+_g$ transition for H_2 and D_2 including an analysis of the predissociation widths (Dickenson et al., 2010; Dickenson et al., 2011). The energy levels of the C ^1P_u state of D_2 and H_2 have been used to assess the validity of two distinct theoretical methods : coupled equations and multichannel quantum defect theory (MQDT), work published (Glass-Maujean et al., 2011) in collaboration with M. Glass (LPMAA, UPMC) and Ch. Jungen (LAC, Orsay). The work was supported by the PNPS (Stellar Physics National Programme) and by the ANR project SUMOSTAÏ led by Ch. Jungen. A high resolution specific scanner for reading image plates has been jointly funding by UPMC and CNRS in 2011.

Highlight: The most prominent HD lines at extreme UV wavelengths were measured by laser spectroscopy with ultra-high precision ($\Delta\lambda/\lambda=10^{-8}$). These data, together with FTS absorption measurements ($Dl/l=10^{-7}$) in an extended range at SOLEIL synchrotron, provided a reference database for comparison with quasar spectra observed at high redshift, in purpose to probe a possible variation of the proton-electron mass ratio $m=m_p/m_e$ on a cosmological time scale (Ivanov et al., 2010). For each line, sensitivity coefficients $K_i=d\ \ln l_i/d\ \ln m$ were determined from quantum calculations by varying the mass ratio m and using *ab initio* potentials.

b) High resolution VUV spectroscopy of CO

The CO molecule, used as tracer for H_2, gives rise to a rich photochemistry in the ISM. Lines of the most abundant isotope $^{12}C^{16}O$ are often saturated and the knowledge of other isotopic species is thus essential. In collaboration with S. Federman (Univ. of Toledo) and G. Stark (Wellesley College), we have been conducting exhaustive study of CO and its isotopologues taking advantage of the worldwide-unique VUV-Fourier Transform Spectrometer installed on the DESIRS beam line at the SOLEIL synchrotron. Main results concern the region between 92.97 and 93.35 nm, where many bands belonging to different Rydberg series are overlapping, have been unraveled thanks to the high instrumental resolution (350,000) and to numerical simulation of each band. Oscillator strengths and predissociation rates could be derived for $^{12}C^{16}O$ (Eidelsberg et al., 2012), and similar analysis are in progress for other isotopes (to be published). Our results helped to the development of theoretical models dealing with the interaction between Rydberg and valence states (Lefebvre-Brion et al., 2012). In addition, a large database on the $^{12}C^{16}O$ A-X bands is almost completed and will be available soon (SESAM database).

c) VUV spectroscopy and photophysics of molecules mainly relevant to exobiology

This work was carried out in collaboration with M. Schwell (LISA, Paris 7) and H. Baumgärtel's group (ICB, Berlin) using synchrotron radiation as excitation source at BESSY (Berlin) and SOLEIL (St Aubin). It involved absorption studies of spectra in the far UV (6-35 eV), including measurement of absorption cross-sections, mass spectrometry, ionic dissociation channels and phenomena related to autoionization. Recent investigated molecules are acetic acid, acetonitrile (S.Leach et al 2007, 2008 ; M.Schwell et al 2008a), acetamide (M.Schwell et al 2012a), amino acids (M.Schwell et al 2009), purines and pyrimidines (M.Schwell et al 2008b), formamide and its methyl derivatives (S.Leach et al 2010a), diacetylene (M.Schwell et al 2012b) and dicyanoacetylene.

Diverse applications of spectroscopy included: (i) Measurement, through CN radical interstellar UV absorption spectra, of the cosmic background radiation temperature, explaining why it differs from the temperature measured by COBE (S.Leach 2012b). (ii) Study of the part played by VUV radiation in exoplanets (S.Leach 2011). (iii) Implementation and application of a graphical method for testing the validity of published values of the heat of formation for molecules and molecular ions (S.Leach 2012a).

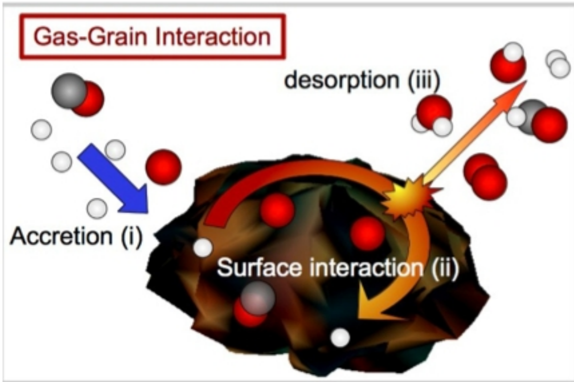
Highlight :Exobiology experiments in space were also conducted, such as the survival of plant seeds in the projects of ESA EXPOSE-E and EXPOSE-R on the exterior of the Columbus module of the International Space Station from 2006 to 2012. From the measured partial survival of arabidopsis thaliana seeds it has been possible to determine the protective and destructive structures and parameters, and to calculate the probability of transfer of life between Mars and Earth for these seeds in a direct flight through space (Zalar et al 2007a,b,c; Tepfer et al 2012). This work has been conducted in collaboration with D.Tepfer's group (INRA, Versailles).

4.2.4. Theme 4. Gas-Solid Interactions and Heterogenous Catalysis

Scientific context : Dust grains account for about one percent of the interstellar medium mass. These (sub)micronic particles provide surfaces on which chemical species can accrete, diffuse and react together. Molecules formed on grain surfaces range from the most simple, molecular hydrogen, to complex organic species like e.g. dimethyl-ether. Without any clear spectral signature, most of the complex molecules remain as minor constituents of interstellar ice mantles in cold and dense cores, and not accessible to astronomical observations. In the close environment of protostars (hot cores or hot corinos), the thermal and radiative processing of the mantles lead to the release of complex organic species in the gas phase, which become accessible to (sub)millimeter telescopes. However it is difficult to separate the effects of pure evaporation from subsequent processing in the gas phase. The analysis of meteorite and cometary samples provides additional constraints on the evolution of ice mantles. Most chemical models describing the surface chemistry in the ISM and star forming regions rely on phenomenological descriptions of the processes. The study of gas/surface interactions is at the interface between fundamental physics and astrophysics, where the interplay between theory, experiments and observational results is extremely fruitful and complementary.

Main objectives: Characterizing and understanding the fundamental molecular physics occurring on astrophysically relevant cold surfaces and discovering new synthesis pathways was the main object of our research activity. We have successfully achieved these goals, together with continuing to develop the technology required for such a work.

Scientific results: The gas-grain interaction theme can be described in three different stages. The first phase (i) concerns the accretion, sticking and accommodation of the gaseous species on a cold surface. On the contrary the last stage (iii) is the desorption, the return to gas phase. In the meantime (ii), the interaction on the surface itself, may include diffusion, reactivity, including energetic aspects, or specific interaction like Nuclear Spin Conversion.



We present an overview of our work and publications, following this organization, illustrated on the cartoon “Gas-grains Interaction”.

(i) Accretion:

We have studied the sticking efficiency of Hydrogen compounds on silicates and water ice, which is dependent on the gas temperature, and derived an analytical formula. (E. Matar et al. 2010) (H. Chaabouni et al. 2012), in collaboration with ISMO, Orsay.

(ii) Energetic aspects :

Energy released upon H_2 formation : (E. Congiu et al. 2009) (J. L. Lemaire et al. 2010) (L. Gavilan et al. 2012a, accepted)

-Impact on the morphology of water : (M. Accolla et al. 2011). Collab. with Catania.

(iii) Diffusion properties, specific surface interactions :

- Diffusion of H atoms on water : (E. Matar et al. 2008)
- Bulk diffusion of H_2CO in water: (J. Noble et al. 2012). Collab. with PIIM (Marseille).
- Nuclear spin influence, ortho and para states of H_2 (L. Amiaud et al. 2008) (Chehrouri et al. 2011) (L. Gavilan et al. 2012c, accepted), in collaboration with LPMAA (Paris).

(iv) Reactivity and Heterogeneous catalysis

- H_2 catalyzed formation (L. Gavilan et al. 2012b, accepted)
- H_2O formation : (H. Mokrane et al. 2009), (F. Dulieu et al. 2010),
- H_2, H_2O, Modeling and Monte Carlo simulation of the chemistry on the interstellar grains (Cazaux et al. 2008), (Cazaux et al. 2010), collab. with Kaypten Institute, (NL).
- CO_2 formation : (Noble et al. 2011), collaboration with Univ. Strathclyde (UK)
- NH_2OH formation : (Emanuele Congiu et al. 2012) (E. Congiu et al. 2012), in collaboration with Leiden

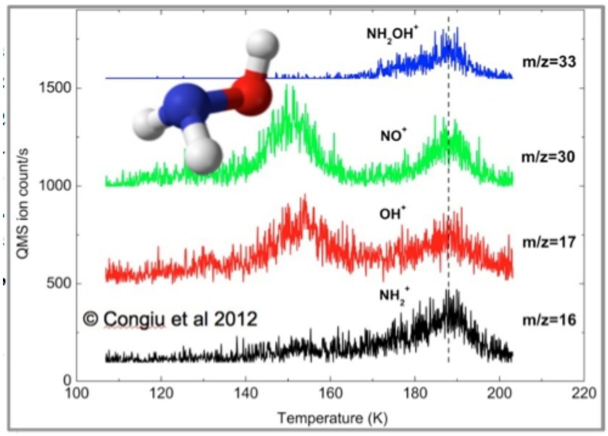


Fig. 4.2.3: Desorption spectra of different compounds observed after NO irradiation with H, on amorphous silicate surface held at 10 K. Adapted form Congiu et al 2012, ApJL.

Observatory (NL) and LPCMR (Paris).

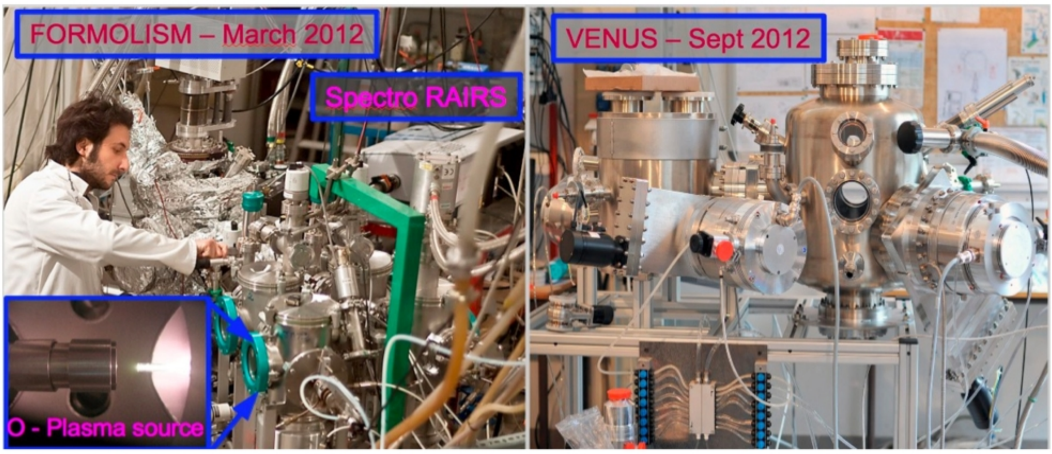
(v) Desorption processes:

Selective desorption, influence of substrate, role of isomers and isotopes : (Fillion et al. 2009) (Lattelais et al. 2011), (Kristensen et al. 2011) (Noble et al. 2012) in collaboration with LPMAA, LCT (Paris) and Strathclyde (UK).

Highlight: Among the different aspect of our research, the synthesis of NH_2OH, is the most emblematic success of our team. It follows H_2O and CO_2 formation. This molecule has the advantage for a broad audience, to be considered as a missing link to the presence of amino-acids observed in meteorites. This work has been done in association with H. Linnartz, Leiden Observatory, and P. Parent & C Laffon LPCMR Paris.

4.3. Technological developments

The FORMOLISM experimental platform located in Cergy Pontoise, is an ultra-high vacuum (UHV) chamber coupled to two triply differentially pumped atomic or molecular beams aimed at the temperature-controlled (6K-300K) sample. During the 2007-2012 period, FORMOLISM has been the main (but not unique) scientific instrument providing scientific results. Two complementary contracts, SESAME région Ile de France (HONIRISM, 2007-2013), and ANR contract ("IRHONI" 2007-2011, PI J.-L. Lemaire), have supported this development. Significant improvements have been achieved (see picture below). A *Reflection-Absorption Infrared Spectrometer* is now operational. Lower temperatures can be reached (6.3 K, vs 9 K previously). *The O-beam technique* is now well handled and our home made O-beam has currently 70% of dissociation rate, far above any commercial devices (around 20%). For now, unique in the laboratory astrophysics community, one of the atom/molecular beam is temperature-controlled (25-400 K). Thanks to this specific technology, we have derived the sticking coefficients of hydrogen compounds (Matar et al 2010, Chaabouni et al 2012).



We have also introduced a larger variety of samples. Our studies, initially focused on *water ice*, can be performed on *silicates* or on *graphitic samples* as well. The production of different (in composition and morphology) well characterized silicate samples has been achieved in collaboration with a German laboratory. H_2 formation will be studied on this sample.

The development of a new experimental set-up, called VENUS *Vers de Nouvelles Synthèses started in January 2012*, in order to increase the throughput of the Platform, and extend it to real time monitoring reactivity. This setup will be equipped with a new real-time RAIRS, 3 to 5 beams with adjustable fluxes, and a rotatable cryogenic sample-holder.

4.4. Production and visibility

We present here present here some key indicators, summed over the whole pole 3.

	2007	2008	2009	2010	2011	2012	Total
ACL	27	25	17	25	53	15	162
INV**	2	11	4	8	8	6	38

** invited conferences only, presented by members of Pole 3

During the period 8 thesis have been defended, 4 are in progress. Members of Pole 3 have been jury members of 23 french PHD thesis, 7 international thesis, 4 Habilitations.

18 international collaborations have been achieved by publishing at least one article. In particular we have strong collaborations with various Spanish and Dutch colleagues.

17 french collaborations have been established. Among them, the collaboration with LPMAA, is the most productive (8ACL), and is related to theme 3 and 4.

4.5. Summary

Molecular physics dedicated to astrophysics have made impressive progresses during the last five years. The Pole Molecules in the Universe of the LERMA laboratory, as well as the LPMAA laboratory have qualitatively and quantitatively contributed to the development and visibility of this field, placing Paris in a leadership position.

Interplay between fundamental physics and observational constraints is very fruitful, and collaboration with Theme 2 LERMA has grown over the period (Sulfur chemistry, o-p H2 and deuteration...). Progresses on both sides unveil clear new challenges, and need for extended collaborations, that will be proposed for the next years.

Integration of the LPMAA will permit to accelerate the theme convergences, initiated with the reactivity subject, (gas and solid phase). The complementarity of expertises inside this new perimeter leads us to reorganize our themes. New synergies appear more clearly inside the future unified Pole “Molecules in the Universe”, and with other poles of LERMA (2 and 4).

5. Pole 4: Instrumentation and remote sensing

Thematic Pole 4

Have contributed to research in Pole 4 since 2007 :

Teaching and Research staff : *E. Defer, P. Encrenaz, A. Maestrini, C. Prigent, M. Salez, F. Viallefond, M. Wiedner*

PhD Students: *F. Bernardo, Y. Brouet, V. Galligani, G. Gay, P. Gellie, C. Jung, J. Kolassa, W. Miao, M. Paul,J. Treuttel, H. Wang, K. Zhou*

Postdocs: *M. Benzaza, J. Siles, F. Yang*

Engineers: *G. Beaudin, F. Boussaha, M. Caillat, A. Coulais, F. Dauplay, B. Delforge, Y. Delorme, A. Féret, L. Gatilova, C. Jimenez, J.-M. Krieg, R. Lefèvre,N. Moreau, B. Ooghe, J. Treuttel, C. M. Zwölf*

5.1. Introduction

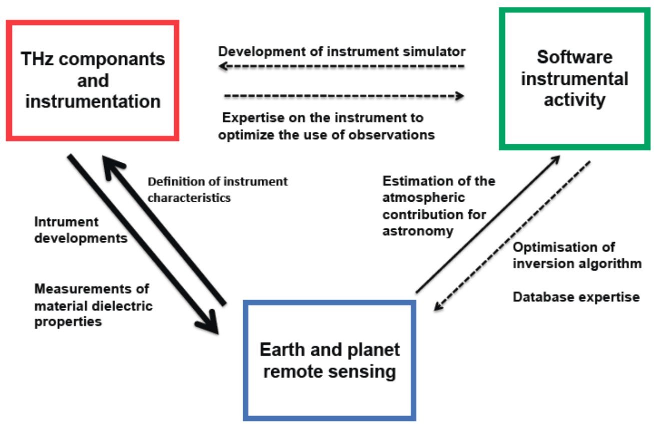


Fig. 5.1.1: Links between the three components of Pole 4. Bold lines indicate strong interactions, solid lines good interaction, and dotted lines mention links that could be strengthened.

Pole 4 comprises the research activities in instrumentation, both hardware and software, as well as the satellite Earth and planet remote sensing studies that are closely linked to the instrumentation developments. LERMA is a key actor in Europe in the research activities on milllimeter to THz components and instrumentation, with active participation in space borne missions within international collaborations. The modelling of the instrumentation, the processing of the data, and the development of Virtual Observation strategies are part of new research fields (duly recognized by Section 7 of CNRS for instance). The Earth and planet remote sensing activities of LERMA are internationally recognized. LERMA is one of the leading groups in atmospheric and surface analysis from satellites, with the production of Earth geophysical variables for use by the climate and meteorological communities.

5.2. The THz Instrumentation Group

The main goal of the THz instrumentation group, also called GEMO (*Groupe Expérimental Micro-Ondes*), is to advance basic knowledge in THz devices, and to develop new technologies or circuit concepts in order to be able to propose some instruments as PI or as a key partner in international consortia. LERMA THz instrumentation group is specialized in THz heterodyne detection , which provides unique insight of the physics and chemistry of the interstellar medium and the atmosphere of planets, including the Earth. The group is working closely with astronomers and physicists of LERMA or LESIA to define its research strategy.

The THz instrumentation group has delivered critical parts of space instruments, the Microwave Instrument for the Rosetta Orbiter (MIRO) and the Heterodyne Instrument for the Far Infrared onboard Herschel (HIFI) and is actively participating in international consortia to build new instruments. It proposed a balloon-borne heterodyne instrument working in the 2.4-2.7 THz band to CNES (CIDRE which stands for Campagne d'Identification du Deutérium par Réception hEtérodyne) and it is part of the consortium of the Sub-millimetre Wave Instrument (SWI) for the JUICE mission (JUpiter ICy moons Explorer).

The THz instrumentation group has three main R&D axis: THz Hot Electron Bolometer mixers (HEB), integrated receivers based on Superconductor Isolator Superconductor (SIS) junctions or arrays of junctions, and Schottky diodes technology for THz frequency multipliers and mixers.

5.2.1. Highlights of the 2007-2012 period

This section highlights the group main successes. The details are given in the following sections.

1. Development, fabrication and test of two SIS mixers in the 480-640GHz band for HIFI on the Herschel satellite, which have state-of-the-art in-flight performances.
2. The project CIDRE enters a Phase A at CNES.
3. The LERMA THz instrumentation group is part of the SWI consortium, which is on the preselected instrument payload of JUICE.
4. Development and fabrication of a 2.5 THz Hot Electron Bolometer (HEB) mixer with state-of-the-art noise figure.
5. Design of the world's first electronic source working at room temperature in the 2.5-2.7 THz band.
6. Establishment of a novel planar Schottky diodes process for building THz frequency multipliers or mixers.
7. First demonstration in the 370-520 GHz band of an array of small SIS junctions pumping an SIS mixer integrated on the same circuit..

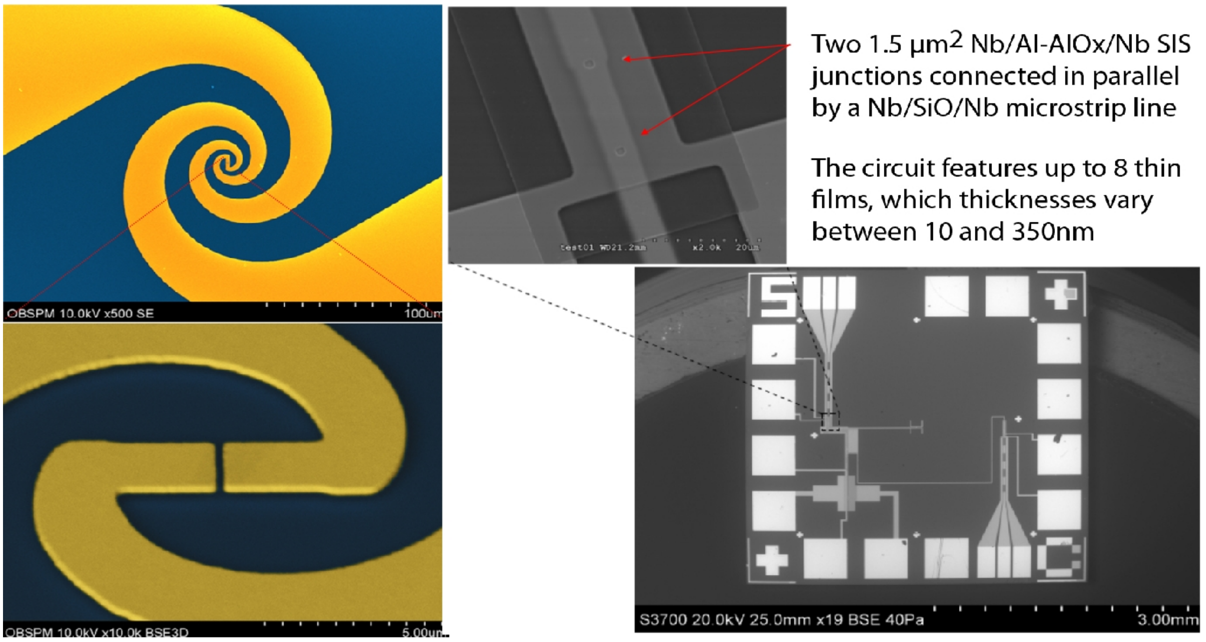


Fig. 5.2.1: SEM (Scanning Electron Microscope) pictures of LERMA 2.5 THz HEB mixer chip (Left). The fabrication was performed by LERMA staff members in the cleanroom of Laboratoire de Photonique et Nanostructures-CNRS. SEM pictures of an integrated SIS receiver fabricated at LERMA (right).

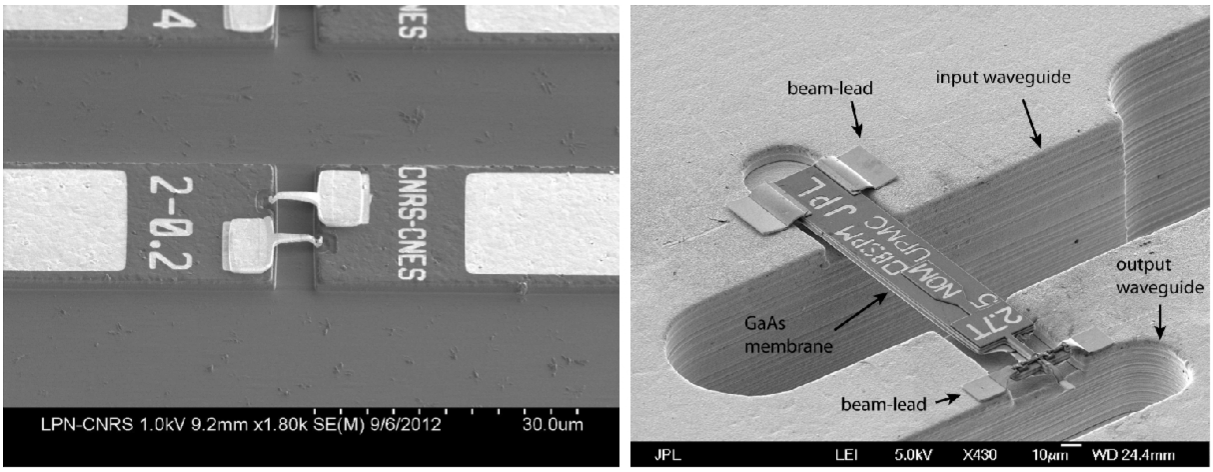


Fig. 5.2.2: SEM pictures of nano-Schottky diodes designed at LERMA, fabricated by LERMA at LPN-CNRS with GaAs substrates grown by LPN-CNRS (left). SEM picture of the 2.7 THz frequency tripler designed by LERMA and fabricated by Jet Propulsion Laboratory (right).

5.2.2. Large instrumental projects

a) *Herschel HIFI Mixer*

LERMA HIFI band 1 SIS mixers at 480-640 GHz have shown excellent in-flight stability and noise performance. They feature devices designed at LERMA and fabricated by LERMA staff members in the cleanroom of the Institut de RadioAstronomie Millimétrique (IRAM). Out of seven bands, band 1 was involved in 38% of the proposals for HIFI, leading to numerous journal papers (T. de Graauw, al. 2010).

b) CIDRE

Campagne d'Identification du Deutérium par Réception hEtérodyne is a project to design and build a 2.7 THz heterodyne receiver, which will be flown by a balloon to 40km altitude to observe HD and OH in the universe. As deuterium has only been formed in the Big Bang and is now destroyed in stars (astration), the ratio of D/H is a measure for the star formation history since the beginning of the universe. In molecular clouds basically all of the deuterium is locked in HD, whose fundamental transition lies at 2675 GHz, which CIDRE will be able to observe. OH is an important molecule in the O2 and water cycles, whose chemistry is still poorly understood. Observations of OH (with CIDRE at 2510 and 2514 GHz) will shed light on these chemical processes.

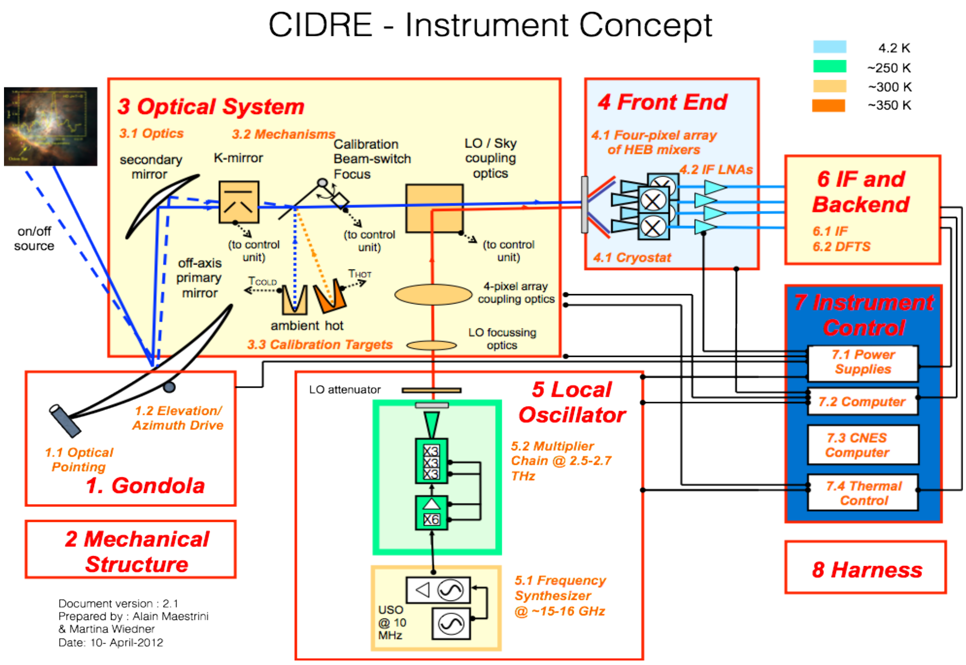


Fig. 5.2.3: CIDRE instrument concept.

Last but not least CIDRE is also meant to be a demonstrator of the THz technology recently developed at LERMA, and a test bed for future space mission as well as instrumentation for ground based telescopes. The key components of CIDRE will be the hot electron bolometer (HEB) mixers and the local oscillators (LO). The research and development of the past years allowed us to design and produce one of the world's best HEB mixers. LERMA played a leading role in the design of the multipliers that led to the construction by JPL (USA) of the first multiplier chains at 2.5-2.7 THz. These components will allow us to build a state of the art balloon experiment. CIDRE was selected by CNES for phase A study in 2011 and LERMA is currently working on a detailed design in partnership with GEPI (for the optical and thermo-mechanical design of the telescope), DT-INSU (for the thermal study of the gondola including the instrument, and the mechanics of the receiver and the backend), and with technical expertise from CNES balloon division.

c) SWI-JUICE

The Submillimeter Wave Instrument for JUICE is a 10 kg / 50 W heterodyne instrument with two channels at 550 GHz and at 1200 GHz that will observe the atmospheres of Jupiter and Ganymede. It features a 30 cm offset-parabola dish that can move along two axis. Its spectral resolution is 100 kHz and its absolute frequency accuracy is 10^{-8} which has to be guarantee over the entire mission. The instrument is lead by MPI in Lindau, Germany, with other members of the consortium coming from the USA (JPL), Japan, Sweden (Omnysis), Switzerland and France (LERMA & LESIA). LERMA is responsible to deliver the reference frequency (USO) at 10 MHz and two W-band synthesizers working at 88-104 GHz. The synthesizers will be built by the French industry up to Ka-band (29-35GHz) while LERMA will design and build the multiplication stage from Ka-band to W-band. The last stage multiplier of the 275 GHz local oscillator is expected to be designed by LERMA using an existing design from the work of one of our former Ph.D. students who defended her thesis in 2009. Her work was part of an R&D program financed by CNES and ESA.

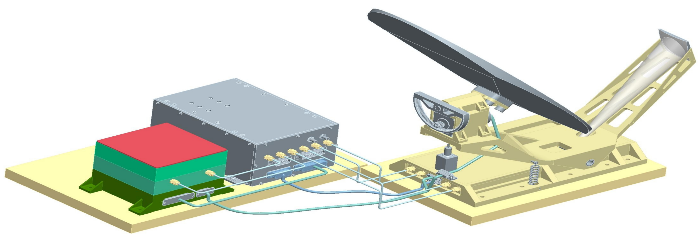


Fig. 5.2.4: 3D model of the SWI-JUICE. LERMA is responsible of the delivery of two W-band synthesizers.

d) ISMAR

THz instrumentation group has worked closely with the remote-sensing group to propose to the FP7 program to build additional channels at 875 GHz and at 424 GHz for the ISMAR instrument operating on an UK Meteorological Office aircraft. This instrument is dedicated to the study of clouds in the Earth atmosphere. LERMA proposed to build channels with receiver front-end based on the Schottky diode technology developed in partnership with LPN. This proposal was part of a consortium lead by Météo-France, who ranked it highest among the French proposals, but Météo-France failed to be financed by EU. It will be resubmitted soon.

5.2.3. Research and Development

LERMA has a strong involvement in R&D programs to study new types of devices or new circuit topologies. This research is intended to advance the knowledge of their respective fields and to give LERMA the possibility to lead the development of instruments or critical parts of instruments. The following R&D programs are in the continuation of previous year R&D programs.

a) HEB mixers

The main R&D program of the LERMA THz instrumentation group is on hot electron bolometers that are the most sensitive devices for heterodyne receivers working above 1.4 THz. The group is working on innovative designs of arrays of HEB mixers. Currently, the LERMA THz instrumentation group is actively studying the possibility to implement 4 HEB mixers on a thin membrane of dielectric with micro-mirrors as focusing elements.

The LERMA THz instrumentation group is developing its own HEB process in partnership with LPN, i.e. staff members of LERMA are working in the LPN clean-room. The HEB device fabrication process established by LERMA requires fewer steps than competing one's, potentially improving the uniformity of arrays of THz HEB mixers. As highlighted earlier, one of the mixers designed and fabricated by the LERMA THz instrumentation group is one of the most sensitive mixers worldwide at 2.5 THz (state-of-the-art noise figure). This R&D axis is mainly financed by CNES and the FP7-RADIONET program.

The THz instrumentation group is also actively working on the coupling of the radiation produced by THz Quantum Cascade Lasers to HEB mixers. QCLs need to be cryogenically cooled. They can be used as local oscillators provided that they operate in a single mode and that they can be phase-locked. LERMA is collaborating with Université Paris-Diderot-MPQ and IEF for testing QCLs with its HEB mixers.

b) Schottky diodes process and novel associated circuits

Schottky diodes are essential to build frequency tunable local oscillators with sufficient power to pump THz mixers. Schottky diodes are necessary to build low-noise receivers working at room temperature or at temperatures in the range of 120-150K that can be attained in space with passive cooling. The ability to work in a wide range of temperatures, including room temperature, is a key advantage of Schottky diodes over alternate devices for planetary missions like JUICE, or for the remote sensing from space of the Earth.

LERMA launched an important R&D program in partnership with LPN to setup a Schottky diode process on GaAs with the potential to reach the state of the art. Staff members of LERMA are working in the LPN clean-room for processing the Schottky devices, while LPN is growing the semiconductor material. Developing a process to demonstrate truly functional THz circuits with optimum performances is a long-term endeavour that has been being supported by CNES and CNRS for several years. With this process, the LERMA THz instrumentation group intents to build its own THz circuits for several projects like CIDRE, SWI-JUICE or EUFAR-JRA1 and for the next generation of heterodyne instruments.

As a mater of fact, the LERMA THz instrumentation group has a leading position in designing THz Schottky circuits such as frequency multipliers and mixers. For Jet Propulsion Laboratory it has designed the first electronic source working at room temperature at 2.5-2.7THz. In addition, the group has led some important research in Europe in the design of combined mixer and frequency multiplier circuits as well as multi-symmetry frequency multipliers. This research is intended to miniaturize the circuits and therefore to facilitate the fabrication of arrays of Schottky receivers.

The vast library of THz circuit designs that the LERMA THz instrumentation group has built for other groups can be utilized for its own process, giving it a long sought independence. Actually, state-of-the-art circuits designed for JPL are subject to ITAR regulations and cannot leave the USA.

c) Fully integrated SIS receivers.

Up to about 1.25 THz, the most sensitive high-resolution heterodyne receivers are based on Superconductor-Isolator-Superconductor (SIS) tunnel junction mixers with a noise temperature approaching the quantum noise limit for coherent receivers. Such receivers are in wide use in ground-based telescopes such as the Atacama Large Millimeter Array and in the Herschel Space Observatory. A conventional submillimeter receiver consists of a single mixer quasi-optically coupled to an external local oscillator.

Over the 5 past years, the LERMA THz instrumentation group has undertaken the development of low-cost, compact, lightweight and low power consumption heterodyne receivers by integrating on the same circuit a SIS mixer and a local oscillator made of a one dimensional (1D) array of small SIS junctions connected in parallel by superconducting micro-strip lines, which can be viewed as a discretized Josephson transmission line (DJTL). Tests in the 370-520 GHz band performed on a demonstration circuit have shown that the SIS mixer was pumped by the array of small SIS junctions. This is an important step toward building fully functional wideband integrated SIS receivers. Several publications in international journals have been published, and, as a side product of this research, a patent on the use of Josephson junction array made of high Tc superconducting materials as sub-millimeter source has been jointly filed in 2010 with the High Tc Superconductors and Signal processing group of Thales-CNRS (UMR 137).

d) Measurements of the complex dielectric constant of material at sub-millimeter wavelengths

LERMA THz instrumentation group set up a measurement bench for measuring, up to 360 GHz, with an AB Millimetre vector analyzer, the complex dielectric constant of sands and rocks similar to those found on the surface of planets and asteroids. These measurements are important for understanding the data provided by space-borne radiometers or large ground-based telescopes working at sub-millimeter wavelengths, and are performed in collaboration with the remote sensing group in Pole 4.

In addition to give valuable data to scientists, this bench is used since 2011 by fourth year under-graduate students of the Ecole Polytechnique Universitaire of the Université Pierre et Marie Curie for their 60 hour microwave project. They learn the basics of dielectric constant measurements at millimeter and sub-millimeter wavelengths practicing on a world-class research equipment. This educative experiment could be extended to other students of the university since it connects research and education in an efficient way : the physics behind the experiment is at the level of the students, the practical work is difficult, but students can acquire by the end of their project useful data for scientists of the group. The interest and the motivation of students have been found very high during the past two years.

5.2.4. Research collaborations

The group has worked closely with astronomers of LERMA or LESIA to define its research strategy and has built long-standing national and international collaborations, over the years.

a) Laboratoire de Photonique et Nanostructures (LPN-CNRS).

The most important collaboration is with LPN-CNRS, which is a partner and has excellent facilities for developing key technologies necessary to build THz receivers. Staff members of LERMA are working in LPN clean-room.

b) Jet Propulsion Laboratory.

The LERMA THz instrumentation group has a strong and long-lasting collaboration with Jet Propulsion Laboratory. The group collaborates on THz sources based on frequency multiplication and on Schottky mixers. Many journal publications have been written in common. This collaboration strengthened when the Observatoire de Paris-LERMA signed a Technical Assistance Agreement with the Department of State of the United States to exchange ITAR-controlled information on Schottky technology. This contract facilitates the collaboration, in particular for the project SWI-JUICE. In addition, two former Ph.D. / post-docs of LERMA have found permanent staff positions in the team that the group is collaborating with.

c) Collaboration with groups in China.

An important international collaboration is with the Purple Mountain Observatory, Nanjing, China, on the design of superconducting mixers and on the processing of the Intermediate Frequency (IF) signal. Over the past four years one PhD thesis has been defended and another one has started. In addition, a lecturer of the University of the South East, Nanjing, China, worked at LERMA for 12 months with members of the Schottky technology group under a grant from the Chinese Academy of Sciences. The Scientific Council of the Observatory of Paris granted him an affiliation with LERMA for two years to continue his collaboration.

d) Rutherford Appleton Laboratory.

Since 2006, the LERMA THz instrumentation group collaborates with RAL on several ESA and EU-funded R&D projects concerning the development of Schottky diode technologies. A former Ph.D. student of LERMA-GEMO is now permanent staff in the team that the group is collaborating with.

e) Participation in national and international research communities.

The LERMA THz instrumentation group participates in the GdR (Groupement de Recherche) “Microwave radiometry for the study of the atmosphere” (see details in next section) and the International GdR ”Semiconductor sources and detectors of THz frequencies”. It is also a member of the Groupe d’Intérêt Scientifique “DIspositifs Avancés Microondes Optoélectroniques et Nanométriques“(GIS DIAMON) that includes 11 laboratories in and around Paris (public, academic (CNRS, Universities), industry (Thales) and Defense (DGA).

5.2.5. Equipment and lab facility upgrade

During the past 4 years, the LERMA THz instrumental group made major investments for its laboratory fabrication and test equipment:

- Complete upgrade of the micro-assembly laboratory of the LERMA THz instrumentation group.
- Acquisition of an electronic microscope and a sputtering machine to deposit NbN and Nb thin films. This important piece of equipment was acquired by LERMA with a SESAME grant from the region Île de France. It will be used for R&D programs of the LERMA THz instrumentation group and other research groups in Paris, belonging mainly to Paris Sciences et Lettres IDEX.
- Acquisition of a 1.4 THz and a 2.7 THz local oscillator chain from Virginia Diodes Inc, USA, two high-end 20 GHz and 40 GHz synthesizers, a 40 GHz spectrum

analyzer and several W-band power amplifiers and sources, for testing HEB and Schottky mixers or frequency multipliers. These sources can also be used for other applications like molecular spectroscopy in collaboration with other scientific groups in France.

- Upgrade of LERMA precision diamond saw for cutting and thinning GaAs wafers in preparation of the project SWI-JUICE. Efforts have been put in securing operations due to the health hazards that thin particles of GaAs can lead to.

5.3. Earth and Planet Remote Sensing activity

The Earth and Planet Remote Sensing component at LERMA revolves around the microwave radiometry from satellites. Different aspects are covered, including the analysis of satellite observations, the modelling of radiative transfer, and the development of inversion methods. It is based on a solid collaboration with the instrument group of LERMA and projects couple science and instrument studies.

The activity of this component overlaps three INSU divisions: O*cean-Atmosphere*, C*ontinental Surfaces and Interfaces*, A*stronomy and Astrophysics*. This is an ideal situation to exercise multidisciplinary activities, but very often lelads to a difficult administrative position (to sollicit new positions for instance).

A GdR was formed in 2008 around the microwave radiometry: 'Microwave radiometry for the study of the atmosphere ' (http://aramis.obspm.fr/~gdr/GDR/Home.html). It is led by our group. It strengthens the links between the French labs involved in microwave remote sensing of the Earth atmosphere. This GdR has connections in Europe and in the US and it organizes annual roundtables and workshops.

We explore two main research areas: the analysis of clear and cloudy atmospheres and the characterization of terrestrial and planetary surfaces. The aim is first to understand the physical environment and second, to accurately estimate atmospheric and surface information from satellites. The complexity of the problems to be solved has led us to develop methodologies that combine the analysis of a large variety of satellite observations at different wavelengths, along with model outputs and in situ measurements. The Earth is our primary focus, but we are also involved in the analysis of other objects of the solar system (i.e, Titan, comets), using similar observation techniques and methodologies.

A transfer of know-how has been established between the CNRS and a start-up issued from this group (Estellus). Part of the operational aspects of this activity is now performed by Estellus.

Despite very limited manpower, this component benefits from a large international recognition, with strong collaboration with many labs in France (e.g., LMD, LEGOS, CESBIO, LA) in Europe (e.g., University of Kiruna, Köln University, UK Met Office) and in the US (NASA/GISS, City College NY, AER), and active participation in a number of international projects and committees (GEWEX, ITOVS).

5.3.1. Analysis of clear, cloudy and rainy Earth atmospheres

Compared to visible and infrared satellite observations, microwaves are less sensitive to clouds and to a certain extent microwaves can probe through the clouds. Microwave satellite data up to 190 GHz are now available operationally for meteorology to provide profiles of temperature and water vapour even under cloudy conditions, but their use is still limited over land surfaces, due to the contamination of the signal by the surface radiation. Thanks to our estimation of the land surface microwave emissivity at global scale (see section below), we developed methods of **inversion of atmospheric profiles over land with microwaves**, for example for the operational algorithm of the Saphir instrument on board the Indo-French Megha-Tropiques mission (Aires et al., QJRST, 2012; Bernardo et al., QJRMS, 2012). Our estimate of the surface contribution is also adopted for the retrieval of precipitation over land (Co-I of the Global Precipitation Mission science team). It paves the way for the use of microwave observations over land in the operational weather forecast centres.

As part of the objective to optimize the use of satellite data, the **synergy of visible, infrared, and microwave observations** has been rigorously quantified for the retrieval of temperature and humidity profiles over ocean (Aires et al., JGR, 2012). It showed the impact of microwaves, even under clear atmospheres. This work, initiated through an ESA contract, is now extended over land by a PhD student (Paul et al., JGR, 2012).

Regarding cloudy atmospheres, we focused over the last years on the **analysis of the ice phase in the clouds and its quantification**. The impact of ice clouds on the global Earth energy budget is still unclear, with orders of magnitude differences in the ice cloud amounts predicted by Global Climate Models (GCMs), as well as from present satellite observations. To reduce these problematic uncertainties, observations at millimeter and sub-millimeter wavelengths have been suggested. Today, these measurements are not available from Earth observation satellites, and our team actively contributed to promote the development of a millimeter sub-millimeter instrumentation on board satellite. First, we carefully analyzed the sensitivity of this wavelength range to the cloud ice phase, from multi-wavelength radiative transfer calculation using state-of-the-art radiative transfer model (ATM, ARTS) coupled with realistic meso-scale cloud simulations (Meso-NH). Retrieval algorithms for both ice and liquid clouds and rain were developed, based on these simulation, to prove the interest of the millimeter sub-millimeter observation to quantify the cloud ice phase and rain (Meirold-Mautner et al., JAS, 2007; Mech et al., IEEE TGRS, 2007; Chaboureau et al., JAMC, 2007; Defer et al., JGR, 2008). This work was performed in the framework of ESA, EUMETSAT, and CNES contracts, in close collaboration with French (LMD, LA) and European Partners (Köln University, University of Kiruna). It leads to the submission of a mission to ESA 8th Earth explorer call (the CloudIce mission; Buehler et al., AMT, 2012) that was not accepted (first on the rejected list). However, very recently, EUMETSAT decided that the next generation of European meteorological satellite (MetOp-NG) will carry a millimeter-submillimeter instrument (ICI). In order to prepare the exploration of this wavelength range, ESA supports the development of an airborne demonstration. The ISMAR (International Sub-Millimeter Airborne Radiometer) is currently built by the UK Met Office and ESA for an implementation on the UK Met Office BAe-146 aircraft (Charlton et al., 2009). Our team is involved in the definition of the instrument specifications, on the elaboration of the validation strategy of the demonstrator and on the assessment of the theoretical performances of the instrument. An extension of the ISMAR instrument to higher frequencies (up to 874 GHz) was suggested to FP7 by a consortium led by LERMA (both the technical group and the remote sensing group), but this proposal has not been supported yet. One of our PhD students, supported by CNES and EADS-Astrium, works on realistic radiative transfer simulations from observational and model based atmospheric profiles at the millimeter and sub-millimeter wavelengths, concentrating now on the retrieval of snowfall, a variable that is still very difficult to measure from satellite.

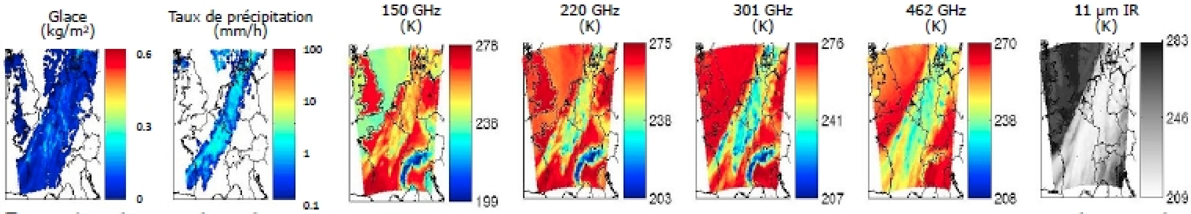


Fig. 5.3.1: Sensitivity of the millimeter / sub-millimeter to the presence of ice. Simulations using state-of-the-art radiative transfer model (ATM) and outputs from mesoscale cloud model (Meso-NH).

We demonstrated in the past the link between the presence of graupels in convective clouds as reported from passive microwave (and sub-millimeter wave in the future) and the occurrence of lightning flashes. We were involved in a series of studies dealing with the analysis of lightning and cloud observations as recorded by ground- and space-based instruments in order **to document the electrical and microphysical properties of the convective clouds** over Europe and the Tropics. In addition, in preparation to the future space-based Meteosat Third Generation (MTG) Lightning Imager (LI), our group designed a validation and verification strategy of this innovative instrument for EUMETSAT.

5.3.2. Multi-satellite estimations of Earth surface parameters and their analysis

Our activity on the continental land surfaces is initially based on passive microwave satellite observations. We calculated microwave emissivities directly from satellite observations, with the help of auxiliary data to remove the contribution of the atmosphere and the modulation signal by the temperature of the surface. Microwave emissivity atlases have ben produced, on a monthly basis, over 15 years. They are distributed to the community and used in a large number of institutions, internationally. **A land surface microwave emissivity parameterization** (TELSEM for Tool to Estimate the Land Surface Emissivities at Microwaves) is based on this data set and this software is now distributed with the European community radiative transfer model (RTTOV) (Prigent et al., IEEE, 2008; Aires et al., QJRMS, 2011). Once these emissivities are calculated, they can be used for a large variety of applications. First, by inversion of microwave observations over land, surface skin temperatures can be estimated, regardless of cloud cover. A long time record of land surface temperature from microwaves has been produced and evaluated (Catherinot et al., JGR, 2011). This complements the infrared observations that are blocked by clouds. Second, with a good knowledge of the land surface contribution, the atmospheric properties, even close to the surface, can be extracted from the satellite observations as described above.

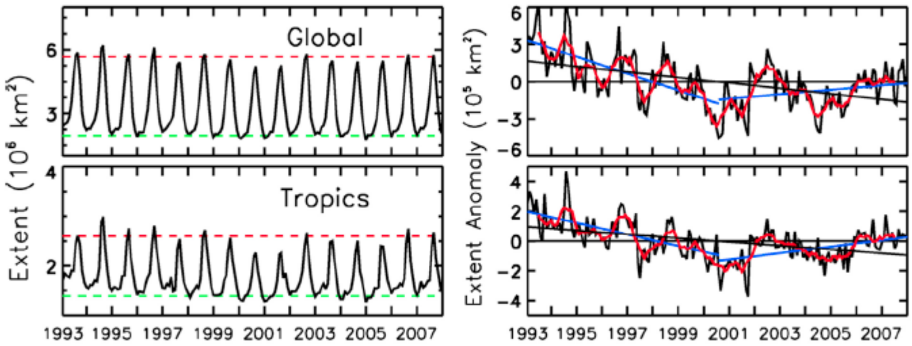


Fig. 5.3.2: The surface water extent and their anomalies from 1993 to 2007. Left: Monthly-mean surface-water extent for 1993– 2007 in black, for the globe (top) and the Tropics (30°S–30°N). Right: Corresponding deseasonalized anomalies (black) with the 6-month running mean (red); statistically significant changes in surface water extent (black and blue) estimated

Finally, these emissivities are sensitive to a large range of surface properties (soil moisture, standing water, vegetation, snow…), and as a consequence, they can help provide information on these parameters, potentially combined with other satellite observations with complementary sensitivities. We have developed methods to take advantage of the synergy between the different satellite observations, and we applied it to the estimation of various surface properties. We produced a **global estimate of wetland extent** for the last 15 years. The analysis of this dataset showed that the wetland extent has decreased (Figure 7), and the population pressure on these sensitive areas has been evidenced (Papa et al., JGR, 2010; Prigent et al., GRL, 2012). This dataset has been distributed to more than 40 institutions around the world. The wetlands are a major source of atmospheric methane, a very powerful greenhouse gases, and our dataset is a unique information for the modelling of methane emissions (e.g., Ringeval et al., GBC, 2010; Petrescu et al., GBC, 2010; Hodson et al., GRL, 2011). It also helps evaluate hydrological modeling (Decharme et al., JGR; 2008, JC, 2011), or is used for the estimation of river water storage (Frappart et al., JGR, 2008; HESS, 2010). Using a combination of satellite observations and land surface model outputs, **latent and sensible fluxes** over land have been estimated (Jimenez et al., JGR, 2010). Our group significantly contributed to the GEWEX LandFlux activity and co-led the international LandFlux inter-comparison (Jimenez et al., JGR, 2011; Mueller et al., GRL, 2012). A PhD thesis is also underway to produce **soil moisture estimates** at global scale from combined satellite observations, including passive and active microwaves and thermal infrared. Other activities included the evaluation of infrared derived surface temperature, a key variable for the radiative budget of the planet that is still subject to significant errors (Jimenez et al., JGR, 2012). We also contribute to a better understanding and estimate of the IR land surface emissivity (Jimenez et al., JGR, 2010; Paul et al., JGR, 2012), in order to improve the surface skin estimation from infrared observations and the retrieval of atmospheric parameters in the low atmosphere from surface-sensitive infrared channels. Note that our general expertise in the retrieval of surface parameters from multi-satellite observations also led to fruitful collaboration with oceanographers, for the **retrieval of sea surface wind speed** (Quilfen et al. JGR, 2007) and for the preparation of a future ESA satellite missions for the retrieval of sea surface temperature.

We work very actively on the retrieval of a large number of surface parameters from multi-satellite observations. Our products (some of them unique) are distributed to a wide international community and we are part of international committees (GEWEX, ITOV) and numerous projects (CNES, ESA, NASA, NOAA) related to these activities.

5.3.3. Analysis of planetary observations

The Cassini mission orbits around Saturn since 2004, and flies by Titan every 3 weeks. Analysis of Titan surface combines Cassini microwave observations in passive and active modes. The **presence of dunes on Titan** has been evidenced, with distribution related to the latitude and terrain altitude (Le Gall et al., Icarus, 2012) as well as **young craters. Lake and seas of liquid ethane and methane** were also discovered, and their behaviours are still under investigation. These spectacular results have also generated article in the international press, as well as TV shows. These studies are performed in collaboration with JPL, Bordeaux Observatory, Paris VII, and IPGP.

The ESA Rosetta mission will complete the most detailed study of comets ever attempted. It carries two microwave instruments: MIRO and CONSERT. In order to analyze the asteroid observations (Steins and Lutetia) and to prepare the analysis of these observations, **measurements of dielectric properties** of porous granular materials and meteorites have been undertaken on a large range of frequencies encompassing those of MIRO and CONSERT. A PhD student (Yann Brouet) set up all the necessary instrumentation with the help of the technical group and is conducting these measurements. Measurements at 190 GHz currently in progress on a lunar simulant with a quasi-optical bench mounted in transmission, and experiment in reflexion will soon be conducted with different samples.

5.4. The software instrumental activity

The software instrumental activity of this pole focuses on astrophysical data processing and storage. These data come both from instruments (e.g., ALMA, NOEMA, Planck, SKA) and from numerical simulations. Our activity concerns all the aspects and problems related to data consolidation, data storage and perpetuation, data diffusion and sharing.

5.4.1. Data consolidation activity

This double activity is based on one hand on raw data processing and on the other hand on data characterisation. The developments for interferometry imagery (Gildas, Gipsy), for preparing SKA (S3-tools), for the bolometric corrections of Plank-HiFi, for Ramses-simulations extractions (amr3cube) and for characterization of Earth atmosphere and surfaces belong to raw data processing. The works for building generic data-models fitting to all the conceptual requirements induced by instruments (ALMA, NOEMA, SKA) or by simulation (Sim-DM) belong to data characterisation. Naturally, these works are strongly linked to Poles 1 and 2.

5.4.2. Data storage and perpetuation activity

Significant efforts are needed to ensure that data will always be understood in a univocal way and handled in a consistent manner: the developments for converting data to widely used formats (e.g. conversion of Alma output to a CASA compliant format) and the contribution to the creation of new international standards, by participating to the activity of the International Virtual Observatory Alliance (IVOA). Indeed some actors of our entity contribute actively to the development of the IVOA and its standards. These contributions namely focus on the Theory Interest group and on the Grid and Web Services working group. The Simulation Data Model (Sim-DM) proposed and developed jointly with the MPE/GAVO is now the IVOA international standard for storing and diffusing numerical simulations. In the same context, we recently started working on an ontological grammar for describing and characterising physical data (with their related constraints). This grammar (called PDL) permits to achieve interoperability (between the described data) with a physical sense (and not only in a computer-science sense). We are now collaborating with the IVOA instances for PDL to be accepted as a new international standard. Due to the multidisciplinary aspects imbedded in standards, these activities are strongly linked with Poles 1, 2 and 3.

5.4.3. Data diffusion and sharing activity

The goal of this activity is to discover, search and retrieve data. Among the services developed in this context, we can mention:

- The Starformat project (http://starformat.obspm.fr): The StarFormat database contains results of heavy numerical simulations computed in order to study the problem of star formation, essentially molecular cloud formation, evolution and collapse. The goal of this database is to give access to observers, or more generally to any scientist working on a related field, to the results of these numerical simulations, which could be useful to help prepare or analyse observations.
- Stark-b portal (http://stark-b.obspm.fr): Stark-b is a database of calculated widths and shifts of isolated lines of atoms and ions due to electron and ion collisions, devoted to modelling and spectroscopic diagnostics of stellar atmospheres and envelopes. Thanks to the VAMDC framework, it is possible to query and extract data in a standardized way. Specific tools to read and manipulate those formats are currently under development.
- The on-line IPOPv2 service for the computation of opacity tables on the basis of the Opacity Project data (http://opacity-cs.obspm.fr:8080/opacity): In the framework of the new phase - IPOPv2 - of the international Opacity Project (OP), a new service is proposed on the basis of the latest release of OP opacities. The user may construct on-line opacity tables that can be conveniently included in stellar evolution codes in the format most commonly adopted by stellar physicists, i.e., the OPAL format.

The technical problems, common to these three components of our software activity, are: the difficulty in processing huge volumes of data, the optimization of algorithms and numerical methods, the data mining, and the network constraint limits for the transfer of huge volumes of information. These problems are software-instrumental research topics that federate the different actors involved into our group: we work together to provide innovative solutions by combining the best existing products and above all by contributing to the development of new technologies, when the existing do not fit to our needs.

6. Additional missions and services

This chapter describes LERMA's activities carried out over the reporting period that were common to all four thematic poles, namely: Productions other than publications (instruments, software, databases), Interactions with the non-academic environment (economical, cultural, societal), Teaching by research, and Laboratory life and organisation. Most of these activities also strongly involve our technical and administrative Support Pole.

6.1. Productions other than publications

Besides publications, LERMA also had a major scientific production in terms of hardware and public software, as well as databases and related on-line services offered to the community. Those including astrophysical applications contribute to the national *Services d'Observation* (SO) defined and managed by INSU. They are carried out in part as mandatory duties by astronomers, belonging to the special CNAP body of civil servants, and staffed by support personnel dedicated by the lab to these tasks. These contributions are listed in the Services d'Observation table included in the appendices, and mentioned along with the productions below, where applicable.

LERMA also contributes indirectly to running major service facilities. Co-founding laboratory of IRAM, the LERMA ancestor has been reinforcing the Institute's staff, in various ways, some, major. M. Guélin, who had been working for IRAM for about 30 years came back to LERMA as emeritus a few years ago. J. Pety, currently detached at IRAM, has been working there for about 10 years now. Several young LERMA doctors have been hired as postdocs at IRAM and keep tight scientific links with the lab. This can be viewed as a different contribution to observatory services SO3. In a close future, contributions to the ALMA operations and data services will connect additional SO3 services with SO5 data services, as listed below in the following sub-section.

6.1.1. Instrument hardware

LERMA's instrumentation group (GEMO) has contributed to instruments on large international facilities during the reporting period. The major achievement is the novel design and realisation of the 600 GHz channel 1 of *Herschel*'s heterodyne spectrometer, HIFI. It turned out to perform remarkably well since the beginning of the mission in 2009, with stability and sensitivity above specifications, and is by far the most requested channel of the HIFI spectrometer (27% of HIFI requests, twice as much as the average share).

After the HIFI channel 1 delivery by GEMO, and the completion of the HIFI local oscillator chains design by A. Maestrini for JPL, Maestrini joined our lab, and an intensive phase of R&D was undertaken by the instrumentation group (see Pole 4 results section. The resulting innovations led to the submission of several proposals for instruments on future balloon and satellite missions:

1. The state-of-the-art performance reached with a new design for a 2.5 THz mixer based on in-house made Hot Electron Bolometers, and the design of the world's first electronic source working at room temperature in the 2.5-2.7 THz band, in collaboration with JPL, convinced CNES to finance a Phase A study of the CIDRE

balloon project, currently in progress. JPL recently proposed CNES to join the project.

2. GEMO's past involvement in space missions (MIRO/ROSETTA, SAPHIR/MEGHA-TROPIQUE) and its innovative improvements in the manufacturing of sub-micronic-Schottky elements (including a novel planar Schottky diode process for building THz frequency multipliers and mixers) allowed it to participate to the SWI (Sub-millimetre Wave Instrument) proposal as part of the payload on board JUICE, the next ESA Large mission to Jupiter.
3. Several feasibility studies and proposals for mm and sub-mm spectro-radiometers for remote Earth observations, based on the development of new Schottky diode circuits and on novel multi-pixel receiver designs have been completed in collaboration with the Rutherford Appleton Laboratory (UK), and industrial partners (see below the section on Interaction with the non-academic environment).

6.1.2. Instrument Software

The *Herschel, Planck* and ALMA projects have been national igh priority projects over the period. Although it is still lying much further ahead, the SKA project is another high priority already. LERMA's softwre contributions to these instruments have been very significant, and have contributed to the SO2 instrumentation services of INSU:

1. Design and prototype of the HIFI double-sideband calibration and deconvolution algorithm for spectral surveys; architecture of the scientific simulator of the instrument, and implementation of the core components of the simulator.
2. Delivery to both parties of an Herschel-IRAM interface for spectroscopic data.
3. Design and prototype of the non-linear electronic calibration for *Planck* HFI detectors, as well as complete prototype pipelines.
4. Design of the ALMA data model and of the architecture of the archive; implementation of the data model, of data feeds and various interfaces.
5. Extension of the ALMA data model for the SKA EMBRACE prototype, in order to validate the application of the concept to phased array interferometers.
6. Development of sky models of the high-redshift Universe for the science case of SKA, and delivery to the project.

6.1.3. Scientific Software

LERMA scientists and software enginners have also produced new public scientific codes, or major enhancements of existing ones, that are being used by a very large scientific community:

1. RAMSES-MHD, the MHD Riemann solver for the adaptive mesh refinement self-gravitating hydro code RAMSES created by R. Teyssier.
url: `http://magnet.ens.fr/index.cgi?ramses-mhd`
2. ZEUS-3D+, a fully parallel conservative version of the Zeus code, with added physics including non uniform viscosity and resistivity (Author P. Lesaffre)
url: `http://magnet.ens.fr/index.cgi?zeus-3d`
3. Contributions to the MESA stellar evolution code by F. Delahaye
url: `http://mesa.sourceforge.net/index.html`

4. IRIS: is a generic 3D radiative transfer code aimed at post-processing dynamic 3D simulations and providing spectra and images (author L. Ibgui et al). url: `http://arxiv.org/abs/1211.4870`
5. In addition major parts of a widely used freeware data processing package, GDL, have been delivered by one of the software development team member (A. Coulais) who supervised a large number of students on this project `http://gnudatalanguage.sourceforge.net/`

6.1.4. Production of large datasets and databases

Several LERMA researchers produce large theoretical or experimental datasets, which are essential tools for interpreting astrophysical observations. They are also actively contributing to their dissimenation to the whole astrophysical community, via the development and maintainance of public databases and/or online services. These activities contribute to the SO5 Service d'Observations of INSU (data centers). Our current database services fall in two main categories:

(i) Atomic and molecular databases

The databases Stark-B (Stark effect broadening profiles, `http://stark-b.obspm.fr`), Molat (UV spectroscopy, `http://molat.obspm.fr`), Sesam `http://sesam.obspm.fr`, Tipbase (fine structure atomic data, `http://tipbase.obspm.fr`) and Topbase (LS-coupling term energies, f-values and photoionization cross sections, `http://topbase.obspm.fr`) are constructed and managed by Pole 2 and Pole 3 researchers. They are connected with the new European VAMDC framework (VO standards for Atomic and Molecular Data distribution), headed by M.-L. Dubernet (LPMAA).

Two interactive online services were also deployed: one for computing stellar opacity tables `http://opacity-cs.obspm.fr:8080/opacity/`) in the framework of the Opacity Project and the other for Stark broadened profiles of hydrogen `http://stark-h.obspm.fr/`.

(ii) Astrophysical simulation databases

Pole 1 and Pole 2 have members have been conducting large grids of state-of-the-art astrophysical model calculations in order to provide optimal tools for the interpretation of observations with current and future instruments. The resulting data are made public on various web sites (eg. in CDS tables linked with a publication). In addition, three major databases have been made compliant with the SIM-DM (data model) standard of the Virtual Observatory Alliance and have been the first services in the world implementing this norm (moreover their implementation helped in defining and adjusting the SIM-DM). These databases are: GalMer (HD simulations of galaxy interactions and mergers, `http://galmer.obspm.fr`), StarFormat (MHD simulations of the formation of clouds and of the collapse of dense cores, `http://starformat.obspm.fr`) and PDR (stationary models of photon-dominated interstellar clouds, led by LUTh with contributions from LERMA, `http://pdr.obspm.fr`).

6.2. Interactions with the non-academic environment

6.2.1. Industrial and economic partnerships

Pole 4 (both the remote sensing group and the GEMO microwave instrumentation group) are involved in many contracts with the space agencies (CNES and ESA), in close collaboration with industrial and academic partners, in France and in Europe.

The remote sensing group participates with the space industry (e.g., EADS, Thales) and engineering companies (e.g., CLS, SULA) to the definition of instrumentation for satellite Earth observations. ESA is financing most of these studies (the group has been involved in 7 ESA studies within the last 5 years). Several studies were devoted to the definition of millimetre and sub-millimetre instrumentation, with EADS/Astrium. This resulted in the selection of a millimetre and sub-millimetre instrument (ICI) for the future European operational meteorological (MetOp-NG), to be launched in 2020.

Another visible connection of LERMA with the private sector is the creation of a spin-up company, named Estellus (http://www.estellus.fr). It provides services in atmospheric and environment sciences, using Earth satellite remote sensing observations. A transfer of know-how has been signed between CNRS and Estellus on the development of new methodologies to process satellite data for meteorological and climatological applications. The company is hosted at LERMA, at Paris Observatory. It works in close collaboration with Pole 4 members, as well as with other public labs and institutes in France (LMD, CESBIO, IFREMER, Météo-France).

Tight connections are also developed between the GEMO instrumentation group and industrial partners (Alcatel/Thalès, EADS, SULA, RPG) on instrumentation projects. These collaborations lead to a very effective know-how transfer, but have never yet taken the form of a contract, although thoughts are given to develop this formal aspect. Another important link with industry goes through shared doctoral students, which are then hired by the company, and keep close links with the laboratory during their career.

6.2.2. Outreach and cultural partnerships

The LERMA researchers share a strong dedication to the popularisation of scientific culture and to outreach activities. They regularly give conferences ant Science Fairs and Festivals (eg. the annual *Fête de la Science*) and to high school students, give interviews and write articles for the media, participate in interdisciplinary exchanges, and collaborate with cultural associations (eg. art-science projects). Boyond these individual initiatives, LERMA is also engaged in major outreach projects that are reaching an even larger public.

LERMA is coordinating the European project EU-HOUMW **“Hands-on Universe, Europe: Connecting classrooms to the Milky Way”**, which has benefited from a Comenius funding from the Life Long Learning Programme of the European Commission. It consists in the development of the first network of **small radio-telescopes** conceived for education. 3-m dishes operating at 21cm have been installed in 5 different countries, including one on the LERMA site in Paris Observatory, and a specific Web interface has been developed to remotely control these instruments from European secondary schools. **Specific innovative activities** have been developed inspired by modern research based on the kinematic study of the HI line in the Milky Way and education science: kinesthetic activity, rotation curve and mapping of the Milky Way, enabling the young generation to tackle the science in action. Beside on-line observations, the proposed tools included a simulator of observations based on professional data, as well as an archive gathering data acquired with the EU-HOUMW radio-telescope network. One antenna will later be installed on an astronomical platform dedicated to education, which is being built on top of Jussieu.

This challenging project has involved staff from different LERMA teams namely software engineers (B. Albert, M. Caillat, Y. Libert, A. Radiguet), microwave engineers (M. Ba Trung, M. Gheudin, J.-M. Munier), mechanics (L. Pelay, J.-M. Isac, G. Cornudet), astronomer (P. Salomé), associate professors (A. Maestrini, E. Congiu, A.-L. Melchior) and has already been **presented in various events**: in-service teacher training sessions, Heritage Days in Paris Observatory, *Salon des Jeux Mathématiques*, activities in License at UPMC, conferences and show for Amateur Astronomers, European project STENCIL, secondary schools, etc. This project has also inspired an original artistic exhibit based on the EU-HOUMW radio data “This is Major Tom to Ground Control”, prepared by Véronique Béland at Le Fresnoy (*Studio national des arts contemporains*).

Fig. 6.2.1: In foreground, the 3m dish radiotelescope recently installed in Paris, as part of a new european pedagogic network EU-HOU.

F. Dulieu at LERMA/UCP has developed for the Cergy-Pontoise University the “*Maison Universitaire de Diffusion des Savoirs*” (MUDS). Its role is to develop the **interaction of the university with various audiences**, such as schools, teachers, medias or curious citizens. Through MUDS, links with local communities (such as Gennevilliers MJC, or Science associations) are developed. Astrophysics can be a very good tool to promote science, especially because it attracts both female and male students, contrary to most other *hard* sciences. LERMA is official partner in a funded project based on a mobile inflatable planetarium. This planetarium can house 30 children or 20 adults, and will be set-up in various places (schools, high schools...), mostly in Val d'Oise and Hauts-de-Seine. Four LERMA members are involved in the project.

P. Encrenaz is chairing the ***Sciences à l’Ecole*** programme of the Ministry of Education, which has the goal to support and encourage projects of scientific culture in secondary school teaching, in order to contribute to increase the number of scientific vocations among the young generation.

F. Combes has co-chaired the **French Strategic Committee for the International Year of Astronomy in 2009** (IYA09) playing a key role in the success it has encountered: **a few millions persons** were impacted in France by the IYA09. This committee labelled 327 projects, and organised the International Opening Ceremony at UNESCO with 1000 participants.

J. Lequeux has published in 2008 and 2009 two fascinating books on 19th century science:

François Arago, un savant généreux ; physique et astronomie au 19e siècle, and *Urbain J.-J. Le Verrier, savant magnifique et détesté*. He also coauthored a remarkable book on the history of the Paris Observatory: *Observatoire de Paris, des origines à nos jours,* published in 2012. He also co-organised major exhibits at Paris Observatory, in 2011 *Le Verrier, les coulisses de la découverte de Neptune* and, in 2012 *L'astronome du roi et le satellite* in honour of J.-D. Cassini (1625-1712) and of the success of the NASA-ESA mission to Saturn.

6.2.3. Societal debates

Two researchers of LERMA (P. Encrenaz and F. Combes) are members of the French Science Academy. They frequently offer their expertise, and write scientific and technical reports for Academy committees that investigate special issues, and write scientific or technical reports, which can contribute to the advancement of the sciences and their applications, or address social questions associated with the development of sciences and formulate advice and recommendations aimed at political institutions and distributed to citizens at large..

They participated for instance in the Academy debates and reports on: space exploration, national and European supercomputing capabilities and organisation, the debated issues of global warming, and “risks and precautionary principle”, as well as the quality of the Science teaching, the dissemination of science to the public, and international actions to defend threatened scientists (CODHOS: *Comité de Défense des Hommes de Science*).

One LERMA researcher is chair of the COFUSI, which is controlling and advising the French Committees of the 27 scientific international unions, developing international scientific relations, and providing French representatives to the International Council of Scientific Unions (ICSU).

Protection of the radio frequency spectrum is another key issue in the science-society debate, with more and more Radio Frequency Interferences (RFI) observed, even in protected bands. LERMA participates in the frequency protection, for astronomy as well as for Earth observations, through the national representative of the radioastronomy committees of the International Telecommunication Union (UIT), devoted to the management of the radio frequency spectrum resources.

6.3. Training by research

6.3.1. Graduate studies

With 27 teaching and research staff members, LERMA has a very strong involvement in higher education at *Licence* (undergraduate) and Master (graduate) levels, in our 4 hosting institutions. Several of our colleagues have had significant responsibilities in a number of *spécialités* and *parcours* (e.g. Balbus and Hennebelle at ENS, Panis, and previously Encrenaz at UPMC). At master level, Cobut has been in charge of an engineering Master in Cergy, *Contrôle et Qualité en apprentissage* and Maestrini is co-responsible for a *Microwaves and Telecommunication* Master at UPMC. In addition, 4 of our colleagues are much involved in the creation of a new international master *Space and Applications* at the recently created *Université des Sciences et Techniques d'Hanoï*. Five other colleagues have the responsibility of teaching modules within Ile-de-France Masters.

In addition, over the 2007-2012 period, our research staff has provided supervision for the research internships of 32 students in L3 (last year of License), 19 first year Master students (M1), and 27 second year Master students (M2).

As a complement 3 LERMA teaching and research staff have organised 2 CNRS thematic (summer) schools for PhD students and young researchers over the period.

6.3.2. Doctoral studies

LERMA is traditionally heavily involved in training by research at doctoral level. One LERMA membre (P. Encrenaz) was the directore of the doctoral school *Astronomie et Astrophysique d'Ile de France* (ED 127) for many years. And during the reporting period, two LERMA members have been acting as members of the boards of the doctoral scools ED 389 (*La Physique de la Particule à la Matière Condensée*) and 417 (*École Doctorale Sciences et Ingénierie*).

a) Statistical data

Over the reporting (from 1st of January, 2007 until June 30th, 2012), 30 PhD theses were successfully defended in LERMA, and an equal number of PhDs have been started. 60% of the PhD students were enrolled in *École Doctorale* ED 127, *Astronomie et Astrophysique d'Ile de France*, while the other 40% belonged to one of 8 different ED's, namely: ED 129, 389 or 417 (to which LERMA is officially affiliated), ED 107 or ED 381 (alternative doctoral schools in physics at ENS and UPMC), and, for a very small number of theses in co-supervision with external institutions, ED 52, 227, or 422 (respectively with ENS Lyon, *Museum National d'Histoire Naturelle*, and Orsay University). The multiplicity of these affiliations is a direct consequence of the multidisciplinary research in LERMA.

In total almost half of these theses have an external co-supervisor, who brings complementary expertise and experience to the student. From these, a small number (barely one every second year) is done in the framework of an official *cotutelle* which implies a formal agreement with a foreign University, and the delivery of a double diploma.

All theses were completed in less than 3 years and a half. In 2 cases, one because of a very serious illness, the other one following a decision of homeland return, the theses were not completed.

For comparison, the number of PhDs defended over the preceding 4 years period was 24. Hence this figure is remarkably stable, averaging to 6 per year. Normalised to the total number of active research staff excluding emeriti (43) the ratio, although modest, is larger than the national average by ca 50%.

b) Their careers after LERMA

A very important issue is to follow up the new PhD's career, in order to judge of the effectiveness of his/her training by research. To this aim, LERMA has been keeping track of the following employments of all but one young LERMA doctors since 2000.

Among the 30 students who defended their PhD since January 2007, 22 are presently postdocs, 4 have permanent academic positions, one has a temporary University teaching position and 3 have found jobs outside of the academic world. These are interesting informations, but because postdoc cumulated durations nowadays often reach 4 or more years, we need to look at least as far back into the past, if we want to comment on the professional future of our PhD students.

Among the 24 successful PhD between 2004 and 2007, 8 (33%) have permanent academic research positions in France, 2 (8%) abroad, 3 (12%) have academic engineering positions, 7 (29%) obtained a permanent position outside of the academic world (as engineers in large technological companies, or as highschool professors), 3 (12%) are still employed as postdocs, and 1 (4%) has not given feedback. The total fraction of former LERMA Ph.Ds obtaining a permanent academic position in France thus reaches 46%, which is an excellent result. For comparison this fraction was 38% in 2011 at the IAS Institute for Ph.Ds earned 6-10 yr earlier (https://www.ias.u-psud.fr/website/modules/content_the/index.php?id=9), and 40% over the whole ED127 (http://ecole-doctorale.obspm.fr/-Devenir-des-docteurs-de-l-ED-127-)

c) PhD integration and supervision on lab scale

In order to improve the quality of training by research in LERMA, the Lab Council has installed a Committee in charge of PhD students, chaired by B. Sémelin. This committee maintains a log of the theses proposed, and offers complementary support and advice to the students. One of them is elected as representative in the Lab Council.

Several events are organised in order to favour the students integration and training. They are obviously invited to the yearly *Newcomers' meeting* every fall, where an introduction to the laboratory is given by the management team, as well as information on the available resources, rules and procedures, with emphasis on security procedures. Every year a *Journée des doctorants* is organised, with all 1st and 2nd year student presenting their works (in 15 to 20 minutes each) to their fellows and a comparable number of more senior staff. These meetings trigger lively discussions and favour interactions among the students. At the Observatory and at ENS the students and postdocs are in charge of the organisation of a bi-weekly journal-club, open to all, which is excellent training for them, and quite stimulating for their more experienced colleagues. Every year the PhD students are also much involved in the visit of the laboratory by a group of graduate students from the Astronomy and Astrophysics Master of Ile-de-France.

d) Future improvements

With 25 staff members having earned an *Habilitation à Diriger les Recherches* (HDR), our 20 +/- 5 doctoral students can be well taken care of. Our survey shows a high success rate of their later careers. We would be in favour of an increase of the number of PhD students, but financial support is a very severe limitation. On the other hand not as many undergraduate internships (at bachelor L3 or master M1 levels) are offered every year as might, or ought to be: this number should be increased, in spite of the severe limits in office space at our Paris premises.

Because training of young generations is a high value mission of a research institution, the efforts will obviously by carried on, and new resources searched in order to increase the numbers.

A new difficulty arose recently with the tentative enforcement of the rule: one lab = one doctoral school. Ways around will have to be established for our multidisciplinary and multi location case.

6.4. Laboratory Life and Organisation

It is not an easy task to describe how the laboratory works: it really is a complex network of relations and combination of talents, where the dedication of the vast majority of its people is a key ingredient to success, while formal hierarchy and procedures, at least in our minds, are of minute importance. With of order 150 people aboard on average, including visitors and interns, with direct expenses amounting to 1.8 M€/year on average, complex experimental and instrumentation platforms, and commitments in many national and international projects, a fair level of organisation is nevertheless necessary. It is the purpose of this section to try and describe the various aspects of this organisation, as it actually is, and how it can be improved.

6.4.1. Management structure

Because of its multi-site nature, the LERMA management has to be a subtle compromise between site-specific entities and centralised bodies. Local functional considerations play a fundamental role in everyday life, and even more so because our scientific strategy is deployed in close relation with the scientific orientations of our 4 hosting institutions, and neighbouring laboratories. On the other hand, laboratory scale synergies are essential to our scientific accomplishments, to a strong team spirit, and to the efficient use of our resources.

Over le last reparting period, and thanks in part to the 2009 AERES recommendations, the management structure of LERMA has strongly evolved from a mainly site-based organisation to a mainly cross-site, lab-scale organisation. This management reorganisation into transferse Poles occurred progressively, first for the administrative support activities, then for the tehcnical support activities, and finally in 2011 for the scientific research activities, taking benefit of the prospective work started for the 2014-2018 project. In this way the laboratory has progressively evolved from a federation of 7 independent functional teams hosted in our 4 different institutions, which still was the situation 4 years ago, to a more integrated laboratory structure, which we believe (and can already observe) has a better capacity to use its many potential inner synergies, with a better efficiency. This inner evolution of the lab also prepares for its enlargement, as foreseen in our 2014 project.

Below we describe in more detail the initial site-based management structure in place, at the beginning of the reporting period, and the transverse poles subsequently created.

a) Initial site-based management structure

At the beginning of the reporting period, LERMA was structured in 7 functional teams, one in each of our 3 secondary hosting institutions, ENS, UPMC and UCP, and the other 4 at the Observatory: 1 in Meudon and 3 in Paris, where Astrophysics, Instrumentation and Remote Sensing were managed as 3 independent entities. At this time the recurrent financial resources were shared among the 7 teams on a *per capita* basis, with slight adjustments depending on the local charges and the nature of activities.

This system had the major advantage of simplicity and was very time effective, but had the major drawback of insufficient communication and scientific exchanges among the lab components and scientific exchanges inside the Laboratory, that resulted in a lack of satisfaction internally, and a firm recommendation from the 2009 Visiting Committee in order to improve the situation by the creation of larger teams. In addition, the restrictions on technical and administrative staff positions were a strong incentive to optimise the use of available manpower for the support functions. The resulting transverse reorganisation into a shared Support Pole and 4 Thematic Poles is described in the following sections. This action helped to evolve towards a structure where the decisions would derive from the scientific orientations at lab level, while preserving the capability to successfully run projects in all 4 of our hosting institutions.

b) Aministrative and Technical Support Pole

An essential component of a research laboratory is its internal support human resources, carried out in LERMA by technicians and engineers attached to 3 main *Branches d'activité professionnelle* (BAP): instrumentation engineering (BAP C), software and computer support (BAP E), and administration (BAP J).

Each LERMA site benefits from the support of a local administrative agent (in charge of everyday administration, accounting, and logistics), a local computer manager (in charge of maintaining the local computers, printers, and network resources), and technicians an/or engineers involved in local instrumental platforms or software projects.

Since 2008 the administrative agents had been grouped within a trans-site Administrative Team, with the progressively increasing capability, for each of the agents, to take care of operations at other remote sites. This is not fully interoperable yet, because not all institutions give appropriate remote access to their financial and human resources information systems, but the situation is improving. The administrative team is co-led by V. Audon, as Administrative Manager and L. Girot as Financial Manager, in a very smooth and efficient way.

The next step in setting up shared resources at lab level was the nomination in 2009 of J.-M. Krieg as technical director, in charge of all technical issues in the lab, and acting as deputy director for the management of the technical agents involved in computing, instrumentation, and experimental physics. The resulting technical team is composed of a computer support team (*BAP E* agents), coordinated by M. Caillat, and an intrumentation and experimental physics team (*BAP C* agents), coordinated by J.-M. Krieg himself. Thanks to this trans-site organisation, the technical manpower is then easily redistributed among the higher priority projects, following the guidelines of the lab scientific strategy.

In 2012, the Administrative Team and the Technical Team were further grouped under the shared Support Pole of LERMA. Our technicians and engineers are now affiliated to this Pole, as principal affiliation for most of them, with the major exception of engineers with highly specific technology expertise and mostly involved in R&D activities, who are mainly affiliated to a Thematic Pole, either in Instrumentation (Pole 4) or experimental physics (Pole 3).

c) Thematic Research Poles

The new scientific structure in terms of transverse Thematic Research Poles arose from our internal discussions during the *Journées du LERMA* in March 2011 and the prospective work carried out within LERMA during the last 18 months. It crosses geographic and administrative borders, and was made possible by the nearly complete sharing of our support services, through the Support Pole.

The 4 transverse thematic poles are: Galaxies and Cosmology (Pole 1), Interstellar Medium and Circum/stellar plasmas (Pole 2), Molecules in the Universe (Pole 3), and Instrumentation and Remote Sensing (Pole 4). Their contours are consistent with the perimeters of the 5 Labex that LERMA is involved in: Pole 1 is involved in the ILP Labex at UMPC ; Pole 2 is involved in the ICFP Labex at ENS and in the Plas@par Labex at UMPC; Pole 3 is involved in the MIChem Labex (UMPC); and Pole 4 in the ESEP Labex (OP).

The scientific poles are defined by common scientific objectives on the lab-scale, regardless of geographical or administrative considerations. Their staff members are involved in one or several project teams, each lead by a PI. Projects have a life cycle, which vary from a couple of years to lifelong. Some projects, obviously, are transverse to the poles. As a result the teams have versatile composition and varying durations. Project funding and resources, on the other hand, are managed from a single geographic site, which is that of the project PI. In this dual configuration Science is the pilot, while local management serves as flight engineer.

Today the 4 thematic poles are run by a coordinator , helped by 2 assistants, together broadly covering the thematic spectrum of the Pole. They have been in charge of leading the prospective work of their Pole, and coordinating the writing of their Pole specific sections of the reports for the present quinquennial review. In preparation for the near future, the coordinator of the project for Pole 3 is a member of LPMAA. Beginning of 2012, the Thematic Pole coordinators have become members of the *Conseil de direction*, together with the persons in charge of our Meudon, Cergy and ENS sites.

6.4.2. Decision making process

Two bodies are involved in decision-making, along with the Laboratory management team: The *Conseil du LERMA* (Laboratory Council), which is an elected body representative of all categories of staff members, and the *Conseil de Direction* (Executive Committee), which is an executive body nominated by the director.

a) The Conseil du LERMA and its committees

The Laboratory Council is an advisory committee to the director, composed in majority of elected representatives of the personnel, including 2 representatives from the technical and administrative staff, and one representative of the PhD students. Its missions derive both from the CNRS-Institutions contract creating the *Unité Mixte de Recherche* (UMR=Laboratory), and from the *Observatoire de Paris* internal regulations, as the UMR is also a scientific department of the Observatory. A few inconsistencies between both sets of regulations have invalidated our own internal regulation documents, currently under revision. In the meantime, the laboratory keeps running on the basis of the UMR regulations, cosigned by our 5 stakeholders, namely CNRS and the 4 hosting institutions.

The Laboratory Council is invited to debate and vote on scientific orientations, acceptance of new laboratory members, use of resources, and all matters regarding the working conditions and organisation. All LERMA membres are entitled to add items to the proposed agenda. It is a lively democratic circle of debates, which the personnel cherishes, and which certainly influences the course of decisions and orientations. The Lab Council meets about 4 times a year. A summary of decisions is sent to the Lab by email immediately after the meetings, and a report is written, and immediately circulated by email to all LERMA staff after approval by the Council.

In order to improve the involvement of the Council in topics considered as of importance to the Lab, seven Council sub-committees have been set up:

1. Hosting and premises (chaired by J.-F. Lestrade): because workspace and capability to cope with geographic dispersion is a standing difficulty, the Council set up a dedicated committee.
2. Scientific animation (chaired by Hennebelle and Wiedner.): this committee played a key role in organizing the program of the first LERMA 2-day residential meetin in March 2011, and the 1-day internal LERMA workshop on prospective in January 2012.
3. Doctoral studies (chaired by Sémelin): training by research is an essential topic, taken special care of by this committee.

4. Communication (temporarily chaired by the director): next to the operational communication structure already in place (see dedicated section below), this committee is reflecting on how to improve internal and external communication tools.
5. Outreach (chaired by Dulieu): this committee is the place where outreach experiences in our various Institutions can be shared.
6. Training and careers (chaired by Champion): this committee is the place where questions related to our personnel training policy, as well as career evolution can be carefully examined.
7. Budget (chaired by Girot): this last committee is a useful place for explaining the budgetary situation and financial constraints, and for debating on the evolution of spending internal rules.

b) The Conseil de Direction

The *Conseil de Direction* (Executive Committee) is the place where specific decisions related to the Laboratory resources and the implementation of its scientific objectives are prepared, specific actions (and potential problems) are discussed concerning the lab management, and corresponding work is delegated. Before 2009, the Conseil de direction met only 3-4 times a year. After 2009, this was increased to once a month to improve synchronization between the director and "the base". Extra meetings are organised when needed by the circumstances.

Until 2011, the *Conseil de Direction* was composed of the direction team and of the heads of each of the 7 functional site-based teams. As a consequence of our reorganisation into transverse Thematic Poles, the composition of our *Conseil de direction* evolved in January 2012: it is now composed of the coordinators of the 4 thematic poles, of the director's representatives in 2 of the 3 secondary hosting institutions (ENS and UCP), as well as the person in charge of our Meudon site, and of the direction team proper (Director, Deputy Director, Technical Director, Administrative Manager and Financial Manager), bringing the board to a total of 12 members. It is our project to fully implement this renewed management structure over to the future contract. In order to prepare this evolution the present director of LPMAA or her representative has been systematically invited to the Board meeting and discussions since the beginning of 2012.

A subsidiarity principle is applied as far as possible, where decisions are taken at the level of relevance. Delegation is an important mechanism, under this respect. The intricacy of institutional relations in our distributed structure makes delegation a tricky exercise. The future nomination of a delegate director, with explicit responsibilities, for each of our secondary hosting institutions is one of the practical means that will be implemented for improving the situation. It will be effective and satisfactory if communication is adequate (a weekly executive meeting will be installed).

6.4.3. Scientific animation and social events

LERMA organises several regular series, where lab members from all sites are invited to participate: a weekly scientific seminar, a *PhD Students Day* every spring where all 1st and 2nd year students present their work, a *Newcomers' Day* every fall, where new staff is introduced to the Laboratory project, its facilities and regulations, and a New Year's celebration in early January, with the traditional *galette des rois.* seminars, and LERMA meetings (the *Journées du LERMA*). In addition, a is organised ever

The common *Séminaire du LERMA* is organised on Fridays afternoons on a very broad range of topics. Speakers are temporary guests, lab members, or invited speakers. On average 25 talks are scheduled monthly. In complement a monthly *Séminaire du Campus Parisien* is jointly organised by LERMA and IAP, where prestigious speakers from around the World are invited to give reviews of their work

From 2006 to 2010 our group at ENS has organised a monthly bi-seminar in MHD involving all MHD groups in Ile-de-France, where in the same morning an experimentalist or observer, and a theoretician gave complementary views of a given topic.

Two journal-clubs are organised on a regular basis by PhD students or postdocs, one at the Observatory, and one at ENS. A similar meeting is regularly organised in Meudon on Thursdays at teatime, hence the name T+. These meetings address research in progress topics, discussing recent publications and new results. In addition, the extragalactic journal-club, which meets weekly, has periodically a common meeting with the GEPI extragalactic people, hosted also at Denfert-Rochereau.

In order to enhance internal exchanges and social interactions between the various LERMA sites, and following a recommendation of our 2009 visiting committee, we have organised in March 2011 a whole lab residential meeting (the *Journées du LERMA*). This meeting took place over 2 full days in a small country resort in Ardon (Sologne), and turned out to be a very successful event both scientifically and socially, as judged from the unanimous positive feedback. The oral presentations of the ongoing work were deliberately organized (by the Lab Council committee on scientific animation) to follow a transverse thematic approach, rather than a site-based approach. In addition to a dramatically improved mutual knowledge of the others' work areas, new interactions started, and new collaborative projects were discussed. The success of this format set the basis and motivation for our new organisation into 4 transverse Thematic Poles and a shared Support Pole. Decision was taken to renew the experience (within 2 years or so), and to encourage short 1-day thematic meetings on transverse topics, like radiative transfer, large observing projects on e.g. ALMA and available tools, numerical methods, data handling.

This meeting was followed in the fall of 2011 by intensive preparation of our laboratory quinquennial project 2014-2018 within our newly created thematic poles with several informal meetings, and a final full day LERMA meeting in Meudon in January 2012, where the proposed project of each Science Pole was presented and discussed by all LERMA members. Our 2014-2018 project document is the result of this common prospective exercise.

6.4.4. Internal and external communication

Internal communication is based on mail exchanges, teleconferences, visio-conferences using web-based tools, and face-to-face meetings. A well developed mailing list system has been installed, with both information lists, and forum type lists, and a careful maintenance of mail archives. A wiki platform has also been started for the debates and information of the future LERMA project, with open read-write access to all lab members.

A well developed intranet system, with constantly updated internal informations is locally in operation at all our sites, but not yet at LERMA scale. It is a high priority project for the coming year.

For external communication we distinguish between institutional (e.g. presentations of the Laboratory on institutional websites) and scientific communication (news, press releases, press conferences, ...). Our functioning is based on a team of communication correspondants in each host Institution, coordinated at lab level by our Administrative Manager, V. Audon, who had an earlier experience in the CNRS communication service, and is the official LERMA communication correspondant for CNRS and UPMC. A *Chargée de mission* (C. Cabrit) was also nominated to ensure coherence of our institutional communication messages to our various partners.

6.4.5. Health and Safety

This important topic is taken care of by the management team with a strong support from agents (N. Champion, R. Lefèvre, F. Levrier and H. Chaabouni, supervised by A. Germont until his recent retirement) who are part-time dedicated to the monitoring and application of health and safety rules, in close cooperation with the *Ingénieur Hygiène et Sécurité* of each of our 4 hosting institutions. An additional function has been recently created by CNRS, with regard to laser security issues. The person in charge is one of the LPMAA engineers, H. Elandaloussi, in anticipation of the future lab merging.

These important issues are dealt with in our internal regulation documents (*Règlement intérieur*), which must be signed by all newly recruited agents, after they receive a security training adapted to their functions. A formal document, describing in detail all Health & Safety issues and recommendations, the *Document Unique Hygiène et Sécurité* is updated yearly, and closely followed up by our H&S agents.

Computer and network security issues are also taken care of carefully, but within a distinct organisation, obviously involving our computer team in the first place. M. Caillat is in charge of assisting the Director with respect to the security policy, and of the communication with the IT security teams of CNRS and of our host institutions.

6.4.6. Lifelong training and careers

Our laboratory has had a *Plan de Formation d'Unité* since its creation. A team of 2 staff members is designanted (presently P. Landry and D. Lopes) to inform and assist our staff on the various offers in lifelong training, in relation with the *Formation Permanente* services of CNRS and of our hosting institutions. Our staff benefits of order 30 training periods each year, lasting between half a day and a week. Training and carreer issues are also discussed in one of our dedicated Laboratory Council committees.

7. Analysis of Laboratory Resources

7.1. Research environment and its evolution

LERMA has 4 governing institutions in addition to CNRS. These institutions are Higher Education and Research Institutions (*Établissements d'Enseignement Supérieur et de Recherche)*, formally *Établissements Publics à caractère Scientifique, Culturel et Professionnel* EPSCP):

- 2 universities, the *Université Pierre et Marie* Curie (UPMC), administratively known as *Paris 6* and the *Université de Cergy*-Pontoise (UCP),
- 2 *grands établissements*: the *Observatoire de* Paris (OP), and the *École normale* supérieure (ENS).

These institutions themselves belong to larger goups of institutions, or *Poles de Recherche et d'Enseignement Supérieur* (PRES): OP and ENS are members of the PRES *Paris Sciences et Lettres* (PSL), UPMC is member of the PRES *Sorbonne Universités* and UCP of the PRES *Cergy Universities* and *Universités de Paris Grand Ouest* (UPGO).

Our lab, which receives staff positions, premises, funding, and is involved in teaching in all of these institutions, is thus multiply linked to the Research and Higher Education French system,. Our success rate in the recent governmental funding campaign *Investissements d'Avenir* testifies to the efficiency and fruitfulness of these links:

- capitalizing on our earlier experience at ENS with the CEMAG HPC mesocenter, we offered to our PSL partners to submit a joint *EquipEx* project, and later to join the GENCI initiative Equip@Meso, which resulted in the successful MesoPSL project, hosted by the Observatory, that is now starting operations.
- LERMA also joined 6 different *LabEx* projects, 4 have been successful in the first selection, and a 5th one in the second selection:
  - ICFP (*International Center for Fundamental Physics*) with the Physics Department at ENS,
  - ILP (*Institut Lagrange de Paris*, in Cosmology), led by the *Institut d'Astrophysique de Paris* (IAP) within UPMC,
  - MIChem (Multisccale Interaction in Chemistry, for the Astrochemistry segment of the project), led by the *Institut Parisien de Chimie Moléculaire* within UPMC,
  - Plas@Par (*Plasma in Paris*) led by LERMA (C. Stehlé) within UPMC,
  - and ESEP (*Exploration Spatiale des Environnements Planétaires*), led by LESIA at the Observatory (within PSL).

In addition 2 of our groups of Institutions (PRES) have been labelled during this *Investissements d'Avenir* campaign as IdEx (PSL and Sorbonne Universities).

It would be awkward not to rejoice of this impressive number of outstanding labels, but it is not demonstrated yet that these ambitious projects at the end will bring more resources than they consume. At the minimum they are clearly indicative of very healthy partnerships at the highest level in all the major fields of our activities.

7.2. Main resources

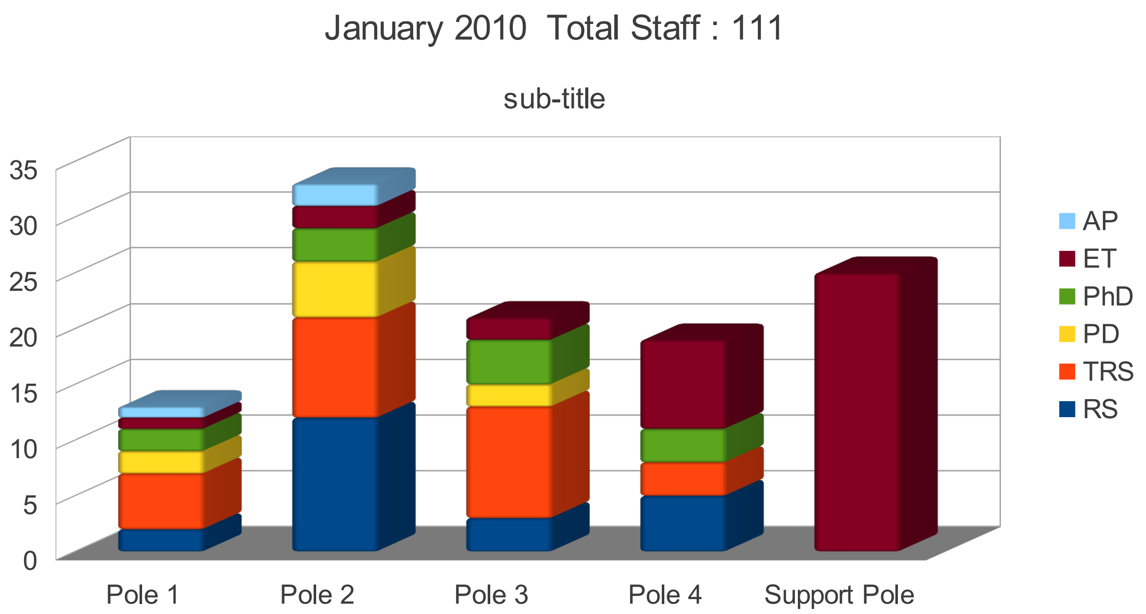
7.2.1. LERMA personnel and its evolution

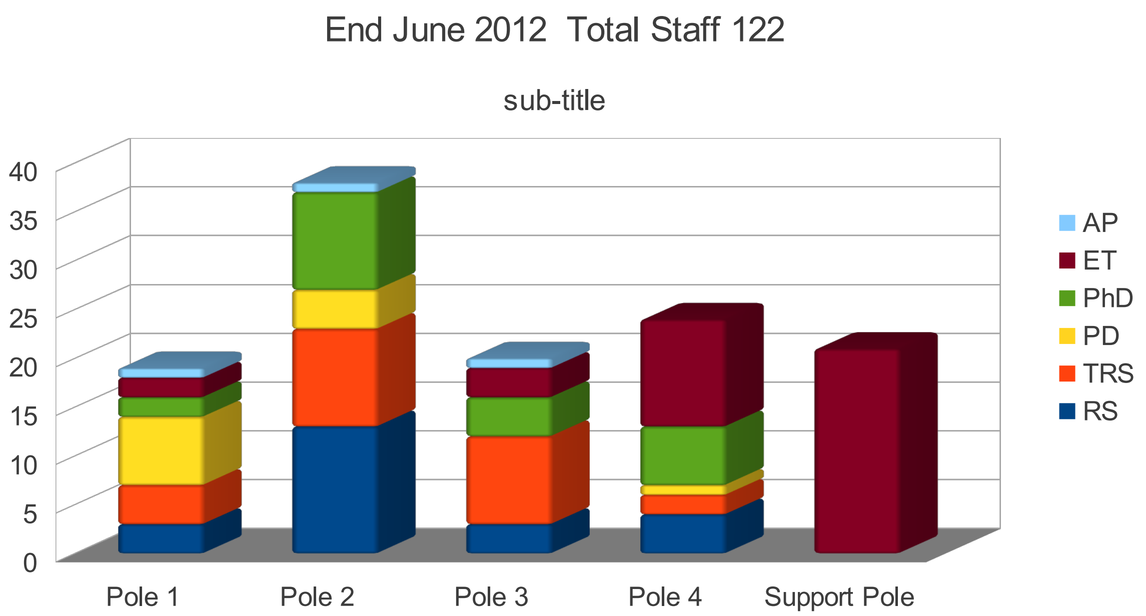
There were 122 staff, including 22 PhD student, 15 postdocs and 7 emeriti in LERMA at the end of June 2012, and 45 arrivals since January 2010, the starting date of the current Contract. Taking departures into account, this amounts to a net increase of 11 staff members over this 2.5 yr period. A graphical representation of the tabular data requested by AERES, and attached as appendix to this set of documents, are given below for both dates, showing, for each of the 5 Poles, the distribution of staff categories, as accounted in the AERES tables:

- RS: Research Staff (permanent positions)
- TRS: Teaching and Research Staff (permanent positions)
- PD: Post-doctoral researcher
- PhD: PhD student
- ET: Engineering and Technical staff (permanent and temporary positions)
- AP: *Autre Personnel*, in practice long term senior teaching/research staff under contract plus one isolated case of an apprentice.

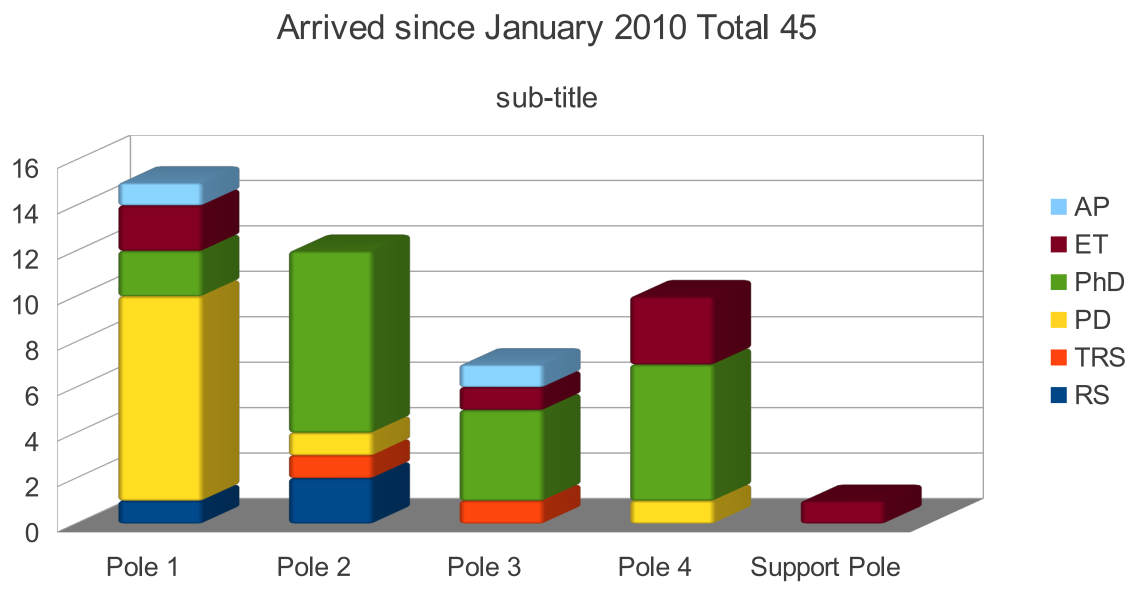
The increase in staff (+11) over this period is entirely due to the increase of the number of PhD students (+10) and of post-doc researchers (+3). The figure for PhD students is amplified by an exceptionally high number of thesis defences during the last quarter of 2009, and an abnormally low number of fresh student recruitments at the same time. The smaller increase of the number of post-docs on the opposite, is representative of the regular increase of post-doc financing through various grants.

In the meanwhile the number of permanent research positions has decreased by one unit, identically to the number of permanent engineer positions. These small numbers are unfortunately representative of a regular decrease of the number of permanent positions in Astronomy in France.





This last graph shows the same distribution of staff numbers, for the personnel arrived after January 1st, 2010, until the end of June 2012. It is not surprising that most of the entering flux is constituted of PhD students and post-docs. Pole 1 has had an exceptionally flux of new post-docs, in part due to F. Combes' ERC senior grant.



The overall impression from these numbers is satisfactory, given the relatively tense situation with respect to permanent positions over recent years in France. The picture becomes far more worrying when analysing the distribution of ages of the permanent research staff.

The histograms below show the distribution of ages for our permanent research staff, now excluding the 7 emeriti researchers, astronomers of professors (their number stayed almost constant aver the whole reporting period, with respectively 1, 3, 2 and 1 at the end of the period, for Poles 1, 2, 3 and 4 respectively).

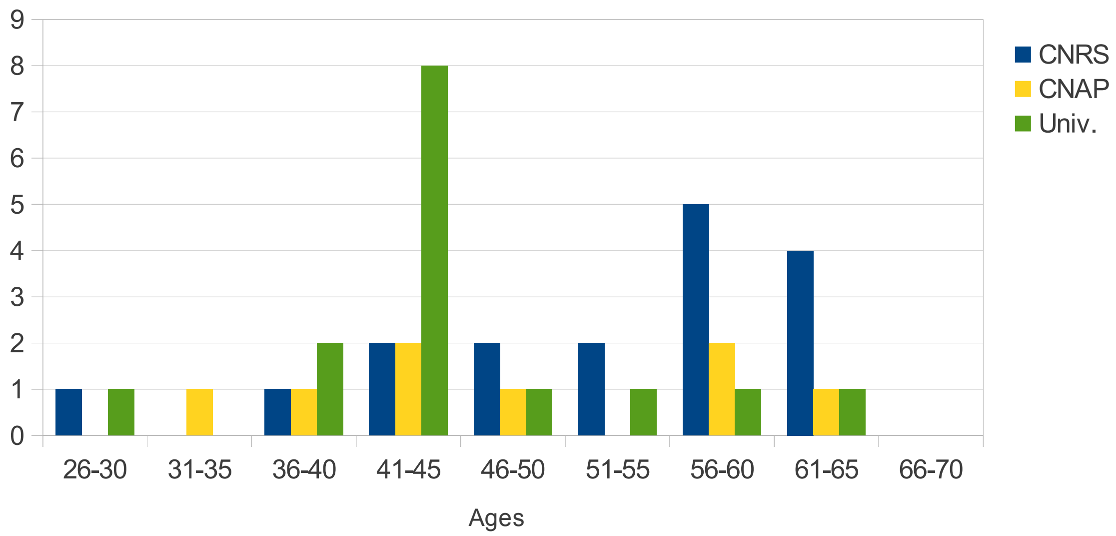


Fig. 7.2.1: Histogram of the ages of CNRS research staff (RS), astonomers and University professors (TRS) on June 30th 2012.

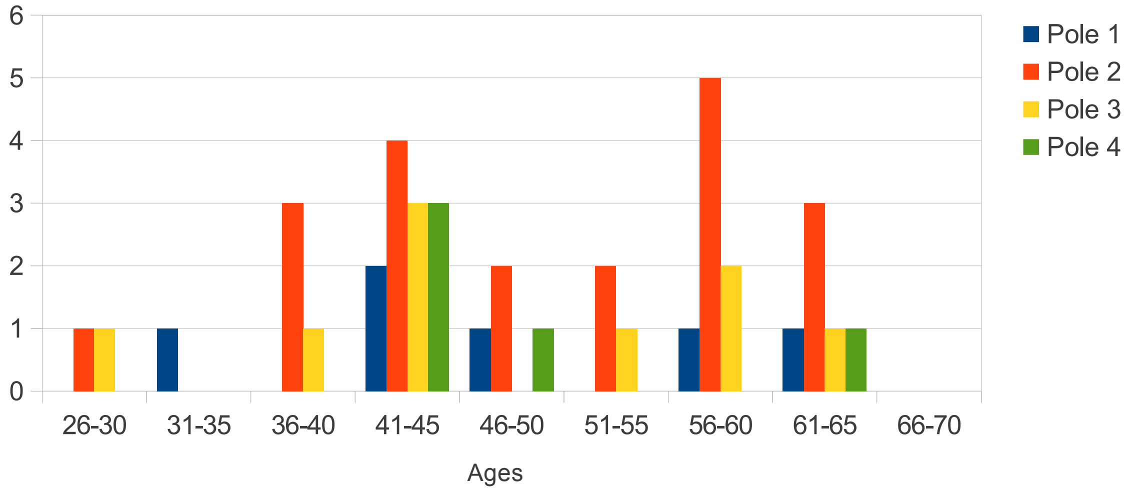


Fig. 7.2.2: Histogram per Thematic Pole of the ages of permanent research and teaching staff on June 30th, 2012.

The distribution is reasonably flat for CNAP astronomers; our University staff also shows a good renewal rate, but with a peak around 45 years that will require special care and efforts in their promotion to Full Professor satus (normally expected around that age). One the other hand there is a clear age imbalance for our full research CNRS personnel this is predominantly older than 55, and is not being renewed. This is not favourable for our future capacity for intensive experimental and observational research, which is difficult to reconcile with a heavy teaching agenda or *Tâches de service*. The most affected Poles under this respect are Pole 2, showing a strong peak of personnel over 55, and Pole 3 (Molecules in the Universe), where 2 of the only 3 CNRS researchers have been emeriti for many years now.

7.2.2. Financial resources and their evolution

A simple picture of the financial resources of LERMA is given in the financial tab of AERES tabulated forms attached to this report.. The consolidated yearly cost of LERMA is not known to date, as we are missing cost figures from the budgets of 3 institutions (OP, ENS and UCP) out of the 5 employing the LERMA personnel: it is however likelym fro; our ozn estimates, that the total charge for this personnel approaches 6 M€, while the funds received by the lab vary between 1.5 and 2 M€ per year, or 20 to 25% of the *consolidated cost* of LERMA which sums up to ~8 M€ per year, not including overhead costs (buildings,facilities, back office, ...) which likely nearly double this figure. Of the funds received (1.5 to 2 M€ yearly), about 2/3 are also salaries, implying the non surprising evidence that over 90% of the money directly spent for running LERMA is salaries.

It appears in the tabulated form data for 2010 and 2011, tab 3.1, where recurring funding and project funding from our stakeholders are added as single figures, that these represent roughly 25% of the direct funding of our activities. The other 75% come from short term contracts with ANR, EU, ERC, CNES, ESA, and other funding agencies. Details of these contracts are given in tab 5 of the same table.

7.2.3. LERMA premises and their evolution

With the exception of one researcher still located in the Ivry-sur-Seine temporary premises of UPMC, LERMA researchers are presently grouped in 4 geographical sites:

- The Paris Campus of *Observatoire de Paris* (OP), located in Denfert-Rochereau (14th arrondissement), hosting Pole 1, most of Pole 4, and part of Pole 2 (stellar feedback and dense cores).
- The physics lab of *École Normale Supérieure* (ENS) rue Lhomond (5th arrondissement) host the largest part of Pole 2 (ISM and MHD team).
- The Meudon Campus of OP hosts a smaller part of Pole 2 (Stellar plasmas) and Pole 3 (theoretical molecular calculations).
- The Neuville-sur-Oise campus of *Université de Cergy-Pontoise* (UCP) hosts the experimental team of Pole 3.

The office and lab space made available by the 4 institutions is adequate for our everyday needs. The new cross-site management structure of LERMA adopted since 2011 has been definitely helping in connecting people involved in related work at distant sites.

However the pressure on office space is extremely high in our main Denfert-Rochereau site (where LERMA management is located), and keeps rising with the influx of postdocs generated by

The most severe constraint is the absence of shared space in our main location, various funding grants (ERC, etc...). This is damageable not only for everyday work conditions, but also for the needed face to face exchanges with lab members from the other 3 sites, to whom we cannot offer temporary office space for joint meetinfs. A solution, including the creation of open work space is dramatically needed, especially with the heavy construction work starting now on the ENS laboratory premises, which is expected to last for about 2 years. The temporary relocation envisaged by ENS in Montrouge will degrade the dispersion even further.

Starting in 2014, the merging of LERMA with LPMAA will create a strong component of our Pole 3 activities on the Jussieu Campus of UPMC, located not far from ENS in the 5th arrondissement. Aftere 2015, new office space in Jussieu will also become available to host the Plasma group of Pole 2, as part of the Plas@Par LabEx.

The situation will then improve after 2015, but not the excessive pressure on the OP office space in Paris, where about additional 300 m² of versatile office space is dramatically needed.

7.3. In house facilities

7.3.1. Technical platforms and their evolution

LERMA is operating two shared experimental platforms (FORMOLISM in Cergy, a temperature-controlled ultra-high vacuum chamber to study chemico-physical processes in conditions close to those encountered in the Interstellar Medium, and the 10-m VUV spectrograph in Meudon). The lab is also much involved in running a shared clean room facility within the *Pôle Instrumental* de l'Observatoire, run by GEPI (a LERMA engineer, F. Boussaha is now in charge of the clean room management).

FORMOLISM is a ultra-vacuum experimental chamber equipped with various sets of sources and diagnostics, installed on the LERMA UCP premises, dedicated to the study of physical and chemical processes on low temperature surfaces. It recently evolved into an experimental platform opened to external teams experiments. Visitors to date have included: J.H. Fillion and X. Michaut from LPMAA/UPMC, G. Vidali from Syracuse U., NY, V. Pirronello and G. Manicò from Università di Catania, Sicily, and P. Parent and C. Laffon from LPCMR/UPMC). Long-term visiting postdocs have also been hosted.

The high resolution VUV spectrograph of Meudon allows 50-300 nm emission or absorption spectroscopy of e.g. H_2 isotopologues, lanthanides and multi-charged ions. Access is offered to the community through the ESA ground based facilities of the ESA Erasmus center: `http://www.esa.int/Our_Activities/Human_Spaceflight/Human_Spaceflight_Research/MEUDON_-_VUV_Observatory`. It is complementary to VUV apparatus such as the DESIRS beam line at SOLEIL synchrotron and the high precision XUV laser of the Dutch Laser Center (Amsterdam). The measured spectroscopic data are distributed via the MolAt database.

The clean room is a shared facility of the Observatory equipped with a set of instruments (vacuum evaporator, sputter coaters, plasma etcher, mask aligner, scanning electronic microscope, dicing saw, ...). This facility is used to develop optical (microlens networks, phase screens), and electronic components (SIS junctions, HEB devices etched on thin membranes, ...). The clean room is part of a local network of small clean rooms inside Paris (C*entrales de proximité en micro- et nanotechnologie*" which involves also ESPCI, ENS, P6 UPMC, and P7 UPD). Research teams from these different institutions get shared access to the various equipments of each partner through one to one agreements. These facilities are essential complements to the national technological facilities to which our engineers are granted access in Ile-de-France, respectively run by LPN in Marcoussis and IEF in Orsay.

7.3.2. Computational resources and their evolution

LERMA is very well equipped in computational resources.

At Tier 2 level, the CEMAG mesocenter, equipped with a 2 TFlops shared memory Altix computer has been run by LERMA Pole 2 at ENS since late 2006. This machine has been intensively exploited throughout the reporting period for MHD simulations. With the tight cooperation started among the PSL institutions in 2010, we proposed that ENS, OP, ENSCP and ESPCI join forces to propose an evolution of this facility, with the aid of the EquipEx program. This allowed the creation of a larger scale mesocenter run by PSL, called MesoPSL, which is now starting operations (PI J. Laskar of IMCCE).

The ERC funded Momentum project of Pole 1 (F. Combes) was able to purchase a large dedicated 10 TFlops cluster, hosted by OP within the mesocenter container.

LERMA is also running several additional team scale clusters and servers, which fulfill all needs of smaller scale computing, while the national and European Tier 0 and 1 facilities fulfill the other end, within present capabilities.

8. Summary and Conclusions

This last section presents a summary analysis of the LERMA achievements during the reporting period. Emphasis is put on the results obtained, in the light of the laboratory peculiarities. A short review is then given of whether and how the recommendations of the 2009 visiting committee have been implemented while these achievements were pursued.

8.1. Principal achievements

8.1.1. Forefront observing projects on large facilities

As illustrated in this report, several LERMA teams lead (or are engaged) in forefront international collaborations on large observing facilities. They have met significant successes during the past 5 years:

a) The Planck Surveyor

The performance of the HFI instrument on board Planck has gone beyond expectations: its lifetime has been twice that foreseen and the results, soon to be delivered to the community, will renew major fields of astrophysics for many years from cosmology to the galactic foregrounds. Planck's architect and HFI Instrument Scientist is our former director, and several Pole 2 researchers are now Planck scientist (1) , members of the core-team (2) or associate (1) and lead (and contribute) some of the scientific analysis on the galactic foregrounds, in particular on their polarized emission.

b) Herschel/HIFI

The receiver built by LERMA (Band 1) is the most frequently used HIFI channel. It has been perfectly performing so far.

- The GT-KP we are leading on the HIFI instrument has provided unique results on the first steps of molecule formation in space. An exceptional molecular richness of the diffuse interstellar medium is revealed that challenges traditional chemistry models.
- A breakthough has been made on high redshift galaxies, first with the PdB Large Program, identifying a gas fraction of 50% at z=1-2, then with the first detection of molecular gas at intermediate redshifts, and with Herschel observations of clusters, used as gravitational lenses to amplify remote galaxies up to z=5-6. These works tend to establish for the first time the cosmic molecular gas evolution.

c) ALMA

Researchers from LERMA have been involved in ALMA preparation and in observations since its Verification Phase. Their success rate in in the Early Science call is significant, with 18 proposals selected with at least one LERMA co-I, and 1 as PI, in a total 100 selected projects. The result of Cycle 1 selection is expected to be announced soon.

d) IRAM

Several large programs on the IRAM instruments are led by LERMA:

from the feeding of activity in galaxies of the local Universe and cooling flows in galaxy clusters to.

- First detections and mapping of molecular gas in cluster filaments and proven association of cold molecular gas with the cooling flows.
- Unique results on the dynamics

  of gas inflow feeding active galaxy nuclei obtained with the NUGA key project at IRAM interferometer.
- Identification of thin filaments showing strong velocity shear in diffuse molecular gas obtained with the single dish and the interferometer..
- Most sensitive measurements of physical conditions and magnetic field intensities in star forming regions.

8.1.2. Close coupling of complementary expertise

a) Observations vs numerical simulations

Another strength of LERMA is the close interaction between theoreticians, numericists and observers. This kind of interaction is now common in most laboratories. In LERMA, the numerical simulations performed are among the most competitive.

- High-resolution MHD simulations and analytical work elucidated the key interplay of turbulence, thermal instability and gravity in defining the structure of molecular clouds and the Initial Mass Function of stars, as well as the coupled impact of magnetic fields and radiative feedback on the formation of proto-planetary discs, binaries and massive stars.
- Significant breakthroughs have also been achieved in the approach of dissipative processes in turbulence and their coupling with (non-equilibrium) chemistry, that cannot be addressed by direct numerical simulations - with the goal of finding signposts of turbulent dissipation.
- One of the goals of these simulations is to predict molecular line intensities and line profiles, in order to interpret the observations.
- The Epoch of Reionization (EoR) has been fully simulated, taking into account the Lyman-alpha transfer, and testing the assumptions widely made in the literature. The HI-21cm absorption signal is predicted to have a larger contrast than initial estimates, leading to more easily detectable signals with the upcoming radio telescopes LOFAR and SKA.

Noteworthy new outputs of the interaction between observations and simulations are the production of databases of synthetic objects, interfaced with virtual observation capabilities.

- High resolution calculations of galaxy mergers (GalMer) provided cutting-edge results on radial migration, thick disk, and metallicity gradients in galaxies
- Adaptive mesh refinement MHD simulations of molecular clouds formation, dense core condensation and protostellar collapse(StarFormat) are now also publicly available.

These very extensive studies at complementary scales show the way to a much more direct future connection between detailed knowledge physics of interstellar medium and star formation, and the most active field of the formation and evolution of galaxies, up to large redshifts.

b) Laboratory Astrophysics vs modelling

Challenging laboratory experiments are developed to probe key physical processes ruling the evolution of the environments under study.

- Supersonic plasma jets and radiative shocks are studied using pulsed power electric facilities, high power lasers, and numerical simulations. These experiments provide new insights on the formation, structure, temporal evolution and instabilities of magnetised protostellar jets and accretion shocks.
- The FORMOLISM experimental set-up at Cergy-Pontoise has allowed the observation of the formation of hydroxylamine NH_2OH, a precursor molecule of amino-acids, on interstellar ice analogue surfaces.

c) Multidisciplinary Research

By its research themes, methods and projects, LERMA is a truly multidisciplinary laboratory. The joint project with LPMAA will reinforce this point, with the added contribution of physicists to the researches on the Earth and planetary atmospheres (Pole 4), and on molecular physics (Pole 3).

As research in astrophysics has developed in close connection with several branches of physics and mathematics, LERMA & LPMAA scientists have obtained innovative multidisciplinary and interdisciplinary results through their tight network of collaborations with neighbouring disciplines:

- In mathematics and theoretical physics both for the development of advanced numerical codes and for theoretical cosmology. These collaborations will be strengthened by the development of the meso-PSL infrastructure.
- In Earth sciences in the field of the dynamo process, in which the knowledge on the emergence of magnetic field in the Earth core is ported to the study of stellar dynamos. Advanced experiments on the dynamo and their modelling are developed by physicists at LPS-ENS who work in close collaboration with LERMA-LRA.
- In remote sensing, where we have demonstrated how our expertise in microwave radiometry can be used either for characterizing surfaces (e.g. wetlands) or for analysing critical parameters in the atmospheres (e.g. ice clouds or rain), a type of information that is used in global change models.
- In molecular physics, because molecular lines are among the best diagnostics in remote sensing of the Earth and planetary atmosphere as well as interstellar and circumstellar environments, from our immediate neighbourhood to extragalactic high redshift environments. The research involves forefront laboratory spectroscopy, and innovative theoretical developments in molecular dynamics.
- In low temperature surface physics with the deployment of laboratory astrophysics experiments focused on the surface processes controlling the formation of molecules, as well as their release into the gas phase.
- In micro and nano-physics for the development of advanced detectors, which use state

of the art devices jointly developed in-house and in national technology facilities.

- In plasma physics where high energy density facilities can now be used to mimic astrophysical shocks and jets in the lab.
- In information science for the deployment of innovative interfaces providing interoperable access to astrophysics, physics and chemistry databases (VAMDC, StarFormat, PDR), as well as novel concepts for the definition of large facility data models (ALMA, SKA).

A testimony of this tight network can be found in the key role of LERMA scientists in LabEx projects at interfaces with physics: ILP, ENS-ICFP, Plas@Par and MIChem, and in interdisciplinary programs funded by CNRS and INSU (PCMI, EPOV, GDRs Dynamo, microwave radiometry for the study of the atmosphere, semi- and supra-conductor sources and detectors at THz frequencies, GIS *Dispositifs Avancés Microondes Optoélectroniques et Nanométriques* DIAMON ...).

d) New synergies

Since 2007, new synergies have been created within LERMA and have already brought promising results.

- The *Plasma physics - Star formation* connection worked on jets in young stars and accretion columns, based on high energy density lab experiments, observations, and numerical simulations of both experiments and astrophysical environments.
- The *Earth atmosphere - Ground-based observation* connection has been renewed with the collaboration of our radio-interferometry experts, geophysicists specialized in the characterization of the Earth radiative properties at sub-millimetre wavelengths, and instrumentation specialists. This collaboration has led to their common project to design a new generation of radiometers that would be differentially sensitive to ultra-thin ice or liquid cloud formation, for that reason capable to improve both real-time correction and observation planning for ALMA, through a much more accurate modelling and monitoring of the atmosphere above the instrument.
- The *Observation - Experiment - Theory* connection in ISM physics is taking a new start with the growing capabilities, both in the lab and on computers, to investigate the kinetics of physical and chemical processes involving molecules on grain surfaces, which are key ingredients to the evolution of diffuse gas flows.
- The fast growth of computer capabilities opens hope to connect scales in very large simulations in more advanced ways than re-zooming or approximate subgrid modelling: star formation is an obvious domain where such fast progress is expected, but it is also conceivable e.g. to start feeding more realistic dissipative ISM physics into galaxy formation simulations.

The project for the next 5 year period amplifies these synergies with the merging planned with LPMAA and the LUTh ISM team, along with the development of our ambitious projects.

8.1.3. A high visibility laboratory well coupled to its environment

With more than 12000 citations counted from the ADS database to date to our refereed publications and many worldwide invitations of our team and project leaders during the reporting period, the research work done within LERMA has a fair level of international visibility. The multidisciplinary character of our work, though, and our pioneering approaches to some of the fundamental questions of the Universe, in cases at distance from mainstream astrophysics, do not facilitate its immediate adoption by the community at large. This can be viewed as an originality, and a weakness. But we believe that our fundamental duty is to work ahead of mainstream developments, not behind.

Another point of view is the nomination of LERMA members as experts in national and international organisations: several of us have served in various national committees and agencies. At the national level ANR: F. Combes is chair of the Astronomy panel, AERES: E. Falgarone was scientific delegate for Astronomy, INSU: M. Gerin was in charge of long wavelength astronomy, CNES ... At international level LERMA members are serving in: Telescope time allocation committees (member or chair of IRAM, Herschel, ALMA, ESO, ESA and NASA programme committees), Science advisory boards (chair of IRAM SAC, *Herschel* and *Planck* core Science teams, chair of HPC computing working group of AstroNet, GEWEX, ...), Grant selection panels (ERC) and Editorial boards (Astronomy & Astrophysics).

While our essential mission is to contribute to fundamental knowledge, and to its diffusion, our activities give us a few other connections to the social and economical environment, mostly through contracts with industry for the development of electronic components and systems, as well as for the development of data (commercial) exploitation tools in Earth remote sensing. A significant role has been played also in the definition of the instrumentation of the next generation of European operational meteorological satellites.

LERMA's strongest coupling to society though is teaching and pedagogic outreach. The large majority of our research staff has statutory teaching (heavy) duties. It is our choice that the Laboratory has deployed activities in 4 very different institutions of higher education, and it is our belief that our staff's involvement in a broad range of physics, maths and engineering education is a strong asset. But it is also our conviction that the statutory duties of University professors are by far too heavy, turning this strength into a threat for research.

8.2. Implementation of the 2009 recommendations

Excerpts from the previous AERES report are quoted in red.

8.2.1. Broad statements and recommendations of the research unit

Broadly, the scientific achievements of LERMA are outstanding. [...]

The international Committee was baffled by the complexity of the French system and in particular of the LERMA [...]. Given this complexity, the laboratory's achievements are great. Our first obvious recommendation is not to add any more complexity. The move towards a smaller number of teams is mandatory.

The choice to organise the laboratory as the combination of 4 large thematic poles supported by a shared administrative and technical pole obeys this recommendation. The creation of novel research structures by the Ministry in the meanwhile, especially the *laboratoires d'excellence* (LabEx), went in the wrong direction, but their conversion into transverse team projects made things easier. As a matter of fact the mapping of our 4 thematic poles onto the 4 LabEx into which we are involved is straightforward.

The population pyramid shows a fair balance between junior and senior scientists. Recruiting young full-time scientists and assistant-professors is mandatory, however, to maintain this balance in the future.

A laboratory has little handle on the recruiting of full time scientists : with only 4 newly hired CNRS full time researchers since 2007, the goal is barely achieved. On the other hand a slightly more satisfactory number, 6 young assistant-professors and assistant-astronomers have been hired during the period.

The committee also notices varying ratios of the number of PhD students to permanent scientists among the different groups. Each team has to think about their situation and possible strategies to increase the involvement of graduate students.

LERMA on average stayed above the national PhD statistics, with uneven ratios among groups, but no strategy really works in a context where increasing the number of PhD funding supports is not a priority at higher level.

Recommendation : As soon as feasible, the senior staff should agree on a global (2-page) strategic vision for the laboratory, based, for example, on the obvious medium-term possibilities with Herschel, Planck, etc. and on longer-term possibilities with Alma and other big forthcoming projects.

The laboratory project has been developed, obviously very much along these lines, but also based on an ambitious program of numerical simulations backing our theoretical developments, along with fundamental and experimental physics, data management and instrumentation objectives.

Recommendation : The "conseil de direction" must meet more often to synchronize the management and "the base" in both directions. One has to ensure that leaders of the active groups are invited to the « Conseil de Laboratoire » meetings on a basis of at least 5 to 6 times a year. The management has to truly delegate some work (with "chargés de mission").

Progress has been made in the first place with monthly meetings of the *Conseil de direction*. Team leaders are also regularly invited to the *Conseil de laboratoire*, which meets at least quarterly. Moreover the installation of the internal committees, with Council representatives in charge, very much went in the direction of a larger involvement of lab members into the decision making processes.

Recommendation : LERMA must further improve cross-team communications. Physical separation is certainly a problem but there are now new ways of staying in touch (teleconferences, video-conferences...), in addition to email, and these should definitely be investigated.

Our new thematic poles are multi-site, helping cross-team communications. Teleconferences are used, but our attempt to develop the use of video-conferences at large did not produce significant results, yet, as it was not considered as a high priority by lab members. The project still holds, though, to broadcast e.g. the weekly LERMA seminar. On the other hand Skype and internet forums are more and more used and help reducing physical distance.

Recommendation : Every other year, the laboratory could organize a two-day all-LERMA meeting in order to improve cross-boundary scientific communications and social interactions; the latter are not unimportant for scientific collaborations! This meeting could either be at a "neutral" site not part of LERMA, or else it could rotate among the different LERMA sites. Although the latter might have some logistical challenges, it would have the advantage of getting all LERMA staff familiar with all the sites that comprise the research entity.

The organisation of the *Journées du LERMA* in Sologne in March 2011 followed this recommendation, and proved a widely recognized success. It was followed by a full day all lab meeting in Meudon in early 2012, and by several meetings of the newly defined thematic poles, which took place in our various premises. It is a collective decision to further improve the situation along these lines, still trying to keep the total meeting rate within reason.

Recommendation : The laboratory needs to organize better the interactions between students and post- doctoral fellows in the different groups, based on a series of actions that can be set up in part by the young researchers themselves; a small budget should be allocated for it: regular dinner with seminar speakers, the ability to invite their own speakers, regular (e.g. 4 times a year) internal meetings to discuss their own research, ...

PhD students and post-doctoral fellows are now in charge of 2 regular informal meetings (journal-clubs) at lunch time. They also participate to the various events organised at lab level (*Journée des doctorants*, *Journée des nouveaux arrivants*, ...), which help socialization and quality of exchanges.

Recommendation : The committee wishes the Observatoire de Paris to have a “Livret d'accueil” and series of commitments to help post-docs (and PhD students) from abroad to go through the hurdles of French bureaucracy (« carte de séjour, aide au conjoint, Sécurité Sociale, logement, transport... »).

The effort has been conducted at the Observatory along with its member laboratories. The next phase in developing support to foreign students, post-docs and visitors will take place at PSL level, where such improvements are now programmed.

It will be critical for the success of any database/VO activity to advertise the product to its potential user base, and measure its impact (by hits on the web sites, down-loads of data, usage in publications). The GalMer site is impressive and could also be made into an appealing interactive tool for teaching/outreach.

Such improvements are also being done for our newly developed services, like StarFormat and VAMDC services. They are mandatory for services offered within the datacenters framework being currently enforced by INSU. LERMA is actively participating to this evolution, with the installation of the restructured data expertise center of *Observatoire de Paris.*

8.2.2. Specific appreciation team by team and/or project by project

a) Dynamics of astrophysical systems (DSA)

Recommendation : If the team at large wants to continue to be primarily end-users of code rather than producers (this is understandable and is in line with the philosophy of the Horizon project for example), it should strengthen collaborations that ensure that the people who will develop the code for next generation architectures are aware of their needs.

It was a partial misunderstanding which motivated the first of these recommendations, as 3 researchers of our teams involved in numerical simulations are actively participating to or leading high performance code development, e.g. .MHD solver of the RAMSES code, high performance radiative hydrodynamics code LICORICE and resistive MHD code GORDON. Our connections with the *Institut du Calcul et de la Simulation* at UPMC, and with the *Maison de la Simulation* in Saclay, along with the involvement of several colleagues in teaching numerical physics further fulfill this recommendation.

Recommendation : Grands Établissements should help by improving the middle-scale (méso-équipement) front-ends of these major computing efforts.

It was LERMA's initiative to develop the PSL HPC middle-scale facility (*mésocentre*), which proved successful. F. Combes ERC funding allowed her to significantly boost the available front-end equipments. A similar *mésocentre* project at UPMC complements the range of accessible machines, with emphasis on visualisation problems.

b) Instrumentation and teledetection (IT)

Recommendation : The work program must be controlled and mutually agreed between the laboratory management, GEMO and a supervising committee that must be set up by the management.

The necessity of planning activities with instrumentation projects as targets has been well understood, and close collaborative work is ongoing between lab management and the THz instrumentation group. The effort is focused on 3 developments in parallel, which take benefit of the main technological achievements of the group: one for astronomy, with the small scale preliminary CIDRE program currently under feasibility study with CNES, one for planetology with a participation to the sub-millimetre wave instrument SWI for the JUICE mission (proposal to ESA), and one for Earth remote sensing, with ongoing studies for ice cloud dedicated novel sub-millimetre channels on board future missions.

c) Atomic and Molecular Physics+Experiments (PAME)

Recommendation : the (Meudon) group must find more focus. Plasma physics and molecular kinetics are among the most important paths to encourage for the future.

As a matter of fact, the group split into one Plasma physics group, now part of Pole 2, and one Theoretical molecular physics group, now part of Pole 3. Both groups are entrained by the new dynamics in place in Physics at UPMC, with one Plasma physics LabEx on one hand, and a Molecular Physics LabEx, on the other hand.

Recommendation : All the senior scientists should take part in the decisions within this (Cergy) group.

This recommendation followed a highly painful crisis in Cergy. The situation is now back to (almost) normal.

Recommendation : In a similar manner as for GEMO, it is recommended that the management and governing bodies of the LERMA be involved in a long-term plan to ensure sustainability of the team within LERMA. Laser plasma physics experiments constitute a possible federative theme for the whole PAME team.

This recommendation has been taken earnestly, and the management has very strongly encouraged the groups to invest into the new UPMC projects. As a matter of fact our plasma physics group took the lead of the plasma physics project of the University, and LPMAA decided to join forces with LERMA, in order to build a major molecular physics component within the University.

Recommendation : Increase collaboration between PAME and the astrophysics teams at LERMA. The connection to astrophysics seems too loose. Convergence should also be sought with LUTH theoretical approach of the hydrogen formation on grains. A bi-monthly meeting would bring synergies between these teams.

Again the wishful thinking of the committee was in a sense filled beyond hopes, as the LUTH team as a whole decided to join forces with LERMA on our common approaches to ISM physics. The new orientation towards kinetics on grain surfaces will reinforce the synergies.

d) Gravitation, Relativity and Primordial Universe (GRUP)

Recommendation : Having this group remaining in LERMA in its present form is not a viable solution. A new arrangement must be found by the laboratory management with discussions with the GRUP staff and other laboratories whose main topics are much closer to the GRUP activities, in order to find a more relevant framework for active staff members.

The most active member joined the plasma physics group, and another moved to Nice. The rest of the group, as such, vanished, merging into the Galaxies and Cosmology Pole. Connections have been established with the General Relativity group of LUTh, but it was impossible to go beyond informal contacts. There are no successors to the GR activities in LERMA, and research on the Primordial Universe is now taken over by younger scientists with different approaches.

e) Miscellaneous

Remarks on computer support, website homogenisation, security and safety issues were listed: while security and safety are well taken care of, local computer support and website homogenisation still need further efforts.